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Using 4 D CAD and Immersive Virtual Environments to Improve Construction Planning

A Thesis in

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By

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ABSTRACT

The ability to visualize a project via a 4D CAD model (graphical illustration of the construction of a 3D building design with time as the 4th dimension) provides an opportunity to improve an existing construction schedule by identifying inconsistencies and out-of-sequence activities; reducing missing activities; and improving the ability to communicate construction plan information. Over the past ten years, several researchers and industry practitioners identified many such benefits by creating 4D CAD models from a 3D CAD model and construction schedule. In most applications, a personal computer based monitor has been used to view and analyze these models.

This study is an investigation of the potential benefits and challenges of using an immersive, 3D virtual environment to view 4D models. This allows a person to be immersed within the 4D model on a 1-to-1 scale. This study also investigated the use of an Immersive Virtual Environment (IVE) for improving the project planning process by generating and reviewing construction plans in a virtual environment. For this purpose, a group of construction professionals interactively reviewed and generated a construction plan in the immersive virtual environment.

By reviewing their schedules in the IVE, the construction professionals were able to readily identify design, constructability, sequencing, and interdisciplinary interfacing issues. By interactively generating the construction schedule in the virtual environment, the construction professionals developed a plan that resulted in a 28% savings to their original schedule.

A process model that identifies the steps necessary to generate a schedule in an IVE has been developed. This process model may be used to direct future application development for construction planning tools in immersive virtual environments. The technology used, methods applied and results achieved are discussed in detail in this report.

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CHAPTER ONE

INTRODUCTION

The AEC industry has been witnessing a steady increase in the use of desktop 3D and 4D CAD (graphical illustration of 3D models with time as the 4th dimension) tools for project planning.   The idea to link 3D CAD models to construction schedules was conceived in 1986-87 when Bechtel (an international, engineering and construction company) collaborated with Hitachi Ltd., to develop 4D Planner software (Cleveland 1989; Simons et al. 1988). A 4D model involves linking the CPM schedule to the 3D CAD model to visualize the construction schedule; actually showing which pieces of the project will be constructed in what sequence (Kumi and Retik 1997)

4D models display the progression of construction overtime, sometimes dramatically improving the quality of construction plans and schedules (Rischmoller et al. 2001). Several documented studies have shown 4D CAD as a good visualization and schedule review tool. More project stakeholders can understand a construction schedule more quickly and completely with 4D visualization than with the traditional construction management tools (Koo and Fischer 2000; Songers et al. 2001).

Almost all previous 4D applications used personal computer based monitors to view these models. In the case of large and complex facilities, use of these tools for schedule review may be time consuming as 3D objects are visualized on a 2D desktop screen. Advancements in computer visualization have lead to the development of virtual environments that allow immersive, 1 to 1 scale visualization. By using immersive virtual environments, 3D objects may be visualized in 3D environments and at full-scale. This might lead to a more detailed identification of design/ schedule related issues. Immersive virtual environments may help construction professionals interactively plan the construction processes.

This research is focused on studying the feasibility of using Immersive Virtual Environments (IVE) for improving construction planning. For this purpose, a case study project was selected and a group of construction professionals were allowed to interactively review and generate construction plans by immersion in a virtual environment.

This chapter first discusses the current project planning process in the construction industry. Then, a description of the research study, including the relevance, objectives, research approach, research group, research steps and the limitations is provided. Finally, the reader's guide provides a discussion of the contents of this document.

1.1   CURRENT PROJECT PLANNING PROCESS

The construction plan development and review process in the construction industry typically involves the use of paper-based drawings and the expertise of experienced construction planners. These planning and review processes are performed by mentally visualizing spaces. The visualizing capability of some of these planners is commendable. However, different people have varying abilities to accurately visualize construction projects. This results in the development of construction plans that lack schedule reliability and diminishes schedule confidence of the project stakeholders.

Advancements in computer visualization technology have provided construction professionals with desktop 3D CAD and 4D CAD tools that help construction planners visualize and review schedules. There are currently several 4D CAD computer applications that are readily available. The applications include Navigator^{TM} by Bentley Systems, VirtualSTEP, 4D Producer by Common Points^{TM}, fourDviz by Balfour Technologies, and SmartPlant$^{®}$ Review by Intergraph. These tools allow planners to take a 3D CAD model, separate the model into logical work packages, and then link the work packages to a construction schedule. The planner can view and navigate the 4D CAD model, and identify problem areas with the construction schedule or the project design.

While the use this technology is still not wide spread throughout the construction industry, more companies are aware of the benefits of the technology.

Within the last 10 years, advancements in graphical display technology have greatly improved the visual interface between computers and human. Through the use of virtual reality and immersive projection display technology, planners can now interact, one on one, with very realistic views of a project design. Virtual reality in construction has been used to develop and visualize project designs (Haymaker and Fischer 2001); visualize construction operations (Kamat and Martinez 2001); and communicate and train project teams (Haymaker and Fischer 2001). The current use of immersive virtual environments for construction has been limited to research.

1.2. DESCRIPTION OF RESEARCH STUDY

This section provides a summary description of the research study, which includes objectives, relevance, approach, methodology, research results, and scope limitations. A more detailed description of the research methodology is contained in Chapter Two.

1.2.1. OBJECTIVES

The objectives of this research are as follows:

1. To *identify the potential benefits of using Immersive Virtual Environments (IVE) for construction project planning.* Previous documented studies related to this research have focused on (1) tools that help project planners perform schedule reviews, and (2) use of IVE technology for visualization by other industries. These studies did not concentrate on evaluating the benefits of using IVE's for construction planning. Therefore, it was critical to identify the potential benefits and challenges of using IVE for performing construction planning.

2. To *develop a process model for generating construction plans using the IVE.* This research provides a model to assist the development of construction plans in virtual

environments. This process model is proposed to guide construction project planning in immersive virtual environments and to help researchers and programmers develop more robust construction planning methods and IVE display systems.

1.2.2 RELEVANCE

This study benefits two different groups. The first is the construction planners in the AEC industry. These planners can benefit by using the immersive virtual environment technology for project planning. The second beneficiary is the research community. This research provides a process for generating construction plans in immersive virtual environments. This process gives a basis for researchers to further investigate the use of an immersive virtual environment for project planning. The future researchers may also use this process model as a guideline for developing more robust virtual reality systems that enhance the construction planning process.

1.2.3 RESEARCH APPROACH

Since a limited amount of research has been performed on the use of immersive virtual environments (IVE) for construction project planning, an exploratory investigation of immersive virtual environments was a critical first step. From this exploratory investigation, a model was developed to assist construction planners and future researchers in developing construction plans in immersive virtual environments (IVE). To develop this model, the following questions were addressed:

- What resources are necessary to develop a construction plan in the IVE?
- What steps are to be performed to achieve construction plan generation using the IVE?
- What features will make the IVE a robust, yet easy-to-use project planning tool?

1.2.4. RESEARCH GROUP

The research defined within this report is one part of a larger study on the value of immersive virtual environments for reducing nuclear plant construction cost (Baratta et al. 2002). This research study is being performed by a research group that includes: Westinghouse Electric Company (a global nuclear engineering and service company); Burns & Roe Enterprises (a comprehensive engineering, construction, operations and maintenance company); Panlyon Technologies LLC (a nuclear safety consultant); and The Pennsylvania State University's Applied Research Laboratory, Department of Mechanical and Nuclear Engineering and Department of Architectural Engineering. The research group held periodic meetings at The Pennsylvania State University to perform design and constructability reviews for the case study project and to test the functionality of the SEA-Lab Immersive Projection Display (IPD). The SEA-Lab Immersive Projection Display is a display device that uses virtual reality technology (refer to Chapter 4).

1.2.5. RESEARCH STEPS

This study used qualitative, social science research techniques performed through a case study and questionnaire surveys. The following research steps were performed to accomplish the objectives of the study.

1. *Literature Review*: A literature review that includes information on the use of 3D/4D modeling and the use of visualization in the construction industry was performed. A summary of the literature is included in Chapter 3.

2. *Obtain Case Study Information*: The research case study focused on a portion of the AP 1000 nuclear power plant. The case study information was obtained from the designer (Westinghouse) in the form of 3D models developed using Intergraph[TM] PDS. The 3D models included a 9-step installation sequence, 7

assemblies, 5 sets of makeup pieces (each containing 5 pieces), and a total of 40 model objects. A detailed description of the case study design is presented in Chapter 4. The research group placed these models into the virtual environment for design and constructability reviews.

3. *Develop Experiments:* Experiments were performed to test the use of immersive virtual environment for generating construction plans. The researcher designed two experiments. The functionality of the SEA-Lab IPD was enhanced by developing additional features that enabled the performance of these experiments. The functionality of the SEA-Lab IPD and the additional features developed are provided in Chapter 4.

4. *Perform Experiment I*: Exploratory experiments were performed to evaluate the feasibility of performing construction planning using an immersive virtual environment. During the first experiment, the participants were asked to use the new features of the SEA-Lab IPD to generate an installation sequence for the case study project. The experimental procedure and summary of results are provided in Chapter 5.

5. *Perform Experiment II*: The participants of the second experiment were given 3D isometric paper drawings of the case study project and were asked to develop a paper-based schedule. The participants then performed a review of these schedules in the immersive virtual environment to study design and constructability issues. The case study project was also used to evaluate the value-added by the immersive virtual environment in terms of improved schedule reliability and schedule confidence. The experimental procedure and summary of results are provided in Chapter 5.

6. *Analysis of the Results*: The schedules generated by the participants of the second experiments were converted to Primavera P3® schedule files. The researcher then developed five 4D desktop models of the installation sequence generated by the

participants of the experiments by linking the 3D models of the case study project to the Primavera P3® schedule files. These 4D models were used to evaluate the feasibility of using immersive virtual environments for project planning by comparing the original schedules to the reviewed schedules and the schedule generated in the IVE. A content analysis was performed on the surveys completed by each participant. A summary of the content analysis along with the quantitative data from the surveys was used to evaluate the value-added in terms of improved schedule reliability and schedule confidence.

7. *Develop process model*: A process model to assist future researchers and construction professionals develop construction plans in immersive virtual environments was developed. This model consists of four sub processes: (1) develop 3D facility model, (2) organize model by construction assemblies, (3) develop 4D construction plan, (4) review and communicate 4D construction plan. The input, controls, mechanisms, and output of each sub process are explained in detail in Chapter 6.

1.3. SCOPE LIMITATIONS

This research aims to analyze the feasibility of the use of immersive virtual environments for construction project planning. This analysis was performed by investigating the installation sequence of the case study project. This project was selected since it contains complex mechanical equipment and piping associated with 10 different fluid systems. Although the findings of this study are believed to encompass different project types, it is important to realize that these were obtained through a detailed analysis of a single case study project.

1.4. READER'S GUIDE

There are three main sections to this thesis. The first section includes Chapter One to Four. These chapters describe the study and previous studies related to the use of the

IVE for project planning. Chapter One provided an overview of this research. Chapter Two provides justification for the exploratory research methods used for this study. Chapter Three provides a review of existing literature for visualization in construction and 4D CAD. Chapter Four provides an overview of the case study project and the SEA-Lab IPD facility used for this study.

Section Two, which includes Chapter Five and Six, describes different research results. These chapters are developed to directly address the objectives of the study. Chapter Five contains a description of the experimental procedures and the results of the experiments. Chapter Six contains the process model that was developed during the research for generating construction plans in immersive virtual environments. The final section includes Chapter Seven, which concludes the document with a summary of the results, an outline for future research, and a discussion of the contributions of this research.

CHAPTER TWO

RESEARCH METHODOLOGY

This chapter describes the research methodology used throughout this study. The research techniques are discussed first to provide the reader with a detailed explanation and justification for their selection. These research methods are not presented in a chronological order.

2.1.   INTRODUCTION

Exploratory research methods were extensively used throughout this research. The purpose as defined by Marshall and Rossman (1989, p. 78) for exploratory research is to: (1) investigate poorly understood phenomena, (2) identify/discover important variables, and (3) generate hypotheses for further research. The purpose of this study in using immersive virtual environments for construction project planning fits into these categories since studies describing the use of immersive virtual environments for project planning currently do not exist. The research methods concentrated on investigating the use of 4D implemented in virtual environments. An explanation of the selected research methods is provided below.

2.2.   RESEARCH METHODS

Several research methods were used in this research. These methods include a case study research method, uncontrolled exploratory experiment method, survey techniques, and content analysis. These methods are described in detail in the following sections.

2.2.1. CASE STUDY RESEARCH METHOD

A case study research method is used to examine contemporary real-life situations (Yin 1984). By applying the research ideas or techniques to these case studies, one can

examine their validity in real-life. The case study research method is defined as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used" (Yin 1984, p. 23). This research method is a very useful tool for exploratory research as it provides an opportunity to select and examine a particular case.

According to Yin (1984), the four tests commonly used to establish the quality of a case study are:

- Construct Validity: establishing correct operational measures for the concepts being studied.
- Internal Validity (for explanatory or casual studies only, not for descriptive or exploratory studies): establishing a casual relationship, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships.
- External Validity: establishing the domain to which the study's finding can be generalized.
- Reliability: demonstrating that the operations of the study - such as the data collection procedures can be repeated with the same results.

The case study project used for this research address 'if' 4D models immersed in virtual environments can be used to improve construction planning. The case study project for this research is the development of a construction plan and constructability analysis for the construction of the equipment and piping in a complex room in a new nuclear power plant (The Westinghouse AP1000). A detailed description of this case study project is provided in Chapter 4.

The four design tests performed to establish the quality of the case under study and the tactics for dealing with the relevant tests (Yin 1984) are discussed in detail.

2.2.1.1. TEST 1 – CONSTRUCT VALIDITY

The case study tactics suggested by Yin (1984) to establish construct validity are as follows:

1. **USE MULTIPLE SOURCES OF EVIDENCE**: The researcher used uncontrolled exploratory experiments, direct observation, and surveys as the sources of collecting evidence. Two experiments were conducted to test the implementation of 4D models in immersive virtual environments. The researcher participated in these experiments as a passive observer. The discussions of the participants were recorded and documented. The participants completed surveys after each experiment and content analysis was performed to analyze these surveys. The results of the content analysis are documented in Appendix A.

2. **ESTABLISH CHAIN OF EVIDENCE**: The research report has sufficient citations to the relevant portions of the case study. The chain of evidence is also established by the case study data. The data for this study is recorded in the form of surveys completed by the participants, content analysis maps of the surveys, and the 4D models of the schedules developed by the participants. The reader of this research can verify this chain of evidence to establish construct validity.

3. **REVIEW/DRAFT CASE STUDY REPORT**: A team of experts from Westinghouse Electric Co., Burns & Roe, and Panlyon technologies reviewed the case study. An experimental procedure that incorporated the comments and suggestions of the experts was designed to investigate the use of 4D CAD implemented in immersive virtual environments.

2.2.1.2. TEST 2 – INTERNAL VALIDITY

According to Yin (1984), this test is valid for explanatory or casual studies and not for descriptive or exploratory studies. Hence, this test is not relevant to this research.

2.2.1.3. TEST 3 – EXTERNAL VALIDITY

The case-study tactic for establishing the external validity (Yin 1984) is the use of replication. This test deals with the problem of knowing whether a study's findings are generalized beyond the immediate case study (Yin 1984). The process model generated by the researcher is highly replicable. However, further study is warranted to validate generalizations of the research beyond the immediate case study.

2.2.1.4. TEST 4 - RELIABILITY

The goal of reliability is to minimize the errors and biases in a study (Yin 1984). If the procedures conducted by an earlier investigator are exactly followed by a later investigator, the later investigator should arrive at the same findings and conclusions. A prerequisite for this is to document the procedures followed.

The experimental procedures, survey questions, the analyses performed on the survey results, and all other procedures used in this research are documented in appropriate appendices for future reference.

2.2.2 UNCONTROLLED EXPLORATORY EXPERIMENT

An experiment, as compared to other methods of gaining knowledge, is a planned, researcher-induced alteration of situations. A controlled experiment is one in which the investigator intentionally manipulates one or more independent variables. However, in the early stages of a study, it is often most efficient to proceed without any controls at all. An experiment is not valueless because it is uncontrolled (Simon and Burstein 1985). An uncontrolled exploratory experiment provides the researcher an opportunity to decide

what variables might be most important. According to Simon and Burstein (1985), it is important that the exploratory uncontrolled knowledge-gathering experiment be offered "not as a proof, but as the exploration that it really is".

The researcher performed two exploratory experiments to analyze the use of 4D CAD immersed in virtual environments as a tool for construction planning. The experiments are explained in Sections 2.3.4 and 2.3.5. The experimental procedures and a summary of the results are provided in Chapter 5.

2.2.2.1. EXPERIMENT PARTICIPANTS

The participants in the initial case study experiment were four graduate students in the Department of Architectural Engineering at The Pennsylvania State University. These students had a combined construction experience of 8 years.

The participants in the second case study experiment were construction superintendents from Burns & Roe Enterprises. Burns & Roe Enterprises is an engineering, construction and maintenance company. Their services include engineering and construction of nuclear power plants. These professionals were selected by the research group on the basis of their expertise and experience in nuclear power plant design, planning, and construction. The average construction experience of a team member was 26 years.

2.2.2.2. QUESTIONNAIRE SURVEY

Questionnaire surveys are classified by whether they are performed by mail, telephone, or personal interviewing (Simon and Burstein 1985). The mail survey is generally the cheapest. The mail survey gives the respondents time to "think things over" and also avoids interview bias. The telephone survey can be an efficient survey method. The telephone survey is a quicker way of obtaining information but the interview period may be short. The personal interview method provides the

researcher an opportunity to control the sample of respondents but has higher risks of interviewer bias. There are multiple ways of collecting data other than by mail, by telephone or by personal interviews.

In this research, the participants were supplied with questionnaires after the experiments and were instructed to complete the questionnaire. This allowed the researcher to not only make sure that all the participants completed the questionnaire, but also to avoid any interview bias in the process. Proper measures were taken to avoid any bias during the questionnaire construction. The methods used to avoid bias are explained in the next section. The survey questions are included in Appendix B.

2.2.2.3. BIAS

Bias is "a tendency to observe the phenomenon in a manner that differs from the 'true' observation in some consistent fashion" (Simon and Burstein 1985). Two methods may be used to reduce the bias imposed by the researcher. One method is to develop questions that do not necessitate the candidate to answer within the researcher's framework. The other method is to avoid bias during the interpretation Content analysis was performed for each survey to systematically analyze the interview data. The content analysis method is described in the next section.

2.2.2.4. CONTENT ANALYSIS

Content analysis is a widely accepted technique to systematically analyze data obtained through qualitative research (Holsti 1969). Content analysis is defined as 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 (Holsti 1969). A content analysis was developed for the surveys conducted. A summary of the key topics identified in the interview content analyses along with content analysis maps for each survey response is included in Appendix A.

2.3. SUMMARY

This chapter described the research methods used for this research. Due to the limited investigations of the application of virtual reality and visualization tools to construction planning, exploratory research methods were used. The next chapter provides a summary of the published research in visualization and 4D CAD applied to construction.

CHAPTER THREE

LITERATURE REVIEW

This chapter presents the previous research related to the topics that influence the application of 4D CAD and immersive virtual environment display systems for construction planning. Previous studies relevant to this research have been studied carefully and are explained in detail in this chapter. The background research is described in two areas of previous research: (1) Visualization in construction and (2) 4D CAD/ Graphical construction simulation.

3.1   VISUALIZATION IN CONSTRUCTION

The Center for the Management of Information (CMI) at the University of Arizona defines visualization as "transformation and analysis to aid in the formation of a mental picture of symbolic data. Such a picture is simple, persistent, and complete" (Kasik et al. 2002) Visualization techniques are being used in a variety of industries like automobile, appliances and aerospace for various purposes including analysis and testing (Kasik et al. 2002).

In construction, visualization presents the project team with an opportunity to design and evaluate construction projects and to visually communicate the project information. By visualizing a project electronically, potential problems in the design and schedule can be identified prior to the actual construction (McKinney et al. 1998). A project can be visualized in 2D, 3D or 3D CAD linked to the construction schedule, also known as 4D CAD (Koo et al. 2000). Research in the area of 4D CAD visualization is explained in detail in Section 3.2.

A wide variety of 2D and 3D visualization tools and techniques are used to graphically illustrate construction processes and products. For example, the research by Liston and Fischer (2000) studies two visualization techniques – (1) Highlight and (2) Overlay techniques - to review a project schedule. Highlighting is defined as the process of

emphasizing, through visual annotation, related sets of project information within a view and across multiple views. The process of highlighting has two parts: the interaction that defines the task/context and the visualization of the specific project content.

For example, highlighting by selection of objects (e.g., building components, construction activity, contract item, cost item, etc.) would result in highlighting all related items. Other types of highlighting actions investigated were: selection by spatial regions (e.g., components that occupy a space), and temporal regions (e.g., activities that occur during a particular time frame).

Overlaying is defined as the process of placing one set of information onto another set of information that results in one 'merged' view. The overlaying actions investigated were to visually compare and relate project information from: - document to document of the same type (e.g., placing a Gantt chart onto another Gantt chart); object to document of the same type (e.g., placing activities onto a Gantt chart); document to document of different type (e.g., placing a 3D model onto a Gantt chart); and object to document of different type (e.g., placing a building component onto a Gantt chart).

Songer and Diekmann (2001) evaluated the benefits of using 3D visualization and walk-thru technologies over 2D visualization for construction schedule creation. A section of a piping rack for a co-generation power plant was used as a case study. The original 2D drawings of the pipe rack were converted into 2D AutoCAD files. A 3D CAD model for the pipe rack was created using 2D AutoCAD files. These 3D CAD files were then used to create a walk-thru model.

Construction schedules were developed from 2D, 3D, and walk-thru representations for the case study project by 50 participants of varying experience. The participants were divided into three groups. Each group was instructed to create a list of activities and logic diagram using one of the three representations (2D, 3D or walk-thru). The participants were requested to perform the following specific tasks:

1. Extract construction activities for the physical elements of the facility from the plans, and

2. Develop an activity sequence based on the subject's own interpretation of the project.

The results of the experiment show that:

1. The schedules developed using 2D had more missing activities than schedules developed using 3D or CAD based walk-thru environment.

2. The schedules developed using 2D had more missing relationships than schedules developed using 3D or CAD based walk-thru environment.

3. The schedules developed using 2D had more logic errors than those using 3D.

4. Additionally, the participants using the walk-thru model created a "flawless" logic network.

This research illustrates the practical advantages of 3D CAD and the walk-thru function for creating a construction schedule.

Other techniques include using virtual reality technology for visualization of construction projects. Kamat and Martinez (2001) studied the use of visualizing simulated construction operations in 3D. The researchers developed a generic 3D visualization system known as the Dynamic Construction Visualizer (DCV). This system allows simulation model developers to visualize modeled operations with chronological and spatial accuracy in 3D virtual space.

The researchers used OpenGL Optimizer (Silicon Graphics 1998a) and Cosmo 3D (Silicon Graphics 1998b). These scripting languages are more advanced forms of Virtual Reality Modeling Language (VRML). These languages allow managing complex and unpredictable dynamic events. The design objective for developing the DCV was its independence from any particular CAD modeling program. However, depicting construction operations requires 3D models of the simulated entities. The researchers realized that developing a built-in CAD modeling capability within the DCV would severely restrict the quality of 3D models. Thus, the DCV was developed in such a way

that the geometry files from any 3D modeling program (e.g., AutoCAD, Microstation, 3D studio) can be easily imported into the DCV via the VRML format. According to the researchers, the ability to import VRML files makes the DCV independent of any CAD modeling software.

The researchers used a case study of earthwork excavations as an example for demonstrating this new technology. The researchers were able to visualize the entire excavation process (trucks waiting to be loaded, excavator digging the earth and loading trucks, and the trucks dumping the load and returning to the loading site) in 3D. According to the researchers, the purpose of using simulation to design construction operations is to obtain insight into alternate designs and this helps the planner make the most advantageous decisions. This research shows that virtual reality technology can be used to help planners make better decisions by interacting with the virtual environment.

3.1.1 VIRTUAL REALITY DISPLAY TECHNOLOGY AND APPLICATION

Advances in the computing industry have resulted in better software, more available storage, and increasing computing power (Kasik et al. 2002). As a result, the graphical interface between computers and humans has greatly improved. Along with this trend, a migration from static visualization towards utilizing depth sight in the visualization process is taking place (Reeth et al. 1995). Research in the area of StereoMotion: a visualization system realizing true depth sight using stereoscopic display technology has allowed the use of virtual reality visualization (Reeth et al. 1995). Howard Rheingold (1991) defined virtual reality as 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."

Virtual reality (VR) can be classified into two broad areas: 1) Desktop VR and 2) Immersive VR (Bouchlaghern et al. 1996). In immersive VR, a large format or head mounted display is used to immerse the viewer within the virtual space. A variety of such graphical displays that allow stereoscopic visualization have been developed.

Kasik (2002) identified 14 different display type categories. This research is focused on the use of volumetric display technology, e.g., CAVE^{TM}.

CAVE^{TM} (CAVE Automatic Virtual Environment) was designed in early 1991 and was implemented and demonstrated in late 1991 (Cruz-Neira et al. 1993). CAVE^{TM} was developed to help computational scientists to interactively present their research in a one-to-many format on high-end workstations. The CAVE^{TM} that was exhibited by the researchers was a 10'×10'×10' theater made up of three rear-projection screens for walls and a down-projection screen for the floor. These projectors throw full-color workstation fields (stereo images). A user's head and hand are tracked with electromagnetic sensors. Stereographics' LCD stereo shutter glasses are used to separate the alternate fields going to the eyes. This allows the user to get a different image to each eye. Infrared transmitters cause the lens for each eye to stay transparent and switch during the vertical retrace time. The images are produced at 120 fields per second, updating the whole image at 60Hz, producing flicker-free images. Some of the shortcomings listed in the research include: cost, inability to project on all six sides of the CAVE^{TM}, light spillage, fragility, and ability to document.

