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IMMERSIVE VIRTUAL FACILITY PROTOTYPING FOR DESIGN AND CONSTRUCTION PROCESS VISUALIZATION

A Thesis in

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by

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ABSTRACT

Advanced visualization technologies have the potential to revolutionize the Architecture, Engineering and Construction (AEC) industry. An appropriate graphical representation of the facility design makes it easy to communicate complex design and construction information to project participants including the engineers, contractors, owners, and end users. Computer aided design (CAD) and 4D CAD (3D with project schedule) modeling tools enable the users to interact with the models but the media of interaction in such tools typically remains limited to 2D planar visualization.

The goal of this research was to explore the use of advanced visualization technologies for facility design and construction plan communication. This research explains the concept of Immersive Virtual Facility Prototyping (IVFP), a combined virtual model representing the physical facility (product) and construction information (process) displayed in a large immersive and stereoscopic display system. It enables users to view the model in stereo and interact with the model with the aim of evaluating the facility design and construction processes.

The application of an IVFP was studied through an illustrative case study project. Virtual models of the case study project were developed using commercially available CAD, 4D CAD and Virtual Reality Modeling Language (VRML) applications. Focus areas for the case study were construction plan communication and visualization of the facility design. Time studies, surveys and interviews of construction professionals involved in the project were conducted. Their opinions and perspectives of using this technology during the design, construction and operational reviews were analyzed. A large majority of the interviewees felt the use of the advanced virtual models in the immersive display facility was valuable for visualizing the design and construction process. Important recommendations were documented from the interviews and surveys. These recommendations can guide future virtual prototyping efforts in the AEC industry.

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CHAPTER 1

INTRODUCTION

Construction professionals in the Architecture, Engineering and Construction (AEC) industry organize detailed processes, develop intricate plans and conceptualize complex three-dimensional spaces. For each of these activities, adequate representations of a facility design are a prerequisite. The current methods of graphically representing a facility design are typically limited to two dimensions. Creating the mental models of the facility design and visualizing the complex processes involved in construction can only be achieved with significant years of experience. However, with the advent of technology in advanced visualization, there are innovative tools available to designers, constructors, and owners to improve their understanding of facility designs. Prototyping is one such concept that enables users to produce adequate representations of the design by using the latest computer applications for virtual prototyping.

This research investigates the concepts of prototyping with an emphasis on virtual prototyping including its benefits, further developments and areas of application in the AEC industry. To study the feasibility of these prototyping methods, a case study research project was undertaken wherein the construction professionals associated with a project interacted with an immersive virtual facility prototype of a building project. To understand the perception of the industry professionals, surveys and in-depth interviews of the participants were performed.

This chapter discusses the current visualization techniques used by the industry and describes the limitations of using these techniques. Then, it provides a description of this research study with a discussion of the research goal, objectives, research approach, research steps, research contributions and scope. A discussion of the thesis organization is provided at the end of this chapter to assist the reader.

1.1 Current Visualization Methods Used in the AEC industry

The most commonly used method of visualizing facility design in the AEC industry is through graphically representing the design in two-dimensional (2D) drawings. In addition to drawings, scaled physical models or full-scale mock-ups of portions of a project are sometimes built. The 2D drawings are primarily communicated on paper or viewed on computer screens. This form of media (two-dimensional viewing) is most commonly used, but does not allow many of the project participants to visualize the design in three dimensions since they may not have the skills to translate 2D into 3D.

Prototyping can help people visualize product designs. It is not a new concept and has been practiced since early times. The three main types of prototyping are physical, rapid and virtual prototyping. Physical prototyping of large facilities consumes significant time and cost, hence it is not viable to make a full scale mock up of a facility. Rapid prototyping can be understood as a process by which 3D models and components are produced additively, by fitting or mounting volume elements together (Gebhardt 2003). Rapid prototyping can be used to develop scaled models, but it is not feasible for the entire facility. On the other hand, virtual prototyping is creating 3D models by using CAD applications, which are generally viewed on a computer screen. These CAD applications have built-in features to navigate, zoom, and selectively view portions of a model. This provides users to better understand the model, but the two-dimensional media of a computer screen limits the users' involvement, which can be improved by displaying virtual prototypes in an immersive virtual display system.

1.2 Description of Research Study

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

1.2.1 Research Goal

The goal of this research is to define Immersive Virtual Facility Prototyping (IVFP) and explore its applications for design and construction process visualization on building projects in the AEC Industry.

1.2.2 Objectives

The objectives of this research are as follows:

1. *Identify problems and opportunities for improving the construction planning process by observing current plan communication processes.* A detailed time study of typical subcontractor progress meetings was conducted. Time spent on different categories of communication used in the meetings was determined and opportunities to improve the use of time are identified.

2. *Define the term immersive virtual facility prototyping and identify its applicability in the construction industry.* Previous research and documented studies in virtual reality applications have primarily focused on providing better tools of modeling and creating a model that closely resembles reality. This study concentrates on the media (or environment) that is used to communicate the models to the users. It is important to study how the users interact and behave in such an environment so that future display system requirements, including hardware, software and physical environmental characteristics can be defined.

3. *Define the lessons learned from the implementation of Immersive Virtual Facility Prototypes through an analysis of a case study construction project.* This study is an exploratory study that addresses the issue of the practical implication of using virtual reality applications on a building project. Data was collected to understand the perception of the owner, architect, construction manager, subcontractors and the end users of the case study project.

1.2.3 Research Approach

Research in the area of virtual reality applications in the AEC industry has been increasing throughout the past decade, but substantial data or information regarding the practical applications of this technology in the industry remains to be documented. This research was established as an exploratory investigation to study the applications of virtual facility prototyping through a detailed illustrative case study.

The following research questions were set forth for this investigation:

1. What are the current methods used for construction plan communication? How effectively are the communications conducted? What are the potential opportunities for improving the current methods?

2. What are the practical implications of using immersive virtual facility prototyping in construction?

3. What are the potential benefits of using immersive virtual facility prototyping?

4. What is the perception of industry practitioners towards this technology?

1.2.4 Research Steps

Since this research was designed as an exploratory based investigation, social science research techniques have been adopted. These research techniques include a case study, surveys, interviews and time studies. The data collected through these techniques are both qualitative and quantitative in nature. The research steps followed include:

1. *Literature review:* A literature review was performed in the areas of prototyping, virtual prototyping, immersive virtual environments, knowledge extraction, innovation, and communication methods used for construction plan communication.

2. *Obtain case study information:* The case study research was conducted on the School of Architecture and Landscape Architecture (SALA) Building at The Pennsylvania State University in University Park, PA. The case study focused on the use of immersive virtual facility prototyping to visualize and communicate the product design and construction process information to industry practitioners on this project.

3. *Time study of the subcontractor progress meetings:* To understand how effectively and decisively time can be used during typical project meetings, a detailed time study of the communication during subcontractor progress meetings of the case study project was conducted.

4. *Conduct a subcontractor progress meeting in the Immersive Environments Lab (IEL):* A subcontractor progress meeting was conducted in an immersive display system to study the impact of using immersive virtual facility prototypes as a communication and visualization tool in the meeting. The researcher collected survey data regarding the changes in attitude, improvements in visualization and understanding of the project displayed by the project team.

5. *Understand perceptions of key individuals on the case study project through a detailed virtual facility prototype:* Later, a more detailed virtual facility prototype of the SALA building was developed. Several construction professionals and decision makers associated with the SALA Building project were shown the virtual models in the immersive display system. Then, an in-depth interview was conducted to gain a deeper understanding of the implications of using immersive virtual facility prototypes in the AEC industry.

6. *Perform data analysis:* Quantitative and qualitative surveys were taken while performing research step 4 as illustrated above. Also, focused interviews and direct observations were taken. A comprehensive content analysis of the focused interviews from step 5 was also performed.

7. *Document the conclusions and lessons learned:* By conducting the subcontractor progress meeting in the immersive display system various issues regarding the level of detail of the virtual model, and the comfort of users in an immersive virtual environment were identified. Many suggestions and recommendations for improvements are documented in the results. This will help guide future research and implementation efforts.

1.2.5 Research Contributions

The primary research contributions of this exploratory-based research are:

1. A detailed time study of typical progress meetings describing the time spent on different categories of communication;
2. A detailed explanation of the concept of immersive virtual facility prototyping and the application of immersive virtual environments in the AEC industry; and
3. Documentation of the results and lessons learned from the case study application of virtual facility prototypes on an actual construction project including industry participants and other decision makers feedback and suggestions for improvements.

1.2.6 Research Scope

This research focuses on understanding advanced visualization technologies, specifically Immersive Virtual Facility Prototyping (IVFP). It brings about the importance of the media used for product and process design representations. This research aims to establish the value of using advanced visualization in the various facets of design and construction from an industry perspective, e.g., plan communication and visualization of design. Other potential benefits of using immersive virtual facility prototyping have been found in the areas of extraction of tacit knowledge and exploring innovative problem solution development. Systematic data collection in these mentioned areas was not performed in this study.

1.3 Thesis Organization

This thesis is divided in three sections. The first section consists of Chapters One through Three and explains the concept and need for advanced visualization techniques in the AEC industry. Chapter One provides an introduction to this research and explains the objectives, methods and scope of this research. Chapter Two provides a detailed description of the research techniques used for this study. Chapter Three summarizes the existing relevant literature for this study. This includes literature on prototyping, virtual prototyping, immersive virtual environments, knowledge extraction, innovation and construction plan communication.

The second section of the thesis consists of Chapters Four and Five which focus on the application of the technology described in Section 1. Chapter Four describes the case study project and the media (The Immersive Environments Lab) used for the case study experiments. Chapter Five consists of the analysis of the data collected through survey questionnaires, time study and focused interviews with construction professionals.

The third section of the thesis consists of Chapters Six and Seven and describes the results of this research. Chapter Six gives a description of the lessons learned through conducting the case study experiment in the IEL. Chapter Seven outlines future research in advanced visualization and provides a summary of the research results.

CHAPTER 2

RESEARCH METHODOLOGY

This chapter describes the research techniques used throughout this study. Due to the nature of this study, social science research methods have been used and an explanation of their selection is provided. A detailed research process description is also provided in this chapter.

2.1 Methodology Introduction

This research aims to evaluate the use of advanced visualization technologies (specifically immersive virtual facility prototyping) in the AEC industry from an industry perspective. Hence, the intention was to collect data that would draw the opinions and understandings of AEC industry professionals who have interacted with this technology. To understand the nature of this study, the researcher has followed Corbetta's suggestion of responding to three basic research questions (Corbetta 2003):

1. *The ontological question:* Does social reality [in discussion] exist?
2. *The epistemological question*: Is it knowable? and
3. *The methodological question:* How can we acquire knowledge about it?

Accordingly, the three main research questions addressed in this study are 'what is' and 'how much is' the value of using this technology? Can it be measured? And, how can it be measured? 'What', 'how' and 'why' are forms of questions generally faced in exploratory studies. Thus, this research is posed as an inquiry to understand the industrial perspective toward the use of Immersive Virtual Facility Prototypes (IVFP).

Marshall and Rossman (1999) state that an exploratory research strategy is applicable to:

1. Investigating little understood phenomena,
2. Identifying or discovering important variables, and
3. Generating hypotheses for further research.

Limited research on acceptance as well as resistance to using advanced visualization technology has been done in the AEC industry. With limited prior research, it was difficult to base this research on pre-established facts. So, this research was framed as an exploratory investigation with qualitative and quantitative data collection methods. For an exploratory study the common research strategies used are field studies and case studies (Marshall and Rossman 1999). The field study was not viable for this research, so a case study research method was selected.

2.2 Research Methods

Different research techniques were adopted in this study to facilitate comprehensive data collection. These techniques are the case study research method and within the case study, surveys, content analysis, direct observations and interviews were used. An explanation for the selection of these techniques is provided in the following sections.

2.2.1 Case Study Research Method

The case study research method is a common research strategy used in an exploratory study. Yin (1999) states that the distinctive need for case studies arise out of the desire to understand complex social phenomena. This research strategy aptly suits the scope of this study to understand the perspective of the industry professionals towards the use of advanced visualization technology. It helps to provide a holistic approach towards a real life event. The School of Architecture and Landscape Architecture (SALA) Building project was selected as the case study for this research. The reasons for selecting this case study are provided in Chapter Five.

2.2.2 Survey Techniques

A survey is a process of examining a social phenomenon involving an individual or a group, by gathering information through observation or asking (Corbetta 2003). A survey is an appropriate mode of inquiry for making inferences about a group of people from data drawn on a relatively small number of individuals from that group (Marshall and Rossman 1999). Hence, a survey is a research instrument designed to systematically collect the descriptions of existing phenomena in order to describe or explain what is occurring. In this research, it was of utmost importance to ask questions concerning the participants' attitudes and behaviors, for which the survey research techniques are appropriate.

Data can be collected in three different ways in a survey (Corbetta 2003):

1. *questionnaire*, when the question and answer both are standardized;
2. *structured interview*, when the question is standardized and the answer is expressed freely; and
3. *unstructured interview*, when the question and answer both are not standardized.

Questionnaires and structured interviews were used in this research. Questionnaire surveys were conducted to assess the influence of using advanced visualization tools among all the participants in the meeting held in the Immersive Virtual Environment. The responses to several questions were subjective while remaining questions were measured on a Likert scale of 1-5 (Corbetta 2003). These survey questionnaires were intended to measure attitude change; knowledge gain; visualization quality; and ease and comfort of using the technology.

2.2.3 Direct Observation

Direct observation is a method of data collection in which data is gathered through visual observations by the researcher. There are two types of direct observation methods: structured observation and unstructured observation (Yin 1999):

2.2.2.1 Structured Observation

In structured observation, the researcher determines at the outset precisely what behaviors are to be observed and typically uses a standardized checklist to record the frequency with which those behaviors are observed over a specified time period. The type of structured observation used in this research was the time studies of the subcontractor progress meetings, where time spent on the occurrence of pre-defined events was collected.

2.2.2.2 Unstructured Observation

The researcher uses direct observation to record behaviors as they occur, with no preconceived ideas of what will be observed. There is no predetermined plan about what will be observed. This type of observation was conducted during the case study experiments in the Immersive Environments Lab (IEL).

2.2.2.3 Observer Bias

Observer bias is defined as a bias created by the observer seeing what the observer expects to see, or selectively remembering, counting or looking for data that supports the observer's point of view (Yin 1999). It occurs when the observer knows the goals of the study or the hypotheses, and allows this knowledge to influence their observations during the study. The researcher has to thoroughly understand the issues related to the case study and be open to contrary findings. While still in the initial stages of data collection, the preliminary results should be presented to critical colleagues for review.

2.2.3 Interview Protocol

An interview is a method of data collection where the researcher asks questions to the respondents either in person or over the telephone. There are several forms of interview techniques defined by Yin (1999) including open-ended interviews, focused interviews and structured interviews.

1. *Open-ended Interview:* In an open-ended interview, the researcher can ask the respondents about the facts of a matter as well as their opinions about the events. The respondents can also be asked to suggest his/her own ideas about the issues faced in the study. The respondent is given considerable freedom to talk on the topic and to influence the direction of the interview since there is no predetermined plan about the specific information to be gathered from those being interviewed.

2. *Focused Interview:* The respondents in this type of interview are interviewed for a short period of time. The questions asked could be open-ended and could facilitate an easy conversation with the interviewer. This type of interview is conducted to verify certain facts that the researcher thinks have been established. The researcher generally follows a set of questions, which are carefully worded, and derived from the case study protocol. This was the type of interview adopted for this study.

3. *Structured Interview:* This type of interview resembles a formal questionnaire survey. The interviewer asks the respondents the questions using an interview schedule - a formal instrument that specifies the precise wording and ordering of all the questions to be asked.

2.2.3.1 Interview Candidates

Several criterion were used to select the interview candidates in this study. First, the interviewees needed to experience the immersive virtual environment and have sufficient time to form an opinion regarding the use of this technology. Second, all the interviewees needed to be directly involved with the case study project as an owner, designer, contractor employee or end user. The industry participants for this research had: (i) construction experience with an average of 15 years, (ii) no or limited prior experience in using advanced visualization technology, and (iii) an interest in participating and exploring this new technology. End users were licensed architects with an average experience of 20 years.

Individuals from different companies including the Construction Manager (CM), subcontractors, architect, engineers, owner, and end users of the case study project were interviewed for this study. This provided a broad perspective in terms of technicality, feasibility and usability inputs for this technology.