The Applied Research Laboratory at The Pennsylvania State University has an Immersive Projection Display (IPD) similar to the CAVE^{TM} in the Synthetic Environment Applications Laboratory (SEA-Lab) (Shaw 2002). The SEA-Lab provides access to advanced visualization, simulation, and collaboration technologies. The SEA-Lab facility is explained in more detail in Chapter Four. CAVE^{TM} and CAVE-like facilities have been successfully used in research for such diverse applications as the visualization of complex fluid flow patterns around propellers, to assist with urban planning, to visualize the internal operations of complex machinery, and to aid in the design of complex tests.

3.2   4D CAD/GRAPHICAL CONSTRUCTION SIMULATION

4D CAD may be defined as 3D CAD linked to the construction schedule (Koo and Fischer 2000). 4D CAD has been and is being used on different types of construction projects. This section presents the previous research performed in this area to demonstrate the capabilities of 4D CAD. One should note that there are different terms to express linking 3D models to construction schedules; the term 4D is only one among them. The research done in the area of "linking 3D models to the construction schedule" is studied in this review.

The Center for Integrated Facility Engineering (CIFE) at Stanford University has performed extensive research in the area of 4D CAD modeling. Several studies have focused on the use of 4D CAD on different building types. One such research project performed by Haymaker and Fischer (2001) is the Walt Disney Concert Hall project that is a $175 million, 2,400-seat concert hall project located in Los Angeles, California. The complex project and tight spaces made coordination of construction activities a very high priority. The General Contractor (GC) saw the use of 4D visualization of the construction process as a tool for accomplishing four project objectives: schedule creation, schedule analysis, communication, and team building on this project.

The process and tools used by the researchers of this study to generate a 4D model is explained in detail in this section. The architect of the project constructed the 3D models with CATIA (a 3D CAD modeling application). The ability of CATIA to handle very large, complex models, and maintain a high level of accuracy; were some of the features that lead the architect to use it. The construction schedule created by the General Contractor (GC) was in Primavera P3$^®$ and consisted of approximately 7,200 activities. The schedule was developed in such a way that the 3D project was divided into chunks that are relevant to an activity. The schedule activities were organized by building element, floor, area, and sub area; then by phase, system, component, and action. The 3D models in CATIA were imported into Rhino3D^{TM} to allow the addition of names to the geometry and allow for decomposition of the geometry into relevant configurations for

the respective construction activities. The geometry was then converted into VRML files. The 4D models were developed with the prototype 4D modeling software developed by Walt Disney Imagineering and CIFE. The 4D models were generated by linking the Primavera P3$^®$ schedule to the VRML geometric elements.

Developing such a 4D model posed a number of challenges to the researcher. These challenges were related to the geometry, the schedule, and the linking of the geometry to the schedule. The challenges related to the geometry involved inconsistencies in the 3D models obtained from the architect. These inconsistencies resulted in extra work while linking the schedule to the 3D model, as it was difficult to identify a particular 3D element and show the scope of work for its respective activity. The geometry challenges included issues related to the lack of data. Some of the areas in the 3D model lacked enough data to enable 4D simulation. These areas were modified to incorporate the necessary data. The other geometry related issue encountered was the level of detail. Sometimes the level of detail in the 3D model was too little to generate a 4D model and sometimes there was too much detail, which slowed down the computational processing of the 3D and 4D models.

One of the schedule related challenges encountered was inconsistencies in the schedule. Resolving this issue was important from the project standpoint but was time consuming for the 4D modeler. The other schedule related issue was the lack of data (some geometry had no corresponding activity). Resolving this issue was time and resource consuming for the 4D modeler.

The challenges related to linking of 3D model and the schedule included: inconsistencies, other data, and representation of activities with no geometry. Inconsistencies were often found with the way the geometry was defined, as it would conflict with the schedule. This necessitated breaking down and recombining of geometry to get a geometrical configuration to match the schedule activities. Other data such as lay down, staging areas, and temporary support facilities were not a part of the architect's 3D models. These elements had to be added because of their role on the construction site.

The four objectives set forth by the General Contractor (GC) were accomplished by using 4D models. These were:

- Schedule Creation: 4D models were helpful in "planning the lay down areas for the enclosure; 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 4D models helped the GC to identify several conflicts related to the schedule well before the construction started.
- Communication: The 4D models generated were communicated and reviewed by a group of 40 people in the WDI Virtual Reality Cave.
- Team Building: The 4D model was used by the GC to get the attention and collaboration of the subcontractors thereby developing a team.

The researcher of this study questions the use of the word "Schedule Creation". The schedule was created by the general contractor using Primavera P3® and not the 4D modeling software. The 4D models were able to identify problems with the schedule but were not actually used to create the schedule.

Other research that studied the use of 4D CAD was reported in Koo and Fischer (2000). The case study used for this research was a commercial two-story office building project. At the time of the research, one of the three identical buildings under study was already built. A 4D model was generated for the first building and the issues detected were compared to the actual problems encountered by the project manager.

The 3D model consisted of a total of 24,360 entities. The 2D drawings obtained from the architect were converted into 3D model using AutoCAD R14. A Primavera P3® schedule was created based on the CPM–based bar chart schedule of the master plan. The master plan consisted of approximately 300 activities. The project managers organized the schedule by dividing the workspace into several sections on each floor. The schedule

was organized to reflect these subdivisions. The project managers also coordinated with the subcontractors to make sure that a minimum number of subcontractors would be working in a phase at the same time. The 4D model was then developed by linking the 3D CAD element to the respective schedule activity. For this purpose, the researcher used Plant Space Schedule Simulator (Jacobus Technology, Inc.). According to the study, a total of 119 hours were used to generate a 3D model and the 4D model (Schedule preparation – 12hr; 3D CAD model drafting – 69hr; 4D visualization – 22h; and 4D model analysis – 15hr).

The research team (principle researchers and a group of graduate students) was unable to identify any problems with the CPM–based master schedule before generating the 4D model. According to the researchers, this could be attributed to the limited construction experience of the students. The research team found it difficult to conceptualize the construction process by viewing the CPM schedule alone. They also found it cumbersome to relate the components in the 2D drawing with its corresponding activity or activities in the schedule. Also, the variations in the interpretations of the students made it difficult to communicate and discuss whether a certain problem actually existed or not.

After the generation of the 4D model, problems were detected in five areas:

- Inconsistency in the master schedule's level of detail: The CPM–based master schedule contained two different levels of detail. The research team was unable to decide what level of detail was to be adopted in the schedule just by reviewing the CPM–based schedule. The team was able to make this decision after viewing the 4D model. With the help of the 4D model, the research team was able to detect that more detail was required for activities in certain areas of the construction than others.

- Omission of activities in the schedule: The research team was able to identify discrepancies in the schedule after viewing the 4D model. The team identified

that some of the components did not have their associated activity/activities in the schedule. Confirming these associations on a CPM-based schedule was time consuming due to the sheer number of the components and related activities.

- Problems related to the logic of the schedule: Identifying out of sequence work with a CPM-based schedule is difficult. This is because the mutually dependent activities may be located at different parts of the schedule. The research team was able to identify two problems related to the logic in the schedule by viewing the 4D model.

- Problems related to time-space conflicts: The research team identified that three activities (electrical rough in, overhead HVAC rough in, and plumbing rough in) were executed at the same time. By viewing the schedule alone, they were not able to determine if this sequence would create congestion among the workers. In the 4D model the researchers could foresee three different crews working concurrently in a limited space.

- Accessibility problems: The research team after viewing the 4D models detected accessibility problem in the lobby area. An alternative route was identified to resolve this issue.

After viewing the 4D models, the researchers consulted the project manager and found that the two major problems they faced during the construction were congestion in the lobby and imbalance of work for certain phases of the project.

The researchers identified the following advantages of using 4D CAD as a visualization tool: visualizing and interpreting construction sequence; conveying spatial constraints of a project; integration tool: formalizing design and construction information; promoting interaction among project participants; and analysis tool: anticipating safety hazard situations; allocating resources and equipment relative to site workspace; running constructability reviews; 4D models also assist constructions planners in planning the lay

down areas, visualizing the overall project access at critical junctures in the project, performing schedule analysis, and communication and team building.

A study that is very closely related to the current research effort was performed by Rischmoller (2001). This research investigated the use of 4D modeling as a tool for construction planning and scheduling. The objective of this research was to find out how 4D model reviews can help generate more constructible projects by assisting construction planners to optimize construction sequences; identify and resolve schedule conflicts; and provide feedback from construction teams to the design teams. According to the researchers, 4D allows simulating and interacting with construction sequences (schedules) through graphic display devices. This research used the Escondida Phase IV Expansion Project as its case study. The Escondida Phase IV Expansion Project is the largest single-phase expansion of any copper concentrator.

The research team developed a detailed plan/schedule for all the concrete foundations (approximately. 100,000 Cu.m) of the Escondida IV project concentrator area. Plant Design System (PDS) for 3D, Primavera P3$^{®}$ for scheduling and SmartPlant Review (SPR) for 4D modeling were the main commercial tools used to develop the 4D model on the Escondida.

This research adopted an observation-participation methodology to examine a case study. The observation-participation method encourages the researcher to assume a variety of roles within the case study and actively participate in the activities under study. According to the researchers, this strategy addressed the complexity and novelty of understanding the impact of 4D models in a real life context and on a large-scale project. Figure 1 shows the basic process for generating the 4D models developed by the researchers.

The researchers note that the construction planning team involved in the exercise was convinced of the value of improving the schedule through the use of the 4D models. The planning team had the opportunity to evaluate a number of alternative schedules.
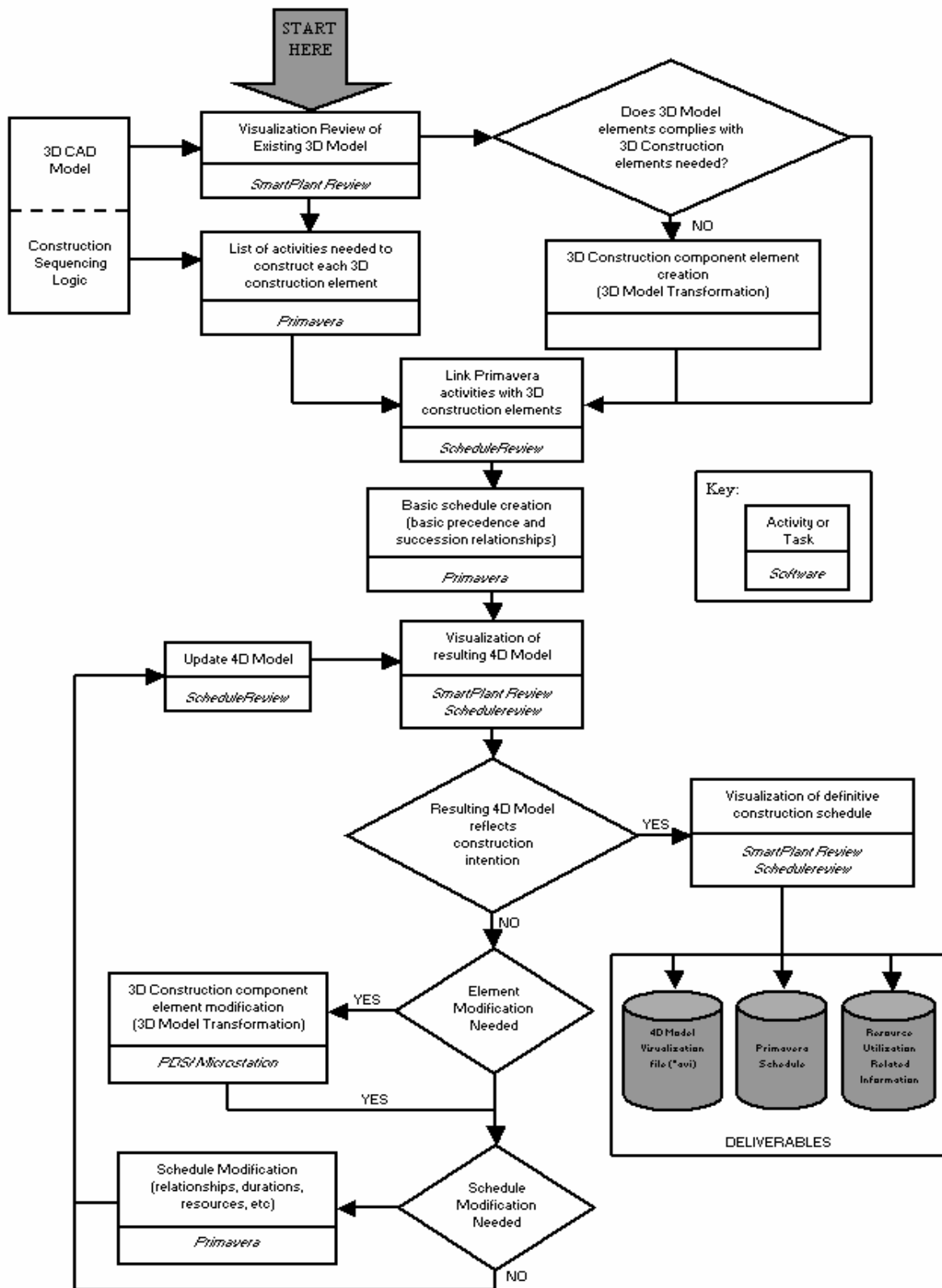
Figure 1: Basic 4D Process Model (Rischmoller et al. 2001)

In some cases the team evaluated up to 20 alternatives for parts of the project as well as for the sequencing of the complete project.

The results of this research (Rischmoller et al. 2002) categorize the benefits of the 4D application to the case study project in four areas:

- *General benefits*:
    1. Reduction of costs by 10%,
    2. Reduction in schedule, from 18 to 16 months,
    3. Improved design reflected in a reduction in errors during construction, and
    4. Reductions in uncertainty and risk reflected in 90% of fulfillment of the construction schedule.

- *Benefits during the engineering phase*: The use of 4D and Computer Advanced Visualization Tool (CAVT) on the project allowed the construction teams to focus on the planning aspects instead of the traditional focus in constructability. However, the quantity and quality of constructability suggestions increased.

- *Benefits during construction phase*: The superintendents, the field engineers and general foremen of all the trades were able to visualize the schedule, the sequence of erection, and the equipment logistics by viewing the 4D model at the job-site. This allowed them to try to find or look for potential interference in the construction plan. They were also able to review the plan to make sure the construction plan was the most cost-efficient method to perform the work.

- *Benefits for the client*: The quality of the products and services offered to the case study project client could be improved by using 4D. Through better construction planning, opportunities to improve the profit margins were offered to the client.

Collier, E and Fischer (1996) demonstrated the use of 4D CAD on the San Mateo County Health Center. The project involved demolition, renovation, remodeling, and new construction on an existing old hospital. The hospital had to be functional at all times and the disruptions to hospital operations had to be minimized. This motivated the project manager of the project to accept the assistance from the researchers to develop a 4D model for construction planning.

The project team created 3D AutoCAD models from the 2D AutoCAD drawings obtained from the architect of the project. The entire site and all the buildings, including 27,000 sq. meters of old, new, and soon-to-be-remodeled buildings ranging in size from 1,800 sq. meters to over 10,000 sq. meters were modeled in 3D. The model contained over 25,000 objects. The Primavera schedule obtained from the project manager was used to generate the 4D model. A detailed 4D model was then generated by linking the 3D model to the schedule using Jacobus Technology's Construction Simulation Toolkit software. The 4D model of this $10 million central utility plant incorporated 100 design drawings and 600 schedule activities totaling 14 months.

The 4D models animated the schedule in different colors to highlight objects under construction during that time frame. For example, red was used when critical path activities were under construction and green was used when non-critical path activities were under construction. The time frame can be viewed on the screen and is illustrated in weekly or monthly intervals, or any other interval the viewer selects. A video of the animation of the construction schedule was also generated. Everyone involved in the project was able to view these videos at the same time without being in front of a computer. The audiences included subcontractors, suppliers, owner representatives, neighborhood groups, and donors. The hospital management, doctors, nurses, and the technical staff were one of the most important groups that viewed the videos. The hospital personnel were able to understand the impact of the planned construction on their department, office, and daily operations.

The researchers also incorporated temporary facilities into the 4D model. The researchers note that this allowed the research team to identify temporal and spatial coordination problems much more easily than with 2D drawings and bar chart schedules. One such problem resolved was when the research team realized that the planned construction sequence would cut the hospital campus in half during much of 1996 and 1997. This would require the hospital staff to go around the construction zone to reach other parts of the hospital. The research team determined that this was unacceptable and the project manager had to develop a new phasing plan.

The researchers of this study identify the benefits of 4D models in reducing coordination problems between on-going operations and construction; improve subcontractor coordination; and improve the acceptance of the construction project by concerned individuals.

4D CAD in the form of 4D workplanner gives construction planners the ability to manage activity space requirements and identify time-space conflicts (Akinci et al. 2000). Songer and Diekmann (2001) quantified the advantages of developing animation-based construction schedule reviews. The schedule was created for a pipe rack model that intentionally include; missing activities, out of sequence work, invalid relationships, and potential crowding or safety problems. Experiments that involved 25 participants reviewed 2D paper-based schedules, made corrections to the schedule, and reviewed the schedule using computer models. The results of these experiments show that the participants while reviewing the paper-based schedule had a difficult time finding all the mistakes and problems in the schedule. However, by using animated schedules they were able to identify more errors and addressed more problems with safety and overcrowding.

3.3   SUMMARY OF THE LITERATURE

Several documented studies have shown the benefits of 4D CAD as a schedule review tool. Despite the lack of a comprehensive cost-benefit analysis, the benefits of 4D CAD over paper-based schedules have been quantified (Songer and Diekmann 2001; Koo and Fischer 2000). However, there is no documented evidence of the benefits of these tools for schedule generation. These tools are limited to performing schedule reviews and lack the ability to allow users to interactively generate schedules.   Also, these tools are desktop based and do not provide full scale visualization. There is very limited research performed to test the feasibility of visualizing 4D models in immersive virtual environments (IVE).

The research in the area of virtual reality applied to construction is also very limited. Previous studies used virtual reality to visualize such aspects as construction operations but there is very limited research done to test the possibilities of using virtual reality and immersive virtual environment display technology for construction planning.   However, several studies in other areas like aerospace, computation, and statistics have successfully used the IVE technology.

This research seeks to identify the potential benefits of immersing construction planners into a 1:1 scale, 4D environment. By immersing in a virtual environment, the planners can identify potential congestion, accessibility, and safety related problems created by their schedule. As a result, the time-space conflicts discussed by Koo and Fischer (2000) may be reduced/ eliminated during the initial stages of a project.

Morad (1991) suggested that there is too much reliance on individual's judgment, intuition, imagination, and ability to visualize and conceptualize spatial components. By immersing an individual in a virtual environment and visualizing a project on a 1:1 scale, the negative aspects of an individual's intuitive reliance may be eliminated and the quality of their judgment may be improved.

The number of people who need to visually comprehend 3D models of physical products has increased dramatically (Kasik et al. 2002). The increase in the processing power, the decreasing costs, and improved ease-of-use of immersive virtual reality displays should enable more people to use this technology in the future.

The next chapter describes the case study project and the immersive virtual environment display facility used for this research.

CHAPTER FOUR

CASE STUDY AND THE IMMERSIVE VIRTUAL ENVIRONMENT DISPLAY FACILITY

This chapter describes in detail the case study used for this research and the tools employed to test the research objectives. The lessons learned from the study of the case and the tools used to develop the process model are explained in Chapter Six.

4.1.   CASE STUDY: AP 1000, ROOM 12306

The research case study focused on a portion of the AP1000 nuclear power plant. The AP1000 is a Generation III+ nuclear power plant that is licensed for construction, but no such plants have been built to date. The study specifically focuses on the installation sequence of the modules and spool pieces that connect the modules in Room 12306 in the auxiliary building of the AP1000 nuclear power plant. Room 12306 lies between the containment building and the turbine building. This room is located on the third level of the auxiliary building, in the northeast corner. The inside dimensions of this room are approximately 46'-0" x 16'-0" x 15'-6". The location of Room 12306 in relation to the containment building is shown in Figure 2.
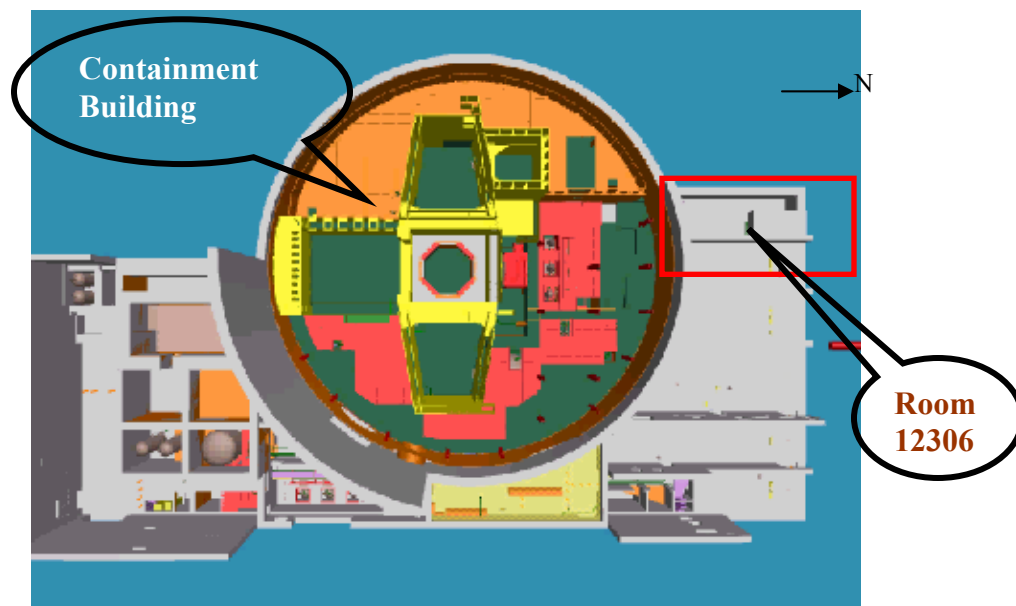
Figure 2: Location of Room 12306 in AP1000 nuclear power plant

A single controlled access is provided to this room from the Turbine Building, through the north wall. Room 12306 contains non-radioactive mechanical equipment and piping and also serves as the containment piping penetration area; therefore contains containment isolation valves for different fluid systems. This room contains components, piping and instrumentation associated with ten different fluid systems. This room also contains a number of pre-assembled equipment modules. Figure 3 shows the different modules and assemblies in Room 12306.
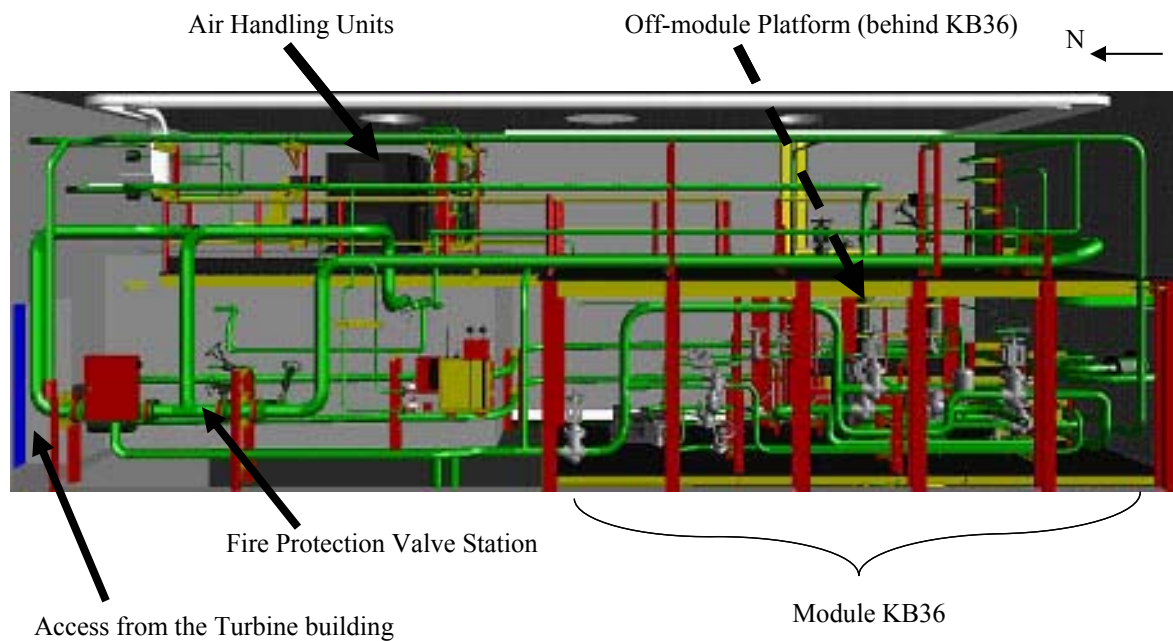
Figure 3: Location of Major Equipment in Room 12306