2.2.3.2 Interview Data Collection

The interviews were conducted in a confidential manner. This encouraged the interviewees to participate in an honest, unbiased and open conversation with the researcher. The researcher conducted 4 personal interviews and 1 group interview with employees from the construction manager and major subcontractors on the project. All the interviews were focused interviews and were recorded for accurate data collection and interpretation. Recording the conversation with the interviewees allowed for an accurate analysis of the interview transcript that was used for a content analysis of each interview.

2.2.3.3 Interview Data Collection Procedure

The researcher took much effort to collect comprehensive and accurate data by performed the following tasks:

1. The interviewees were educated about the use of immersive virtual environments and virtual facility prototyping by showing them an example from the case study project;
2. The interviewees were made aware of the scope of the research;
3. The virtual facility prototypes shown to the interviewees were related to the case study project so the participants where familiar with the details related to the project; and
4. The interview data was collected in confidence.

2.2.3.4 Interviewer Bias

Bias is "a tendency to observe the phenomenon in a manner that differs from the 'true' observation in some consistent fashion" (Simon and Burstein1985). To avoid bias in conducting the interviews the researcher performed the following steps:

1. Questions were designed to get an overall perspective of the participants, e.g., negative as well as positive reactions;
2. The use of words or terms that would naturally opinionate or bias the participants was avoided, and
3. The interviews were tape recorded for an accurate record of the interview and a complete content analysis of each interview was performed.

2.2.3.5 Content Analysis

According to Holsti (1969), content analysis is a research method developed specifically for investigating any problem in which the content of communication serves as the basis of inference. The five characteristics of content analysis adopted from Holsti (1969) and Guba and Lincoln (1981) are:

1. *objectivity* which is formed on the basis of explicitly formulated rules and procedures;
2. *systematic process* which means that the inclusion or exclusion of content or categories is performed according to consistently applied rules;
3. *generality* which means that the findings through this process should have theoretical relevance;
4. *manifest content* which helps the researcher to maintain a focus on the specified words and themes of the document; and
5. *quantitative technique* that allows the researcher to obtain a high degree of precision and attain confidence to the generalization of results.

2.3 Research Process

This section provides a detailed descriptions of the research tasks performed to complete this study.

2.3.1 Review Literature

An in-depth literature review was conducted in the areas of prototyping; advanced visualization techniques; and the use of immersive virtual environments in construction, construction plan communication, tacit knowledge extraction and innovation in construction.

2.3.2 Exploratory Investigation of Subcontractor Progress Meetings

To understand the application of Immersive Virtual Facility Prototypes (IVFP) in construction plan communication, the researcher attended 17 subcontractor progress meetings for the case study project. It was important to investigate the effectiveness of the current plan communication and to seek opportunities for applying visualization to improve the current methods of conducting such meetings. These meetings were held every week at the construction manager's field office. They were led by the construction manager and were attended by approximately 15 to 18 construction professionals representing approximately 7 subcontractor construction companies who were working on the project. The typical agenda of the meeting consisted of discussions on status of the project, progress made by each subcontractor and challenges faced on the project site. The meeting ended with a three-week look-ahead CPM schedule describing the status of the project and future activities.

The researcher performed a detailed time study of the communication held during these meetings. The communication during the meetings was categorized into the following types: descriptive, explanative, evaluative, predictive, decision-making and problem solving discussions. The first four categories were adopted from Liston (2003) and Garcia et al (2003), and the latter two were defined by the researcher. A time study is a data collection technique which consists of recording the time spent on each of these above stated categories. The time spent on each category was noted in intervals of 15 seconds. After the meeting the percentages of time spent on each category were calculated. The quality of communication can be deduced by observing the percentages of time spent on communication categories, which is discussed in detail in Chapter 5. A sample of the time study data collection sheet is included in Appendix A.

2.3.3 Developing Virtual Facility Prototypes for the Case Study Project

The research team consisting of several undergraduate and graduate students from the Department of Architectural Engineering and The School of Architecture and Landscape Architecture has collaboratively worked to develop a 3D CAD model of the case study project. Along with the 3D CAD (product) model, a 4D CAD (3D CAD with project schedule) model was also developed. These models were shown to the construction project team for the case study experiments.

2.3.4 Subcontractor Progress Meeting in the Immersive Environments Laboratory (IEL)

One of the weekly subcontractor progress meetings was conducted in the Immersive Environments Lab (IEL) to study the influence of using an immersive virtual environment and immersive virtual facility prototyping (IVFP) technology for construction plan communication on the project. The IVFP for the case study project was developed by the research team. The IVFP was provided to the construction project team to use as a tool for plan communication and 3D design visualization during the meeting.

In the IEL, the medium of viewing the models is stereoscopic and immersive, which helped the participants interact with the prototype at a one-to-one scale. The meeting was conducted in a similar manner as the other progress meetings, but during the three week look-ahead CPM schedule discussion the prototypes were shown to the project team. During the period of their interaction with the prototypes, the researcher analyzed the type of communication taking place, observed participant behavior, and collected other direct observations (views of the participants). At the end of the meeting, questionnaires to measure the changes in perception, attitude, visualization quality and project understanding were distributed to all the participants.

2.3.5 Understanding Key Industry Participants and Decision Makers' Perceptions

Later, a much more detailed model of the case study project was developed based on feedback from the earlier experiments. This detailed model was then shown to several key individuals belonging to the construction manager, architecture, subcontractors, project owner, and end user organization. An in-depth focused interview was conducted in person and or via a small group with all the participants. The questions were primarily focused toward gaining a better understanding of how the industry perceives the use and growth of this technology. The researcher maintained a conversational manner in the interviews, which helped the participants to engage in open dialog. A content analysis of each interview was developed to consolidate and organize the participants' opinions.

2.3.6 Data Analysis and Documentation

Data collected was both quantitative and qualitative in nature. Quantitative data collection included time studies of the meetings held at the Construction Manager's field office and at the IEL. Qualitative data collection includes documentation of the observations taken during the meetings including changes in behavior of participants, types of communication, traces of extraction of knowledge, references to past experiences, collection of anecdotal evidences, and interaction among the participants during the project meetings. Qualitative data collection also includes the responses of the participants collected through questionnaires on their responses on subjective questions.

2.3.7 Lessons Learned from the Implementation of IVFP

The implementation of IVFP the case study project has provided suggestions for improvements and direction for further research. Suggestions included the incorporation of additional product and process model information in the IVFP. Most of the interviewees also conform to the idea of conducting a study focusing on the development of detailed cost/benefit analyses of using this technology in the AEC industry. The researcher has documented lessons learned and provides suggestions for developing improved IVFP. These suggestions are based on the data collected through various observations and interview data.

2.4 Summary

This chapter has provided a summary of the research strategies used throughout this study and included an explanation for their selection. A detailed step-by-step discussion of the research process was also provided.

CHAPTER 3

LITERATURE REVIEW

This chapter presents the literature review performed for this research. Extensive literature covering different areas of virtual reality applications in the AEC industry, construction plan communication, types of prototyping, and design media representations are covered.

3.1 Concept of Prototyping and its Application in Industries

Prototyping is a well established concept and has been practiced in arts, sculpture, engineering, manufacturing, urban development, planning and similar professions where the skill to visualize a design of a product or process is critical. Many researchers and engineers have defined the process of prototyping and the resulting prototypes in different ways. Many of the available definitions throughout the literature present prototyping as a very broad concept that incorporates both the development of prototypes and its utilization in various organizations. Some have a non-linear perspective while others define prototyping as a systematic linear process. Kelley (2001) defines prototyping as 'a state of mind; a culture and language of the organization'. Schrage (2000) states that a 'prototype will carry the load of communicating how organizations use media to manage their innovation processes'. Prototyping is a practice developed to solve problems and help decision-makers make better decisions more quickly. According to Leonard-Barton (1995), the activities of experimentation and prototyping create two types of new capabilities. First, experimentation creates what has been termed 'requisite variety' in products and processes, e.g., a diverse portfolio of design options. Second, the act of experimenting develops a cycle of innovation; this cycle can constitute such a dominant characteristic of the organization that the ability to experiment and prototype efficiently and competently itself constitutes a competitively advantageous capability.

Retik and Langford (2001) define prototyping as a technique for building a quick, rough version of a desired system or its parts to allow analyses and evaluation of the concept or to explore system possibilities. A prototype can be understood as a representation of an idea or concept on paper, or in the form of physical or virtual models that highlight design characteristics. It could represent a standard example of a particular kind, class, or group of a product. Hence, prototyping can also be understood as a phenomenon that depicts the progression made in design and decision making for the end product. Organizations adopt prototyping practices to improve the design through improved design processes, decision-making or innovation.

Prototype construction is often considered a linear process in which design parameters are given and then prototype building proceeds as a kind of self regulating playful phase in which the participants assemble things which lead to new models of the concept without loosing the previous properties (Krogh et al. 2000). In this way, the companies also have the opportunity to refer to the previously designed prototypes and assess the progress made. Conceptualization of an idea can be very quickly and accurately depicted by engaging users in developing prototypes of the concepts.

Design features of the prototype provide the designer with a set of meaningful engineering aides, thus supporting them in their creative work at a higher level of abstraction. There is a common agreement that design by features has the potential to improve the quality of the design, to speed up the design process, to reduce the costs and to shorten the time taken in production (Vieira and Ovtcharova 1994).

Within the AEC industry, prototyping can be implemented in many areas including the facility (building and infrastructure) product design, process design, organizational structure, financial modeling, operational characteristics and so forth. This research focuses on the prototyping of the physical components and systems within a facility design along with the process for constructing the facility.

3.1.1 Types of Prototyping

Rapid developments in technology are significantly changing the tools available for prototyping. Different industries have used different techniques of producing prototypes in a quick and cost effective manner. The main types of prototyping used today are physical prototyping, rapid prototyping and virtual prototyping.

3.1.1.1 Physical Prototyping

Physical prototypes are frequently used by urban planners, landscape designers, facility designers and constructors to experiment with potential designs and to visualize the properties of the final design. Examples of physical prototyping in the AEC industry include physical scaled models developed by design professionals along with full-scale mock-ups of portions of a facility project. These physical prototypes allow designers, constructors, and owners to better visualize the properties of the final product and experiment with these final design components prior to construction of the entire facility. Often it is used in the early design stages of the project where the external size and shape of the facility are visualized. One such example is shown in Figure 1 which depicts the various concepts of building design for the case study project during its early conceptual stages.

Figure 1: Progression in early design concepts for the SALA Building

Physical prototypes can provide many benefits to the project team including the ability to visualize the quality of the final product; identify constructability issues that may arise in repetitive construction sequences; obtain valuable acceptance of design details by project participants; and allow for physical testing of designed components or systems. Physical prototyping has also been used as a marketing or display tool, e.g., high quality scaled models of building projects or full scale model units completed early in a project. The popularity of physical prototyping is rapidly diminishing in other industry sectors. For example, physical prototypes are comparatively expensive and time consuming to other methods currently available for prototyping in manufacturing (Chua et al. 2003). The manufacturing sector is now shifting toward rapid and virtual prototyping methods that have the ability to provide quick prototypes at a lower cost.

3.1.1.2 Rapid Prototyping

Developments in the current application of rapid prototyping (RP) started in 1979 when the technique of photo sculpturing was developed (Gebhardt 2003). Today its applications can be seen in various fields including medicine, industrial production, manufacturing, and geography. Rapid prototyping (RP) is a form of 'Layered Manufacturing' or 'Solid Free-form Fabrication'. As described by various researchers, rapid prototyping can be understood as a process by which 3D models and components are produced additively, by fitting or mounting volume elements together. Rapid prototyping is a generative production process and is a layer by layer fabrication of three dimensional objects (Cooper 2001).

RP can convert a computer-generated model into a physical prototype model or final component more quickly and at a much lower cost than conventional production methods. The various forms of RP include stereo lithography, selective laser sintering, laminated object modeling, fused deposition modeling and three-dimensional printing. The reason for adopting RP practices in the manufacturing industry has been to shorten the product development time; reduce costs; increase flexibility in product and production phases; and improve quality (Gebhardt 2003). Wagner and Steger (1994) have developed a classification of prototypes as follows:

1. *Design prototypes* which are used for design reviews and contain information regarding only physical characteristics like optical and aesthetic features. They do not address mechanical aspects or accuracy of design.
2. *Geometrical prototypes* which are used for testing and evaluating the form and fit. The focus is on geometry and not on material aspects.
3. *Functional prototypes* which represent a set of features which allow the testing of some functional aspects. The prototype is for a subsystem of a product.
4. *Technical prototypes* which covers all functional aspects of the part and can be used as such, but the manufacturing process is usually different from the one

which will be later used in series production. The technical prototypes may also consist of different material.

RP allows designs to be transferred, duplicated, and understood without the risk of them being misinterpreted.

Even though research and development in this field is providing advanced solutions for the rapid manufacturing of physical prototypes, these prototypes are limited in size by the equipment used to create the prototype. For example, 3D printers can only print 3D objects of a certain size and with specific materials. Therefore, RP is not a viable and productive solution for many of the prototyping needs in the AEC industry since the models must frequently be reduced in scale. Most facility designs contain intricate details and design information that a prototype of reduced scale will not accurately represent to the decision makers' and customers' of the end product. But in the manufacturing industry, RP has been successful and extensively used to create accurate full scale or scaled models of products that can support improved decision making and communication.

3.1.1.3 Virtual Prototyping

Virtual prototyping is not a new technology by itself, instead it is a combined application of various design and computer science application tools. The concept of Virtual Prototyping (VP) has been framed and defined by several researchers as the application of this technology relates to multidisciplinary fields. Some research suggests that a virtual prototype can act as a substitute for experimentations, e.g., designs of drugs, mechanical and electronic products. Substituting the physical prototypes with virtual prototypes also has an economical attraction in many situations.

Definition of a Virtual Prototype

Pratt (1994) states that virtual (or computational) prototyping is generally understood to be the construction of computer models of products for the purpose of realistic graphical simulation, often in a 'virtual reality' (VR) environment. Virtual prototyping with 3D modeling applications provides a means of rapidly developing a graphical representation of a design and provides an opportunity to analyze the design for form, fit, logistics, human factors integration, and general feasibility analysis (Schaaf 1997). According to Schaaf, The US Department of Defense (DoD) defines a virtual prototype as 'a computer-based simulation of a system or subsystem with a degree of functional realism comparable to a physical prototype' and virtual prototyping as 'the process of using a virtual prototype, in lieu of a physical prototype, for testing and evaluating of specific characteristics of a candidate design'. However, all the above mentioned researchers conform to the basic idea of a computer supported creation of envisioned product specification data, e.g. its geometrical properties, that leads to a virtual product having an ability to respond like the real product. Virtual prototyping provides a realization of an intended design or product to illustrate the characteristics of the product or design to users before actual construction. An appropriate virtual prototype can contain the features or specifications of the end product as well as information regarding the processes that will be used to manufacture or construct the product and also its behavior under certain circumstances. Since virtual prototypes can simulate the features of an end product quite closely in a detailed manner, its use can better capture and communicate the clients' ideas and needs and review proposed designs. These prototypes may provide additional abilities to its users, e.g., turning the model, viewing from different perspectives, taking a closer look at any chosen component or viewing a simulation of the performance of the product.

Creating a Virtual Prototype

Once the concept of design of a product has been framed, then validation of the design comes through developing a prototype. A prototype could be created at any stage of the design process that will provide the designers with a visual image of their design. A prototype is developed by combining existing concepts, products, components, and procedures with the new concept. Inputs for the creation of a prototype can be given by various people involved in the project, e.g., manufacturing, marketing and maintenance groups (Krogh et al. 2000).

The product design function of a virtual prototype can be broken down into four phases as suggested by Pahl and Beitz (1984) pertaining to virtual prototyping in mechanical engineering, some of which can be applicable to the AEC industry:

1. *Product planning:* this first phase clarifies the design task to be addressed.
2. *Functional design:* this phase considers all the desired functionality in the new product, subject to the constraints imposed at the product planning.
3. *Configuration design:* this phase covers the specification and layout of assemblies and subassemblies.
4. *Detail design:* this phase documents the design made for the product and includes the detailed drawings of the components.

Construction projects can gain many benefits from the application of virtual prototyping. The use of virtual prototyping techniques help designers to communicate with each other, as well as with the decision makers and end users (Savioja et al. 2003). Several researchers, e.g., Whyte (2002) and Yerrapathruni (2003) have proposed the use of virtual prototyping in the construction industry. According to Issa (2003), a Virtual Reality Integrated Construction System should have:

1. the capability to enable designers, developers and contractors to virtually test a proposed project before its construction;
2. a ‘walk through’ to view the project so as to solve the problems in the early stages;
3. free flow of information between CAD systems and other applications work packages; and
4. the ability to select alternative designs by allowing different plans to be tested.