Images taken in the Immersive Virtual Environment (IVE) display system showing KB36, the off-module platform, the fire protection system valve station, and the air-handling units are presented. Figure 4 shows the user on the first level of Room 12306. A large, 2-level module called KB36 occupies much of the south end of the virtual mockup. Piping, valves, and equipment for the passive containment cooling system dominate the first level of the module.
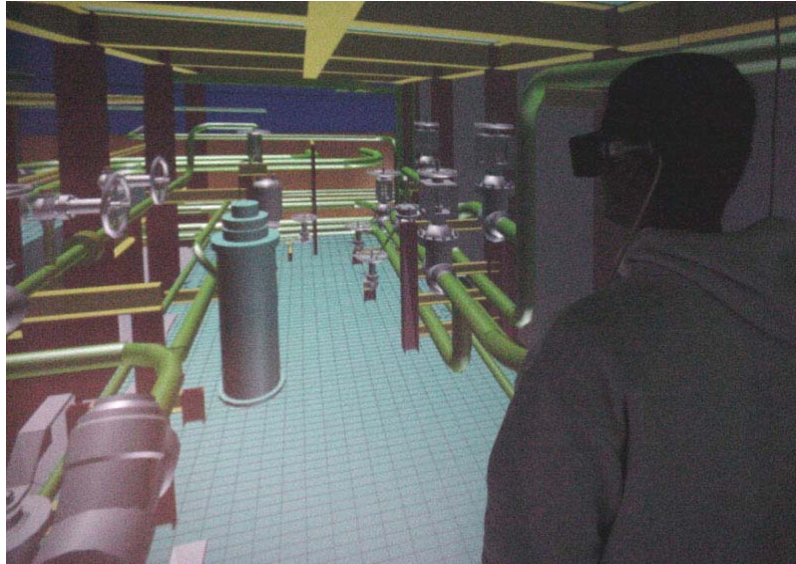
Figure 4: Module KB36 - First Floor

Figure 5 shows the second floor of module KB36. Piping and valves from a number of different systems are present; mainly the chemical and volume control system, liquid radwaste system, and demineralized water system. The figure also shows one of the virtual people called avatars that have been added to increase the sense of presence experienced by the user. The avatars can be programmed to perform many different actions; however, in this case, the avatars are added to provide a better sense of the scale of the image.
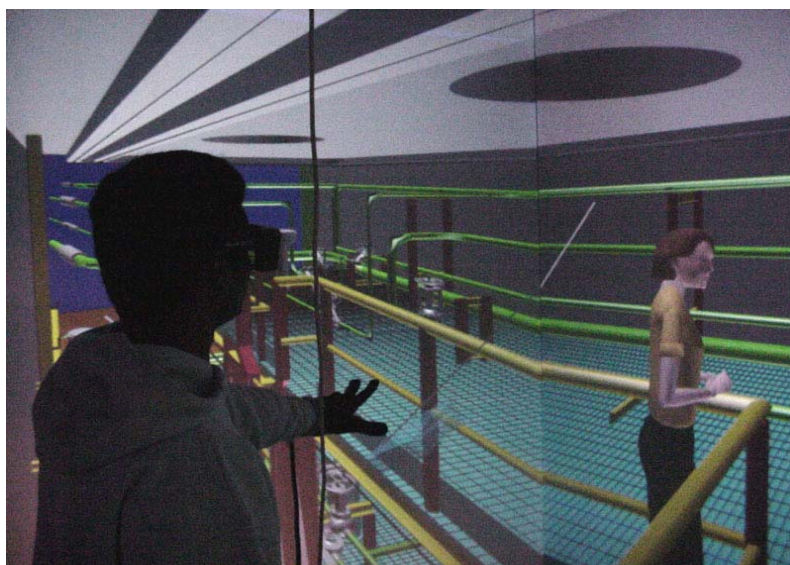
Figure 5: Module KB36 - Second Floor

Figure 6 shows the off-module platform, which supports four air-operated valves. Two parallel pipes, the steam generator blow down lines run from the containment shield wall at the south end to the turbine building at the north end.
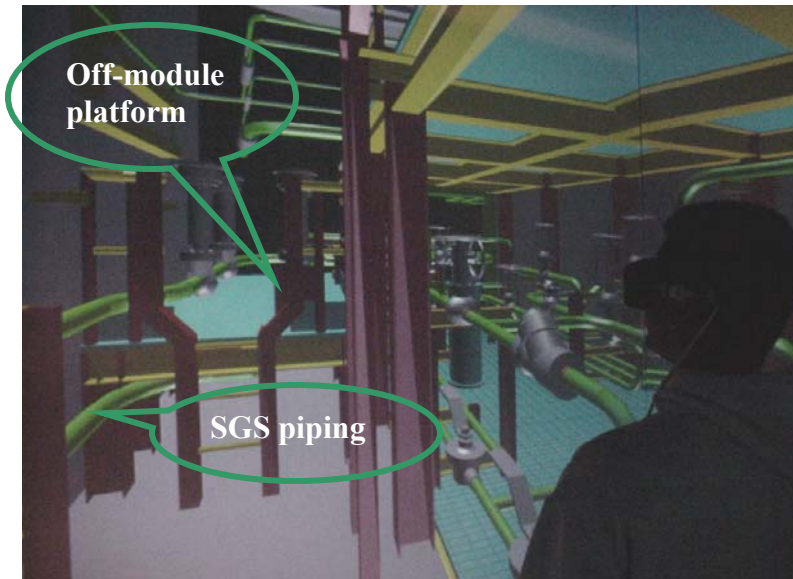
Figure 6: Steam Generator Blow down Valves

The fire protection system containment isolation valve station, shown in Figure 7, occupies the first level of the North end of Room 12306. The valve station will be installed as a prefabricated assembly. In addition, the doorway connecting this room in the auxiliary building to the turbine building is shown. This will be the only access to the room once construction is complete.
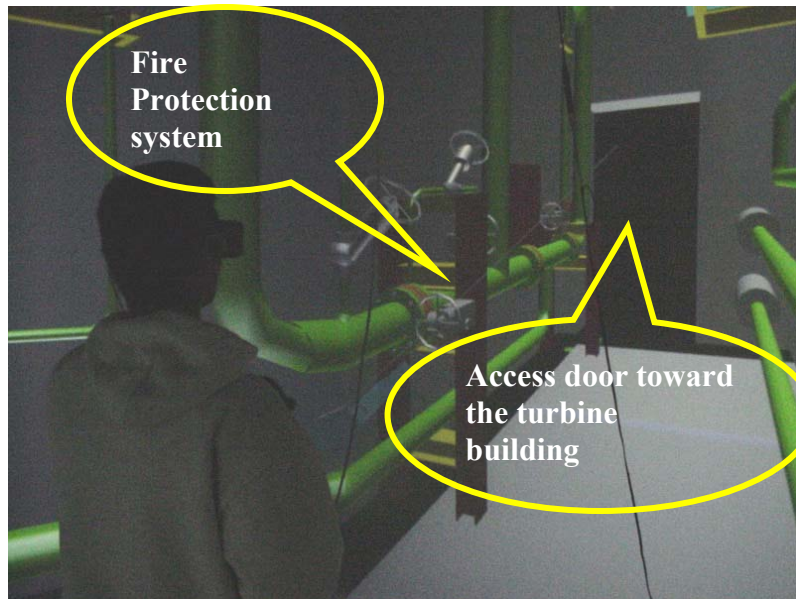
Figure 7: Fire Protection System Containment Isolation Valve Station

Figure 8 shows the air handling units and associated equipment on the second level of the virtual mockup. Hot water and chilled water lines enter the air-handling units. Ductwork connects the air handling units and exits through the wall at the north end.
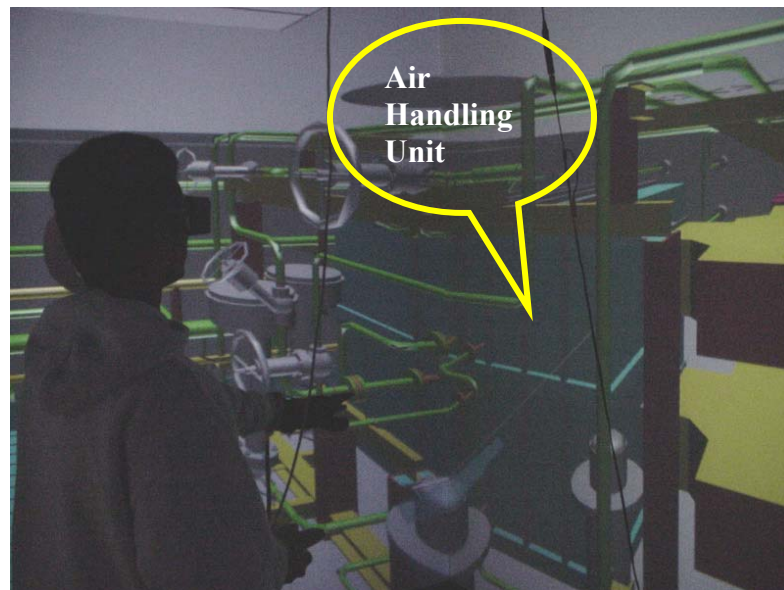
Figure 8: Air Handling Units on the Second Level

4.2.   IMMERSIVE VIRTUAL ENVIRONMENT (IVE) DISPLAY SYSTEM

The Surround Screen Virtual Reality (SSVR) system is an Immersive Virtual Environment (IVE) display system designed and sold by Mechdyne Corporation. The SSVR system is a turnkey virtual reality platform, which includes the display, the projectors, and all of the required hardware. A high-end Silicon Graphics Onyx2 server drives the display. The computer has a separate graphics processor for each of the four walls. A High Bandwidth BarcoGraphics CRT-style projector projects the image generated by the computer on to a Mylar mirror, which reflects the image onto the back of each of the four wall screens. The mirrors allow for a relatively compact footprint for the display.

The typical footprint for a SSVR system is 3 walls and a floor, but the IVE display system at the SEA Lab at The Pennsylvania State University is a custom built system with four walls, which surrounds the user. Accommodations have also been made for the future installation of the fifth display, a top-projected floor. A diagram of the IVE display system at The Pennsylvania State University's SEA Lab is shown in Figure 9.
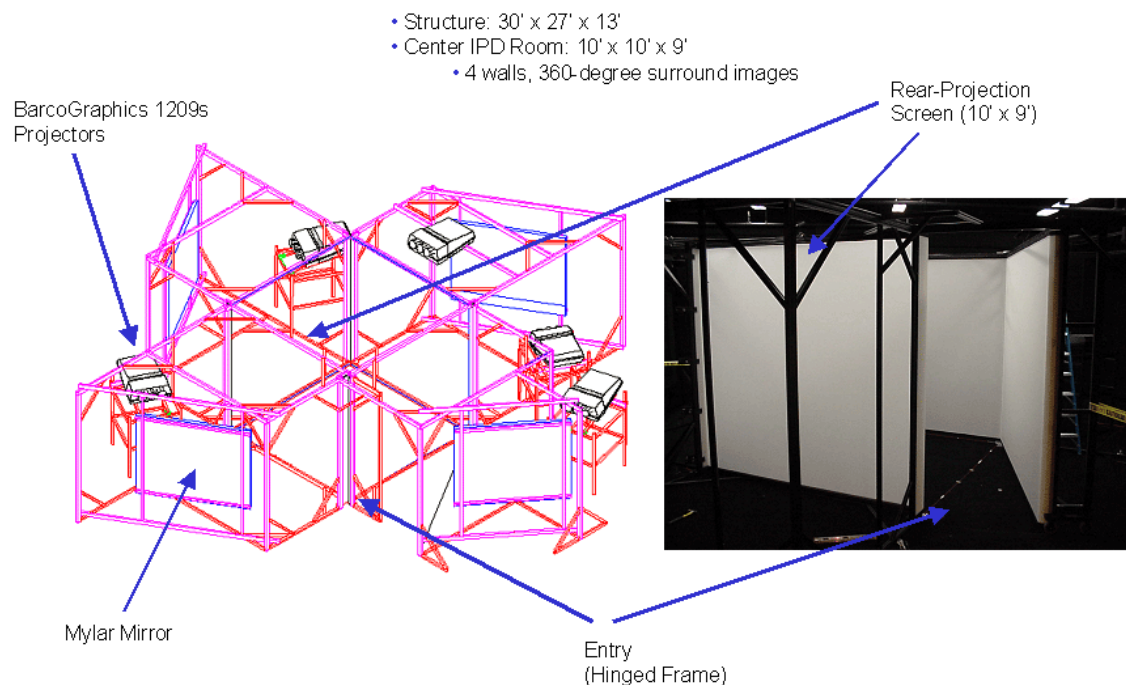
Figure 9: Immersive Virtual Environment Display System at the SEA Lab

The IVE creates a three-dimensional stereoscopic image using an active stereo technique. To create the stereo image, the computer used by the SEA Lab IVE display system generates 96 frames of information per second. Forty-eight are optimized for viewing in the right eye, and 48 are optimized for viewing in the left eye. StereoGraphics CrystalEyes glasses, worn by the user, have LCD shutters in the lenses. The glasses receive an infrared signal from the emitters at the top of each wall, which synchronize the shutters to the image being projected. When the left eye image is being projected on the screen, the right lens of the glasses is blacked out. When the right eye image is being projected, the left eye is blacked out. The switching of the images is imperceptible to the user. Active stereo provides a high quality stereoscopic image, although the projection of the image in stereo causes the image to appear dimmer than the typical monoscopic image.

Many different tools are combined to develop realistic interaction with the virtual mockup. Figure 10 shows the IPD's Motion Star® motion tracking system, developed by Ascension Technology Corporation. The system provides real-time position data, such as X, Y, Z position and orientation angles.
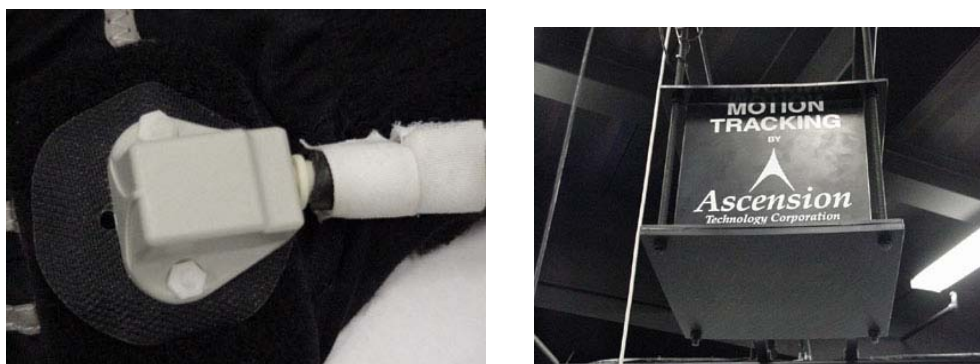
Figure 10: Motion Tracking System (sensor on left and transmitter on right)

The IVE display system at the SEA Lab uses two Fakespace PINCH gloves to recognize gestures. PINCH gloves are cloth gloves with electrical contacts at the tip of each finger. Gestures or pinches may be programmed into applications to perform various actions. When a motion-tracking sensor is attached to the glove, the position of the user's hand

may be tracked in the virtual environment. A PINCH glove with motion sensor is shown in Figure 11.

Figure 11: FakeSpace PINCH Glove with Motion Tracking Sensor

To navigate through the virtual mockup, a specialized 3-D joystick called Wanda is used (see Figure 12).   It has a multidirectional trackball-like sensor, which allows the user to control movement in the virtual environment. The Wanda has three programmable buttons, which may be assigned to different activities in the mockup.

Figure 12: Wanda

4.3.   FEATURES IN THE IVE DISPLAY SYSTEM

A number of features are available to enhance the users experience within the virtual mockup. Gesture recognition, voice recognition, and collision detection are used to improve interaction with the image. A further description of each feature is given below.

4.3.1. GESTURE RECOGNITION

Gesture recognition is made possible using the FakeSpace PINCH gloves. Sensors in the fingers of the gloves recognize when a contact between fingers is made. Pinches between different fingers can be attached to various activities using the Explorer software (refer to Section 4.5.4). Currently, pinching the index finger and the thumb is set to grab the object at the end of the pointer. Pinching the middle finger and the thumb toggles a measuring tape feature. Finally, pinching the ring finger and the thumb moves a virtual crane, if it has been activated.

4.3.2. VOICE RECOGNITION

To expand interaction with the virtual environment, a voice recognition system is used. The system is based on a readily available speech-to-text program. The user wears a microphone connected to the voice server, a PC. The voice server interprets the signal from the microphone, using the Microsoft® speech recognition package. The software translates the signal to text, which is sent to the Explorer program on the main system where it is compared to a list of text commands. If the command appears on the list, that command is executed. A list of voice commands recognized by the system appears in Table 1.

COMMAND	FUNCTION
Auto Tour	Moves the viewpoint through a list of predefined locations
Clear Labels	Clears text labels on objects
Crane	Toggles the crane on and off
Distance	Displays the distance between the viewer and the object
Go To {bookmark}	Moves viewpoint to predefined position
Grab	Grabs the object at the end of the pointer
Gravity	Toggles ground clamping to simulate gravity
Help	Toggles a command reference display
Identify	Announces object name of object at end of the pointer
Next Bookmark	Moves viewer to the next predefined location on the list
Position	Announces the x, y, and z coordinates of the viewer's position
Previous Bookmark	Moves the view to the previous predefined location on the list
Release	Releases objects that have been grabbed
Run Simulation	Runs the 4D model of the installation sequence
Select	Selects object at the end of the pointer
Statistics	Toggles the display statistics on and off
Status	Toggles status display on and off
Tape	Toggles measuring tape on and off
Track	Toggles eye point tracking on and off
Undo	Undoes the previous command or returns a moved object to its original location
Warp	Moves viewpoint to position at end of pointer

TABLE 1: VOICE COMMANDS USED IN VIRTUAL MOCKUP

4.3.3. INTERACTIONS

Using the tools discussed in the previous section, a number of interactions are possible. Possible interactions include use of the virtual crane, grabbing and moving objects, and measuring the distance between objects.

4.3.3.1. CRANE

A virtual crane can be used to move equipment. Giving the "CRANE" voice command spawns the crane. Once the crane appears, the user can move it by pinching the ring finger and the thumb and moving the user's hand in the desired direction. To lift and move an object, the crane must intersect with that object. Once the crane is in position,

the user pinches the index finger and the thumb to hook the object. Then, the crane and the object can be moved together using hand gestures. Figure 13 shows the crane being moved into position over the steam generator blow down valves.
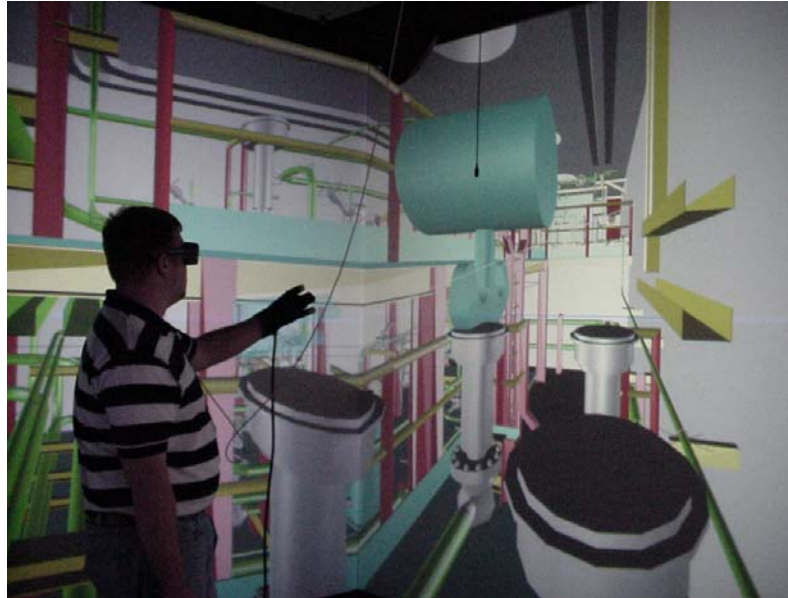
Figure 13: Operating the Virtual Crane

4.3.3.2. GRAB

Figure 14 shows the grab and move functionality being demonstrated. To grab an object, the user pinches the index finger and the thumb while either the pointer extending from the virtual hand or the virtual hand itself is intersecting with the object. Once the grab function is invoked, the object may be carried around or moved until it is released. To release, the user simply releases the pinch, and the object will be left in its position.
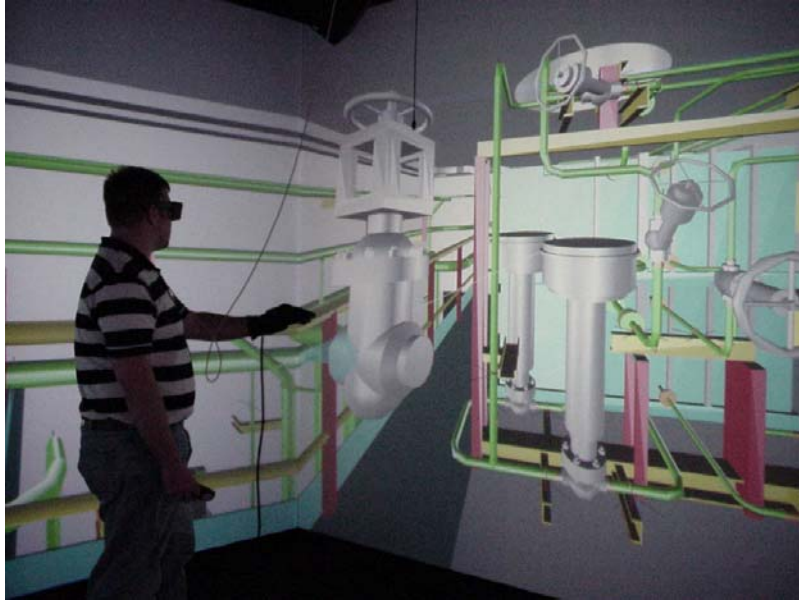
Figure 14: Demonstration of Grab and Move

The grab and move functionality works best with finely resolved models-those models where, for example, each valve is modeled in its own separate file. In the files received from the designer, all of the valves for each system in the area were contained in a single 3D CAD file. These 3D CAD files were subdivided into many separate files so that each valve could be identified and moved. Since the designer used high-resolution part models, the individual valves may be divided further, separating the hand wheel or operator from the body of the valve.   However, this feature is impractical and requires further improvements.

4.3.3.3. MEASURING TAPE

Another useful function is the simulated measuring tape, shown in Figure 15. By pinching the thumb and middle finger, the user can pull out a measuring tape to determine the distance between two points. The distance, in meters, and a line connecting the two points are displayed on the screen. The measuring tape can assist the user in determining clearances between pieces of equipment, pipe welding clearances, reachability of valve operators, welders.
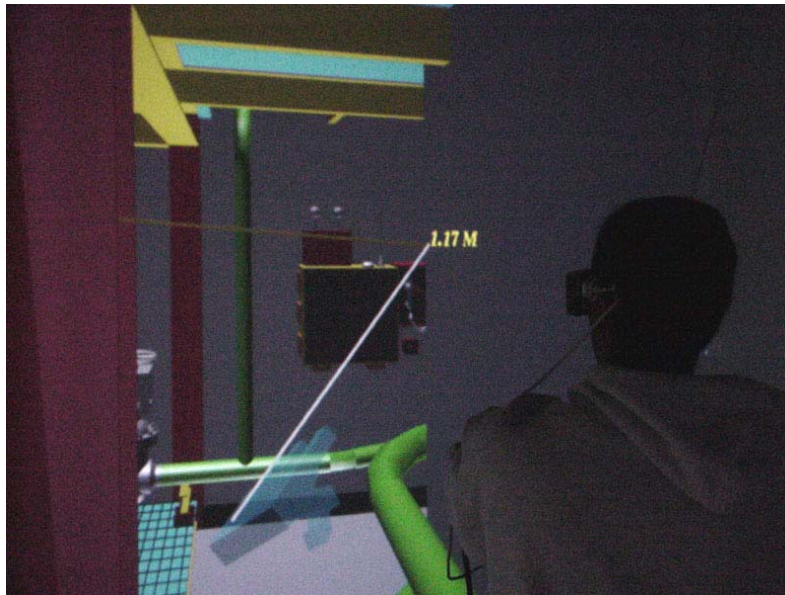
Figure 15: Using the Virtual Measuring Tape

4.4.   MOCKUP CREATION

Currently, some designers use 3D CAD packages to develop their designs. The virtual mockup developed in the IVE display system takes 3D CAD one step further, presenting it full-size (one-to-one scale).

The CAD package chosen by the designer (Intergraph^{TM} PDS) is capable of exporting a file format that can, with only minor changes, be viewed and interacted with in the IVE display system. Bentley MicroStation^{TM} was used for model conversion. This software was chosen because it is capable of reading the AP1000 CAD models developed by the designer using Intergraph^{TM} PDS. MicroStation has the capability of exporting CAD models as Virtual Reality Modeling Language (VRML) files, essential to the creation of the virtual mockup. VRML provides a standard format for the presentation of 3D objects. In addition, the format of the VRML file is very similar to a file format that the IVE display system can interpret.

Perl script is used to convert files from VRML (*.wrl) files to OpenInventor^{TM} (*.iv) files for use in the virtual mockup. Using the Perl script, the VRML file, exported by the CAD package, is converted to an Open Inventor file (refer to Section 4.5.2). Use of the

script allows large numbers of models to be converted quickly. Once the model has been converted to Open Inventor format, it may be directly imported to the IVE display system for viewing. A number of software packages can view the Open Inventor^{TM} files; however, to develop interactive scenes, a combination of software packages is used. An alternate Performer^{TM} binary file (refer to Section 4.5.3) format may be loaded directly to the graphics rendering program. These files load faster than the Open Inventor files, which is important when loading many large models. The conversion process is shown in Figure 16.
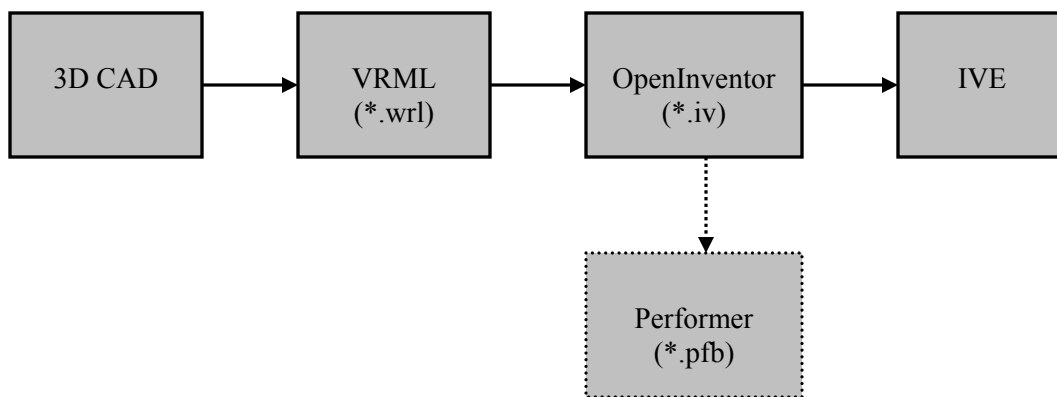
Figure 16: File conversions for creating the virtual mockup

Three primary programs drive the IVE display system: Explorer, Vega, and Performer. Performer drives the graphical display of objects. Vega allows for general interaction with the objects and allows models to be named and defined in an Application Definition File (ADF). Explorer, a program written by Michael Warren at PSU-ARL, allows additional interaction with the objects and controls motion through the environment. A number of options for Explorer can be set using a configuration file (*.cfg). The configuration file has also been referred to as a table-based data file in this research.

4.5.   SOFTWARE DESCRIPTION

A number of software packages, referred to above, have been used during the development of the virtual mockup. They are described in further detail below.

4.5.1. BENTLEY MICROSTATION

MicroStation^{TM} is a design tool that allows users to develop 3D CAD models. The models and all of their components can be graphical simulations of real-world objects. The models used in the virtual mockup were created using Intergraph's PDS software; however, the researcher used MicroStation^{TM} to perform all model conversions from 3D CAD to Open Inventor format for use in the IVE. MicroStation^{TM} allows the user to export models as VRML 1.0 files for viewing.

4.5.2. OPEN INVENTOR

Open Inventor is an object-oriented toolkit used to develop 3D graphics applications. In addition, it defines a standard file format for exchanging 3D data between applications. Open Inventor^{TM} serves as the basis for the VRML standard. Since Open Inventor^{TM} and VRML are related, model conversion from VRML 1.0 to Open Inventor^{TM} is a simple process, which is performed by a Perl script (Perl is a general-purpose programming language originally developed for text manipulation and now used for a wide range of tasks including system administration, web development, network programming, and GUI development). Open Inventor is compatible with all SGI® graphics platforms running Lunix or IRIX.

4.5.3. PERFORMER

OpenGL Performer^{TM} provides a programming interface for developers to create simulations and 3D graphics applications. According to Silicon Graphics, Performer applications may be used to simplify development of complex applications used for visual simulation, simulation-based design, virtual reality, interactive entertainment, broadcast video, architectural walk-through, and computer aided design. For the virtual mockup project, Performer is used to interpret and display the graphical objects created using 3D CAD. OpenGL Performer^{TM} is compatible with all SGI® graphics platforms running Lunix or IRIX as well as Pentium® based systems with Linux.

4.5.4. EXPLORER

Explorer is an interactive data analysis tool for desktop and immersive environments including large format IVE display systems such as CAVE^{TM}. It accepts several standard 3D graphics formats including VRML, DXF, OBJ, OpenInventor^{TM}, OpenFlight, 3DS, and Performer^{TM}. In addition to supporting the graphics, Explorer supports quad-channel sonification of sounds within the 3D environment, providing a truly immersive 3D experience.

Explorer operates in concert with standard six degree-of-freedom motion tracking systems, such as the Ascension MotionStar; to track the position and orientation of the user and several input devices within the immersive environment. This allows the user to use gestures, which facilitates a human centered approach to navigation and interaction with the virtual world. Navigation through the 3D space is simply a matter of pointing to the desired direction of travel.

4.5.5. BENTLEY SCHEDULE SIMULATOR

In addition to the above mentioned software, Bentley Schedule Simulator^{TM} was used to generate desktop 4D models of the sequence generated by the participants of the experiment. Schedule Simulator is a 4D modeling software application.   The Schedule Simulator software allows a user to link the schedule activities to the 3D components to generate a 4D model. The tools in Schedule Simulator allow the user to stop the simulation at anytime during the 4D simulation and view the model step-by-step (forward or backward).

4.6.   SUMMARY

This chapter described the case study project, the IVE display facility and the software used for this study. The next chapter will present the experiments performed to test the facility as a tool for construction planning for the case study project.

CHAPTER FIVE

EXPERIMENTS TO TEST THE APPLICATION OF 4D MODEL IN AN IMMERSIVE VIRTUAL ENVIRONMENT (IVE)

Two exploratory experiments were performed to test the application of 4D models in an Immersive Virtual Environment (IVE). These experiments were performed to evaluate the use of the IVE as a tool for construction planning. The objective was to help the construction professionals identify design, constructability, and safety issues by reviewing/generating an installation sequence in the IVE with the goal of developing an optimum construction plan. The first experiment involved the use of the IVE to generate a construction sequence by two teams of graduate students. During the second experiment, two teams of experienced construction superintendents developed a construction plan for the area using the drawings provided by the designer. These plans were input into the IVE for viewing and evaluating. The experimental procedure and the results are discussed in detail in the following sections.

5.1. SCHEDULE DEVELOPMENT IN THE IVE

An objective of the study was to evaluate the potential for construction professionals to generate a construction plan in the IVE. To perform this evaluation, it was necessary to develop additional schedule generation capabilities within the IVE display system. A number of tools exist in the IVE display system that facilitates the creation of a construction schedule. The user can input commands to the IVE display system using a voice-activated computer that is connected to the display system. First, an "Identify" function allows the user to query an object's name. By pointing at an object in the IVE and passing the "Identify" voice command to the computer, the user can view the name of the object. The "Select" function allows the user to select an object. By pointing at an object and passing the "Select" voice command, the user can select it. Once selected, the object changes color to red. As the user selects the objects, they change color to red. This color change provides a visual means of determining the objects that have not been scheduled for installation. Figure 17 shows the researcher using the "Identify" and "Select" functions in the IVE. These features, combined with the recording of the

graphical object sequence make it possible to simulate the generation of a schedule in the IVE. A more robust application could be developed to automate this process.

Figure 17: "Identify" and "Select" functions in the IVE

5.2. VIEWING 4D MODELS IN THE IVE

Current 4D CAD desktop applications (e.g., Bentley Schedule Simulator™) allow the user to link objects to schedule activities and animate the construction schedule as a function of time. During the animation of the construction sequence, the objects can be shown as wire frame or grayed wire frame (depending on the user's preference) before installation. During the installation, the objects change color (user's preference) and finally, once the installation is complete, the objects appear in full color. Other 4D modeling software have similar functions.

The IVE display system used in this research mimics this functionality using the Explorer software developed at The Pennsylvania State University. Three versions of each object were created in Virtual Reality Modeling Language (VRML). Initially a gray-color version of each object is used as a placeholder, showing the position of equipment before it is installed. Later a red-color version is loaded to indicate that the object is under construction. Finally, the full-color version is loaded to indicate the completion of the installation. However, the design and construction professionals after testing the IVE display system found that the gray version of the geometry did not add much value to the IVE display system. Loading three versions of the same object consumed a large amount of memory and slowed the process. Therefore, the gray version of the geometry was not used.

A table-based data file that consists of a list of start times, finish times, and the name of the objects associated with each schedule activity is used to simulate a 4D model. This data file is also used to control the animation of the installation sequence in the IVE. The user can schedule concurrent activities using the data file.

Once the list of activities and start/finish times of each activity is entered in the data file, the schedule may be visualized in the IVE. The users can stand in the IVE and view the space being constructed around them. Verbal commands can be used to view the time sequenced 4D model. The 4D animation is activated by using the "Animate" voice command. Once the 4D animation of the installation sequence is complete, the user can advance through the installation sequence step-by-step using the "Forward" and "Backward" voice commands. These commands help the user to examine the installation sequence in detail and also check for constructability issues.

5.3. RESEARCH MILESTONES

A flow chart showing different milestones that were reached during the research process are shown in Figure 18 and discussed in detail below.

```
┌─────────────────────────┐
│  Student construction plans │
│  (Experiment 1 – Section    │
│         5.3.1)              │
└─────────────────────────┘
            │
            ▼
┌─────────────────────────┐
│  Changes to the designer's  │
│    plan (Section 5.3.2)     │
└─────────────────────────┘
            │
            ▼
┌─────────────────────────┐
│     Professional's          │
│  construction plans on      │
│  paper (Experiment 2 –      │
│     Section 5.3.3)          │
└─────────────────────────┘
            │
            ▼
┌─────────────────────────┐
│     Professional's          │
│  construction plans after   │
│   review in the IVE         │
│  (Experiment 2 – Section    │
│         5.3.3)              │
└─────────────────────────┘
            │
            ▼
┌─────────────────────────┐
│     Professional's          │
│   construction plans        │
│  generated using the IVE    │
│     (Section 5.3.4)         │
└─────────────────────────┘
```
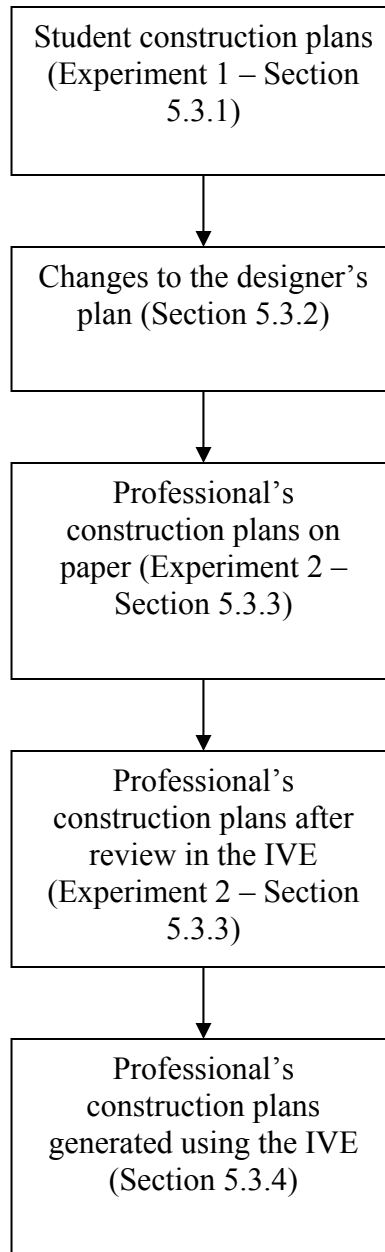
Figure 18: Research Milestones

5.3.1. EXPERIMENT I – APPLICATION OF 4D MODEL IN THE IVE FOR SCHEDULE DEVELOPMENT

The primary purpose of Experiment I was to test the new functionality (refer to Sections 4.1 and 4.2) developed to allow construction superintendents or similar trade personnel to interactively create installation sequences in the IVE.

Two teams of two graduate construction management students participated in the experiment. The participants had a combined construction experience of 8 years. The participants had no prior knowledge of the area under study. Each team was immersed in Room 12306 in the IVE and was given a scripted tour. The students were then asked to develop an installation sequence for Room 12306 in the IVE. The participants were given the freedom to recommend changes to the design and module boundaries.

Each step of the installation sequence generated by the participants was manually recorded. The researchers entered the participant's installation sequence into the table-based data file to allow viewing of the construction schedule in the IVE. The teams were able to visualize their schedules in the form of a 4D model and review their installation sequence.

5.3.1.1 EXPERIMENT I - RESULTS

Each team presented a clear strategy for their work plan; however, each of the teams developed a unique sequence. The sequence was played back and critiqued by the users. Team 1 took approximately 120 minutes and Team 2 took approximately 90 minutes to develop the installation sequence in the IVE and review their sequences, with no prior knowledge of the space. The playback allowed the participants to find additional places where parallel activities could be performed, as well as places where the schedule they had developed could be improved. Standing in the room before and during construction fostered discussion of the actual methods of construction that would be used. For example, the participants discussed the use of spreader beams for lifting pipes into place. They also mentioned module size limitations and accessibility issues for some of the field weld locations. The enhanced spatial perception offered by the IVE allowed the participants to take work-space interference between trades into account while planning a number of parallel activities. The participants rated the development of the installation sequences using the IVE, an average of 8.37 out of 10 in ease of use. The participants rated their confidence in the schedule they had developed an average of 9.1 out of 10.

As expected, this experiment exposed some shortfalls in the strategy and execution planned for the second experiment. The participants mentioned that the granularity and the resolution of many elements in the model was sufficient; however, they recommended that the makeup pieces be cut at the appropriate field weld locations, as they would be during the actual installation. The appropriate changes to the model were completed prior to the execution of the second experiment. The participants suggested additional functionality, such as the announcement of the component name being installed to provide additional benefits to the users.

As a result of the lessons learned from this experiment, a number of changes were made to the mockup to accommodate necessary refinements to the granularity of the schedule activities. Prior to the first experiment, a number of refinements were made to the original model received from the designer to facilitate the model's use for installation simulations. The designer's original installation sequence was comprised of 9 steps, 7 assemblies, and 5 sets of makeup pieces each consisting of 5 makeup pieces, and a total of 40 model objects. Each set of makeup pieces was shown as one installation in the designer's sequence. Since the five sets of makeup pieces were insufficient for developing a realistic installation sequence, each of the makeup piece models was subdivided resulting in more than 25 individual makeup pieces. As mentioned previously, the participants noted that it would be helpful to model the actual pipe pieces cut at field weld locations. After these refinements up to 51 steps, 6 assemblies, 45 makeup pieces, and 75 model objects were available to the construction planners.

During the experiment, it was also noted that the immersive virtual environment could be used as a learning tool, especially for inexperienced construction professionals and construction students. The students can get involved in all the aspects of an entire project by interactively planning the virtual project while immersed in a virtual environment. The students can quickly gain experience and instincts related to construction method selection, activity sequencing, site planning, site logistics, temporary facilities, project safety, and project security.

An example of the constructability issues identified by the participants is shown in Figure 19.
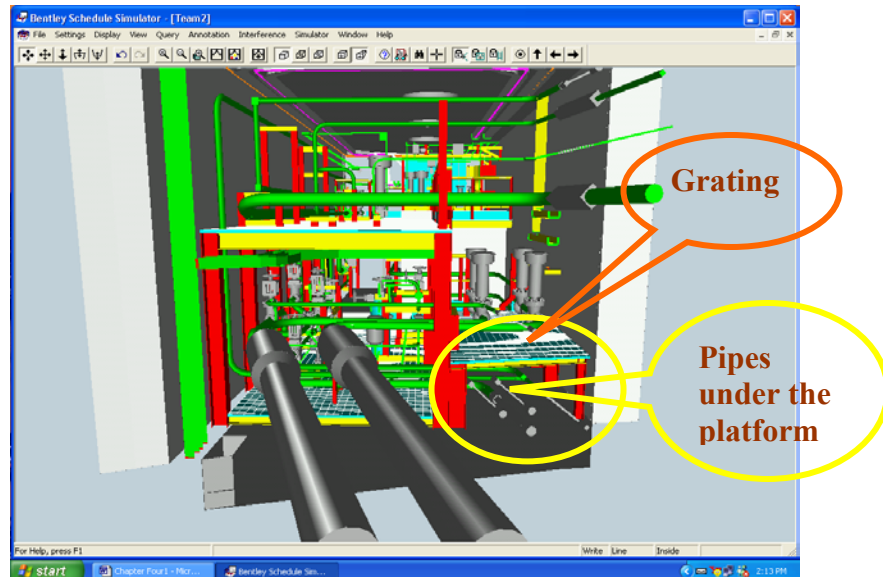

Figure 19: Pipes underneath the off module platform

The participants identified the pipes underneath the off module platform as a potential constructability problem. The participants realized that the clearance between the floor and the grating of the platform does not provide sufficient access to the pipe welders. Each team recommended a different way to deal with this problem. One team installed the pipes before installing the off module platform. The other team recommended separating the grating and the four valves from the off module platform. This team installed the steel supports of the off module platform first, then the pipes underneath the platform, next the grating of the off module platform would be installed, and finally the valves would be installed.

Some of the reactions of the participants are as follows:

- "The IVE allowed us to identify this installation/sequencing conflict as we were developing the schedule and adjust the schedule accordingly. The IVE prevented rework in the field." – *Student 1*
- "The IVE could also be used to generate simple construction activities to show superintendents and foremen the overall sequence of construction and also possibly as detailed as the day to day or week to week schedule. Having different

subs in the space will allow optimizing the overall sequence of activities, not just the optimization of their own portion." – *Student 1*

- "The IVE is extremely helpful in gaining a clear understanding of a project in much less time than blue prints and even 3-D models." – *Student 2*

- "Taking students through the nuclear plant would provide a huge educational experience that cannot be achieved otherwise without going to an actual construction site." – *Student 2*

5.3.2. DESIGN CHANGES

The designer (Westinghouse) of the AP1000 nuclear power plant made a number of changes to the design of Room 12306 after Experiment I. The main purpose of this was to get the design to a level of detail that would be helpful to perform Experiment II. These design changes included field weld locations, module boundary changes, and dividing the makeup piece sets into 41 individual makeup pieces.

The designer then provided 3D isometric paper drawings to the researcher. These drawings were sent to the construction professionals to perform the experiment. Meanwhile, the researcher modified the initial 3D CAD model to include the design changes.

The IVE features were also modified taking into consideration, the recommendations of the participants of the first experiment. For example, while viewing the 4D simulation, the participants felt that it was hard to notice what object was being installed.   This is because the IVE display system provides 360 degrees of immersion and the participants had to turn around and find the object that is being installed. A new feature that enables the computer to announce the name of the object that is being installed during the 4D simulation was added to the IVE display system. This feature verbally guided the user to the object that is being installed.

5.3.3. EXPERIMENT II – APPLICATION OF 4D MODEL IN THE IVE FOR PROJECT PLANNING

The objective of this experiment was to test the use of the IVE as a construction planning tool. The ability of an IVE to help construction planners identify critical issues of a project by reviewing/generating schedules in the IVE was tested in this experiment.

Two teams of two experienced construction superintendents from Burns & Roe Enterprises participated in the experiment. Each team was provided with 3D drawings of the modules, assemblies and makeup pieces in Room 12306 developed by the designer. The 3D drawings showed the pre-set module boundaries and weld locations for the makeup pieces. After spending less than one day reviewing the 3D CAD drawings provided by the designer, each team developed a construction schedule for Room 12306. One team documented the schedule in a Microsoft® Excel spreadsheet with activities broken down by man-hours while the other team created their schedule using Primavera P3® and allowed one day for each activity. Each schedule activity was matched to an object model for display in the IVE. The time scale in the table based data file was scaled to match the length of time the teams allotted for each activity.

Each team viewed their sequence in the IVE after a brief scripted introduction to the IVE display system and Room 12306. After the sequence was played back from start to finish, each team advanced through the sequence step-by-step and evaluated their performance, while discussing their construction strategy with the researcher. A detailed description of the discussions and issues identified is provided in the following section.

5.3.3.1 EXPERIMENT II - RESULTS

Measures for the value of the IVE for schedule/sequence development are based on the constructability issues identified and schedule reliability achieved. Constructability issues identified are further divided into number of module boundary changes and the number of weld locations changes. Schedule reliability is further divided into out-of-sequence activities and schedule confidence.

The results from the experiment regarding the constructability issues identified are given below (change in module boundaries and change in weld locations)

Number of module boundary changes. Figure 20 illustrates the number of module boundary changes made before and after the review of the construction schedules in the IVE by each team. This data shows that the construction planners were able to identify more module boundary changes after reviewing the schedule in the IVE. This demonstrates that the construction planners had a better understanding of the constructability issues while they were inside the IVE.

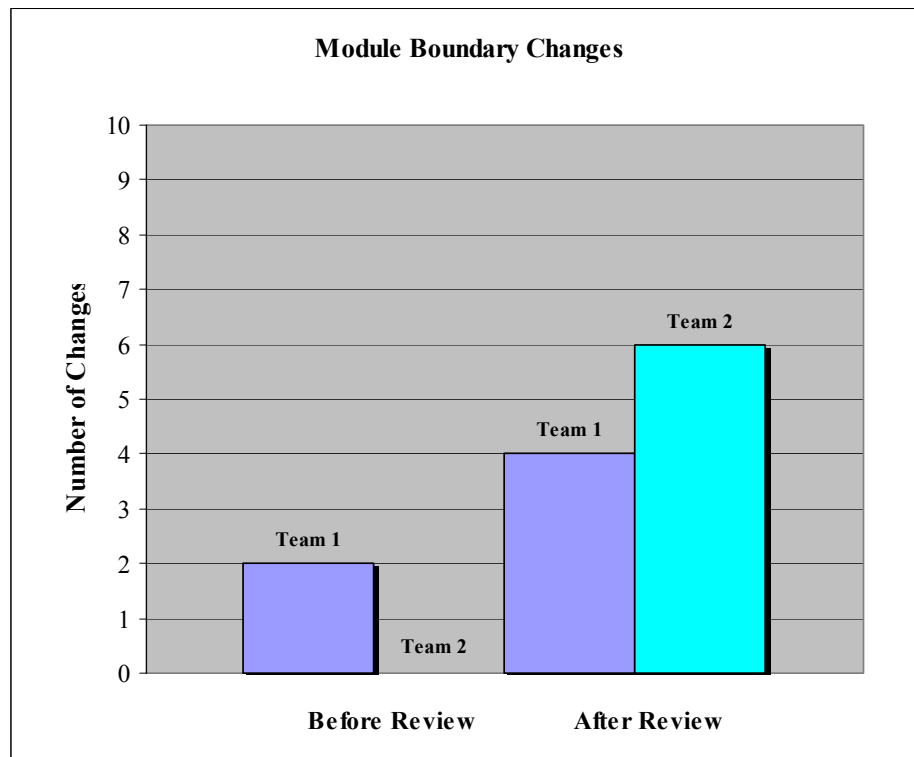
Figure 20: Changes in module boundaries

Changes in weld locations. Figure 21 illustrates the number of changes made to the weld locations before and after the review by each team. This data shows that the IVE helped the construction planners identify the exact weld locations. The planners also mentioned the need to involve pipe fitters and welders into the planning process. According to the

planners, this could be very valuable to avoid delays during the actual construction. The construction planners were not able to identify any such changes while developing the schedule on paper.
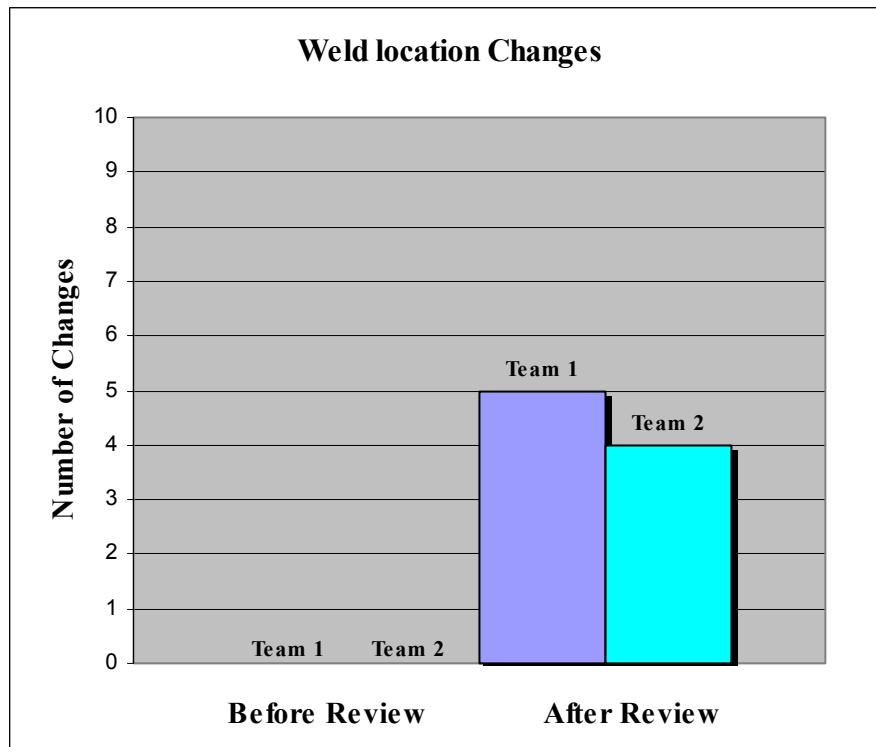
Figure 21: Change in Weld locations: average

During the review, each group found a number of issues with their construction sequences. The construction planners were able to identify out-of-sequence activities in the schedule that they developed in at least four instances.