Benefits of Virtual Prototyping

Virtual prototyping and the use of virtual prototyping tools like 3D CAD and 4D CAD (3D with time) are valuable design and construction analysis tools that have an opportunity to make a significant impact on the AEC industry. These tools can provide the foundation for the rapid development of design alternatives, photorealistic renderings of project designs, simulations of building components, and the creation of building models containing stored data about the building systems and their components.

A prototype is the result of the design and generation of one or more product characteristics, which help the design team to test them against user requirements. As suggested by Wagner and Steger (1994) there are different uses of prototypes which are:

1. *Tool for communication:* Design is a process where a team with different skills and views has to work together on the same product. A prototype of a design will essentially show what the designer has to express.
2. *Tool for visualization:* Facility (building and infrastructure) designs are often complex and intricate. Prototypes offer an adequate representation of the design, which allows the decision makers to understand the concepts of design.
3. *Tool for evaluation:* Design is often a process of iterations. Hence, prototypes provide an opportunity to check the current design and propose changes and improvements.
4. *Tool for establishing milestones:* The progression of prototypes will show the iterations performed throughout the design. Hence, it shows the periodic milestones achieved during the process of developing of the final product.

The use of prototypes early in the project can provide an opportunity to verify the design and the viability of various assumptions for the project.

3.2 Media of Design Representation

Visualization is defined in the Merriam-Webster Dictionary (2004) as a formation of mental visual images or the process of interpreting in visual terms or visible form. Design in the AEC industry is often performed in 2D or 3D. 3D design visualization conveys information about an object by providing a clear visual representation directly perceptible to the human brain so that detailed spatial relationships are revealed which is not possible in conventional two-dimensional planar presentations.

The term "visualization" has been used extensively in many fields including engineering visualization, the entertainment industry, physics, building design, urban planning, and landscape architecture. There are two types of visualization: static and dynamic. Chen (1999) suggests that the term visualization often is used in a static sense, which refers to users expressing how they perceive things in a visual manner using forms such as graphics and charts, rather than in tabular or text formats. Whereas, dynamic visualization means that a user can navigate and interact with the 3-D model in real time. The experience and views a user gains are dynamic as it is similar to the interactions in the real world. The model in such a dynamic visualization is rendered dynamically as the user sees different portions of the model at a reasonable frame refresh rate on the computer monitor. Whereas, the techniques used for static visualization are ray tracing and radiosity which would be useful in a dynamic visualization set up (Chen 1999).

The focus of dynamic visualization is important, as part of a designers' work is to communicate their ideas with their clients. To make the communication effective, 2D planar drawings alone, as used frequently today are not sufficient. These current techniques can show information regarding design, but due to the nature of this presentation they are not easily understood, as people are mostly 3-D oriented. To convey enough information for the clients to understand how a potential design will look and feel, a rich and dynamic presentation of the ideas is important.

The creation of realistic pictures is an important goal in fields such as simulation, design, entertainment, research and education. Certain simulation systems present images that not only are realistic, but also change dynamically. Creating realistic computer-generated images is often an easier, cheaper, and more effective way to see preliminary results than building physical prototypes, and also allows more alternative designs to be considered in a given time period (Chua et al. 2003).

In addition, Schmitt (1995) states that the development of computer graphics has transformed our ability to experience and to design urban space. He also has identified three major applications which are:

1. An ability to reconstruct the past and ancient cities;
2. Applications in the simulation of projects before they are actually built in order to optimize the design of new physical urban centers; and
3. Applications in the creation of a new kind of reality and urban space in the rapidly evolving information territory.

3.2.1 Conventional Techniques

Most of the representations of building designs traditionally and currently are presented as 2D planar drawings. The representations of these designs include plans, elevations, sectional drawings and at certain times perspective drawings or renderings. Historically, the drawings were hand drawn by draftspeople. Such drawings today are frequently made using computer aided design (CAD) software. Graphical renderings are also frequently developed. They can provide a good visual representation of the facility, but they are static in native and do not contain dimensional information. Physical prototypes in the form of scaled models are also sometimes made to present the facility design, typically for commercial and marketing purposes.

Changes in time demands and requirements of facility users and owners have given rise to much more complex facility developments. The rising complexity of these facility designs is often accompanied with tight time schedules. Many methods are not able to address these growing issues in construction well.

The latest developments in computer based design tools, virtual reality applications and improve graphics hardware have provided better techniques for visualizing complex facility designs in a real time, dynamic nature.

3.2.2 Modern Techniques for Visualizing Design Information

Construction is an information intensive and complex industry due to the sheer number of information interfaces and complex relationships among the project participants. Modern technologies can aid the resolution of many problems by providing information channels (media or representation) that would support the use of virtual models as the medium for communication, interaction and integration.

Traditional ways of conveying the ideas or concepts is to show static images of the space with no features for interacting with the space. Virtual reality (VR) technology presents a wide area of applications. Many technologies focus on improving the virtual reality system with an emphasis on closer to reality environments which will “look real”, “sound real”, “feel real” and “respond realistically to user’s actions”. Immersive virtual reality is a VR system that creates the illusion of being immersed in a synthetic world using a head mounted display (HMD) and position tracing sensors linked to the user’s body (Retik and Langford 2001). This produces an Immersive Virtual Environment (IVE) around the user who imagines himself/herself in a computer generated world which allows interacting on a real time with his/her immersed environment.

Research in the field of virtual reality started more than two decades ago, but progress in this field was hampered due to hardware limitations; lack of a commercial market and a lack of manufacturers who mass-produced products that could have driven technological development. However, recent developments with powerful computer graphics systems, better quality display technologies, wide area tracking systems and useable software packages have facilitated the development of affordable virtual reality systems. The essential features of a VR model as described by Tarr and Warren (2002) include:

1. The user can navigate the model and control the system with real time responses.
2. The display of the model should substantially cover the user's vision. This will provide the user with a 'sense of presence' or 'embeddedness' with the virtual environment.
3. The display of the three dimensional objects are in stereoscopic vision which possesses close to realistic shades and textured surfaces.

Described below are a few of the high-end virtual reality systems that are commercially available:

One of the earliest applications of VR popularly known as computer games was the 'driving' or 'flight simulator' (Tarr and Warren 2002). Such systems were either displayed on desktops or projected on front mounted project screens, with real time controls such as steering wheels and dashboards. The second application developed in 1991 was the CAVE™. CAVE™ is a multi-person, room-sized, high-resolution 3D video and audio environment invented at Electronic Visualization Laboratory (EVL) at The University of Illinois at Chicago (see Figure 2).

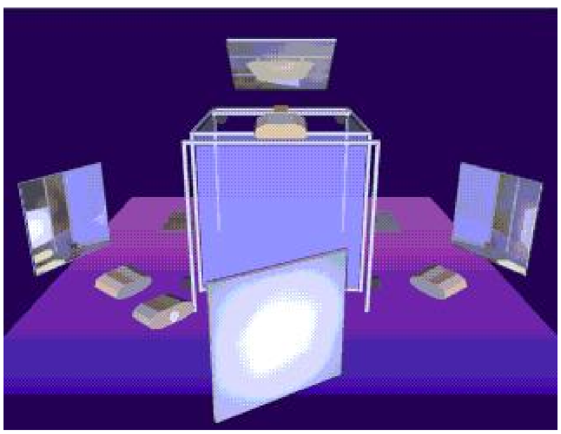

Figure 2: CAVE: Four screen display system

(Source: Electronic Visualization Lab (EVL) 2001)

Graphics are projected in stereo on three walls and the floor, which is viewed with active LCD (Liquid Crystal Display) shutter glasses equipped with a location tracking sensor. As the user moves within the display boundaries, the correct perspective is displayed in real-time to achieve a fully immersive experience (Electronic Visualization Lab (EVL) 2001).

EVL also created Immersadesk® in 1994 as shown in Figure 3. The Immersadesk® is comparatively compact and self-contained compared to CAVE™. It consists of a screen that acts as a drafting table format VR display. It has a rear-projected screen tilted at a 45-degree angle, which substantially covers the user's field of view. The users wear shutter glasses to view high-resolution, stereoscopic, head tracked images and enables him/her to look forward and down. The user's head is tracked, allowing an accurate perspective to be generated. A tracked wand is used so that the user can interact with the environment and it is also equipped with stereo sound (Electronic Visualization Laboratory (EVL) 2003).

Figure 3: Immersadesk: One screen display system

(Source: Penn State Vizgroup - 2002)

Several researchers and virtual reality laboratories are working towards developing virtual reality systems, which possess a more complete sense of realism with built-in interactivity and high-end controllability. Researchers are also trying to investigate the use of virtual reality in behavioral research on vision and the impact on human beings. Based on such a concept, a VR system called the VENLab (Virtual Environment Navigation Laboratory) was created at Brown University, which is currently the largest walkable immersive virtual reality system. It consists of a high-end graphics workstation, stereo head mounted display with a field of view of 80° and a highly accurate wide-area head tracker. The distinguishing feature of VENLab compared to the other VR systems is that it allows the users to use their natural physical movements like in the real environment to produce changes in the virtual environment (Tarr and Warren 2002).

The traditional limitations of the physical prototyping such as weight, measures and material treatment are avoided in virtual prototyping and it may also give an opportunity to compress time during the design phase and reduce design changes or revisions. Design features of virtual prototypes have been identified as meaningful engineering aids for modeling products using high-level semantic data (Schiffner 1994). Thus the principal obstacle in design feature process research is that the successful computerization of product development and the level of interaction that will provide both geometric and non-geometric (process) information. There is a possibility for using features as a basis for modeling product information in different phases of prototyping such as design, analysis and process planning (Ovtcharova and Vieira 1994).

3.3 Construction Plan Communication

Liston (2000) analyzed the amount of time spent on conducting project meetings. According to this study, a typical construction project team utilized 90% of their time during a project meeting to convey the status of the project and only the remaining 10% of their time on discussing “what-if” scenarios. Results of this time study conducted by Liston are shown in current and future practice diagrams in Figure 4. A change in the way time is spent in the future Construction Information Workspaces (CIW), which are a new type of Construction Information Technology (CIT) that enable project teams to interactively visualize a variety of types of project information is predicted.

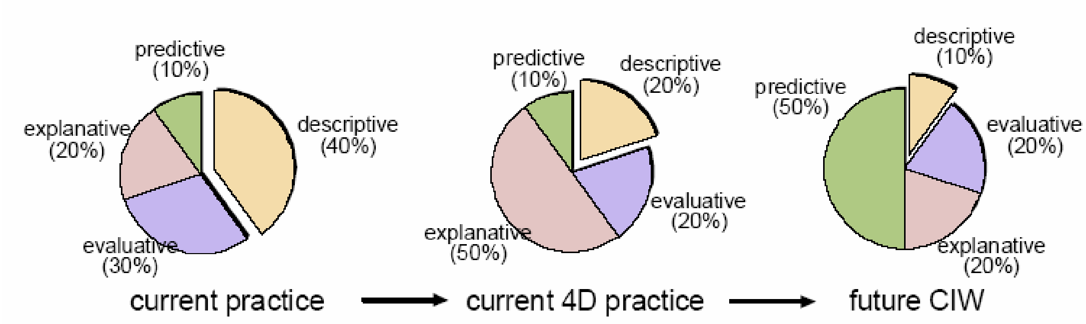

Figure 4: Time spent on project meetings (Source: Liston - 2000)

Also a recent study performed by a California based construction company stated that approximately $1 Million is spent on project meetings for a typical project that lasts for two to three years and costs around $20 Million (Garcia et al. 2003). These facts illustrate an opportunity to introduce advanced visualization techniques and to bring drastic improvement in the way project information is communicated. Also, a study states that 4D CAD modeling and immersive virtual environment can enhance the construction planning and plan communication process which will provide a robust project plan during the design process (Yerrapathruni 2003).

A well-detailed virtual prototype can solve the ambiguities about project design and specifications. It can also serve as an excellent tool for communication among the project participants, stakeholders and potential customers. The communication held during these meetings can be categorized into the following types of communication: descriptive, explanative, evaluative and predictive) which are described by Liston (2000) as follows:

1. Descriptive

This type of communication involves describing various tasks, which are yet to be worked on, or which somebody has worked on. This category caters to questions like "what, when, where, who". Examples include showing the 2D drawings and discussing cost estimates. It has been observed that significant time during the meetings is involved in describing various tasks to other participants.

2. Explanative

This type of communication is involved when discussion is headed in the direction of someone's ideas/proposal. It is trying to justify the actions the speaker would have taken or is yet to be taken. Questions like "why, why not" are discussed here.

3. Evaluative

This consists of the assessment of possible alternatives to a problem or situation. Discussions can lead to weighing the advantages and disadvantages of these alternatives taking into consideration the given limitations and criteria.

4. Predictive

This type of communication would involve either predicting the possible consequences of a decision or estimating the value of an unknown variable during a meeting. An example is the estimation of the cost of an activity during a meeting.

3.4 Summary

This chapter has provided a summary of the relevant literature analyzed for this study. To understand the goal of this research, which is to explore the use of advanced visualization technologies in the AEC industry, a literature review in the areas of virtual reality applications, construction plan communication, types of prototyping, and design media representations was completed. This literature shows that virtual prototyping is a common practice in other industries, e.g., manufacturing. However, it remains in the early stages of development in the AEC industry. It is also important to note that there were very few studies that evaluated the costs and benefits of using virtual prototypes in the AEC industry.

CHAPTER 4

IMMERSIVE VIRTUAL FACILITY PROTOTYPING

This chapter explains the concepts of Immersive Virtual Facility Prototyping (IVFP) presented in this research. It addresses the difference between the traditional methods of visualizing product and process information to the proposed methods in an Immersive Virtual Environment (IVE). The benefits and current applications of IVFP are also discussed.

4.1 Description of Immersive Virtual Facility Prototyping

Research initiatives in the computer tools for the AEC industry in design and construction planning have primarily focused on the development of better modeling applications. Only a few researchers and engineers have focused on the mode of communication or the media used to visualize this information. Advanced computer aided design (CAD) applications have equipped designers with tools to create accurate 3D CAD models and 4D CAD (3D CAD with project schedule) models. These computer generated models are becoming increasingly interactive, yet the medium of interaction is typically limited to a computer screen interface. This limits users to visualizing the information on a small scale, two-dimensional planar display. Complex facility models have a large amount of information, which requires enhanced levels of interaction to adequately understand and visualize the designed facility product and construction process. Increasingly, workers are required to navigate complex information spaces to locate needed data, find patterns in information for problem solving, and use sophisticated representations of information to communicate their ideas (Kohn 1994).

From a research perspective, increased focus has been placed on the manner of design representations that will ease conveying of better quality design information. Such better quality of communication will allow project stakeholders and customers to speed the decision making process and make more informed decisions. This study explores the use of one such media of communication of design representation, the Immersive Virtual Environment (IVE). The description and relevance of the use of an IVE is discussed in detail in the later section. To improve the current methods of displaying computer aided designs in the AEC industry, immersive virtual facility (refers jointly to building and infrastructure facilities) prototyping is introduced. Immersive Virtual Facility Prototype (IVFP) can be defined as a combined product and process model in the form of a virtual prototype displayed in an immersive virtual environment. Figure 5 shows the essential difference between the visualization methods used to interact with the design representations used in the traditional versus the IVFP methods.

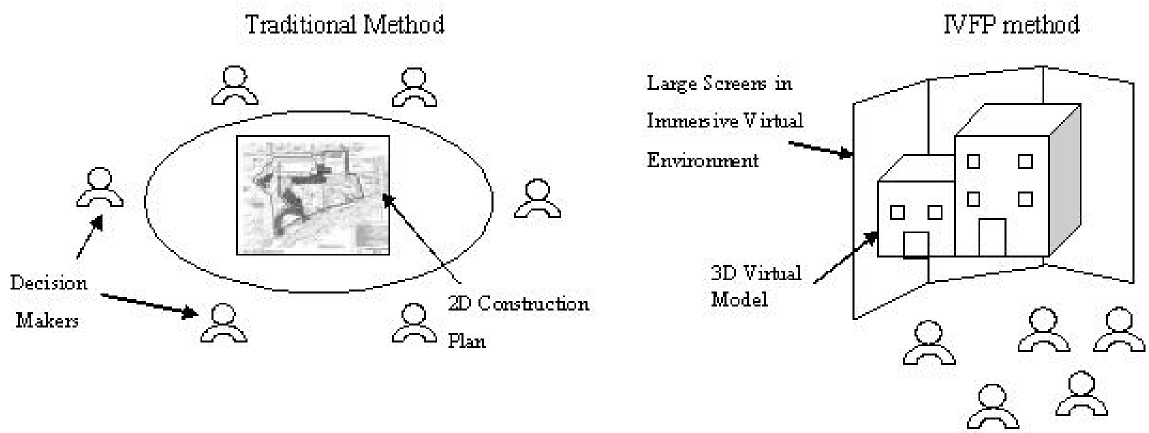

Figure 5: Visualization in Traditional vs IVFP Method

IVFP consists of two important parts: the 'model' and the 'media' used to visually display the model. IVFP provide a method to visualize and interact with virtual prototypes. The increased interaction is obtained by virtual reality applications within an immersive virtual environment, which provides the users with a sense of 'realism' or 'presence'. Presence is defined as a state of consciousness that may be concomitant (existing concurrently) with immersion, and is related to a sense of being in a place.