For example, Figure 22 below shows the Team 1's schedule for 11/22/2002 before review in the IVE. The figure shows the objects already installed in their original color and the objects being installed in black. Figure 23 shows the schedule for 11/22/2002 of Team 1 after review in the IVE. The figures clearly show that Team 1, after reviewing their schedule in the IVE, realized that they could have installed more objects by that schedule date. Even though this did not change the total number of schedule days, it is a significant improvement.
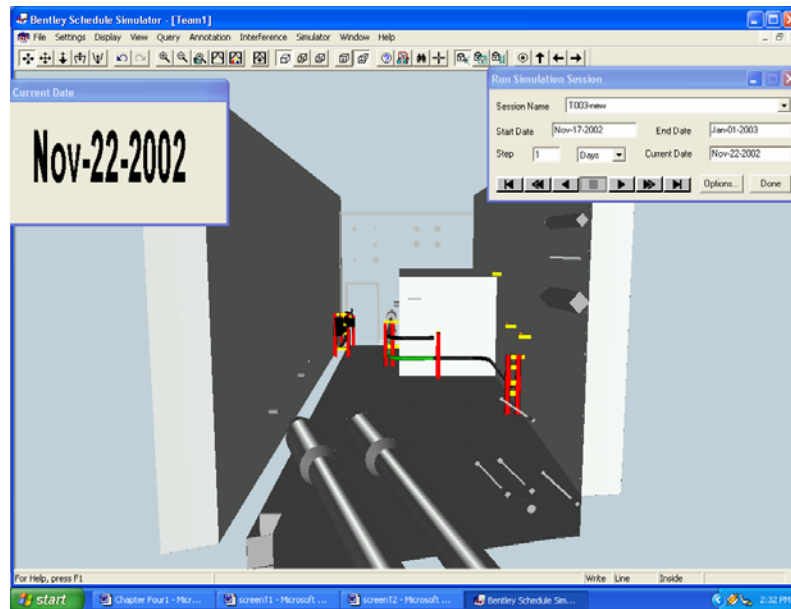
Figure 22: Team 1 – Schedule for 11/22/02 before review in IVE
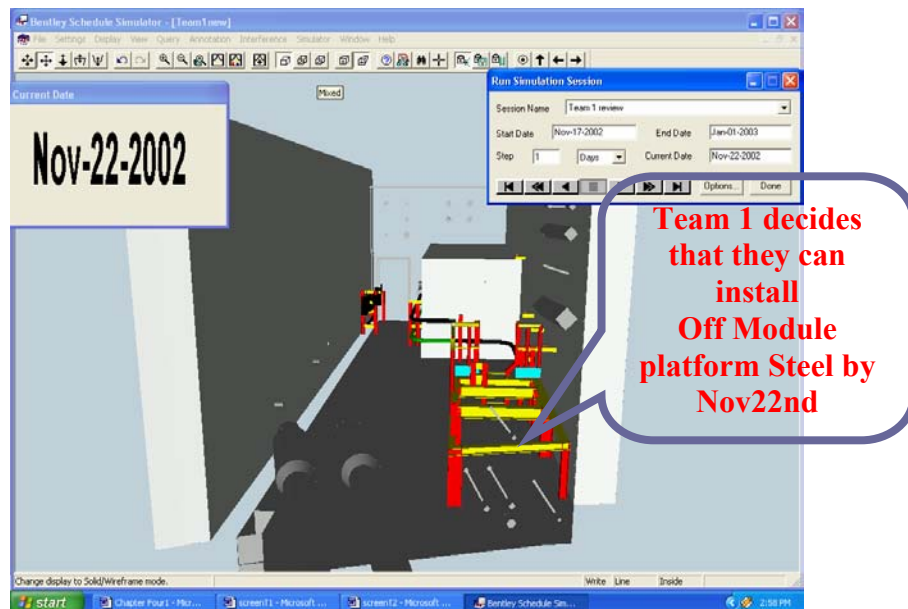
Figure 23: Team 1 – Schedule for 11/22/02 after review in the IVE

An example of the out-of-sequence activities in the schedule developed by the teams is shown in Figure 24. As shown in this figure, the original schedule generated by Team 1 for 12/09/2002 has the makeup piece installed before the off module platform. During the review in the IVE, Team 1 realized that this would make installing the off module

platform difficult as it would be lowered into the room using a crane and might damage the pipes already installed.

Figure 24: Team 1 – Schedule on 12/09/02 before review in the IVE

Figure 25 shows the schedule of Team1 for 12/03/2002 after the review in the IVE. As shown in the figure, the team installed the off module platform before the makeup piece.
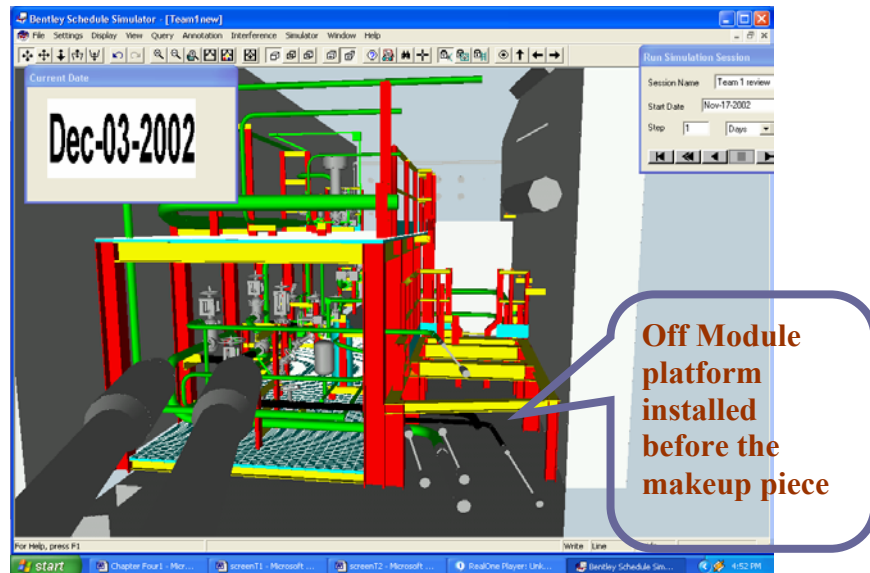
Figure 25: Team 1 – Schedule for 12/03/02 after review in the IVE

Another out-of-sequence example is shown in Figure 26. The figure shows the schedule for 11/21/2002 developed by Team 2. The original schedule developed by Team 2 has the off module platform installed before the makeup pieces underneath the platform. During the review in the IVE, the team realized that welding the makeup pieces would be difficult because of the inaccessibility of the makeup pieces. Also, they realized that the inspectors would not want to go under the platform to inspect the welds.
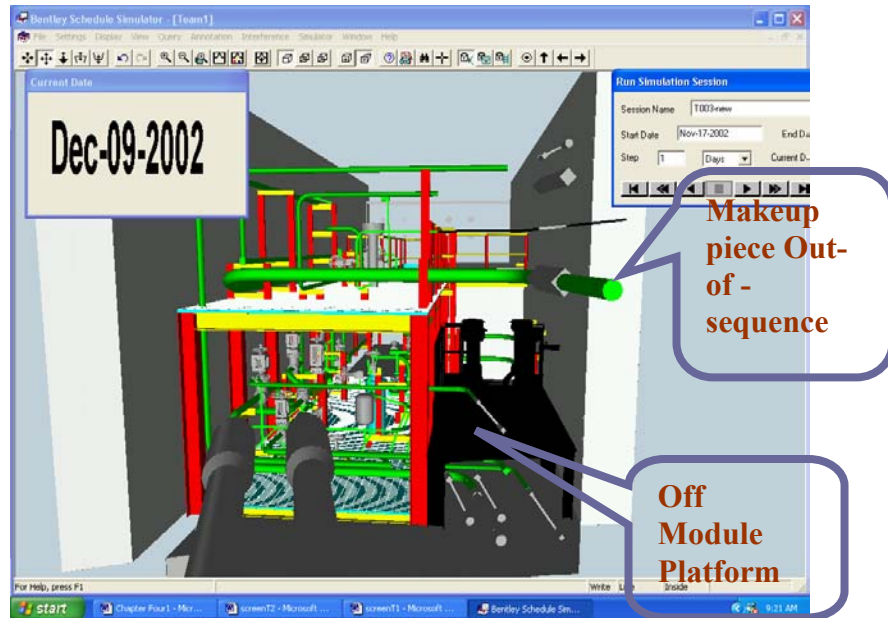

Figure 26: Team 2 – Schedule for 11/21/02 after review in the IVE

Figure 27 shows the schedule of Team 2 after the review in the IVE. As shown in the figure, the makeup pieces are installed before the off module platform.
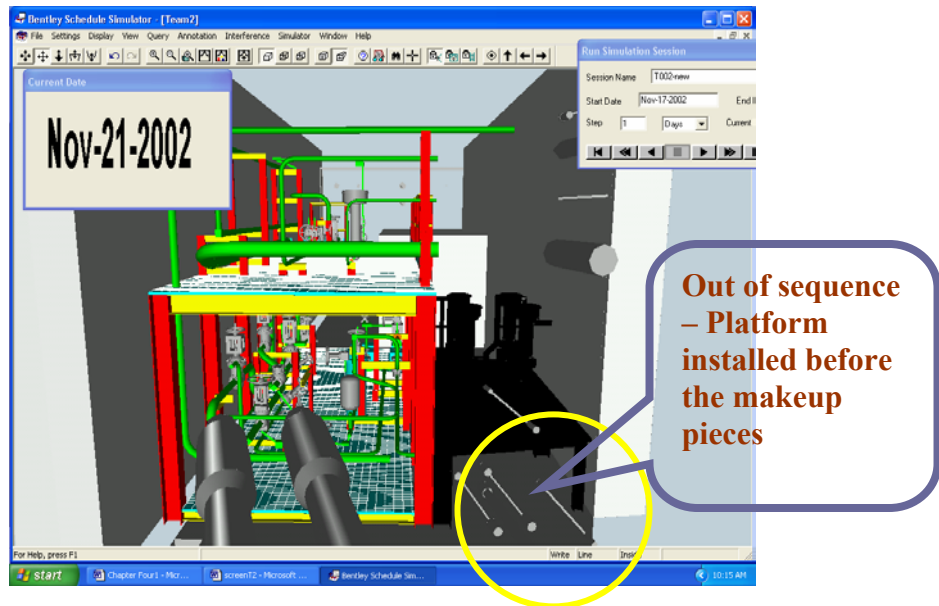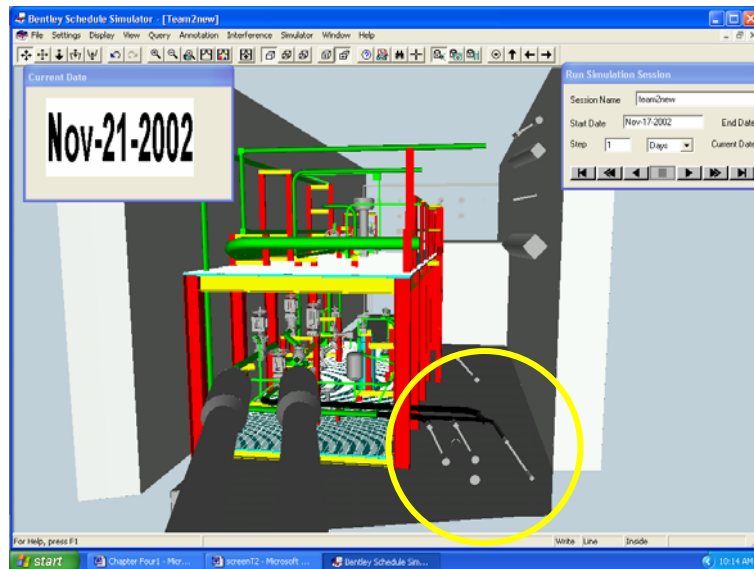
Figure 27: Team 2 – Schedule for 11/21/02 after review in the IVE

Once the participants refined their installation sequence to their satisfaction, the changes were incorporated into the data file. At that time both teams were invited to view the playback of the sequence developed by the other team. This activity was performed to simulate a constructability review where two construction alternatives were presented. The groups discussed each other's development strategy and the associated tradeoffs. The groups agreed that the IVE helped them to visualize the actual layout space better than the 3D isometric paper drawings. The planners also realized that certain welds needed inspection. This resulted in further changes to the installation sequence to facilitate access to the weld inspectors. During the schedule review in the IVE, the planners realized that they could have sequenced more parallel activities

The participants pointed out two areas in particular that would require further study. The first area of interest was the off module platform (shown in Figure 28) that supports four air-operated valves and two four-inch pipes. Using the 3D isometric paper drawings provided, it was unclear that four makeup pieces of varying diameters pass underneath the platform, complicating the sequence of installation. Each group discussed possible strategies for installing the makeup pieces and the platform. One group suggested installing the platform without the grating to allow more access to the area underneath, while the other group suggested installing the makeup pieces first and then the platform.

The groups were weighing the possibility of damaging the pipes underneath during the lift against ease of installation and inspection.
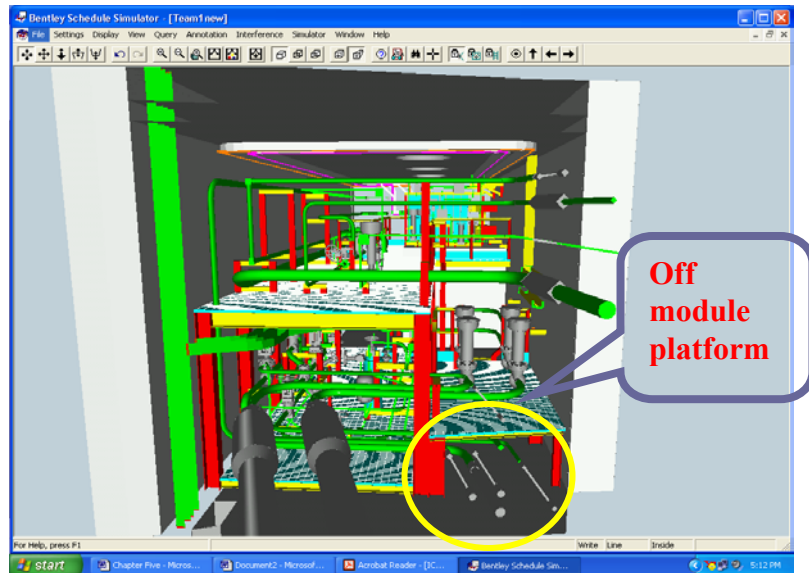
Figure 28: Off module platform supporting the air-operated valves

Another area of interest to the participants was the Fire Protection System (shown in Figure 29). The Fire Protection System was designed for installation as a prefabricated assembly. One group divided the installation of the assembly into two separate lifts.
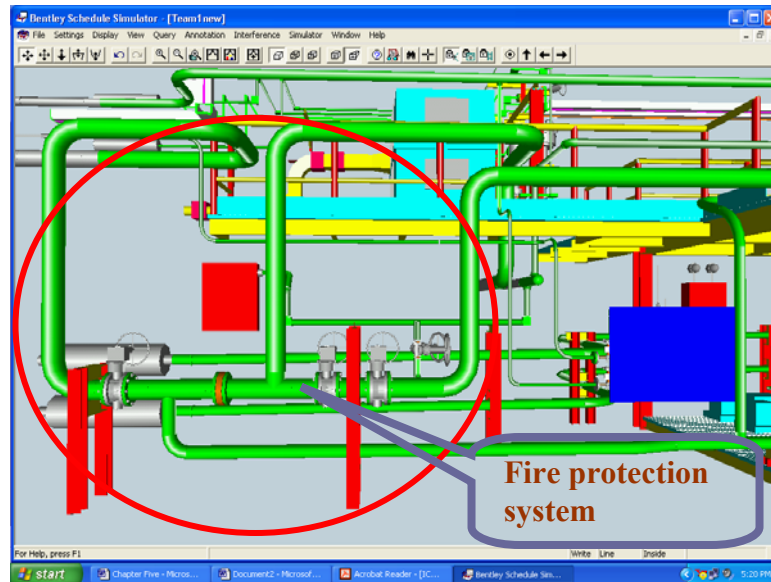
Figure 29: Fire Protection System
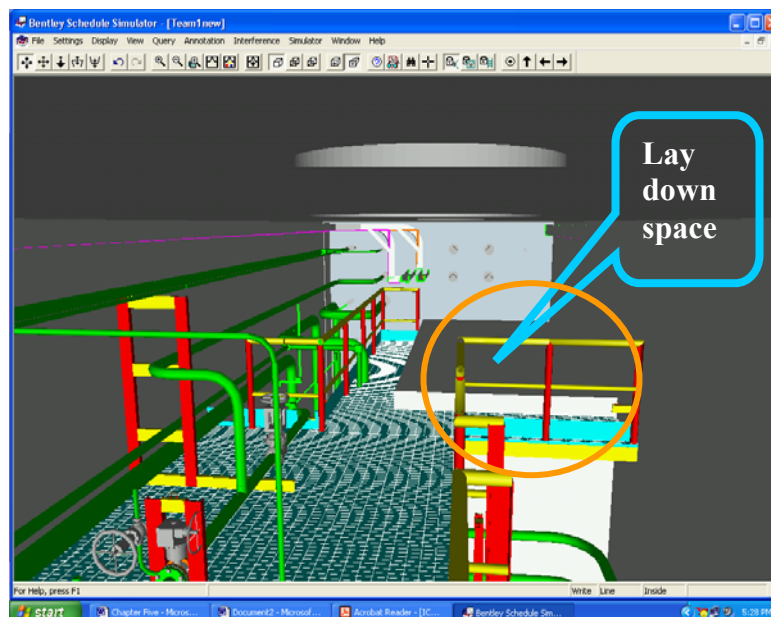
Figure 30: Initial lay down space for the Fire Protection System

The first lift placed the assembly in a lay down space (shown in Figure 30) above its final location. The second lift would move the assembly into place so that installation could be completed. The two lifts were intended to allow access for workers and equipment to a nearby doorway to be maintained. During the review, the measuring tape feature in the IVE

was used to determine if sufficient clearance around the assembly was maintained. The second group chose to install the Fire Protection System in one lift, although they decided that some of the weld locations would have to be moved to improve access and constructability.

5.3.4. DEVELOPMENT OF AN INSTALLATION SEQUENCE IN THE IVE

After the review, the two groups were combined into one and were given the opportunity to develop an installation sequence in the IVE using the interactive scheduling technique. The teams spent less than one hour developing a final sequence using the IVE.

The planners mentioned two points while developing the sequence. First, the IVE gave them a good spatial understanding of Room 12306. This allowed them to develop parallel crew assignments. Second, they gained valuable insight into possible constructability issues. They mentioned several alternatives for field weld locations.

Figure 31 shows the number of schedule days each team planned for the installation of Room 12306 during: (1) the paper based schedule development, (2) review in the IVE, and (3) schedule generation in the IVE.
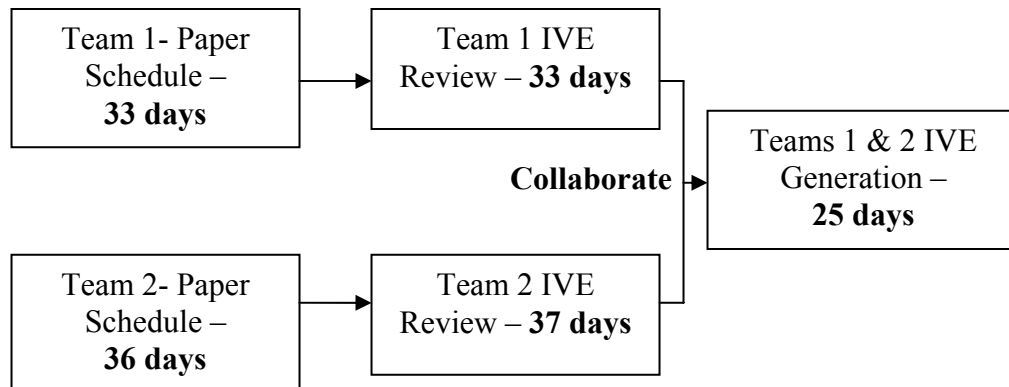
Figure 31: Schedule review and generation process

5.3.4.1. RESULTS

As shown in Figure 31, Team 1 scheduled 33 days for the installation of Room 12306 during the paper based schedule development stage. After the review in the IVE, Team 1 still had 33 days scheduled for the installation of Room 12306, but they made changes to their sequence as discussed in Section 5.3.3. Team 2 scheduled 36 days for the installation of Room 12306 during the paper based schedule development stage and had 37 days scheduled after the review. Team 2 also identified issues noted in Section 5.3.3. The collaborative schedule generation in the IVE resulted in the installation of Room 12306 to be 25 days. The planners managed to identify design issues, constructability issues, and out-of-sequence activities during the review process in the IVE, and were able to reduce the schedule by 28% by collaboratively generating the schedule in the IVE.

The planners may have applied the lessons learned from the activities earlier in the day while collaboratively generating the construction plan in the IVE. In the sequence developed collaboratively, the participant's scheduled three teams to perform the makeup piece installation in parallel, which led to significant savings in schedule time. Based on these findings, additional trials of the experiment are warranted to determine if this significant reduction in schedule is a result of the collaborative planning approach or if it is due to the enhanced sense of spatial perception offered by the IVE display system. The participants mentioned that generating the schedule in the IVE allowed them to recognize additional opportunities for parallel work, which they had not taken advantage of in the schedules they developed on paper using the CAD drawings.

Some of the reactions of the participants are as follows:
- "It made me aware of how much more work could be done in parallel. It allowed me to feel and see the open space areas. It also allowed me to re-arrange the sequence allowing for more efficient and productive construction." – *Planner 1*

- "IVE would, early on, identify problems with constructability issues, design issues, sequence, and inter discipline interfacing challenges" – *Planner 1*
- "It is easy to identify work that can be done in parallel, proper field weld locations and interferences using the IVE." – *Planner 2*

The experimental results provide valuable insight into the effectiveness of the IVE for project planning. The results illustrate that the IVE was a beneficial schedule review tool, as it helped the construction planners to identify constructability issues they could not identify while developing the schedule using the 3D isometric paper drawings. The planners recommended design changes, module boundary changes, and weld location changes to the design, after reviewing in the IVE. The planners did not recommend any such changes while developing a schedule using the 3D paper drawings. It is clear that the planner's spatial comprehension of Room 12306 improved while viewing it in the IVE. The existing visualization techniques (desktop 3D and 4D) do not have the capabilities of visualizing on a 1 to 1 scale. Even though, these techniques can improve schedule reviews, the amount of time taken to perform these activities is far greater than when using the IVE.

The IVE was also found to foster good communication as it generated discussions between the two groups with different construction plans, when given the opportunity to critique each other's plan. This quality of the IVE can be very useful for a project with multiple stakeholders and where a clear dialogue is necessary to satisfy each of their goals. The IVE can help achieve unequivocal communication, eliminating confusion due to individual visualizing capabilities. The ability of an IVE to host a group of 4 to 5 planners at the same time helps set a means of communication between the project participants. The foremen, welders, and crew members can also get involved in the schedule development/ review process and contribute to the development of an optimum schedule.

The IVE can also be used as a schedule generation tool. The planners were able to optimize the schedule by generating the schedule in the IVE, thus improving the schedule reliability and their schedule confidence. The reasons for these improvements could be attributed to either the ability of the IVE to help generate schedules or the combined capabilities of the IVE (review, communication, and generation tool). Nevertheless, it is difficult to diminish the effectiveness of the IVE as a tool for project planning.

5.4   SUMMARY

This chapter described the experiments performed to test the feasibility of the IVE for project planning and their results. The next chapter presents a process model for generating construction plans in the IVE. A recommendation of the new features necessary to enhance the IVE is also provided.

CHAPTER SIX

PROCESS MODEL FOR DEVELOPING CONSTRUCTION PLANS IN IMMERSIVE VIRTUAL ENVIRONMENTS (IVE)

This chapter proposes a logical process for assisting construction planners as well as future researchers to develop construction plans using an Immersive Virtual Environment (IVE). The chapter begins with a discussion of the process and describes the various steps involved for developing a construction plan. Then, a recommendation of the IVE features and tools that would enable efficient development of a construction plan is presented.

6.1.   INTRODUCTION TO THE PROCESS MODEL

The model explained in this chapter contains processes that need to be performed by construction planners and/or researchers to develop logical construction plans in the IVE. The model is organized such that it helps planners/ researchers identify the resources, mechanisms and constraints to perform each process. The scope of the process model is limited to developing construction plans in the IVE. The remainder of this section describes the model development and model description.

6.1.1. MODEL DEVELOPMENT

The process model for generating construction plans in an IVE was developed to define the process performed throughout the research and suggestions from the participants of the exploratory experiments. The model was developed using the $IDEF_0$ modeling method (ICAM 1981). The Integrated Computer Aided Manufacturing (ICAM) Definition Method (IDEF) is a set of structured analysis techniques for performing system analysis. Its main purpose is to provide engineering methods for analyzing and designing complex systems. A summary of the $IDEF_0$ modeling method is contained in

Appendix E. The model and the sub processes are explained in detailed in the following sections.

6.1.2. MODEL DESCRIPTION

The process model for generating construction plans in an IVE is shown in Figure 33. The figure depicts four sub processes of this model. These sub processes are interdependent and can be performed in a sequential order. The next section describes each of these sub processes in detail.

6.2. PROCESS MODEL FOR CONSTRUCTION PLAN GENERATION IN AN IMMERSIVE VIRTUAL ENVIRONMENT

This section describes the different sub processes for developing construction plans in the IVE. These sub processes are: (1) develop 3D facility model, (2) organize model by construction assemblies, (3) develop 4D construction plan, (4) review and communicate 4D construction plan. Figure 32 shows the overall input, controls, mechanisms, and output for the process.

The overall input for the "Develop 4D construction plan in the IVE" process is a 3D design model of the facility. The process is controlled by the construction methods used for developing the construction plan and resource information for the particular construction project. The 4D application in the IVE, the IVE display facility, 3D CAD software, and the project team are involved in the process to achieve the output. The output of the process is a 4D construction plan of the facility. Figure 33 shows the process for developing 4D construction plans in the IVE. Sections 6.2.1 to 6.2.4 describe the processes in detail.
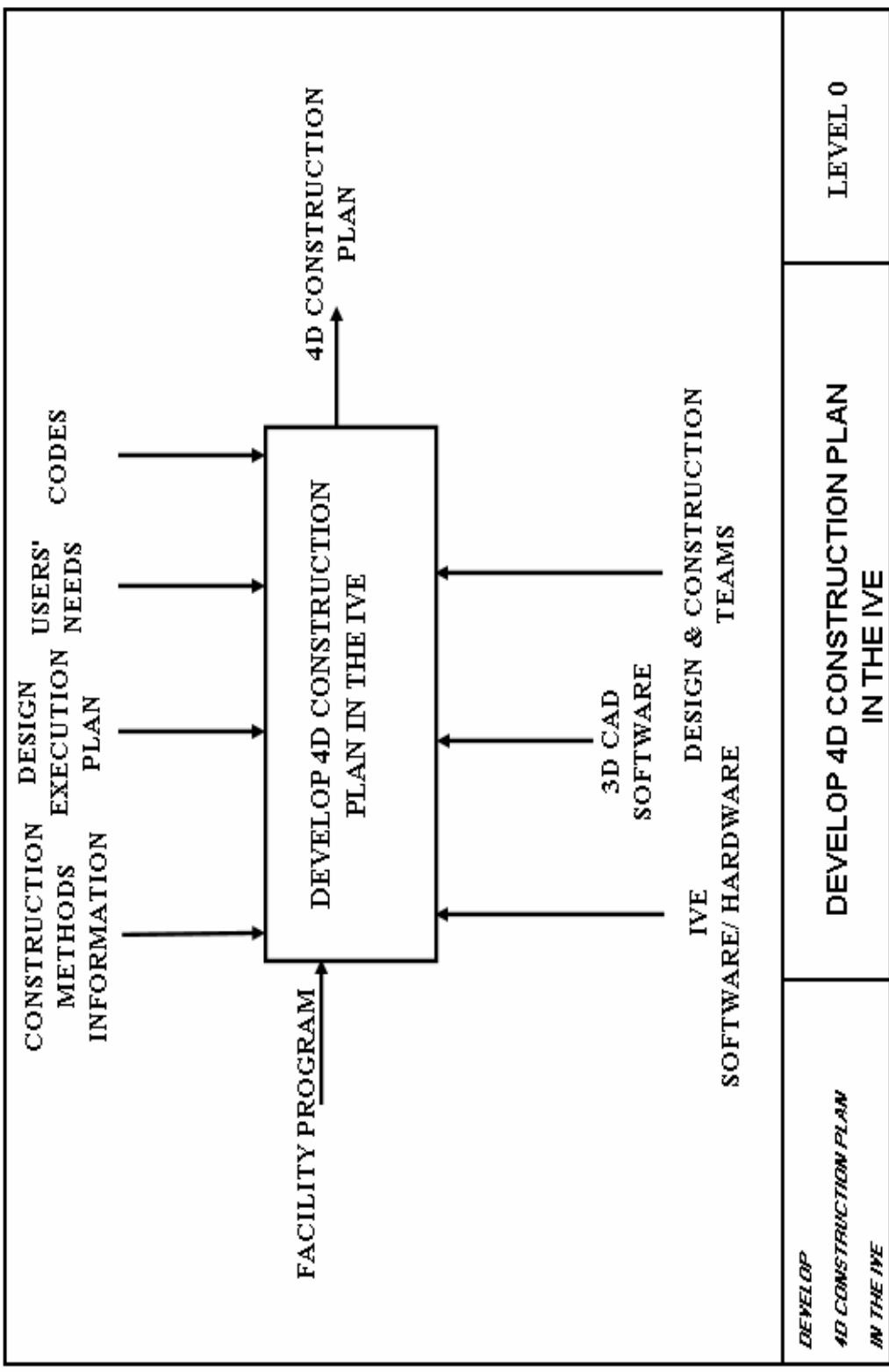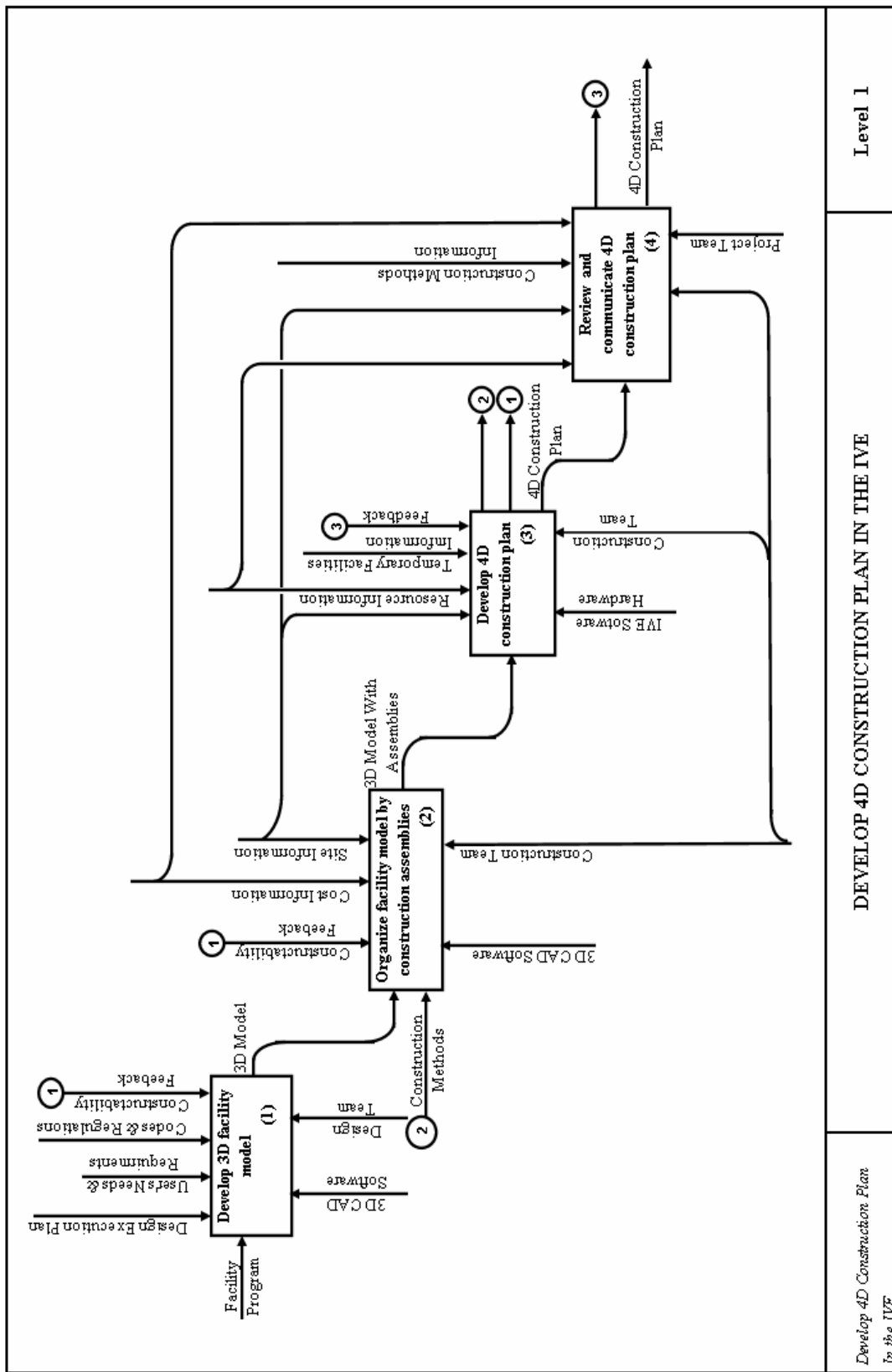
Figure 32: Develop 4D construction plan in the IVE

DEVELOP 4D CONSTRUCTION PLAN IN THE IVE

Figure 33: Develop 4D Construction plan in the IVE

6.2.1. DEVELOP 3D FACILITY MODEL

The process of developing construction plans in an IVE begins with the development of a 3D model of the facility. The facility program is the input for this process. The facility program includes: the design planning information that establishes the type and scope of the design to be performed, the project objectives, and the design parameters (refer to the "Design Facility" model in Integrated Building Process Model) (Sanvido 1990). The design of the 3D model is controlled by the user's design needs and requirements and the design's conformance to building codes and regulations. The design team performs this function using appropriate 3D software tools.

6.2.2. ORGANIZE MODEL BY CONSTRUCTION ASSEMBLIES

The second important function for developing construction plans in the IVE is the organization of the 3D model by construction assemblies. The input of this process is the information in the form of a 3D model. To perform this function, the planners must obtain information about the construction methods and site conditions. The planners must define and divide the facility into appropriate construction assemblies. For example, in the case study project used in this research, each construction assembly (referred to as a module) was defined as a prefabricated unit of pipes, valves, equipment, and structural steel. The case study room was divided into four such major assemblies and makeup pieces that connected these assemblies. The organization of the model by construction assemblies can be performed using 3D software tools by grouping together all the 3D objects defined as an assembly. It would be logical for the construction professionals to perform this task. The professionals may use software tools similar to those used by the designer during the design stage. This will avoid loss of information, geometry, and color of the graphical objects during transformation from one application format to another. The output of this process is a 3D model that is organized by construction assemblies.

6.2.3. DEVELOP 4D CONSTRUCTION PLAN

The third function for developing construction plans in the IVE is to develop the 4D construction plan. The output from the previous process will be used as the input for this process. To perform this task the construction team must obtain information about site conditions, resource availability and temporary facilities interactions. The construction planners develop the construction plan by using the IVE application during this process. A detailed breakdown of this process is shown in Figure 34.

In process 3.1, Define Methods, the construction methods are defined. This function is controlled by the site conditions, resource availability, cost, and the clearances and tolerances provided by the design. The output of this function is the construction methods used for building the facility. The construction methods information is feedback by a return loop into "Organize Model by Construction Assemblies" process if the model is not properly subdivided. At this stage, the construction methods used during the "Organize Model by Construction Assemblies" process are updated. In 3.2, Define Activities and Durations, the planners define the activities and the duration of each activity. The constraints for this function include site conditions, resource information and the construction methods. The output of this sub-process is the work breakdown structure of the construction project.
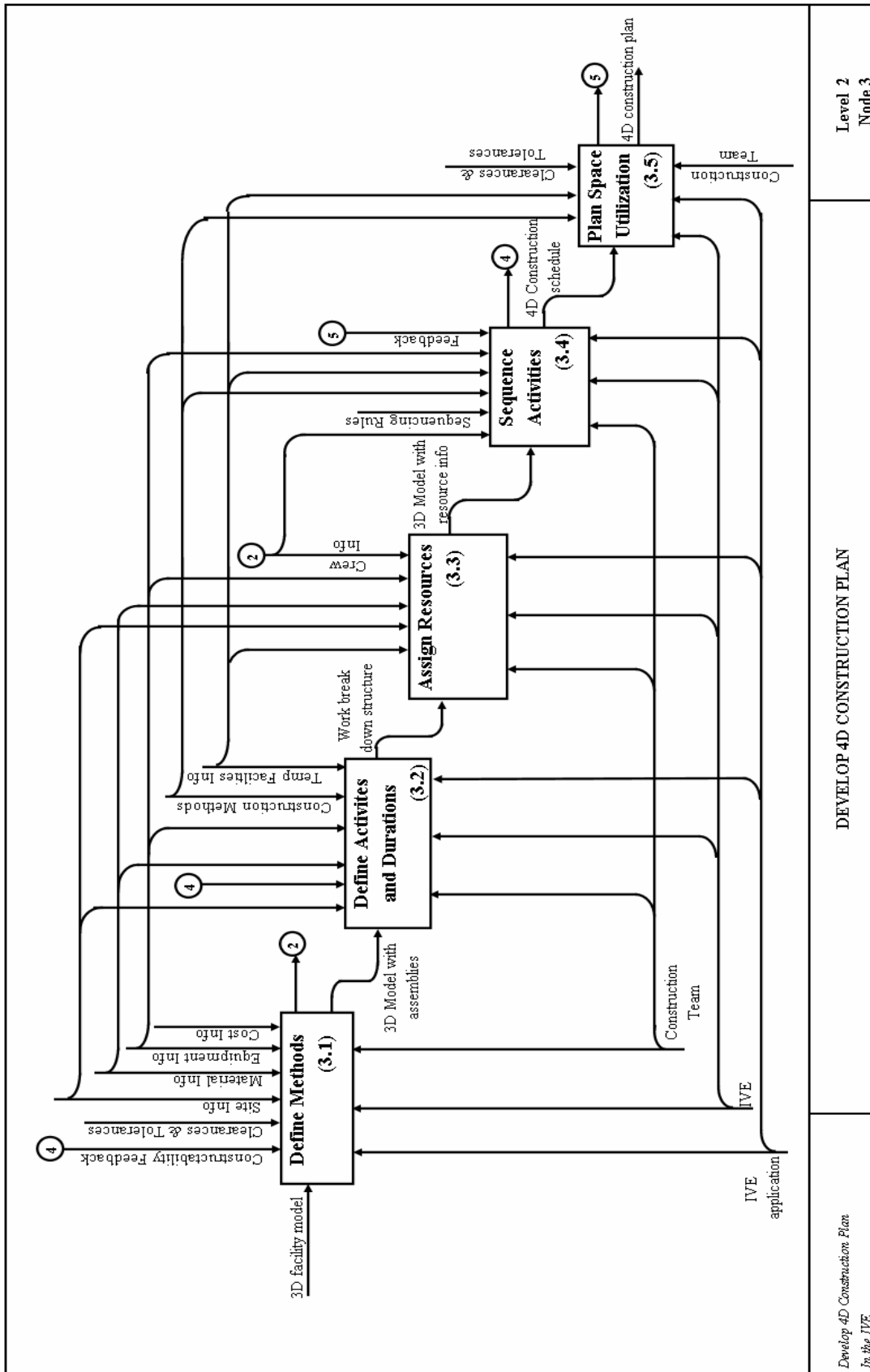
DEVELOP 4D CONSTRUCTION PLAN

Figure 34: Develop 4D Construction Plan

In 3.3, Assign Resources, the resource information (e.g., crew, equipment, material) is included in the model by the planners. The temporary facilities are included to the 3D model and its interaction with the crew and equipment is studied. The constraints in this function are crew, material, and equipment availability, site conditions, and temporary facilities information. The output of this process is the 3D model with important project planning information. In 3.4, Sequence Activities, the planners use the IVE application and the IVE display system to develop a construction sequence for the project. This process is controlled by the resource information, construction methods and the sequencing rules. The output of this process is a 4D construction schedule of the facility. In 3.5, Plan Space Utilization, the planners perform construction coordination of the crew, equipment and plan space utilization. The output of this process is a complete 4D construction plan of the facility.

Definitions of the sub-processes of "Develop 4D Construction Plan" shown in Figure 34 follow:

DEFINE METHODS (3.1): Defining the construction methods to be used for building the facility. Typically these methods include weld specifications, installation specifications, and quality control specifications.

ASSIGN RESOURCES (3.2): Deciding the resource requirements for the construction of the facility and allocating the resources to appropriate sections of the project.

DEFINE ACTIVITIES AND DURATIONS (3.3): Defining the construction activities and assigning duration to these activities. Typically each construction activity is given a unique name and the duration (man-hours or days) is assigned to the activity.

SEQUENCE ACTIVITIES (3.4): Deciding the installation sequence of the components of the project. During this phase, the relationships between different activities (precedence/ succession) are developed.

PLAN SPACE UTILIZATION (3.5): Coordinating the activity space requirements and identifying the time-space conflicts.

6.2.4. REVIEW AND COMMUNICATE 4D CONSTRUCTION PLAN

In this process, the project team uses the 4D application available in the IVE. The constraints of this process include construction methods, resource information, and site conditions. The review process is performed to check the construction plan generated during the "Develop 4D Construction Plan" process. Once the review is complete, the changes in the plan are fed back into the "Develop 4D Construction Plan" process for multiple iterations.

The final construction plan is communicated to other project stakeholders such as the owner, design team, and other contractors/sub-contractors. The feedback from this function is critical to improve the construction plan. The changes from the feedback are made in the "Develop 4D Construction Plan" process. At this stage, multiple iterations of the processes 3,4, & 5 are performed until a satisfactory and complete construction plan is generated. Whenever conditions change and as the project progresses a review and refinement of the construction plan should occur. The output of this process is a refined and complete 4D construction plan.

6.3 FEATURES RECOMMENDED IN THE FUTURE IVE

This section is intended to specify the features required to make immersive virtual environments a robust planning tool in the future. Some of these features were not implemented with this research. The researcher believes that by implementing these features into immersive virtual environments, the construction planning process can become more efficient and yield higher quality construction plans than the current planning techniques. The following list of features is recommended for implementation in the future IVE.

6.3.1   OBJECT AND PROJECT BASED INFORMATION

The user should be able to verbally or via some other interface enter object and project based information into the model in the immersive virtual environments. For example, the user should be able to select an object and verbally enter information such as the expected delivery date of the material, lay-down area for the material, crew assignments, equipment assignments, cost data, and parties responsible for the installation of the object. This requires implementing verbal interaction and interface programs in the IVE system. Along with the addition of robust data structures for the model the user should be able to query this information at any given time. For this purpose, the information related to a graphical object that is entered via verbal commands should be stored and retrieved as desired. This would enable the user to generate a logical construction plan and allow others to better understand the plan.

6.3.2   3D MODEL CHANGES

The user while generating or reviewing a construction plan in immersive virtual environments should be able to make changes to the 3D design model. For example, if the user feels that a pipe or a piece of equipment is too large to install in one lift, the user should be able to change the 3D object while standing inside the immersive virtual environment. This will require development of functions within the IVE that interactively change the 3D object file and communicate the changes to the design files. Additionally, the user (construction professional) should be able to flag objects that the designer is to review.

6.3.3   DISPLAY OF SCHEDULE DATES AND OTHER INFORMATION

During the review of the 4D simulation in the immersive virtual environment, the schedule date and time of the objects being installed should be displayed. This could be performed via small window at a corner of one of immersive virtual environments' walls.

The user should also be able to stop the simulation at any time and query the object and project based information. The user should also be able to make step-by-step simulation.

6.3.4 AUTOMATION OF THE PLANNING PROCESS

An automated process where the sequence generated by the planners is recorded during run time should be implemented into immersive virtual environments. The automation should allow the users to select the object of interest and verbally enter the schedule dates and/or relations (predecessor/successor) between activities. These verbal commands should be automatically recorded so they can be later retrieved for 4D simulation. Schedule calculating capabilities should also be available for generating the project schedule. This automated process would reduce the reliance on support personnel that was a limitation during the schedule generation process in the research project.

6.3.5 DISPLAY OF MODULE BOUNDARIES

Immersive virtual environments should be able to graphically display construction assembly boundaries when desired by the construction planners. This could be performed by delineating/highlighting the boundaries of the object. This would save time by allowing the user to readily identify whether the construction assembly is too large or too small and make necessary changes.

6.4. SUMMARY

This chapter described the process model developed to assist construction planners and researchers to develop a construction plan in immersive virtual environments. Features that should be implemented into the future IVE display systems were also recommended.

CHAPTER SEVEN

CONCLUSIONS

This chapter first provides a summary of the research results. The results are then compared to the current knowledge in various related research fields to identify the contribution of this research. This is followed by the limitations of the research that are inherent to the research methodology. A discussion of future research in the application of the Immersive Virtual Environments (IVE) to project planning is presented. The chapter concludes with a discussion related to observations and thoughts developed throughout the research process.

7.1. RESEARCH SUMMARY

This research analyzed the applications of an Immersive Virtual Environment (IVE) for project planning. By performing an exploratory study, it was possible to identify how the IVE could be used for improving project planning. The IVE was found to be an effective schedule review and schedule generation tool, as well as a robust communication tool.

To assist construction planners in the development of detailed construction plans, a set of features were incorporated into the IVE display system. The features were tested with the help of the participants of the first exploratory experiment (graduate construction management students). By interactively generating an installation sequence in the virtual environment and viewing it in the form of a 4D immersive model, the participants were able to identify constructability, design, and sequencing issues related to the case study project. The participants were able to become familiar with the case study project, generate the installation sequence for Room 12306, and view a 4D model of their sequence within only120 minutes using the IVE display system. The participants recommended a number of changes to the case study design for easier installation. It is important to note that the participants had no previous knowledge of the IVE display system or the case study project.

The participants of the second exploratory experiment (construction professionals) were provided with 3D isometric drawings of the case study project. They then developed construction schedules that were placed into the IVE display system for review. While reviewing their construction schedules, as 4D immersive models, the participants noticed out-of-sequence activities, constructability, and design issues that they did not notice while developing the schedules from the paper drawings. The participants recommended eight additional changes to the size of the assemblies and nine additional weld locations changes after reviewing their schedule in the IVE. After the review, all the participants were combined into one team and generated a new schedule for the case study project in the IVE. The participants reduced the scheduled number of days for the project by 28% by generating the schedule in the IVE. This may be attributed to the participant's realization that an extra crew may be assigned to the space for faster installation. The participants were able to produce a more detailed construction plan using the IVE. However, it is unclear whether this improvement to the schedule was due to the lessons learned from the schedule review process or the collaborative efforts of the participants.

A process for performing schedule generation in the IVE was developed based on the lessons learned from the experiments as well as the feedback from the participants of the experiments. This process identified four main processes for generating a schedule in the IVE: (1) Develop 3D building model, (2) Organize models by construction assemblies, (3) Develop 4D construction plan, and (4) Review and communicate 4D construction plan.

7.2. **RESEARCH CONTRIBUTIONS**

The various contributions of this study are discussed below.

7.2.1. **BENEFITS OF USING IVE FOR PROJECT PLANNING**

The benefits of using the IVE for project planning have been identified as follows:

- *General benefits*:
    1. Improved construction plan development (e.g., reduced schedule from 36 to 25 days);
    2. Ability to develop more detailed schedules with a more detailed understanding of schedule dependencies;
    3. Opportunity to decide weld locations, clearances/tolerances, equipment positioning, and resources during the schedule generation stage; and
    4. Improved schedule confidence and schedule reliability.

- *Schedule Analysis:* The IVE helped the construction planners identify constructability issues that led to design changes, weld location changes, and out-of-sequence activities in the already existing schedule.

- *Schedule Generation:* The IVE helped the construction planners to visualize clearances for pipe fitters, welders, and weld inspectors; the access to the space on a 1 to 1 scale; lay-down areas within the space; and tolerances between assemblies and equipment. The IVE also helped the construction planners to visually comprehend the resource requirements (e.g., the planners realized that they could use an extra crew for faster installation). The IVE allowed the planners to generate a more detailed schedule.

- *Collaboration and Communication:* During the schedule generation in the IVE, the planners discussed different strategies to install the case study project. Each group of planners critiqued the schedule developed by the other group. The IVE provided a

means of communication between the participants. The ability of the IVE display system to host a group of 4 to 5 people at the same time allows different parties in the project (owner, designer, engineers, and subcontractors) to get involved in the schedule development a review process.

7.2.2. PROCESS MODEL

A process model to show the steps involved in the schedule generation process using an IVE has been developed in this study. Construction planners and researchers may use this model to direct future application development for construction planning tools in immersive virtual environments.

7.2.3. DEFINITION OF FUTURE STUDIES

A very limited understanding of the applications of the IVE to construction was available prior to this study. This thesis has identified the potential use of the IVE for project planning. The results of the study are described using illustrative examples that provide future researchers with valuable insights into the effectiveness of this technology. The results and conclusions of this study may be used as a starting point for future research in this area.

The future research should:

- Develop robust yet simple-to-use IVE display systems that do not need the support of technical personnel for generating construction plans.
- Test the IVE technology on different projects and quantify the benefits and challenges related to using this technology.
- Study the benefits and challenges of using large-scale IVE display systems vs. small-scale IVE display systems; and large-scale immersive display systems vs. large-scale non-immersive display systems for construction planning.
- Study the feasibility of using IVE technology in project trailers for day-to-day construction planning.

7.3. LIMITATIONS

The limitations of the research are described in the following sections.

7.3.1. IVE APPLICATION LIMITATIONS

The current functionality of the schedule display application in the IVE system is not sufficient to automate the generation of a detailed schedule. For example, the schedule generation process requires that support personnel be present with the planners in the IVE to manually record the sequence of installation to develop 4D model. The process could be automated so the sequence generated by the planners is recorded during run time and displayed when desired. The current functionality does not allow changes to be made to the objects while generating or reviewing a schedule. If incorporated, this feature would help avoid a planner's reliance on support personnel.

The current 4D simulation does not include features that would enhance the schedule generation and review process. For example, the current 4D simulation in the IVE does not display the schedule dates or the schedule objects being installed. These features should be added to the IVE schedule generation application.

The current schedule generation application in the IVE display system is rudimentary; nevertheless, the results achieved using the current IVE display system suggest that with additional tools, construction planners will be able to develop more meaningful and detailed construction plans in a shorter time period than using traditional planning tools.