Presence governs aspects of autonomic responses and higher-level behaviors of a participant in a Virtual Environment (VE) (Slater and Wilbur 1995). This added sense of presence improves the level of confidence of users related to reviewing design and construction information; increases the identification of design and construction conflicts; and improve the overall understanding of a project design (Yerrapathruni 2003). Table 1 shows the progression in the features of different media of design representations used for visualizing the facility designs.

Table 1: Different characteristics of methods used for design visualization

Model	Primary Content	Media	Views	Interactive Features
2D CAD	Facility design	Paper drawings	Plan, elevation, section, etc.	
3D CAD (product model)	3D components of facility design	Computer screens	Any number of perspective/scale views of the model	3D Navigation through the facility
4D CAD (process model)	3D model integrated with project schedule	Computer screens/ Immersive Virtual Environment	Any number of perspective/scale views of the model	Simulation of various construction processes
IVFP (integrated product and process model)	4D CAD, detailed product and process model	Immersive Virtual Environment	Any number of perspective/scale views of the model	Walkthrough of the facility, animation, etc.

4.2 The Model: Product and Process Model

The model for an IVFP contains information for the users regarding the facility and the process for constructing the facility. The virtual model in an IVFP contains product and process information. The product model is used in the design process and focuses on the physical characteristics of the facility, e.g. geometric and aesthetic features, whereas the process model will contain information about the various processes involved in its construction, e.g., construction sequence and various trade flows around the project site. In addition to the product and process models, performance-based information can be shown regarding the performance of the facilities. The behavior of the facility under prescribed environmental conditions can be analyzed. The results of such a performance based analysis may be numerical or mathematically represented. Different performance analyses, e.g., daylighting, thermal, acoustical, earthquake or structural analyses can be performed using various analysis tools. Output of these analyses, if represented visually in the models, can be added to the virtual prototype to improve the information available to the decision makers. Figure 6 depicts the information models to form a shared information rich environment.

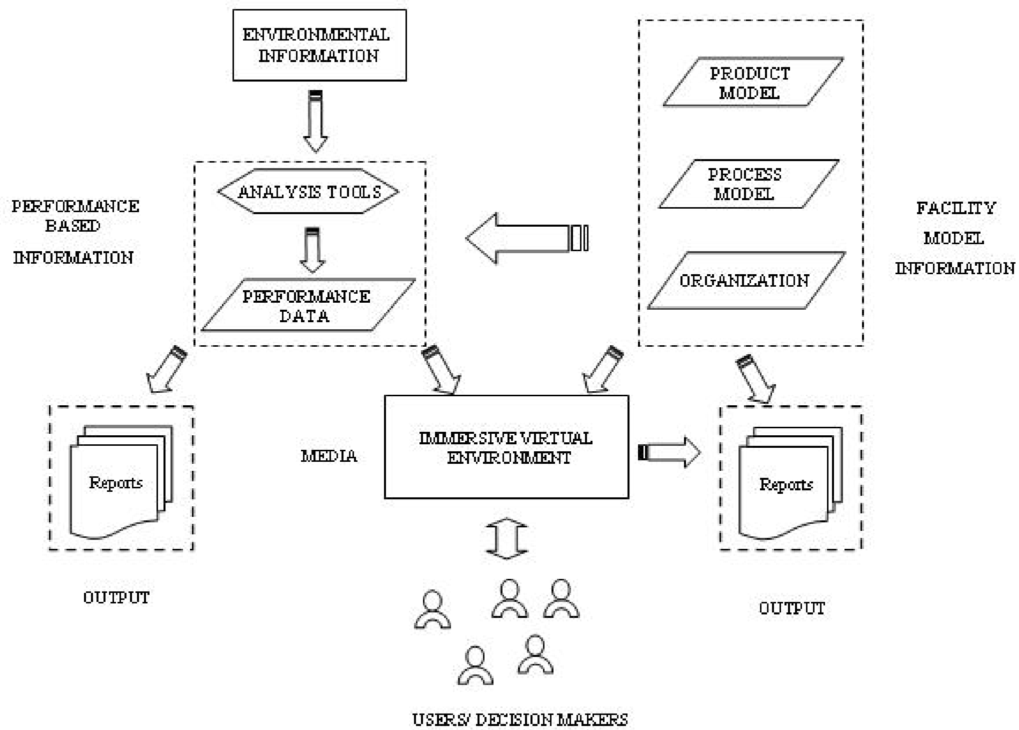

Figure 6: Conceptual framework of Immersive Virtual Facility Prototyping

4.2.1 Product Model

According to Eastman (1999) a product model or a building model contains "full representation of a building and the products that comprise it, whether used during design, construction planning, operation or management." In the design process, the production of separate drawings is replaced by the construction of a virtual building model. A drawing is merely a view of the model at a specific location, as the whole building and its environment are included in the product model. Everything is modeled using three-dimensional building components and library parts that can store information about each component or system.

The product model is then maintained and revised throughout the project. A comprehensive product model of a facility will contain information about all the components (e.g., steel, doors, windows, and walls) and utility systems (e.g., mechanical, electrical, fire protection system). The need for such a comprehensive product model arises, as it provides the viewer with a complete picture of how the space within the facility has been planned to be utilized. With the current traditional methods, the designers and planners have to go back and forth between a number of 2D paper drawings to visualize the space utilization. In the product model, everything is modeled three dimensionally (3D), and the model is maintained, revised and changed throughout the project period.

Apart from the benefits of providing a tool for communication and evaluation, the product model can improve the decision-making process and construction performance by enabling true 'what-if' scenario analyses. The product model can be used for providing the following information:

- complete plan drawings,
- section drawings,
- elevation drawings,
- architectural and construction details,
- bill of quantities,
- window, door and finish schedules,
- renderings and animations, and
- virtual reality scenes.

Hence, the product model is a direct source of construction documentation and provides information for cost control and life cycle cost analyses of project alternatives. Various research organizations and design tools software developers are targeted towards the creation of improved product models. There is currently significant effort focused on the development of CAD applications that support product model information.

4.2.2 Process Model

Hass (1995) states that the virtual prototype is more than an integrated product model. Facility model development resembling the construction of the actual facility; and its behavior in certain circumstances gives rise to creating a facility process model. The process model helps in understanding the various construction processes involved in building the facility and the use of construction resources, thus opening opportunities for optimizing it. Four dimensional CAD (4D CAD) models which are developed by integrating a 3D CAD model with the project schedule is one such process model that visually depicts the sequence of construction. Figure 7 shows a pictorial representation of the progress of construction of a simple office building project.

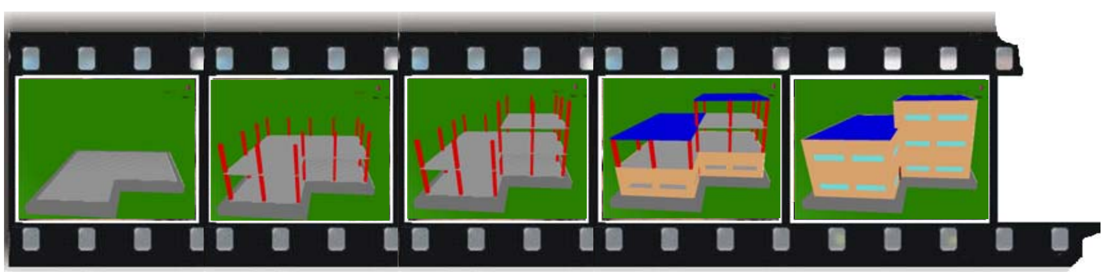

Figure 7: Process model depicting construction sequence (4D CAD Model)

The 4D CAD model gives the construction planner more visual cues regarding the construction sequence and highlights the activities under construction at any given time. It can show an animation of how the entire facility will be built giving the viewer the foresight of the construction of the facility on the project site. The 4D CAD model can also be used to show the different trades flow on the site, giving opportunities for the project manager to improve the coordination of work among the subcontractors. The product model can be used for analyzing the behavior of the facility under different phenomenon, e.g., earthquakes. Various different analyses can be performed including the planning of construction process, performing a sustainability analysis, investigating energy requirements, determining maintenance needs, incorporating crime deterrent features, and performing building acoustical analysis. (Lee et al. 2003).

4.3 The Media: Immersive Virtual Environment (IVE)

The technology to immerse people in computer-generated worlds was proposed by Sutherland (1965). In 1968, a head-mounted display that could present a user with a stereoscopic 3-dimensional view attached to a sensing device tracking the user's head movements were developed (Sutherland 1968). The models viewed in such virtual worlds at that time were simple wire-frame models. The advancement of computer science and graphics technology has given rise to an enormous increase in image quality and a decrease in the cost of equipment that has led to the development of participatory immersive virtual environments, commonly referred to as "Virtual Reality" (VR) (Fisher 1986). Today, VR has found vast applications in various fields and disciplines ranging from engineering to medicine, social and psychological sciences. The current technology developments in the field of VR started in the late 1980s and early 1990s. There is a considerable scope of research and development in this field, and the VR technique has significant potential to be used as an aid in construction, architecture, the movie industry, civil and military aviation. (Woksepp and Tullberg 2001). According to Aukstakalnis and Blatner (1992) the definition of VR is as follows:

"Virtual Reality is a way for humans to visualize, manipulate and interact with computers and extremely complex data. The visualization part refers to the computer generating visual, auditory or other sensual outputs to the user of a world within the computer. This world may be a CAD model, a scientific simulation, or a view into a database. The user can interact with the world and directly manipulate objects within the world. Some worlds are animated by other processes, perhaps physical simulations, or

simple animation scripts. Interaction with the virtual world, at least with near real time control of the viewpoint, in my opinion, is a critical test for a virtual reality".

Virtual Reality systems can be split into two groups: (i) desktop VR (i.e. non immersive VR) and (ii) immersive VR (Kalawsky 1993), where ordinary computer monitors represent desktop VR. The total immersion of the viewer in the virtual world can be achieved by a Head Mounted Display (HMD) or a Cave Automatic Virtual Environment (CAVE™). The CAVE™ system provides the illusion of immersion by projection of stereo images onto the sides of a room-sized cube. These mentioned systems are currently expensive; however, widely used systems with one or several projectors projecting stereo or mono images onto a screen, with or without stereo sound, in front of an audience, described as semi immersive VR are also available.

The potential for application of VR is significant in all phases of the AEC industry like designing, planning, constructing, operating and managing facilities. Its ability to put forth complex 3D information can improve the communication among all the project participants and stakeholders. The rapid progress within the video gaming and aviation industry has accelerated the development of new VR software and hardware. Hence, it is now possible for the construction industry, without great investments, to take advantage of the benefits of VR technology (Woksepp and Tullberg 2001).

Schnabel and Kvan (2001) have used Immersive Virtual Environments (IVE) with architects to visualize ideas from the initial steps of design where the architect is challenged to deal with perception of space, solid and void, without translations to and from a two dimensional media. They have also performed experiments, which have shown that visual perception, mental images, workload, errors, comprehension of design and its communication, frequency of creation, feedback, modification-loops as well as impact on the design-creation, can create alternative solutions to conventional design methods. An IVE offers designers and constructors a tool that allows conceptualization of design ideas in an easier way. Computer based three-dimensional models can be generated more quickly and at a lower cost than physical models. These virtual models, when viewed in an IVE, provide immediate feedback to the users, which is not possible within CAD drawings seen on a computer screen or traditional design media.

4.3.1 Features of IVE

Properly designed, three-dimensional, multisensory virtual worlds are capable of helping users in comprehending abstract information spaces by enabling them to rely on their biologically innate ability to make sense of physical space and perceptual phenomena (Winn 1993). A few of the key features of IVE that have been identified by various researchers include:

1. *Three-dimensional immersion:* The sense of embeddedness or presence that is obtained in full three dimensional immersion enables a users to be one with the virtual environment. By engaging users with immersion, it can make important concepts and relationships more clear and memorable, helping users to build more accurate mental models. Also, in such environments, a user's attention is focused on the virtual environment (Salzman et al. 1999).

2. *Frames of reference (FORs):* Darken and Sibert (1995) state that in the field of psychological research, spatial learning, navigation, and visualization, perspectives or frames of reference distinguishingly brings unique aspects of virtual environment and influences the users learning.

3. *Multisensory cues:* Display systems that provide stereoscopic images via high-end VR interfaces enable the user to interpret visual, auditory, and haptic (touch) cues to gather information while using their proprioceptive system to navigate and control objects in the synthetic environment. This potentially deepens the learning process (Sherman and Craig 2003; Psotka 1995).

4.3.2 Stereoscopic Vision

Human vision is the most active of all senses to absorb information from the environment and has an extremely large processing bandwidth. Our depth perception is associated with stereopsis, in which both eyes register an image and the brain uses the horizontal shift in image registered by the two eyes to measure depth (Julesz 1971). Media of stereoscopic vision involves the users to their maximum, as perception of depth allows the user to maneuver a virtual environment since it gives the ability to see scenes in 3D similar to real vision (Issa 2003).

4.3.3 Full-scale Visualization

Large screens are used in immersive projection display systems for displaying the virtual facility prototypes, as it provides maximum coverage of the user's field of view. One other method that could be used to achieve this is a head mounted display. The users of immersive virtual facility prototypes can view a model at full-scale (1:1) or other modified scales; navigate in real time; and interact with the components within the prototype. The immersion within the virtual environment at full scale can improve communication of users for planning and it may accelerate the decision processes.

Use of IVFP during the early stages of a project may provide the capability to the decision makers to evaluate a design and make informed choices for the project. Evaluation of the design in the early process with respect to different criterion like architectural, usability, constructability and maintainability can allow critical input into the early design stages. IVFP can support the review process and initiate discussions on what-if scenarios during the detailed design phase in order to assess the proposed solutions from different technical points of view (e.g., structural, thermal and lighting). The development of an IVFP involves communication and cooperation among its creators and users. This type of communication can facilitate the conveyance of ideas more clearly due to the active involvement of the project stakeholders. Another added benefit of IVFP is that they are easy to understand for non technical users that may not be familiar with reviewing traditional 2D design documents. The review process can entail an interactive walk-through of the project at full scale prior to the project being built.

4.4 Potential Benefits of IVFP

The complete benefits of IVFP are still being researched, as there have only been a few case study applications. Pertaining to this study, the researcher is proposing the following hypotheses which describe the possible areas of influence through the use of immersive virtual reality.

4.4.1 Hypothesis 1: Beneficial in Design Review and Construction Plan Communication and Visualization

The IVFP present an accurate representation of the to-be-built facility. It possesses product and process information in a single virtual model, which makes it easier to comprehend all the information regarding the features and design of the facility. In the case study application in this study, the researcher has learned that a majority of research participants agreed about the capabilities of IVFP having a potential to improve the communication among the project team members. Also, a virtual model of the facility may have added value in visualizing the design among its users. On certain occasions, the decision makers or the potential clients do not have the technical expertise to conveniently understand the nuances or intricacies of the design of facility. In such cases, a walkthrough of the virtual model before the facility is built can be very valuable.

4.4.2 Hypothesis 2: Beneficial in Knowledge Management within an Organization

Immersive virtual reality still poses challenges to researchers who are trying to understand the various uses of this media. Various researchers have shown that such an environment has potential to aid in conceptual and spatial learning. Research has shown that some people tend to learn in a 3D virtual environment and believe that immersive VR has potential as a learning environment (Rieber 1994). Also, in our knowledge-based society, fluency in understanding complex information spaces is an increasingly crucial skill (Dede and Lewis 1995). In research and industry, many processes depend on people utilizing complicated representations of information (Rieber 1994). Recent research into learning styles demonstrates that the need for an imagery/visual type of interface can no longer be ignored (Salzman et al. 1999).

Use of such an environment in a construction organization can significantly improve the learning of fundamental concepts of trainees, which otherwise is acquired through experience.