The IVE display system used in this research is a very high-resolution system with advanced visualization and magnetic tracking features. This makes the quality of the display system very good, but it also costs a significant amount at this time (over $1 million). This is a limitation that has to be overcome for a wider application of this technology. The advancing technology and computing capabilities, definitely have the ability to develop a robust, intelligent, and affordable IVE display system.

7.3.2. LIMITED CASE STUDY APPLICATION

This research presents the results from the study performed on a single case study. The lack of previous research in this area prompted the researcher to use exploratory research methods on a detailed case study. It is, however, necessary that more studies be performed to generalize the application of the IVE to other projects and construction planning in general.

7.4. FUTURE RESEARCH

The following sections contain suggestions for future research related to the use of the IPD for project planning.

7.4.1. SCHEDULE GENERATION TOOLS IN THE IVE

Future research on the IVE should focus on refining the tools available in the IVE display system for schedule generation. One specific area for providing a significant contribution is in developing a tool that helps a project planner to enter object based or project based information directly into the IVE (e.g., cost, material, equipment data, delivery dates, and crew availability on the schedule date). This would enable the planner to generate more comprehensive construction plans with greater reliability and detail. An additional area that could encourage wider use of the IVE would be to investigate the software and hardware technologies to reduce the cost of the IVE display system. Future research should also focus on performing a comparative study on the benefits/challenges of using immersive display systems and large non-immersive display systems.

7.4.2. IMPACT OF COLLABORATIVE PLANNING

Further research is warranted to study the impact of collaborative planning on a project. The participants in the experiments developed a detailed schedule by collaboratively generating a schedule in the IVE than by individually reviewing the schedule in the IVE.

It is unclear if this was due to a better spatial comprehension offered by the IVE or due to the collaborative effort of the participants. A more detailed study that identifies the impact of collaborative effort is necessary. The author believes that the improved visualization helps facilitate collaboration and provides a common visual mode to foster discussions.

7.5.   CONCLUDING REMARKS

The latest visualization technology enables viewing electronic images as if you were viewing the physical project in real life. Desktop monitors that provide depth perception without any additional equipment are now available. With the advent of the Internet and the World Wide Web it is now possible for two people at different locations to see the same model. Imagine a construction manager at a project trailer, the owner, and designer at different locations engaged in a visual conference by visualizing the same facility in 3D/4D on a 1-to1 scale. The technological advances in visualization are far ahead of those used in the current AEC industry. It is necessary that the AEC industry stays abreast to these technological advances and employs them for the betterment of the building construction process.

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APPENDIX A

CONTENT ANALYSIS

A.1. SUMMARY CONTENT ANALYSIS

A content analysis was performed on each of the questionnaires collected from the participants of experiment 1 and 2. A summary of the analysis is given below:

A.1.1. ADVANTAGES

All the participants agreed that the IVE was a good schedule development and schedule review tool. According to one participant the IVE was "helpful in rearranging the sequence, allowing for more efficient and productive construction". The IVE also helped the participants to realize that they could have performed more parallel work. The participants were able to readily identify design issues, constructability issues, sequencing issues, and interdisciplinary interfacing issues using the IVE. The participants also mentioned that the IVE could be useful to finalize resources, tool requirements and material availability during the pre-construction stage of a project.

A.1.2. DISADVANTAGES

All the participants agreed that the cost of the IVE was one of its disadvantages. They also mentioned that the construction professionals would need training to use the IVE and that they would also require a support group to perform the schedule review and schedule generation activities.

A.1.3. LEVEL OF CONFIDENCE

The participants mentioned that their confidence on the schedule improved after reviewing/generating the schedule in the IVE. Five participants rated their level of confidence on the schedule 8.0 / 10.0 before review in the IVE and 9.0/10.0 after the review in the IVE. The two participants rated their level of confidence on the schedule as 9.0/10.0 before review in the IVE and 9.0/10.0 after review in the IVE and one participant rated his

level of confidence on the schedule as 9.0/10.0 before review in the IVE and 10.0/10.0 after review in the IVE

A.1.4. ISSUES IDENTIFIED

The participants identified a variety of issues related to constructability, design and safety. Some of the issues identified are as follows:

- Pipe lengths, support locations, and weld locations should change to make welding easier and to provide adequate space for field welding and Non-Destructive Test (NDT) of welds.

- Identified that the schedule could be more aggressive with a second crew and do more work in parallel therefore, accelerating the schedule.

- Realized the availability of lay-down areas outside the room.

- Requires revising the sequence of some of the makeup pieces.

- Tolerance between the off-module platform and KB36 module. Requires re-engineering of the off-module supports

- The two air-handling units could be modularized and installed as one unit to reduce schedule time.

- Identified conflicts with the installation of supports of FPS valve assembly. The clearance for welding the supports to the assembly is not sufficient to perform satisfactory welds. The FPS valve assembly should be assembled in smaller pieces.

- 30' SGS pipe is a possible constructability issue. The pipe is too long to install as one piece. The pipe should be broken down into three smaller sections for easier welding.

- The off-module platform grating should be held off until pipe underneath is installed. This would avoid the issue of tighter welding clearances for the pipes underneath.

A.2.   CONTENT ANALYSIS MAPS

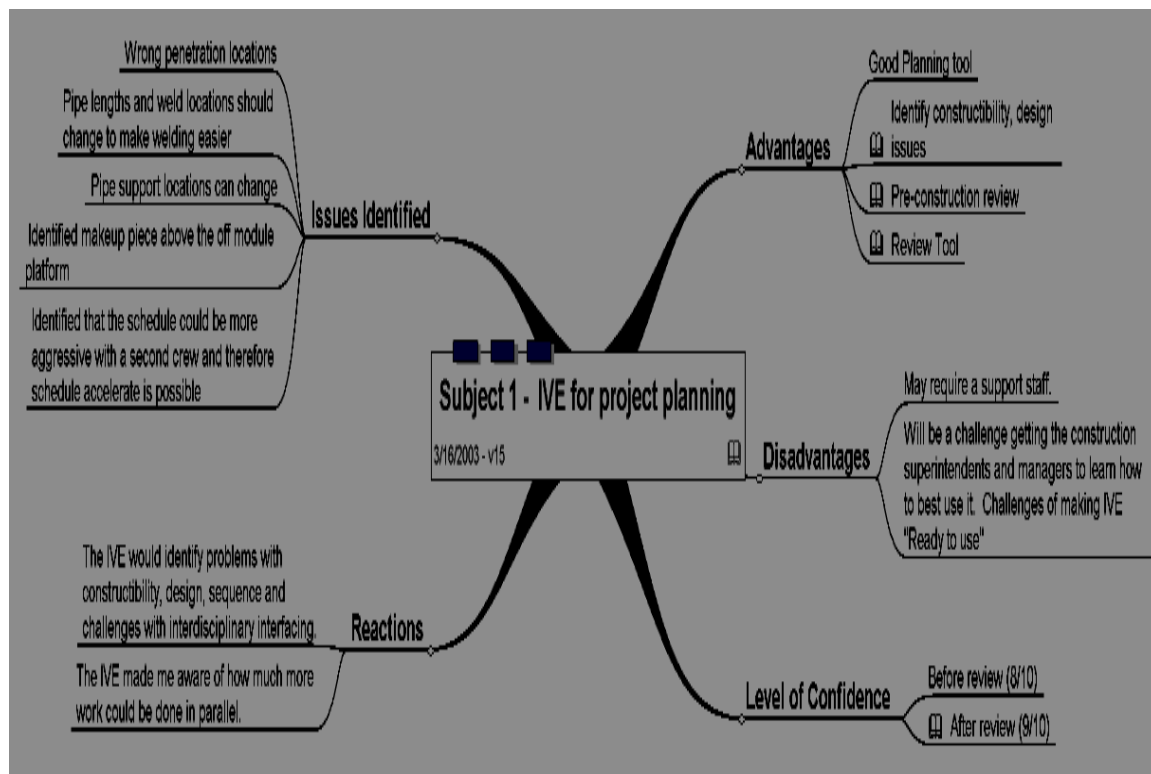Figure 34 to Figure 41 show content analysis maps for each survey performed:

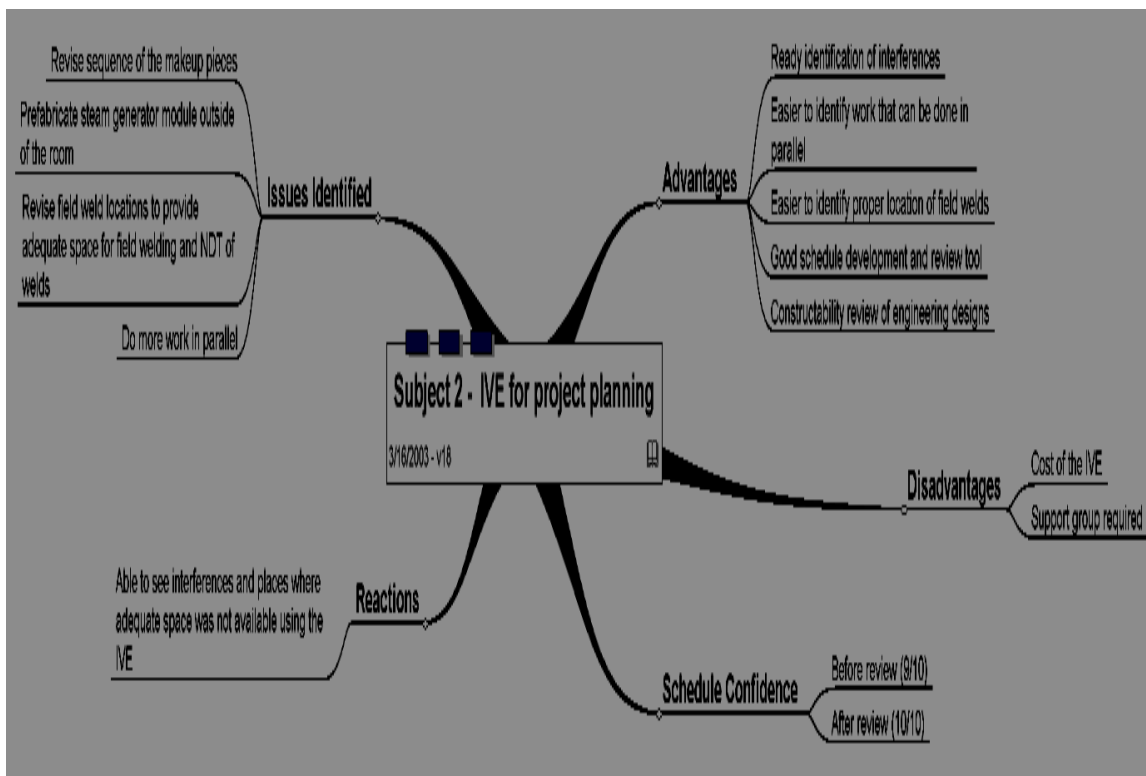Figure 35: Survey Content Analysis – Subject 1
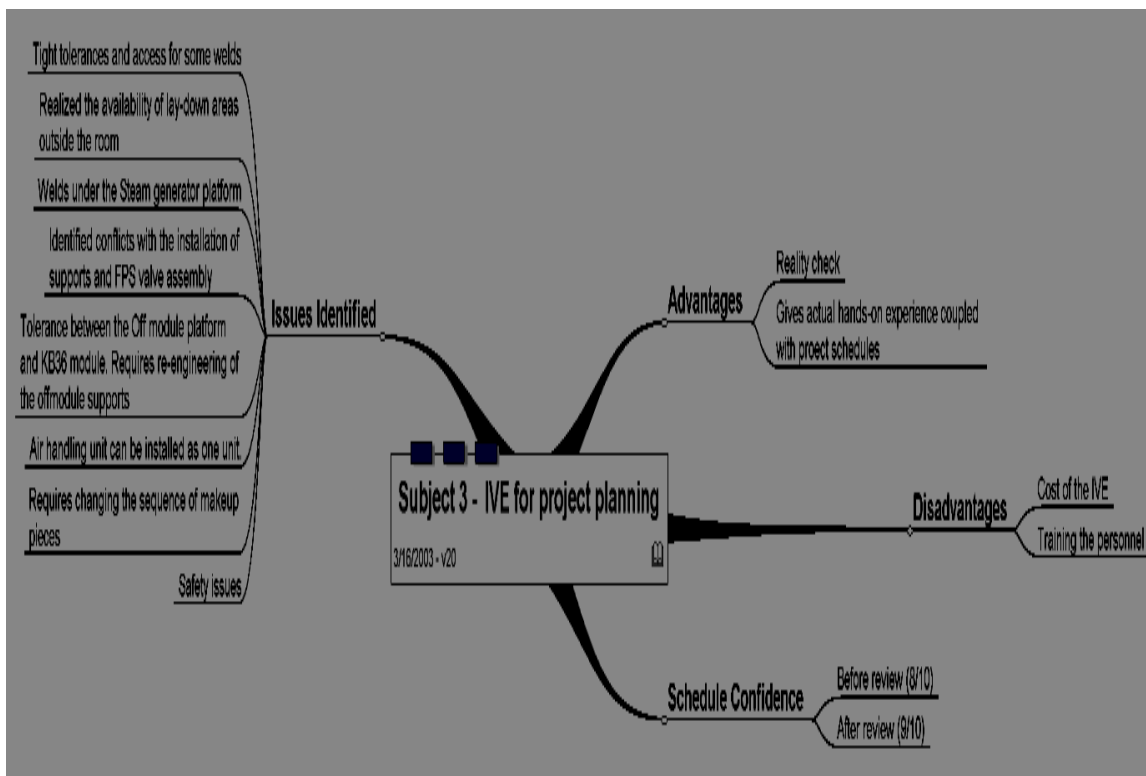
Figure 36: Survey Content Analysis – Subject 2
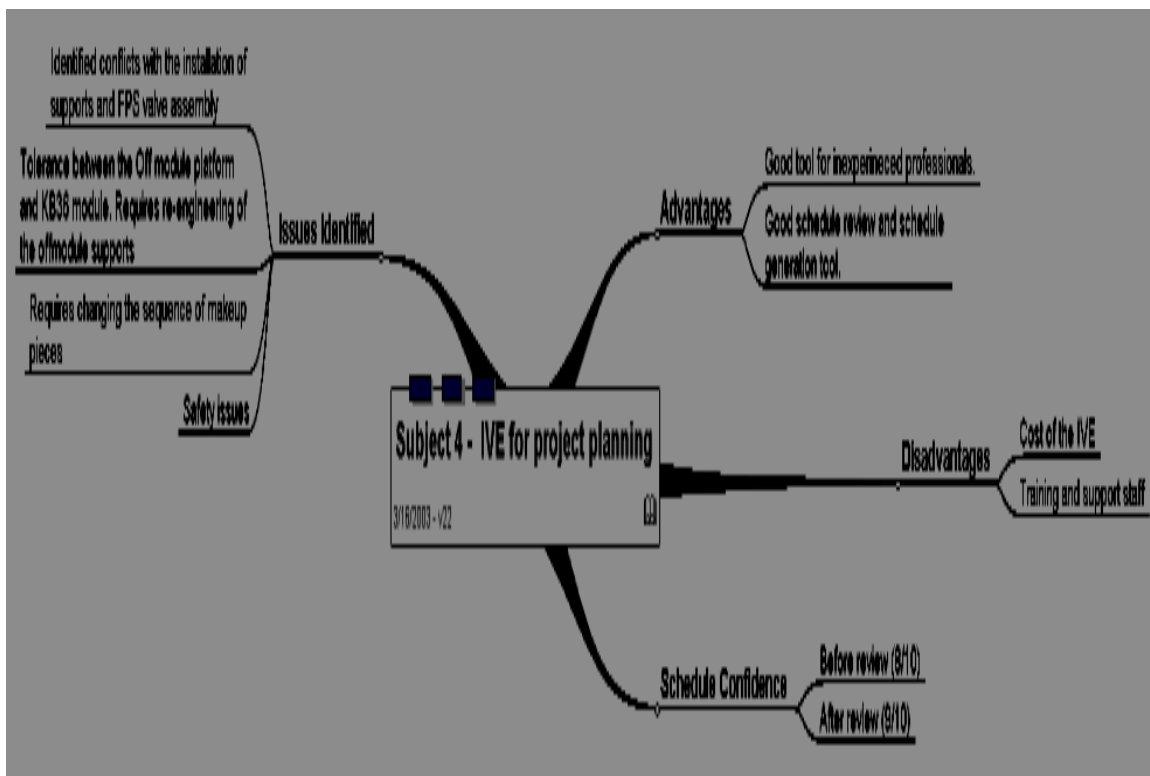
Figure 37: Survey Content Analysis – Subject 3

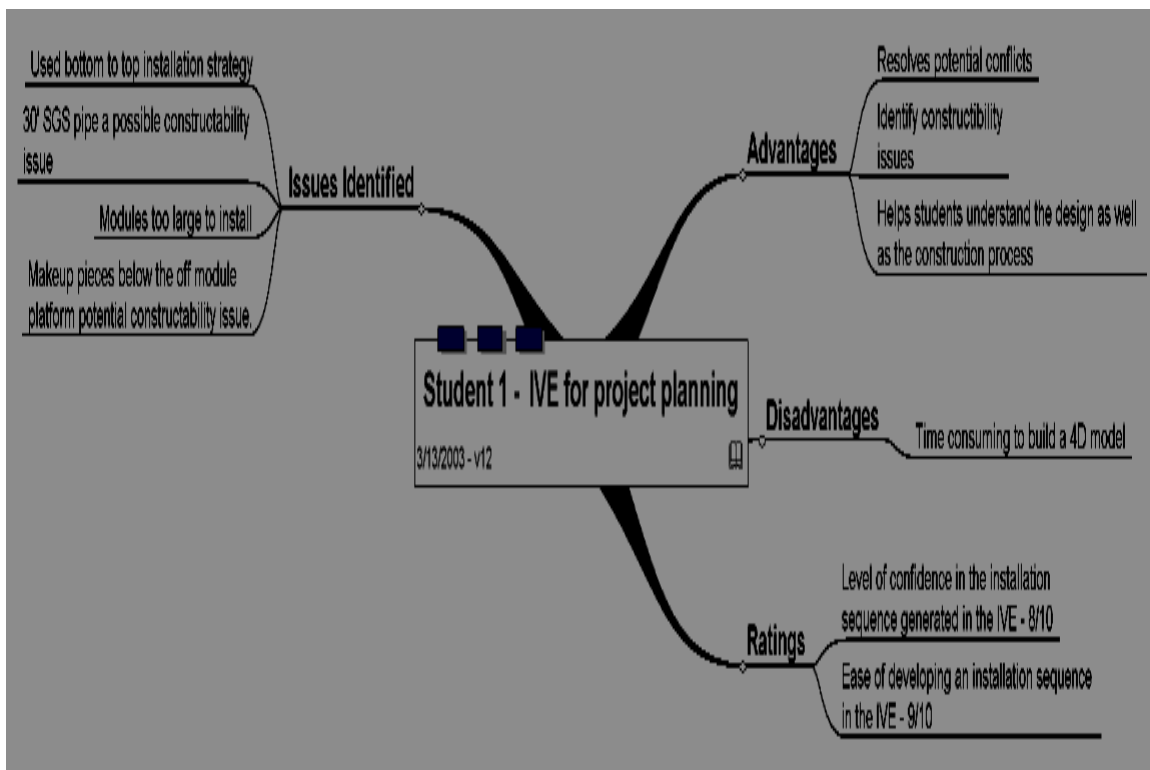Figure 38: Survey Content Analysis – Subject 4

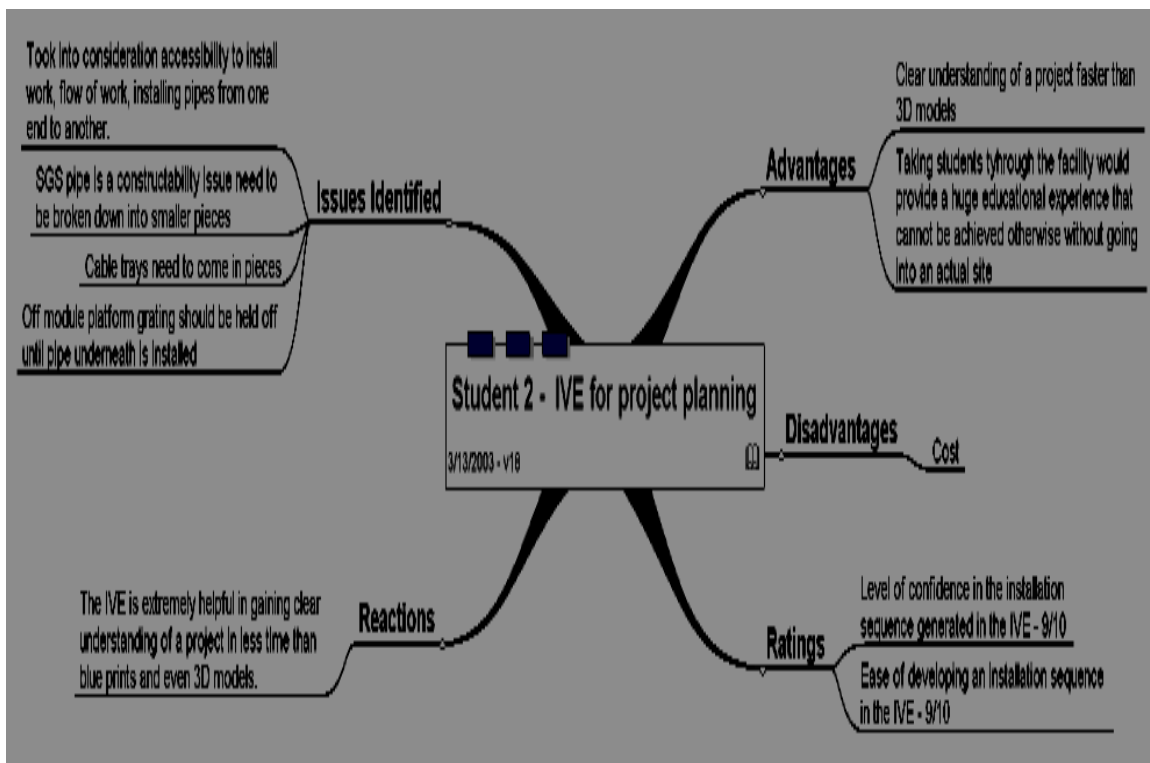Figure 39: Survey Content Analysis – Student 1
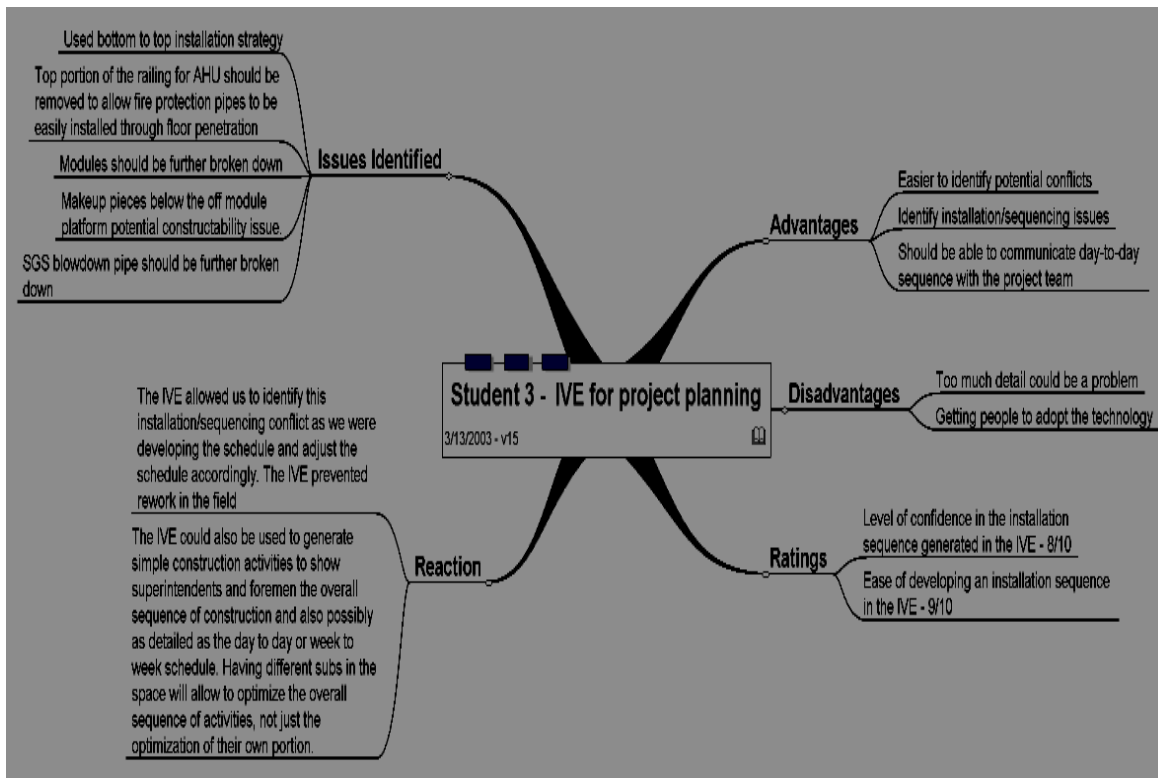
Figure 40: Survey Content Analysis – Student 2

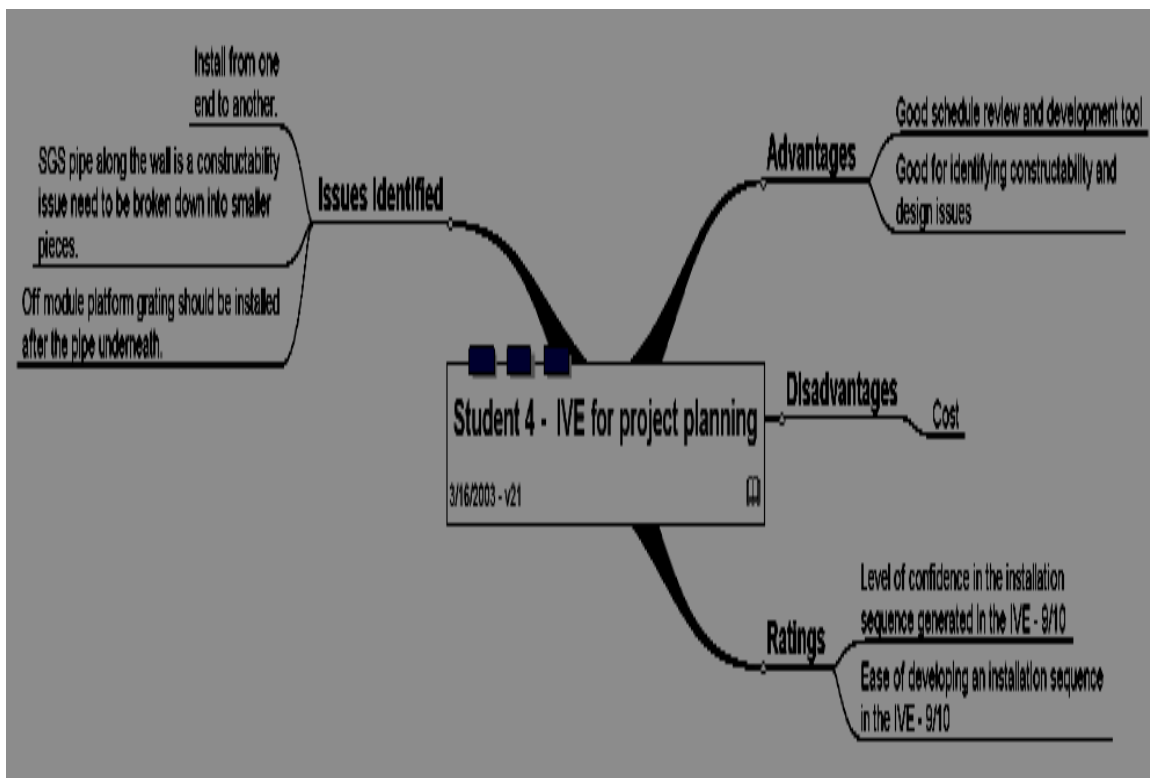Figure 41: Survey Content Analysis – Student 3

Figure 42: Survey Content Analysis – Student 4

APPENDIX B

QUESTIONNAIRE SURVEY

B.1. **EXPERIMENT I - QUESTIONNAIRE**

1. Name

2. Do you have any construction experience? If so, what type of building construction experience do you have? What type of projects and what position/tasks did you perform?