The AEC industry is a project based industry and involves the understanding of complex processes and the exchange of project information among team members with various educational backgrounds and experiences. This study has made attempts to use an immersive virtual environment (IVE) to improve the understanding and learning of abstract concepts related to the facility design. Traditionally, the knowledge within the industry has been passed by the experts to their subordinates or colleagues by either verbal communication or through their close proximity. The knowledge that most of the experts possess is in the form of their experiences, intuitions and gut feelings. which is commonly referred as tacit knowledge (Polanyi 1974). This tacit knowledge is stored semiconsciously or unconsciously in the minds of people and is hardly transferable (Krogh et al. 2000). Current methods of knowledge capture, transfer, and sharing fall short of suggesting appropriate measures to harness this nature of knowledge (Fernie et al. 2003).

It is a hypothesis that when experts interact with an immersive virtual prototype, they tend to reflect back to their past memories and experiences by seeing certain visual cues in the model. These prototypes may provide a method for improving the use and extraction of tacit knowledge from experienced professionals.

4.4.3 Hypothesis 3: Innovative Problem Solution Development

The need for organizations to innovate and furthermore to ceaselessly innovate is stressed throughout the modern management literature on innovation. This need comes from increasing competition and customer demands and new market areas (McAdam 2000). Technology oriented innovation in the AEC industry has been slow relative to other industries due to the nature of risk and reward obtained by such innovative changes in the industry. Macomber (2003) has pointed out the key areas which could drive innovation in the AEC industry, which are: *supply chain optimization*, *knowledge management*, *3D design and wrap-up economic models.*

Construction projects are complex in nature, and involve many variables, and prototyping can assess in the earlier stages the deliverance of optimum results. The prototyping process can fuel innovations, which constantly improves the product design. The ability to observe and play with the virtual model of the planned facility helps in visualizing the design and can initiate thinking of 'what-if' scenarios. Innovative problem-solution development is a continuous process of search and exploration of new ideas or alternatives that will lead to optimizing the available resources. It involves constant brainstorming and playing around with ideas that are of different varieties; and evolves through interplay between the individuals and their expressions of ideas (Schrage 2000). Through immersive virtual facility prototypes the decision makers and project stakeholders can have the capability to evaluate and interact with the virtual models, thereby improving the quality of the design and reducing design changes that frequently occur later in a project.

4.4 Summary

This chapter presented the concept of immersive virtual facility prototyping. It highlighted the importance of both the model and the media of design representations. The relevance of immersive virtual facility prototypes and its benefits have also been provided. Finally, three hypotheses were defined that are later evaluated through the case study for this research.

CHAPTER 5

ILLUSTRATIVE CASE STUDY AND DESCRIPTION OF THE IMMERSIVE ENVIRONMENTS LAB

This chapter presents the illustrative case study developed to explore the applicability and the potential value of implementing virtual facility prototyping from an industrial perspective. An Immersive Virtual Facility Prototype (IVFP) of the case study project was developed and was provided to the construction project team. The focus of this case study was to understand the interaction and behavior of the project team based on their use of the IVFP.

5.1 Case Study Project Description

The case study chosen for this research was the School of Architecture and Landscape Architecture (SALA) Building project located at the University Park campus of The Pennsylvania State University (Penn State). This project is currently under construction and is scheduled for completion in Spring of 2005. The SALA Building is a relatively typical building construction project with the entire facility measuring 111,000 square-foot, but it does have several unique features (see Figure 8). This building is planned to be the first LEED (Leadership in Energy & Environmental Design) certified building on Penn State's campus and is also equipped with the latest innovative technologies for its users (e.g., students, faculty and researchers). The primary goal of the SALA Building is to provide an academic and physical environment that enriches and promotes educational and research opportunities for its users (Penn State: College or Arts and Architecture 2004b)

The construction of the project started in August 2003 and the total construction cost is estimated to be $23.5 million. This new building will have advanced spaces for teaching and learning including multipurpose classrooms; undergraduate and graduate studio spaces; critique and display areas; a model building workshop; photography and copy stand spaces; special computer laboratories; social spaces for faculty and students to interact; administration, faculty, and staff offices; common spaces for broader public events including an exhibition gallery; an amphitheater for lectures and conferences, an arts and architecture library; and spaces for inquiry, interaction, and exploration extending beyond the building into the surrounding landscape (Penn State: College or Arts and Architecture 2004a). After its completion, it will contain a visualization lab to help students visualize their models and explore visualization research in the Architecture and Landscape Architecture areas of building science.

There are several reasons for choosing the SALA Building as the case study project for this research. First, the project site is easily accessible to the researcher. Second, several faculty and students of the SALA were involved in various research efforts related to the building, which facilitated access to information. Finally, the project is relatively typical, yet still has several unique and complex features, e.g., the side curvature of the building facing south, which makes it appropriate for analyzing IVFP techniques.

Figure 8: Rendered model of the SALA Building

5.2 The Model: Virtual Facility Prototype of the SALA Building

Most of the design of the SALA Building was performed conventionally; using 2D CAD modeling with some additional 3D CAD rendered models. The research team developed computer based models to provide the project team with appropriate 3D graphical representations of the project. The research team involved students from the departments of Architectural Engineering, Architecture, and Landscape Architecture from Penn State. First, a 3D CAD model was created in Graphisoft ArchiCAD®, a commercially available CAD application. The model contained the substructure and superstructure of the building. In this model, one can see the piles, steel, concrete slabs, walls, façade, stairs, doors and windows. All the elements in the model have been detailed with the appropriate color and texture (see Figure 9).

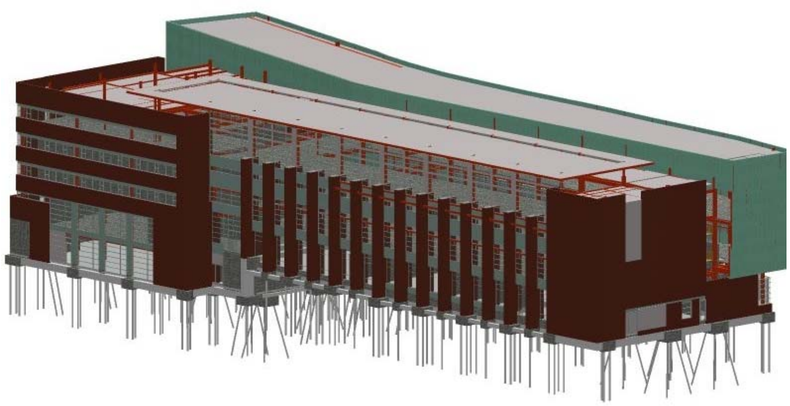

Figure 9: 3D CAD model of the SALA Building

Figure 10 shows the 3D model in a VRML (Virtual Reality Modeling Language) browser, which was used for the case study project.

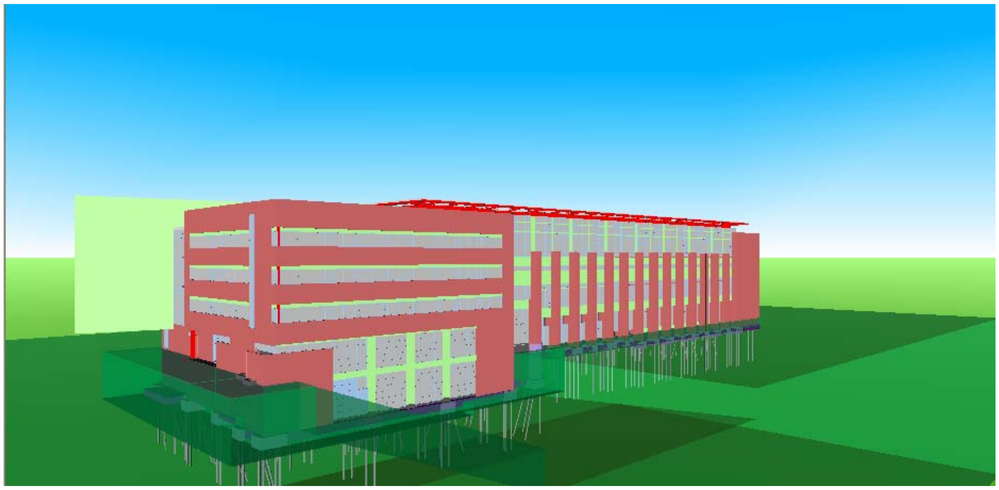

Figure 10: 3D model of the SALA Building in VRML browser

Later, a 4D CAD model was developed in Project 4D™ by Common Point, Inc.(2004), a commercially available 4D CAD modeling.. The 4D CAD model was created by integrating the 3D CAD model as described above, with the original baseline Critical Path Method (CPM) schedule obtained from the Construction Manager (see Figure 11).

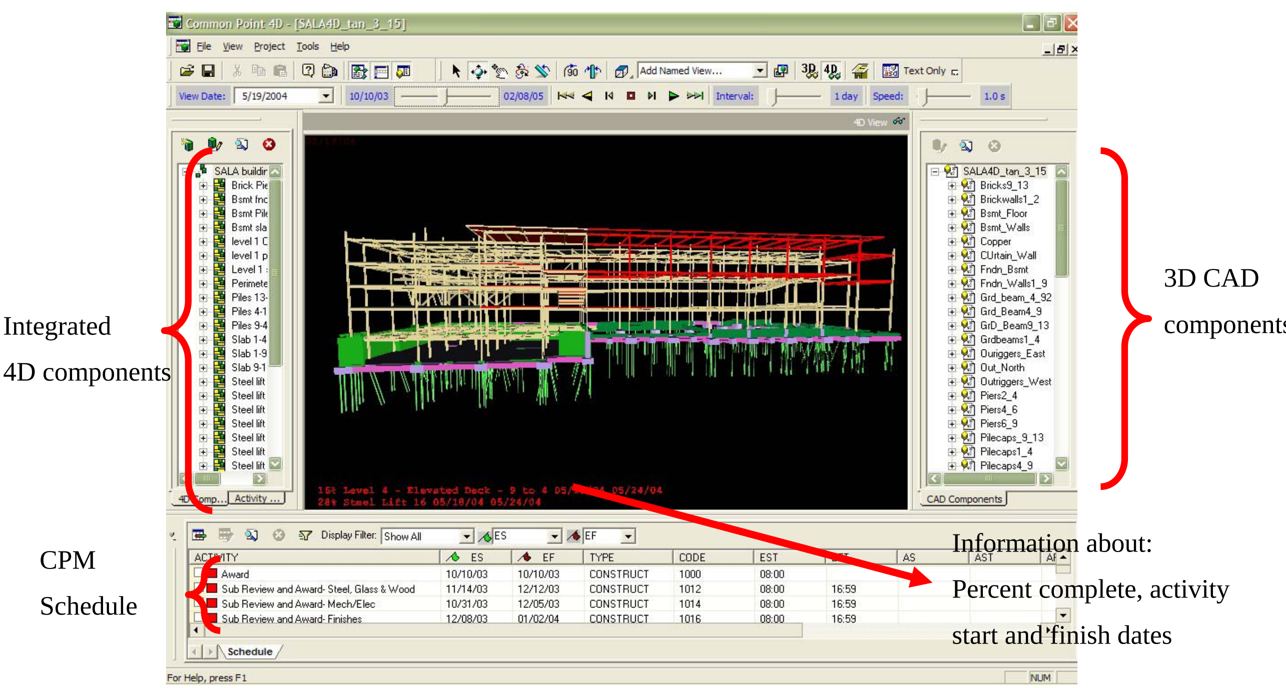

Figure 11: The 4D CAD interface for the SALA Building model

This model shows the construction sequence of the building from the start of construction through the end of the construction of the superstructure. During the execution of the program there is additional information displayed on the computer screen about the schedule dates (early start and finish dates) for the activities under construction and there percentage of completion (see Figure 11).

In addition to the 3D CAD and 4D CAD models, a rendered model created in AutoCAD® by the project’s architect was also made available to the construction project team. It portrays an appropriate depiction of the exterior façade of the building after its completion along with a representation of the scale of adjacent buildings. The model was not developed to contain detailed design information, instead it gives a perspective of the building and also shows some landscape features like other structures surrounding it, e.g. the water tower and adjacent buildings (see Figure12 and 13).

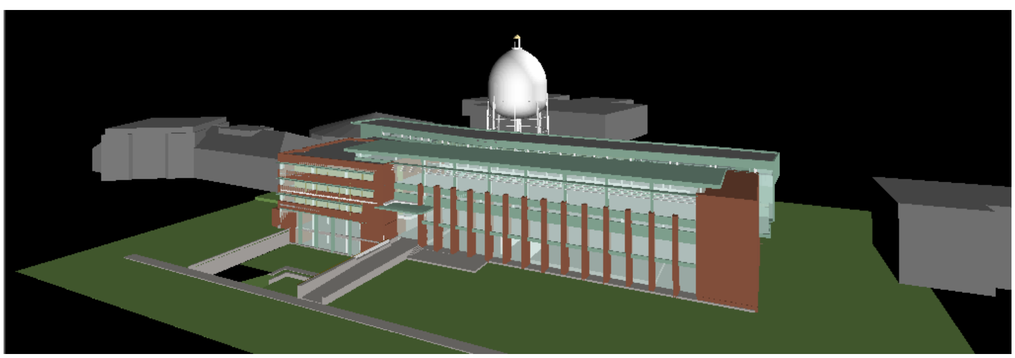

Figure 12: North face of the SALA Building

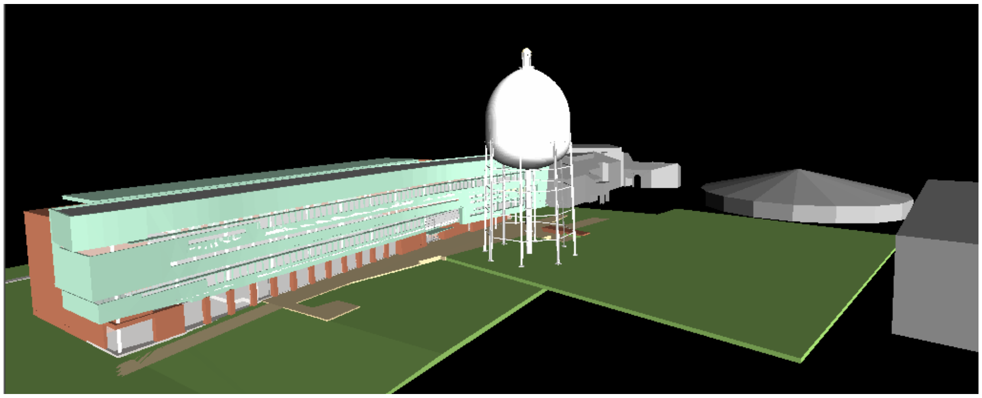

Figure 13: South face of the SALA Building

The project team was provided with several graphical model of the SALA project. In addition to using the commercially available modeling software, several other applications were used to convert the CAD models to Virtual Reality Modeling Language (VRML) format which enabled the models to load into the IEL environment.

5.3 The Media: The Immersive Environments Lab

The medium of display used to view the SALA IVFP was the Immersive Environments Lab (IEL). The IEL is located at Penn State University, and is a joint project of Information Technology Services (ITS), The School of Architecture and Landscape Architecture, and the Architectural Engineering Department.

The IEL is a visualization lab used to explore Architecture, Landscape Architecture, and Architectural Engineering research in building sciences and other disciplines, by utilizing low cost solutions and open source Virtual Reality (VR) techniques. It consists of “three frusta panorama displays” and a high end computing system performing as a graphic workstation (see Figure 14) (Penn State Information Technology Services: Graduate Education and Research Services: Visualization Group 2003). The three screens are six feet by eight feet, rear-projection, passive-stereo display screens, which are aligned at

135° to each other (see Figure 15). It provides an immersive 3D environment for the visualization of 3D models at full or modified scales.