3. When you were developing the installation sequence for Room 12306, what sequencing rules did you consider?

4. Did you identify any constructability issues in Room 12306? If yes, please list them.

5. Did you identify any conflicts in Room 12306? If yes, please list them.

6. Did you find the need to change any module/assembly boundaries in Room 12306? If yes, where and why?

7. On a scale of 1 to 10 (1- very poor, 10- excellent), how would rate your level of confidence in the installation sequence you generated in the IVE?

8. Did you want to make any changes to your installation sequence after reviewing the 4D simulation?

9. On a scale of 1 to 10 (1- very poor, 10- excellent) how would you rate the ease of developing an installation sequence in the IVE?

10. What do you think are the benefits of using the IVE as a schedule development tool?

11. What do you think are the disadvantages of using the IVE IPD as a schedule development tool?

12. Can you think of any additional features that might help improve the use of the IVE as a schedule development tool?

13. How do you see the use the IVE for educational purposes?

14. Is there anything you would like to add?

B.2. **EXPERIMENT II - QUESTIONNAIRE**

1. Name

2. How much experience do you have in power plant construction? And what position/tasks did you perform?

3. While developing the schedule did you identify any constructability issues in Room 12306? If yes, please list them.

4. While reviewing the schedule in the IVE did you identify any constructability issues in Room 12306? If yes, please list them.

5. While developing the schedule did you identify any conflicts in Room 12306? If yes, please list them.

6. While reviewing the schedule in the IVE did you identify any conflicts in Room 12306? If yes, please list them.

7. While developing the schedule did you find the need to change any module/assembly boundaries in Room 12306? If yes, where and why?

8. While reviewing the schedule in the IVE did you find the need to change any module/assembly boundaries in Room 12306? If yes, where and why?

9. On a scale of 1 to 10 (1- very poor, 10- excellent), how would rate your level of confidence in the installation sequence you developed?

10. On a scale of 1 to 10 (1- very poor, 10- excellent), how would rate your level of confidence in the installation sequence you developed after reviewing it in the IVE and Why?

11. Did you want to make any changes to your schedule after reviewing the 4D simulation?

12. What do you think are the benefits of using IVE as a review tool?

13. What do you think are the disadvantages of using IVE as a review tool?

14. Can you think of any additional features that might help improve the use of IVE as a review tool?

15. Where in a project do you see the most value for the IVE (schedule development; schedule review) and why?

16. Is there anything you would like to add?

APPENDIX C

SCRIPT: EXPERIMENT BRIEFING AND TOUR

C.1.   EXPERIMENT BRIEFING

The objective of this experiment is to develop the installation sequence for the modules, assemblies and makeup pieces in Room 12306 of the AP600 nuclear power plant. The room consists of four large pieces and approximately 20 connecting pieces. These pieces connect the large pieces to each other and the other areas of the plant. Each module is a prefabricated unit composed of pipes, valves, pumps, structural steel and steel grating that will be shipped to the site by barge or rail.

The modules are designed to be lifted in to the room from the top using cranes. The modules will be lowered into the room and bolted to anchor bolts embedded in the concrete.

The boundaries of such module/assembly are pre-defined but are subject to change upon the participant's discretion.

The concrete in the room (except the ceiling) is already poured and thus, is not included as an activity in the installation sequence. The ceiling installation may be scheduled as an activity.

Makeup pieces, also known as spool pieces, are pieces of pipe that connect all the modules and assemblies in the room. These makeup pieces are field welded (manual or machine). The length of each makeup piece is pre-defined but is subject to change upon the participant's discretion.

C.1.1.   DESCRIPTION OF THE EXPERIMENT

The researcher and support personnel accompanied the participants throughout the duration of the experiment and guided the participants through the space and helped them navigate the space. The installation sequence was developed by identifying and selecting the module/assembly/makeup piece using the IDENTIFY and SELECT commands, respectively. The objects change color from their true color to red upon selection and remain red through the rest of the installation development process. The researcher manually recorded the

sequence in which the objects were selected. The participants were allowed to restart at any time during the experiment if they were not satisfied. The participants were asked to identify potential constructability issues, design issues, and develop an installation sequence. The participants were encouraged to share their thoughts during the experiment so that the researcher could record the issues identified as well as the decision-making rationale used by the participants. Only questions related to the functionality of the IVE and the systems in the room were be answered.

C.2. Tour

A tour of Room 12306 to explain the module boundaries and the functionality of the IVE was given before the start of the experiment. The tour started at the center of the room (space between KB36 and FPS assembly), the initial viewpoint in the simulation. The participants navigated from the center of the room to one end of the room, then back to the center of the room and then to the other end of the room. The participants were allowed to identify and select the modules in the room to identify their boundaries. The tour ended at the center of the room.

C.2.1. KB-36

Module KB-36 is the largest single piece of Room12306. Most of the piping and valves in the module are part of the passive containment cooling system. The passive containment cooling system is an emergency system that works to prevent containment over-pressurization during an accident. In addition to the passive containment cooling system, a few other systems pass through the module. Makeup pieces for this module connect to the containment, the west wall, the north wall, and the fire protection system containment isolation valve station.

C.2.2. OFF-MODULE PLATFORM AND SGS BLOWDOWN VALVES

The off-module platform sits next to module KB-36. On top of the platform sit four air-operated valves. Two pipes pass through the air-operated valves. These pipes are the steam

generator blowdown lines. Within Room 12306, the blowdown lines start at the shield wall at the south end and end at the wall to the turbine building at the north end. Four makeup pieces attach to the valves on the off-module platform.

C.2.3. FIRE PROTECTION SYSTEM CONTAINMENT ISOLATION VALVE STATION

The fire protection system containment isolation valve station is an assembly containing a few pipe sections and a number of valves. These valves may be used to isolate the fire protection system in case of an accident. Four makeup pieces are connected to the FPS assembly. These makeup pieces connect to the north wall, KB-36 (2), and to the stairwell.

C.2.4. AIR-HANDLING UNITS

The air-handling units provide heating and cooling for the area. The AHU may be installed in pieces or as a pre-assembled skid. Makeup pieces for this module have not been modeled separately.

APPENDIX D

SAMPLE TABLE-BASED DATA FILE

```
// Explorer Config File

explorer {
    pos 0 0 0 0 0 0;
    id_type object;
    max_speed 1;
    glove_grab 0;
}

crane {
    scale .25;
}

bookmark {
    pos   0.000 0.000 0.000 0.000 0.000 0.000;
    voice "go home";
    key   "1";
}


bookmark {
    pos   -1.232 1.869 0.417 90.0 0.000 0.000;
    voice "go to valve space";
    key   "2";
}

bookmark {
    pos   -5.583 0.201 0.139 0.000 0.000 0.000;
    voice "go to spool";
    key   "3";
}

bookmark {
    pos   -1.427 1.467 -0.736 0.000 0.000 0.000;
    voice "go to tilted valve";
    key   "4";
}

bookmark {
    pos   4.789 2.280 2.254 -45.0 -25.000 0.000;
    voice "go to interference";
    key   "5";
}

bookmark {
    pos   3.020 2.546 0.397 165.000 0.00 0.000;
    voice "go to penetration";
    key   "6";
}

bookmark {
    pos   -2.396 -0.352 1.233 90.000 -20.000 0.000;
    voice "go to steam generator valves";
    key   "7";
}

bookmark {
```

```
    pos   -4.460 1.011 2.767 -90.000 0.000 0.000;
    voice "go to second floor";
    key   "8";
}

bookmark {
    pos   0.896 0.654 2.767 -105.000 0.000 0.000;
    voice "go to air handler";
    key   "9";
}
// installation sequence events are input in the following manner:
// object (start time) (end time) "object name";
sequence "Room12306"
{
    speed 1.0;
    object 1.0 1.1 "P0:North and West Wall";
    object 1.0 1.1 "P0:Floor";
    object 1.0 1.1 "P0:East Wall";
    object 1.0 1.1 "P0:Penetration 1";
    object 1.0 1.1 "P0:Penetration 2";

    object 2.0 10.0 "P1:Module K B 36 W L S";
    object 2.0 10.0 "P1:Module K B 36 P C S";
    object 2.0 10.0 "P1:Module K B 36 F P S";
    object 2.0 10.0 "P1:Module K B 36 D W S";
    object 2.0 10.0 "P1:Module K B 36 C V S";
    object 2.0 10.0 "P1:Module K B 36 V P C S";
    object 2.0 10.0 "P1:Module K B 36 V D W S";
    object 2.0 10.0 "P1:Module K B 36 V C V S";
    object 2.0 10.0 "P1:Module K B 36 Chemical Addition Tank";
    object 2.0 10.0 "P1:Module K B 36 Recirculation Heater";
    object 2.0 10.0 "P1:Module K B 36 P C S Pumps";
    object 2.0 10.0 "P1:Module K B 36 Steel";
    object 2.0 10.0 "P1:Module K B 36 Supports";
    object 2.0 10.0 "P1:Module K B 36 Grating";
    object 10.0 20.0 "P36:Makeup Piece 22";
    object 20.0 30.0 "P33:Makeup Piece 19";
    object 30.0 40.0 "P12:F P S Piping and Valve Assembly";
    object 40.0 50.0 "P14:F P S Piping and Valve Assembly V F P S";
    object 50.0 60.0 "P32:Makeup Piece 18";
    object 60.0 70.0 "P34:Makeup Piece 20";
    object 70.0 80.0 "P2:Off Module Floor Supports and Steel";
    object 70.0 80.0 "P4:S G S Blowdown Makeup Piece";
    object 70.0 80.0 "P4:S G S Blowdown Piping and Valves V S G S";
    object 70.0 80.0 "P4a:S G S Blowdown Piping";
    object 70.0 80.0 "P3:Off Module Pipe Supports";
    object 70.0 80.0 "P6b:S G S Blowdown Piping Makeup PLW101";
    object 70.0 80.0 "P5b:S G S Blowdown Piping Makeup PLW91";
    object 70.0 80.0 "P7a:S G S Blowdown Piping Makeup PLW103";
    object 80.0 90.0 "P38:A H U 1";
    object 80.0 90.0 "P39:A H U 2";
    object 80.0 90.0 "P40:A H U Valves";
    object 90.0 100.0 "P37:Off Module Platform";
    object 100.0 110.0 "P5a:S G S Blowdown Piping Makeup PLW90";
    object 100.0 110.0 "P50:A H U Makeup Piece 7";

    object 100.0 110.0 "P13:F P S Piping and Valve Assembly P C S";
```

```
    object 110.0 120.0 "P6a:S G S Blowdown Piping Makeup PLW100";
    object 110.0 120.0 "P48:A H U Makeup Piece 5";
    object 110.0 120.0 "P27:Makeup Piece 13";
    object 120.0 130.0 "P31:Makeup Piece 17";
    object 120.0 130.0 "P51:A H U Makeup Piece 8";
    object 120.0 130.0 "P9:Off Module Wall Supports and Equipment";
    object 130.0 140.0 "P30:Makeup Piece 16";
    object 130.0 140.0 "P49:A H U Makeup Piece 6";
    object 130.0 140.0 "P17:Makeup Piece 3";
    object 140.0 150.0 "P29:Makeup Piece 15";
    object 140.0 150.0 "P46:A H U Makeup Piece 3";
    object 140.0 150.0 "P16:Makeup Piece 2";
    object 150.0 160.0 "P28:Makeup Piece 14";
    object 150.0 160.0 "P47:A H U Makeup Piece 4";
    object 150.0 160.0 "P15:Makeup Piece 1";
    object 160.0 170.0 "P20:Makeup Piece 6";
    object 160.0 170.0 "P44:A H U Makeup Piece 1";
    object 160.0 170.0 "P26:Makeup Piece 12";
    object 170.0 180.0 "P25:Makeup Piece 11";
    object 170.0 180.0 "P45:A H U Makeup Piece 2";
    object 170.0 180.0 "P35:Makeup Piece 21";
    object 180.0 190.0 "P24:Makeup Piece 10";
    object 180.0 190.0 "P7b:S G S Blowdown Piping Makeup PLW104";
    object 180.0 190.0 "P23:Makeup Piece 9";
    object 190.0 200.0 "P19:Makeup Piece 5";
    object 190.0 200.0 "P8a:S G S Blowdown Piping Makeup PLW93";
    object 200.0 210.0 "P18b:F P S Makeup Piece PLW631";
    object 200.0 210.0 "P7c:S G S Blowdown Piping Makeup PLW105";
    object 210.0 220.0 "P8b:S G S Blowdown Piping Makeup PLW94";
    object 220.0 230.0 "P18a:F P S Makeup Piece PLW630";
    object 230.0 240.0 "P10:Standard Service Module";
    object 230.0 240.0 "P22:Makeup Piece 8";
    object 230.0 240.0 "P21:Makeup Piece 7";
    object 230.0 240.0 "P11:Fire Hose Station";
    object 240.0 250.0 "P41:Raceway";
    object 240.0 250.0 "P42:HVAC";
    object 240.0 250.0 "P43:ceiling";
}
```

APPENDIX E

DESCRIPTION OF IDEF$_0$ MODELING METHODOLOGY

IDEF$_0$ PROCESS MODELING METHODOLOGY*

The process portion of the "d" was developed using the IDEF$_0$ modeling methodology. This appendix describes the IDEF$_0$ methodology.

E.1. THE IDEF$_0$ MODELING METHODOLOGY

In this section, the ICAM Definition (IDEF) Method is described. The structure and schematic representation of the IDEF$_0$ methodology is discussed, and the diagramming methodology is explained. For a detailed description, the reader is referred to publications by the Integrated Computer Aided Manufacturing organization (Integrated 1981).

The Integrated Computer Aided Manufacturing (ICAM) Definition Method (IDEF) is a set of structured analysis techniques for performing system analysis. Its main purpose is to provide engineering methods for analyzing and designing complex systems, and is used to understand and manage such systems (Wallace et al. 1987). IDEF supports multiple views of the system, and allows the system to be modeled from three different perspectives:

E.1.1. Schematic Presentation

Each box in the diagram represents a function that is an activity, action, process, operation, or a transformation (Integrated 1981). One or more inputs are transformed into one or more outputs using the mechanisms provided. The transformation process is controlled by one or more controls. Data is defined as any information or physical object that is transformed, constrains the function, or results from the function. The date entities are represented schematically in Figure E.1.

Five entity types are used in the IDEF$_0$ modeling methodology: function, input, output, control, and mechanism. Each is briefly described below (Integrated 1981):

- This description was adapted from Sanvido et al. (1990).

Function: An activity, action, process, operation, or transformation that is described by an active verb and an object is a function. The box in Figure E.1 shows the function.

Input: An input is an entity that undergoes a process or operation, and is typically transformed. It ensures the left of the box, and may be any information or material resource.

Output: Shown exiting the right side of the box, outputs include entities, such as data, which result from a process or objects that are created by a function.

Control: Control elements are entities that influence or determine the process of converting inputs to outputs. Controls may limit the activity or allow the activity to occur but will not be affected by the activity itself. On the diagram, controls are shown entering the topside of the box.

CONTROL

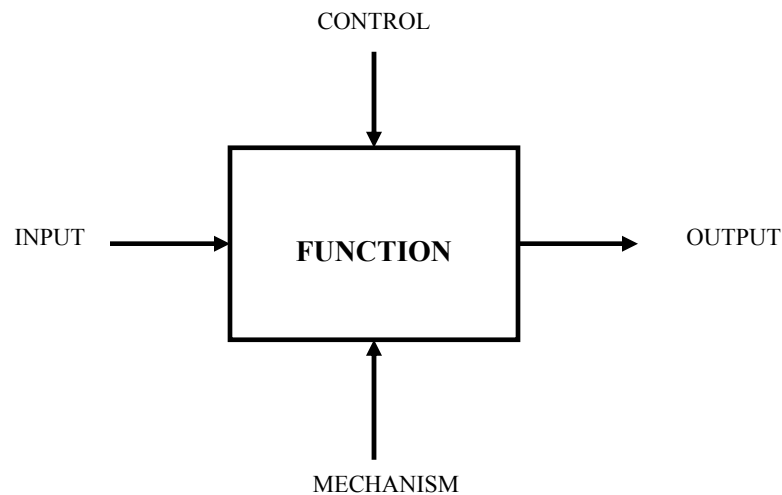INPUT → **FUNCTION** → OUTPUT

MECHANISM

Figure E.1: Schematic Presentation of the Function Box

Mechanism: Shown on the bottom side of the box, mechanisms are entities, such as a person or a machine, which perform a process or an operation. It describes how a process is accomplished.

An example is shown in Figure E.2, which demonstrates the use of each data entity type.
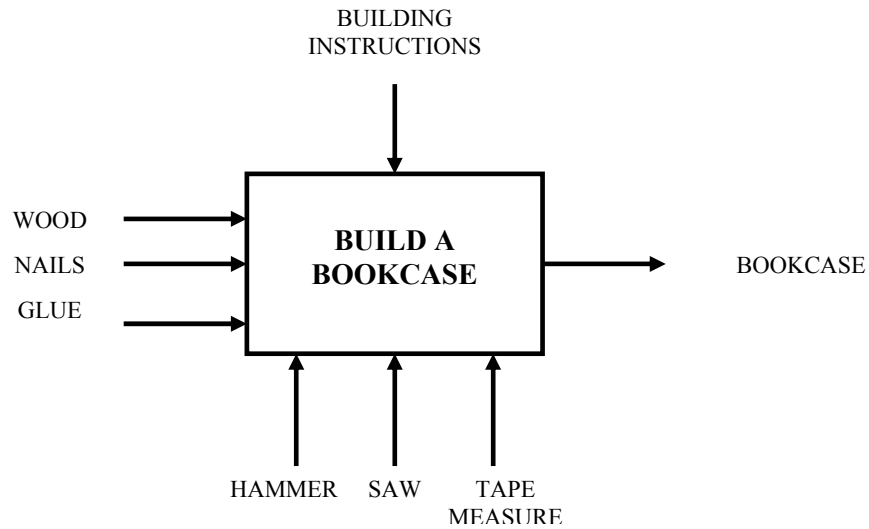

Figure E.2: Example of a Function Box Center

E.1.2. STRUCTURE OF IDEF$_0$

IDEF$_0$ represents a system by means of a model composed of diagrams, text, and glossary. The model is a series of diagrams with supportive documentation that divide a complex subject into its component parts (Integrated 1981). The diagrams consist of boxes and arrows that express the functional activities, data, and function/data interfaces. Text accompanies each diagram that narrated the activities in the diagram. In the glossary, all terms used in the diagrams are defined.

Hierarchy of IDEF$_0$ Diagrams:

IDEF$_0$ starts by representing the whole system as a single box with arrow interfaces to the environment external to the system. This box is decomposed into between three to six functions, each of which may be further decomposed into subprocesses. This top-down decomposition process may be continued, generating between three to six "child" or detail diagrams for each function on any given level. A hierarchy of diagrams results, as shown in Figure E.3.

Gradual Exposition of Detail:

The number of functions in each diagram is limited to a minimum of three and a maximum of six. This limits the level of detail and complexity in any diagram while preventing the diagram from

being trivial. The level of detail is also controlled by the position of the diagram in the hierarchy of diagrams. Each level of decomposition increases the amount of detail, resulting in a gradual exposition of detail. Decomposition along any given node is discontinued when the level of detail is sufficient for the application of the model.

Modularity of IDEF$_0$ Diagrams:

When a box is decomposed, the scope of the function and its interface arrows create a bounded context for the subfunctions. The scope of the detail diagram fits completely inside its parent function, and the interface arrows of the parent box match the external arrows of the detail diagram. Therefore, all arrows that enter or exit the detail diagram must be the same arrows that interact with the parent diagram.

Numbering the IDEF$_0$ Diagrams:

The highest level in the model which is the single the box representation of the system is labeled A-0. The next level of decomposition shows the major functions of the system and is called the A0 level. Each box in this level is labeled from A1 through A6. Further decomposition leads to additional digits placed after a decimal point, so that the diagram resulting from decomposing the first function on four successive levels represented by A1.111. This numbering system allows the user to retrace the steps of decomposition through the parent function of each diagram. The models developed in this report place the decimal after the letter, e.g., D.1.

E.1.2. TUNNELED ARROWS

To maintain integrity of the model, the diagrams must remain consistent from one level to the next. All data entities that interface with a function box must appear on its detail diagram as arrows entering or leaving the boundaries of the detail diagram. Exceptions may be made, however, with arrows that are tunneled. Tunneling indicates that the data conveyed by these arrows are not relevant to the particular level of detail.

Examples of tunneled arrows are shown in Figure E.3. Tunneling on the connected end (e.g. C3, O1) indicates that the data entity may not be shown in lower levels of detail. Tunneling on the

unconnected end (e.g. I1, C2) represents data entities, which may not be present in the higher level diagrams.
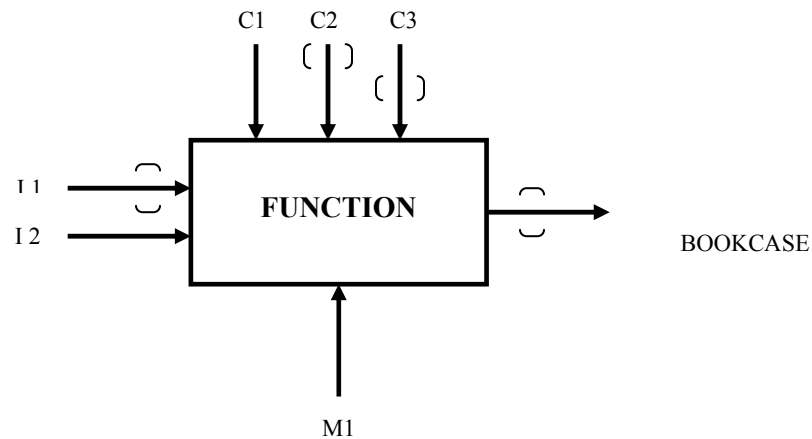
Figure E.3: Example of Tunneling

It is possible for tunneled data entities to not appear for several levels, and then reappear as a tunneled arrow. To reduce confusion, such data entities should be labeled at their origin.

E.1.4. READING IDEF$_0$ DIAGRAMS

The IDEF$_0$ model is a series of diagrams arranged in a hierarchical manner. The model is a read top-down, and the following sequence should be followed in reading it (Integrated 1981):

1. Scan the boxes in the diagrams to get a general impression of what is being described.
2. Refer back to the parent diagram and note the arrow connections to the diagrams. Try to identify a "most important" input, control, mechanism, and output.
3. Find the central theme of the current diagram. Try to determine if there is a main path linking the "most important" input or control and the "most important" output.
4. Mentally walk through the diagram from upper left to lower right, using the main path as a guide. Study the overall content of the diagram.
5. Read the text provided to gain a further understanding of the author's intent.