Figure 14: Three large screen display system in the IEL

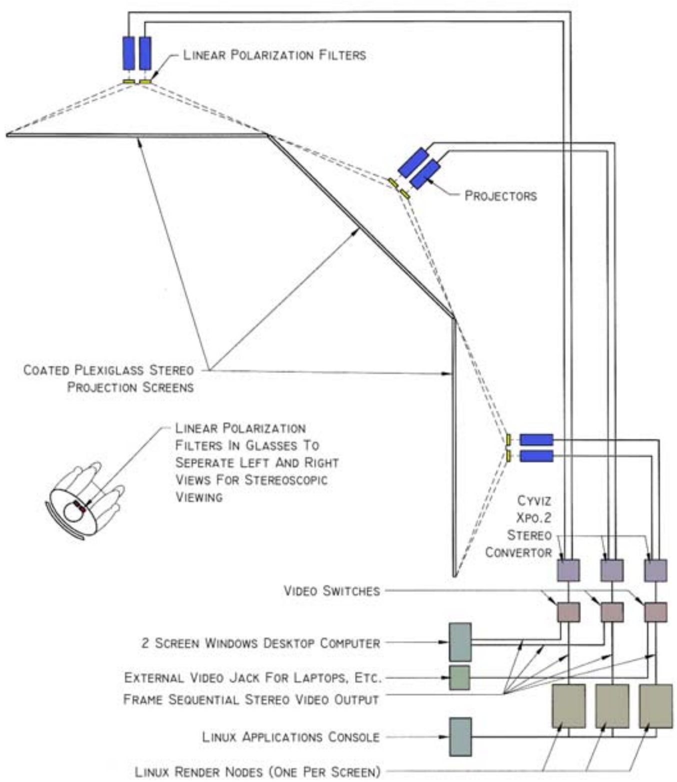

Figure 15: Schematic diagram of the IEL (Penn State Information Technology Services: Graduate Education and Research Services: Visualization Group 2003)

The IEL provides a familiar desktop computing environment with several different commercial CAD applications and other useful software that enable stereoscopic vision. It is also equipped with multimedia tools and includes video conferencing capabilities via the access grid. Users can view the stereoscopic models with polarized glasses as shown in Figure 16 and can navigate a model by using a joystick control in real time. Full-scale stereoscopic vision makes the users feel immersed within the environment.

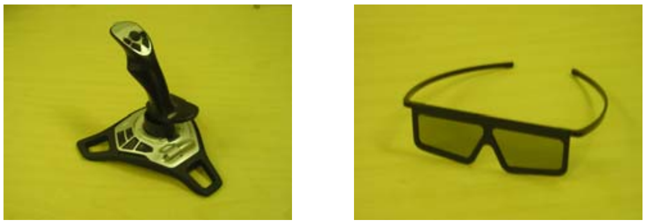

Figure 16: Joystick and passive stereo eyeglasses used in the IEL

The exploitive use of the IEL for multimedia presentations has been widely accepted by architecture students (Kalisperis et al. 2002). With this facility, the students can have their presentation, a video and a walk thru display of their 3D model displayed in all three different screens. This may also serve as a good teaching tool to explain the concepts of architectural design to students having no or less prior experience of visualizing space. Students and faculty belonging to other disciplines like mechanical engineering, chemistry, bioinformatics, and construction are also benefiting from this facility.

The desktop application (graphical loader) used for loading the SALA IVFP was ClusterLoader, which was developed through a combination of C++ for core application development, and JAVA for Graphical User Interface (GUI) development. The loader application's primary function is to stereoscopically display virtual reality models (VRML97 format) at full scale or modified scale (Penn State Information Technology Services: Graduate Education and Research Services: Visualization Group 2003).

5.4 Summary

This chapter provided a description of the case study research project. Then the model and the media used for the case study research experiments were explained. The model provides a visual display of product and process information. These models and the IEL facility were used throughout the case study experiments described in the next chapter.

CHAPTER 6

CASE STUDY EXPERIMENT PROCEDURES AND ANALYSIS OF RESULTS

This chapter describes the case study procedures adopted to meet the defined case study objectives. One of the objectives of this case study research is to study the implementation of Immersive Virtual Facility Prototypes (IVFP) and to capture and compile the recommendations provided by industry practitioners who participated in the case study. The results and data analysis are presented in this chapter. A discussion of the recommendations for further improvement in the development of IVFP is also provided.

6.1 Case Study Research Group

The research in the field of advanced visualization technologies in the AEC industry is an ongoing effort with contributions from multidisciplinary departments at The Pennsylvania State University. This research group consists of faculty members and students from the Department of Architectural Engineering; The School of Architecture and Landscape Architecture; and Information Technology Services. Several undergraduate and graduate students from these departments have collaboratively worked to develop the virtual facility prototypes for this case study project. The construction manager, other companies on the project team and the end users of the case study project have also diligently participated in this research.

6.2 Case Study Procedures

The following presents a sequential order of research activities performed:

6.2.1 Investigation of Subcontractor Progress Meeting at the Field Office

One of the objectives of this study was to explore the use of advanced visualization technologies for construction plan communication. The researcher attended a total of 17 Subcontractor Progress Meetings held by the Construction Manager of the project at their field office. The motive for attending these meetings was to study how the meeting time was utilized for decision-making, plan communications and construction planning discussions. This aided in the identification of areas for improving the productive use of meeting time with the help of advanced visualization technologies. It is important to assess the manner in which these meetings were conducted and understand the topics discussed in these meetings. A detailed description of the agenda of a typical subcontractor progress meeting is provided in the later section.

The Construction Manager (CM) held subcontractor progress meetings to review progress of the work and resolve issues that arose during the construction phase. These meetings were held once every week at the Construction Manager’s field office. Attendees generally included the Construction Manager's Project Manager, Superintendent and Project Engineers along with the Project Manager/Superintendent of the subcontractor companies, e.g., steel, concrete, electrical, mechanical, masonry and surveying. The average duration of these meetings during the early stages of the project was forty minutes. Out of the seventeen progress meetings that the researcher attended, there were around ten to fifteen construction professionals attending each meeting.

6.2.1.1 Description of Subcontractor Progress Meeting

The agenda for a typical subcontractor progress meeting included the following items:

1. General Business

The following are the main items discussed under General Business:

- Safety & housekeeping,
- Contracts,

- Change orders & pricing,
- Submittals;
- Request for Information (RFI);
- Certified and OCIP payroll, and
- Activities for LEED.

2. Subcontractors' Progress Discussion

The subcontractors working on the site would vary according to the progress of the project as progressed. During the early and middle stages of the project, subcontractors were working in the areas of site work, concrete, steel, electrical, mechanical and masonry. During the meeting, current work undertaken and progress made by all subcontractors was discussed. Current field observations, problems, and conflicts faced by each subcontractor were addressed. A review of plans for progress for subsequent work to be performed was discussed with each subcontractor.

3. Project Schedule

A review of the construction schedule was performed and, if needed, corrective measures and procedures to recover the project schedule were proposed. The Construction Manager distributes a three week look ahead schedule (in MS Excel format) followed by a discussion of the feasibility of attaining the proposed schedule for each trade contractor.

6.2.1.2 Time Study Results

A detailed time study of the forms of communication used throughout the meetings was conducted by attending the 17 subcontractor progress meetings. Time spent on each predefined category of communication was measured. The communication categories used are as follows: descriptive, explanative, evaluative, predictive, decision making, problem solving discussions and other discussions. The first four categories were adopted from Liston (2000) and Garcia et al. (2003), and the latter three categories were developed by the researcher. Descriptions of these categories are as follows:

1. Descriptive:

This type of communication involves describing various tasks, in the future or past. This category caters to questions like “what, when, where, who”. (e.g., showing the 2D drawings, cost estimates). It has been observed that significant time during the meetings is involved in describing various tasks to other participants.

2. Explanative

This type of communication includes discussion that is tailored in the direction of someone’s ideas or proposal. This discussion aims to justify the actions that the speaker would have taken or is yet to take. Questions like “why, why not” are discussed in this category.

3. Evaluative

This consists of the assessment of possible alternatives to a problem or situation. Discussions can lead to weighing the pros and cons of these alternatives taking into consideration the given limitations and criteria.

4. Predictive

This type of communication would involve either predicting the possible consequences of a decision or estimating the value of an unknown variable during a meeting. Example: estimating the cost of an activity during the meeting.

5. Decision Making

Decision making can be defined as a process of selecting one alternative out of many alternatives concerning any of the project issues or approaches. Discussions directly related to such processes during the meeting are included in this category.

6. Problem Solving

Problem solving discussions consist of resolving different problems or challenges faced on the project. Frequently, problem solving discussions require input from all the project team members since many problems faced on the project site involve more than one trade contractor. Such discussions lead to exploring various alternatives to solve the problem.

7. Other Discussions

This section includes communication on topics unrelated to the project and also includes moments of silence during the meetings.

A data collection sheet as presented in Appendix A was used for the time study. This instrument was used for measuring the time at an interval of 15 seconds. Then, a percentage of time spent on each category was calculated. From the time study analysis for the case study project, the largest percentage of time was spent on descriptive and explanative forms of communication which was collectively 72%. A total of 16% of the time was spent in problem solving discussions and only 1% of the time was spent on predictive and evaluative type of communication (see Figure 17).

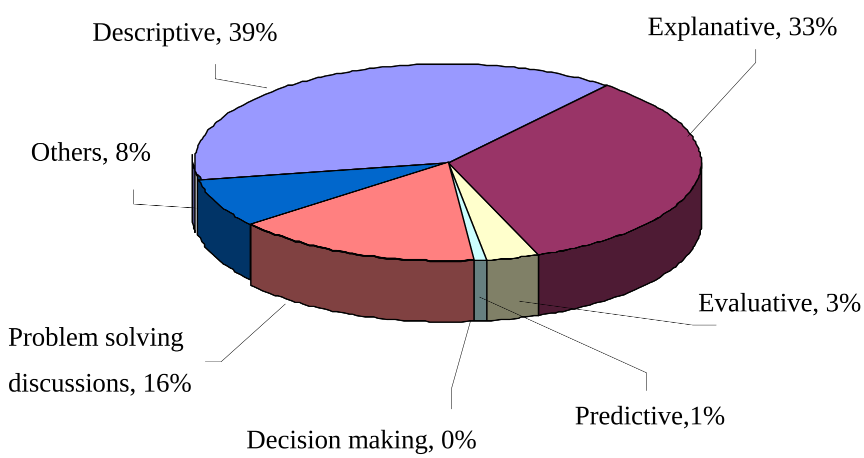

Figure 17: Average distribution of communication time during progress meeting

Therefore, a hypothesis was developed that the utilization of time could be altered if the project team members used more visual and interactive communication methods on the project during their meetings. It may reduce the time spent on discussions to explain construction activities and design, which could be better used in discussions regarding 'what if' scenarios, alternative designs and construction processes.

6.2.2 Exploratory Investigation of Subcontractor Progress Meeting in the IEL

With the cooperation of the project team, a subcontractor progress meeting was held in the IEL on March 30, 2004. The IEL was configured with a U shaped conference table so that all meeting participants could see the large screens (see Figure 18). There were eighteen construction professionals representing six construction companies at the meeting. The meeting was conducted in a similar format as the typical meeting conducted in the Construction Manager's field office. During the meeting, the project team was able to use the three available models (the 3D CAD model, the 4D CAD model and the architects' rendered model) to discuss schedule and design issues. The models were provided as a tool for communication and exchanging ideas among project team members (see Figure 19).

Figure 18: Subcontractor progress meeting in the IEL

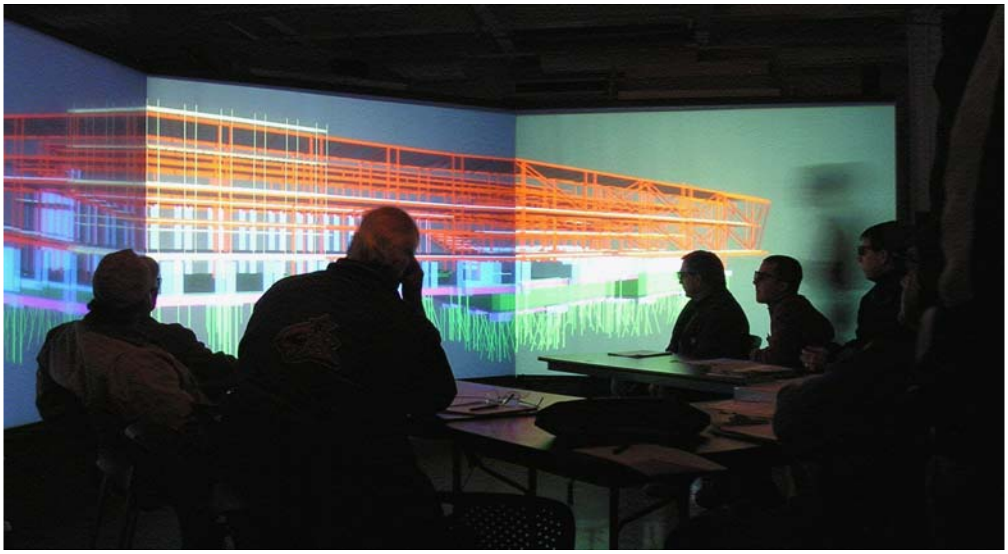

Figure 19: Construction professionals viewing the steel structure of the SALA Building in the IEL

6.2.2.1 Direct Observations and Results

All construction professionals who participated in the meeting provided positive feedback to the display of the models. Most stated that they obtained an improved perspective of the project based on their interaction with the IVFP. They were able to visualize certain areas of the structure more clearly after seeing the models in the IEL. Figure 20 shows the interaction of these professionals in the IEL.

Figure 20: Construction professionals discussing details of the model

While the professionals were using the models, direct observations were taken by observing changes in behavior and collecting anecdotal evidence from the participants (e.g., specific quotes or discussions). At the end of the meeting, a survey designed to measure their changes in perception, attitude and improved project understanding was distributed. Several quotes were collected which signify appreciation and better visualization by using this technology, which are as follows:

Quote from construction manager:

"…excellent, fantastic…this detail really steps out… "

(while viewing the complex curvature of the building façade on the south side)

Quote from trade contractor:

"…I couldn't visualize that it was this much distance [between floor slabs] until I saw the model…"

(while viewing the 3D CAD model)

One of the participants also reflected back to his previous experience from another project on the Penn State campus while viewing the 3D CAD model. The participant referred to potential challenges with the overhanging cantilever section in the SALA

Building model which was similar to the previous project. By providing more detailed design representations, experienced professionals can perform better planning and help avoid unwanted time, consuming and costly choices in the construction planning processes. There also has been certain contradictory observation which has given rise to some important research questions:

1. Only 2 out of the 7 surveys collected were supportive of conducting another progress meeting in the IEL. This raises questions about why the majority of the professionals did not want to hold another meeting in the IEL? What are the impediments to using the IEL facility?
2. A few team members agreed that IVFP are a better tool for visualization, but did not find the virtual models of the SALA project of more value. Therefore, is visualization important on a relatively typical project like the SALA Building? Or did the virtual models contain enough information?
3. Interactions among the team members and discussions on alternative plans after seeing the IVFP were very limited. Hence, does the IVFP provoke the team to think of better alternatives?
4. What is the appropriate time/phase for using IVFP? Since, most of the high impact design decisions are made by the time the project reaches the construction phase, flexibility of making an alternative choice may be diminished.

6.2.2.2 Survey and Results

Following the progress meeting in the IEL, data was collected through a survey (see Appendix B) with both quantitative and qualitative questions. The quantitative data in the survey consisted of the responses of the participants to several questions on a Likert scale of 1 to 5 (1- being strongly disagree to 5- being strongly agree). Seven out of eighteen questionnaires were received giving a 39% response rate. At least one questionnaire was received from each of the construction companies involved in the progress meeting. The results of the survey are included in Table 2. These results show that all the participants agree that advanced visualization technologies serve as a better tool for communication among other participants, stakeholders and the owners of a project.

The team discussed several details of the model and showed enthusiasm about this technology. There were valuable discussions related to better visualization of the curvature on the south face of the building, realization that several specific activities on the project needed to be accelerated, and the need for improved coordination among the subcontractors. There were concerns expressed by the project manager to the concrete subcontractor while viewing the 4D CAD model about the progression of the concrete schedule since it seemed the subcontractor may hinder other subcontractors who were expected to move into a location occupied by the trade.

Table 2: Quantitative data summary of the survey

Questions from the IEL Survey	**Trade 1**	**Trade 2**	**Trade 3**	**Trade 4**	**Trade 5**	**CM1**	**CM2**	**Average Response**
I have a better understanding of the construction sequence of the building structure after viewing the 4D model.	4	5	3	4	4	5	5	4. - Agree
The IEL would be a good environment for future progress meetings.	3	3	3	3	4	4	2	3. - Neutral
After seeing the model I feel there should be changes in the schedule.	3	3	3	3	2	3	4	3. - Neutral
This model reminds me of experiences I encountered on past projects.	3	4	3	3	2	3	2	3. - Neutral
I have more confidence in the schedule after seeing the model.	2	3	3	4	3	2	5	3. - Neutral
The immersive 3-D model could be a valuable communication tool on the project.	4	5	4	3	5	5	5	4. - Agree
Using this model early could help avoid delays in construction.	3	4	2	4	4	5	4	4. - Agree
The model doesn't carry solutions to problems faced on site.	4	3	4	3	4	4	5	4. - Agree
A lack of a detailed representation of the facility often leads to vague and unclear conversations between trades.	4	4	4	4	3	3	2	3. - Neutral
The 4D CAD model with construction space occupation of each trade marked by frameworks will increase the value of the model.	4	5	3	5	3	4	5	4 - Agree

All the above numerical responses are defined on a Likert scale that ranges from 1- strongly disagree to 5- strongly agree.

6.2.3 Exploration of Detailed Virtual Facility Prototype

After the initial subcontractor progress meeting in the IEL, a much more detailed virtual facility prototype of the project was developed. The detailed model helped in the spatial understanding of the interior of the building. Several key professionals associated with the case study project were shown the model and then interviewed. A group of industry practitioners, the project owner, and end users were invited to the IEL to examine the detailed virtual facility prototype. They either had an influence in the decision making process or design for the project, or in managing the construction on the project site. The individuals belonged to five different groups which are the architecture firm, construction manager, subcontractor companies, owner, and end users. One of the objectives of these interviews was to compile a comprehensive list of recommendations suggested by the industry practitioners, owner and end users involved in the project. The detailed virtual facility prototype of the SALA Building contained 3D components belonging to the complete substructure and partially complete superstructure with steel, slabs, walls, stairs, doors and windows. Also, a 4D CAD process model showing the construction sequence of the SALA project was developed. All the individuals were interviewed to get an in-depth understanding of their perception of the prototype and its use in the project. The nature of all the interviews was focused and an open discussion type conversation was maintained. The questions asked during these interviews are presented in Appendix C.

6.2.3.1 Content Analysis of Interviews

A content analysis of all the interviews was performed to systematically interpret the data collected. Though different questions were asked to the individuals according to their responsibilities and roles that they assumed there are common categories addressed by many participants. Table 2 shows the opinions of the various professionals interviewed.

Table 3: Content analysis of the interviews in a tabular format

Questions regarding	**Construction Manager and Subcontractors**	**Architect**	**Owner's Representative**	**End Users**
Benefits of using this technology	• End users can envision the final product better; • Valuable since there is frequently a lack of information and such a model can provide a big picture of the project; • Tremendous value in sales and marketing; • Provides instant feedback to the user; • Very good teaching tool; • It will help in learning from past projects.	• It gives good idea about the basic spatial configuration, size, shape of the space; • It is helpful for owners.	• It is helpful for owners; • It can be a time saver; • The ability to walkthrough the building is very helpful.	• It shows a big picture early on the project; • It can help lessen design changes, if used earlier can point out many problems; • It could have helped in earlier design stages and helped in redesigning certain sections of the buildings.
Complexity of the SALA Project	• Very complex	• Very complex	• Very complex	
Lack of Visualization in 2D drawings	• Many times information is provided but hard to visualize through 2D drawings; • For complex projects some design intent cannot be communicated through 2D drawings.			• Two skins on the south walls were not realized; • Canopy on the front entrance was not visualized; • Huge trusses for the cantilever were not discovered.
Details Visualized through the IVFP	• Windows near trusses for the overhanging cantilevered section.			• Brick piers protruding on the 4th floor; • Daylighting for an office room was limited.
Constraints	• Cost effectiveness	• Cost effectiveness	• Cost effectiveness	
Motivation for Industry use	• In costly and complex projects	• Where architectural practices demand 3D modeling in designing	• In costly and complex projects	

6.2.3.2 Discussion of Interview Results

Table 3 summarizes the feedback received from all the interviewees. The general opinion of the interviewees was that the prototype has given them a good idea about how the end product is going to shape up but it needs many detailed information and additional enhanced features in the immersive virtual environment. Several interviewees saw items that they had not visualized through 2D drawings, e.g., brick piers on the north face of the building extended until approximately 18 inches on the 4^{th} floor. Many of them expressed their wish to interact with the model at an earlier stage in the project.

Direct observations were also taken while the participants were interacting with the model on a one to one sacle. The following are several quotes from interviewees.

Quote from architect:
"It has given me a good idea about the basic spatial configuration, size and shape of the interior space."
(while navigating through the interior parts of the 3D CAD model)

Quote from the end user:
"This model [if used] could have saved us $2 Million on the project…"

6.3 Recommended Features for Future IVFP

The following are suggestions provided by the interviewees after they interacted with the virtual models of SALA Building in the IEL. Their suggestions are shown in a tabular format (Table 4). The recommendations suggested are visually represented in a schematic user interface shown in Figure 21.

Table 4: Recommended features suggested by Industry Practitioners

	Construction Manager and Subcontractors	Architect	Owner's Representative	End Users
IVE features	• Capability of showing/hiding layers in the IVE; • Capability to show the dimensions of the components present.			
Process Model Features	• Capability to change the percentage of completion in a 4D environment that will reflect visually on the models, when made schedule changes it should be able to incorporate that change entirely; • Capability to show different trades flow on the project site with various colors.			
Additional Information	• MEP information; • Should include many other parameters that affect the project on site	• Information regarding finished material, views out of the building, landscape etc.	• Should model a complete office space showing all the furniture and finished materials; • Performance analysis will be helpful	• MEP, performance based models should be incorporated • Temporary structures like scaffolding, cranes, staging
Time to use the model	• Early in design conceptualization stage			

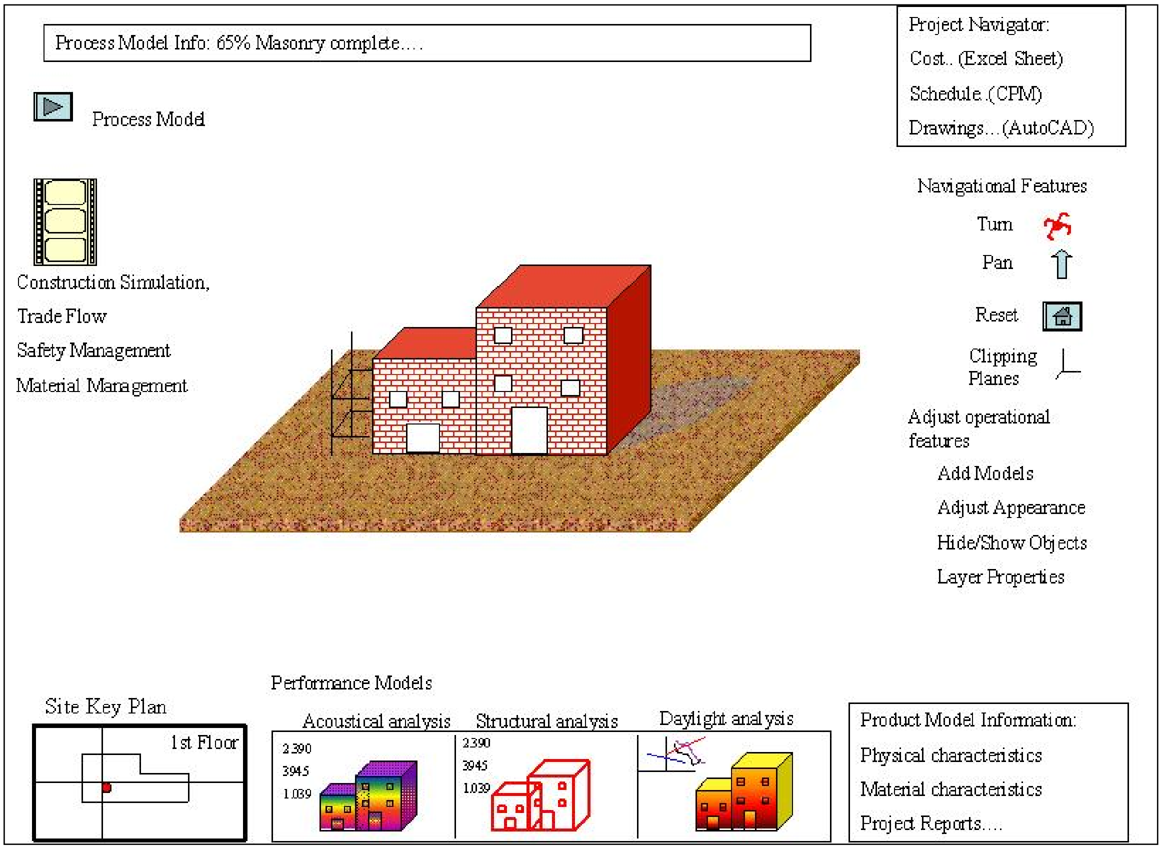

Figure 21: Model of a recommended IVFP

6.4 Summary

This chapter has provided detailed information about the case study procedures used for this research. A discussion on results and their interpretation is also provided. A list of recommendations from industry practitioners was defined so that the future IVFP can be improved.

CHAPTER 7

CONCLUSIONS

This chapter provides a summary of this research. First, it briefly explains the contributions and limitations of the research. Then, a discussion on the possible future research in the exploration of advanced visualization technology and its applications in the AEC industry is presented. Finally, concluding remarks are provided.

7.1 Research Summary

This research was framed as an exploratory based study from the perspective of the AEC Industry and end facility users. This study collected data related to current and proposed prototyping methods in the AEC Industry. Advanced visualization techniques and the included application in the AEC Industry was explored and the concept of Immersive Virtual Facility Prototyping (IVFP) was explained.

To study the industry perspective of using IVFP, a case study project was analyzed for implementation of this technology. Virtual facility prototypes of the case study project were developed and shown to the architects, construction manager, subcontractors, owner and end users. Their perceptions and concerns towards using IVFP were measured by conducting quantitative and qualitative based surveys and by conducting personal interviews with the industry practitioners. From this data collection it has been deduced that IVFP can serve as a good tool for construction plan communication and can help in design visualization. During this investigation various concerns and facts about using such technology in the AEC industry were identified. List of criteria for future developments of IVFP were identified

7.2 Research Contributions

Experienced design and construction professionals frequently have difficulty in visualizing the design of a facility with the current available methods. Technological advances in computer aided design and virtual reality applications provide unique support to create facility designs that will help project stakeholders visualize in three dimensions. This research has explained the concept of Immersive Virtual Facility Prototyping (IVFP). The aim was to understand the limitations of the media used to communicate the facility product and process design and to explore a media which better supports the project stakeholders. During the implementation of the virtual facility prototypes in the case study project, various suggestions and opinions were collected. Key project participants and decision makers of the case study project were interviewed and a content analysis of their interviews was performed. Many issues in design visualization were identified by the industry practitioners while viewing the virtual models, including:

- Required information is frequently present in the 2D drawings but it is very hard to visualize the complex details;
- The design intent of the facility design cannot be completely understood from 2D drawings;
- Understanding of the spatial configuration of a complex project is extremely difficult with 2D drawings.

Many suggestions were provided to improve the existing virtual models for the project including:

- The models should contain additional information regarding mechanical, electrical and plumbing utility systems;
- Temporary structures e.g., scaffolding and location of cranes on the site, should be shown; and

- Landscape features around the building can be beneficial for understanding the overall layout of the building.

Surveys were also conducted for this research. The results show that several project team members conform to the idea of using this technology for construction plan communication. Many project team members believe that IVFP, if used early in the conceptual design stage, could lead to greater satisfaction by the owner and will also reduce design changes and resolve ambiguities about the design intent while the project proceeds through the construction phase.

7.3 Limitations

The data collected for this research has focused on the specific industry practitioners involved with the case study project; hence some of the findings of this research can not be generalized. Since only the key individuals and end facility users of the case study project were involved, the number of these individuals was not statistically significant.

Before the adoption of any new technology, industry will typically seek a cost-benefit analysis to identify its worth. However, a cost-benefit analysis of the use of visualization technologies is complex and is susceptible to various arguments by the industry and research community. The benefits of using advanced visualization technology are particularly difficult to estimate in terms of monetary gains. The benefits are both tangible and intangible. Tangible benefits can include the discovery of conflicts in the schedule, which would have remained unspotted and lead to a loss of time and money. They can also include the identification of innovative solutions that save money or add quality through improvements in the design. Assigning a dollar amount to these benefits is frequently viewed with skepticism, as being unable to spot these conflicts while construction proceeds is frequently assumed as unlikely. Intangible benefits can be in terms of the increase in the confidence of the project manager or superintendent regarding the project schedule; getting a more timely commitment from other project participants or stakeholders; improved visualization that leads to an increased understanding of the project; or an exploration of innovative solutions to issues addressed on the site.

During case study experiments, there also have been certain observations which have provoked in depth research in analyzing the behavior of the participants in such an environment. Interactions among the team members and discussions after seeing the virtual models in the IEL were very limited, which indicates that users have to become familiar with the environment and technology before such technology could be productively used in design and construction planning. This is inconsistent with the previous research by Yerrapathruni (2003) where many interactive discussions occurred in a CAVE™ facility used by industry practitioners for construction planning.

7.4 Future Research

The following sections contain suggestions for future research.

7.4.1 Next Generation of IVFP

This research has explained the concept of IVFP and performed a practical application through a case study project. More improvements in details of the IVFP and improved levels of interaction with the model have to be achieved for a successful implementation of this technology in the AEC industry. The additional features that the interviewees suggested included the ability to turn on/off layers, an ability to show the detailed information about the 3D components and ability to measure the dimensions of the 3D components while navigating through the model. Other items like creating an IVFP process which can be displayed in an immersive virtual environment should also be investigated.

7.4.2 Time Study of Project Meetings

It was observed from the subcontractor progress meetings that the amount of descriptive and explanative communication was improved. It could be argued that the subcontractor progress meetings are not designed for decision making. Issues like change orders, submittals, and request for information are discussed in such meetings. Most of the decision making and coordination discussions occur in other meetings like the owner's meeting or coordination meetings. For future research it would be appropriate to try to conduct a time study of other meetings, e.g., owner's meeting and coordination meetings.

7.4.3 Knowledge Management in Immersive Virtual Environment

Knowledge is a vital resource for a project-based industry like construction. The forms of knowledge present in such an industry can be classified as explicit and tacit (Krogh et al. 2000). Explicit knowledge can be formulated in sentences, expressed while communicating or captured in drawings. Tacit knowledge is stored in senses, as skills in bodily movement, individual perception, physical experiences, rules of thumb, and intuition (Polanyi 1974). Such tacit knowledge is often very difficult to describe to others. The AEC industry involves understanding of complex processes and exchange of project information among team members from various educational background and experiences. In many academic areas too, students' success now depends upon their ability to envision and manipulate abstract multidimensional information spaces (Gordin and Pea 1995). This research had made attempts to understand how to use immersive virtual reality (VR) to support the learning of abstract concepts for designers and constructors of the case study project. It is a hypothesis that experts reflect back to their knowledge and experience relatively easily, if visual cues are seen in the virtual facility prototypes. During the case study experiments, the researcher observed that there were instances where experts had mentioned about construction issues witnessed on similar past projects.

Due to the defined scope of this research, substantial data supporting knowledge extraction in an IVE was not obtained. A detailed case study specifically looking at the knowledge management benefits of this technology could be accomplished to address this issue. A detailed model developed from the thorough input from industry practitioners and experiments with professionals in an IVE could give substantial data for this research.

7.4.4 Human Behavior in Immersive Virtual Environment

It has been challenging for researchers to focus on the use of VR related interfaces for practical applications. Many of the team members from the case study project were reluctant and intimidated by the virtual environment provided by the IEL. The primary reason may be that most of these constructors have very little exposure to any VR related applications. It could be argued that the users of such an environment will not be completely receptive to large quanties of information that are visually represented. This problem could possibly be tackled by familiarizing the users with the virtual environment.

A detailed analysis of user behaviors in an IVE is of utmost importance, since an inherent resistance in human nature could be a possible impediment in the exploration of this technology. A psychological study of users from various educational backgrounds belonging to different stages of their career paths could be very valuable.

7.5 Concluding Remarks

The latest virtual reality applications can provide project stakeholders with a full scale , 3D walkthrough of the fully completed building even before its construction. This capability can be of immense value to the designers, constructors and other decision makers on a facility project. The technological advances in the field of design visualization are far ahead of the current methods used on typical projects. It is of utmost importance to study the resistance and impediments that this technology faces on real-life projects. This research has attempted to understand the perspective of AEC industry practitioners and the facility end users towards utilizing immersive virtual facility prototyping on an actual project. Several suggestions for improvements and directions for further development of IVFP have been defined.

BIBLIOGRAPHY

Aukstakalnis, S., and Blatner, D. (1992). *Silicon Mirage : The art and science of virtual reality*, Peachpit Press, Berkeley, CA.

Chen, W. (1999). "3d city: prototyping techniques for urban design modelling." *Proceedings of the 4th International Conference on GeoComputation,* Virginia, U.S.A.

Chua, C. K., Leong, K. F., and Lim, C. S. (2003). *Rapid prototyping: principles and applications*, World Scientific Publishing Co. Pte. Ltd., Singapore.

Corbetta, P. (2003). Social research : theory, methods and techniques, SAGE Publishers, London, U.K.

Cooper, K. G. (2001). Rapid prototyping technology : selection and application, Marcel Dekker, New York.

Darken, R. P., and Sibert, J. L. (1995). "Navigating large virutal spaces." International journal of human computer interaction, 8(1), 49-71.

Dede, C., and Lewis, M. (1995). "Assessment of emerging educational technologies that might assist and enhance school-to-work transitions." National Technical Information Service, Washington, DC, U.S.A.

Eastman, C. M. (1999). Building product models: Computer environments supporting design and construction, CRC Press LLC, Boca Raton, FL.

Electronic Visualization Lab (EVL). (2001). "The CAVE : a virtual reality theater."

Electronic Visualization Laboratory (EVL). (2003). "ImmersaDesk."

Fernie, S., Green, S. D., Weller, S. J., and Newcomebe, R. (2003). "Knowledge sharing: context, confusion and controversy." International Journal of Project Management, 21(3), 177-187.

Fisher, S. (1986). "Virtual Interface environment." *IEEE/AIAA 7th Digital Avionics Systems Conference*, Texas, U.S.A.

Garcia, A. C. B., Kunz, J., and Fischer, M. (2003). "Meeting details: methods to instrument meetings and use agenda voting to make them more effective."

Gebhardt, A. (2003). Rapid prototyping, Munich : Hanser Publishers ; Cincinnati: Hanser Gardener Publications.

Gordin, D. N., and Pea, R. D. (1995). "Prospects for scientific visualization as an educational technology." *The Journal of the Learning Sciences*, 4(3), 249-279.

Guba, E. G., and Lincoln, Y. S. (1981). Effective evaluation, Jossey-Bass Publishers, San Francisco, U.S.A.

Haas, S. (1994). "Virtual prototyping: exceptations and realizations of a new working paradigm." *Proceedings of the IFIP WG 5.10 workshops on virutal environments and their applicaitons and virtual prototyping*, Providence, RI, USA, 341-345.

Holsti, O. R. (1969). Content analysis for the social sciences and humanities, Reading, Mass. : Addison-Wesley Pub. Co., [1969]. Reading, Massachusetts.

Issa, R. R. A. (2003). "Virtual reality: a solution to seamless technology integration in the aec industry." 4D CAD and Visualization in Construction: Developments and Applications, R. R. A. Issa, I. Flood, and W. J. O'Brien, eds., Lisse : Exton, PA : A.A. Balkema Publishers, 243-260.

Julesz, B. (1971). *Foundations of cyclopean perception*, The University of Chicago Press, Chicago, USA.

Kalawsky, R. S. (1993). "Exploiting virtual reality techniques in education and training: technological issues." *A report prepared for AGOCG (available at www.agocg.ac.uk/reports/virtual/vrtech/title.htm)*, Loughborough University of Technology.

Kalisperis, L. N., Otto, G., Muramoto, K., Gundrum, J. S., Masters, R., and Orland, B. (2002). "Virtual reality/space visualization in design education: the VR-desktop initiative." *Proceedings of eCAADe2002, design e-ducation: Connecting the Real and the Virtual*, Warsaw, Poland, 64-71.

Kelley, T. (2001). The art of innovation: lessons in creativity from IDEO, America's leading design firm, New York: Currency/Doubleday.

Kohn, M. (1994). "Is this the end of abstract thought?" New Scientist, 37-39.

Krogh, G. V., Ichijo, K., and Nonaka, I. (2000). *Enabling knowledge creation : how to unlock the mystery of tacit knowledge and release the power of innovation*, Oxford University Press, Inc. 2000, New York.

Lee, A., Marshall-Ponting, A. J., Aouad, G., Wu, S., Koh, I., Fu, C., Cooper, R., Betts, M., Kagioglou, M., and Fischer, M. (2003). "Developing a vision of nD-enabled construction." The Center of Excellence for Construct IT, Salford, U.K.

Leonard-Barton, D. (1995). *Wellsprings of knowledge: building and sustaining the sources of innovation*, Harvard Business School Press, Boston, Masschusetts.

Liston, K. (2000). "Assessing and characterizing the use of visualization techniques for AEC decision making tasks," Ph.D. Thesis Proposal, Stanford University.

Macomber, J. (2003). "Follow the money; what really drives technology innovation in construction." Winds of change Integration and Innovation in Construction: Proceedings of the Congress, American Society of Civil Engineers: Construction Institute, Honolulu, Hawaii.

Marshall, C., and Rossman, G. (1999). *Designing qualitative research*, Sage Publications, Inc., Newbury Park , CA.

McAdam, R. (2000). "Knowledge management as a catalyst for innovation within organizations: a qualitative study." Knowledge and Process Management, 7(4), 233-241.

Ovtcharova, J., and Vieira, A. S. (1994). "Virtual prototyping through feature processing." Virtual prototyping : virtual environments and the product design process : proceedings of the IFIP WG 5.10 workshops on virtual environments and their applications and virtual prototyping, 1994, Coimbra, Portugal, 78-90.

Pahl, G., and Beitz, W. (1984). Engineering design, The Design Council, London, London, U.K.

Penn State: College or Arts and Architecture. (2004). "The Stuckeman Family Building for the School of Architecture and Landscape Architecture." Accessed: July 9, 2004, 2004.

Penn State: College or Arts and Architecture. (2004). "Giving to Penn State: Stuckeman Family Building (SALA)." Accessed: July 9, 2004.

Penn State Information Technology Services: Graduate Education and Research Services: Visualization Group. (2003). "Immersive Environments Lab." (gears.aset.psu.edu/viz/facilities/iel), Accessed: July 8, 2003.

Polanyi, M. (1974). *Personal knowledge : towards a post-critical philosophy*, University of Chicago Press, Chicago.

Pratt, M. J. (1994). "Virtual prototypes and product models in mechanical engineering." *Proceedings of the IFIP WG 5.10 workshops on virutal environments and their applicaitons and virtual prototyping*, Providence, RI, USA, 113-128.

Psotka, J. (1995). "Immersive training systems: Virtual reality and education and training." Instructional Science, 23(5-6), 405-423.

Retik, A., and Langford, D. (2001). *Computer Integrated Planning and Design for Construction*, Thomas Telford, London.

Rieber, L. P. (1994). "Visualization as an aid to problem-solving: examples from history." *Proceedings of the National Convention of the Association for Educational Communications and Technology*, Nashville, TN.

Salzman, M., Dede, C., Loftin, R. B., and Chen, J. (1999). "A model ofr understanding how virtual reality aids comples conceptual learning." Presence: Teleoperators and Virtual Environments, 8(3), 293-316.

Savioja, L., Mantere, M., Olli, I., Ayravainen, S., Grohn, M., and Iso-Aho, J. (2003). "Utilizing virtual environments in construction projects." *Electronic Journal of Information Technology in Construction*, 8, 85-99.

Schaaf, J. J. C., and Thompson, F. L. (1997). "System concept development with virtual prototyping." *Proceedings of the 29th conference on Winter Simulation*, Atlanta, Georgia, United States, 941 - 947.

Schmitt, G. (1995). "Virtual Reality in Architecture." *Proceedings of Virtual Reality World '95: IDG Conferences and Seminars*, Munich, Germany, 113-124.

Schnabel, M. A., and Kvan, T. (2001). "Design communication in immersive virtual environments: an initial exploration; Architectural Information Management." *19th eCAADe Conference Proceedings*, Hensinki (Finland), 472-478.

Schrage, M. (2000). *Serious play: how the world's best companies simulate to innovate*, Harvard Business School Press, Boston, MA.

Schiffner, N. (1994). "Integration of virtual prototyping applications with a distributed conferencing system." *Proceedings of the IFIP WG 5.10 workshops on virutal environments and their applicaitons and virtual prototyping*, Providence, RI, USA, 58-66.

Sherman, W. R., and Craig, A. B. (2003). *Understanding virtual reality: interface, application, and design*, Morgan Kaufmann Publishers, Boston, USA.

Simon, J. L., and Burstein, P. (1985). *Basic research methods in social science*, Random House, New York, NY.

Slater, M., and Wilbur, S. (1995). "A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments." *Framework for Immersive Virtual Environments Conference of the FIVE Working Group*, London, U.K., 603-616.

Sutherland, I. E. (1965). "The ultimate display." *Proceedings of IFIPS Congress*, New York, U.S.A, 506-508.

Sutherland, I. E. (1968). "A head-mounted three dimensional display." *Proceedings of the Fall Joint Computer Conference*, Montvale, N.J., U.S.A, 757-764.

Tarr, M. J., and Warren, W. H. (2002). "Virtual reality in behavioral neuroscience and beyond." Nature Neuroscience, 1089-1092.

Vieira, A. S., and Ovtcharova, J. (1994). "Virtual prototyping thrugh feature processing." *Proceedings of the IFIP WG 5.10 workshops on virutal environments and their applicaitons and virtual prototyping*, Providence, RI, USA, 78-90.

Wagner, J., and Steger, W. (1994). "Rapid prototyping: An approach beyond manufacturing technology." *Proceedings of the IFIP WG 5.10 workshops on virutal* *environments and their applicaitons and virtual prototyping*, Providence, RI, USA, 32-47.

Whyte, J., and Bouchlaghem, D. (2002). "Implementation of VR systems: a comparison between the early adoption of CAD and current uptake of VR." *Construction Innovation*, 2002(2), 3-13.

Winn, W. (1993). "A Conceptual Basis for Educational Applications of Virtual Reality." *TR-93-9*, Human Interface Technology Laboratory, University of Washington, Washington.

Woksepp, S., and Tullberg, O. (2001). "Virtual Reality in Construction-A state of the art report." *1*, Department of Structural Mechanics, Chalmers University of Technology, Sweden.

Yerrapathruni, S. (2003). "Using 4D CAD and immersive virtual environments to improve construction planning," M.S. Thesis, The Pennsylvania State University, University Park, PA.

Yin, R. (1999). *Case study research: Design and methods*, SAGE publications., Newbury Park, CA.

APPENDIX A

Data Collection Sheet for the Time Study

<table>
<tr><th colspan="6">DATA COLLECTION SHEET</th></tr>
<tr><th colspan="6">Weekly Subcontractor Progress Meeting</th></tr>
<tr><td colspan="6">Attended by:

Date:</td></tr>
<tr><th>Category of communication</th><th>Addressed by</th><th>Responded by</th><th>Record time by (|) for every 30 sec (.) for every 15 sec</th><th>Total Time</th><th>Notes (Issues discussed, anecdotal evidences etc.)</th></tr>
<tr><td>Descriptive</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Explanative</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Evaluative</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Predictive</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Decision making</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Problem solving discussions</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Others</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Total duration of meeting</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Commitments</td><td colspan="5"></td></tr>
<tr><td>Other items provided in the meeting</td><td colspan="5"></td></tr>
</table>

APPENDIX B

Immersive Environment Lab Survey

IMMERSIVE ENVIRONMENTS LAB SURVEY

This is an anonymous survey and you can skip any question(s). This survey is conducted for the sole purpose of research and all the data collected will be kept strictly confidential. Please give your comments and provide your responses on a scale of 1-5 (1 –strongly disagree and 5 –strongly agree) . Thank you for your time and cooperation.

Acronyms used in the Questionnaire:

- IEL: Immersive Environments Laboratory
- 4D CAD: (3D CAD + Time as 'schedule')

General Information:

1. What is your trade / scope of work?
   ____

2. How many years of construction experience do you have?
   __________________ years

3. What type of building construction experience do you have?

Answer the following questions on a scale of 1-5 (1 –strongly disagree and 5 – strongly agree):

Strongly Disagree	*Disagree*	*Neutral*	*Agree*	*Strongly Agree*
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5
1	2	3	4	5

4. I have a better understanding of the construction sequence of the building structure after viewing the 4D model.

5. The IEL would be a good environment for future progress meetings.

6. After seeing the model I feel there should be changes in the schedule.

7. This model reminds me of experiences I encountered on past projects.

8. I have more confidence in the schedule after seeing the model.

9. The immersive 3-D model could be a valuable communication tool on the project.

10. Using this model early could help avoid delays in construction.

11. The model doesn't carry solutions to problems faced on site.

12. A lack of a detailed representation of the facility often leads to vague and unclear conversations between trades.

13. The 4D CAD model with construction space occupation of each trade marked by framework will increase the value of the model.

14. Did you see something in the model which you had not mentally visualized? If so, please describe.
15. Did you identify any constructability issues? If yes, please list them.

16. What are the current challenges that you face in the project? Can this technology help you in resolving these challenges? If yes, state how can it be helpful.

17. Can you identify any reason(s) why this technology can not be adopted in the industry?

18. What additional items would you like to see included in the model?

The 4D CAD model:

19. could be helpful in performing construction space planning?

20. could make it easier to visualize the space coordination required with other trade contractors?

21. Other Comments:

This part is *optional.* Please return this page separately from the rest part of the surveying.

Are you interested in a 20-minutes interview, at your convenient time, about integrating visual technology with trade sequencing and space planning?
If so, please leave your contact details.

Contractor Name: ______________________

Contractor's job description in this project:

____
___

Name: ____________________

Position: __________________

Phone number: (___) ________

Email: ____________________

We sincerely appreciate your time and effort in sharing your ideas and thoughts with us. We are going to contact you in the nearly future to schedule an appropriate time to meet for the interview.

Trade contractor:

A. What is the biggest challenge in the erection of steel on the SALA project?

B. Do you wish to see any more details in the models? If yes, state what you would like to see.

C. How would rate your level of confidence in the steel erection sequence? Was the 4D CAD model helpful in evaluating the sequence or schedule?

D. Did you identify any conflicts in the steel construction sequence in the 4D CAD? If yes, please list them.

For the Construction Manager:

A. Do you think this tool could be beneficial in schedule development? Why or why not?

B. Would you wish to have a 3D / 4D CAD model for the owner's meeting? Why or why not?

C. Would you wish to change the schedule after seeing the 3D CAD and 4D CAD model? If yes, what would you revise?

D. Did you identify any conflicts in the steel construction sequence in the 4D CAD? If yes, please list them.

E. Could you visualize the construction space requirements for each trade in the 4D simulation?

APPENDIX C

Interview Questions

INTERVIEW QUESTIONS

1. How complex or typical is the SALA building? Did you have any particular challenges in visualizing this project through 2D drawings?

2. Have you ever made any mistakes in visualizing the design? Can you provide any examples?

3. Has a lack of visualisation of any project lead to any delays or other negative impacts on the project?

4. Do you feel the virtual facility prototyping applications you experienced in the Immersive Environments Lab were beneficial? Why or why not?

5. Have you ever used 3D CAD applications or any advanced visualization applications on projects?
   - If yes, what applications, modeling was performed and was it valuable?

6. Was the model detailed enough?
   - What more detailed information would you like to see in the model?
   - Which detail stood out, the most in the model?

7. Did you see any details in the model that you had not visualized?

8. How did it help you in the SALA building project?
   - If yes, in what areas did it help you?

9. Will this model help in improving the current state of progress made on the project?
   - What kind of issues will it solve?

10. Do you think that the problems could be avoided or minimized if you had the model early in the project?

11. What part of the model you saw was more applicable to your field? Do you feel there was enough information in the model pertaining to your field of work?

12. How realistic do you think were the models? How would you describe the emotions or feelings you had when you were viewing the virtual prototype?
    - Excited?
    - Nervous?
    - Intimidated?
    - Curious/anxious?
    - Uncomfortable?
    - Quite normal

13. The research community tends to believe that the best application of this technology is in communication of design information among the project participants. Would you agree or disagree with this perspective? Why?

14. Do you think that the industry will adopt this technology?

15. What are the impediments to implementing this technology in the industry?

16. What do you feel would be the benefits of implementing this technology?

17. What do you envision are the most appropriate areas of application of this technology in the AEC industry?

18. If you were the owner/technology officer responsible, will you invest in such a technology?
    - If no, why will you not invest?

19. What improvements, changes or research would encourage you to invest in this technology?

APPENDIX D

Calculation of Time Study for the Subcontractor Progress Meetings

Meetings	Duration in min	Categories of Communication							
		Descriptive	Explainative	Evaluative	Predictive	Decision making	Problem solving discussions	Others	Anecdotal Evidences
1	41.50	8.00	13.25	0.00	2.25	0.00	15.00	3.00	none
2	32.00	13.00	11.00	2.25	0.00	0.00	4.50	1.25	none
3	29.00	16.75	7.75	0.00	0.00	0.00	2.00	2.50	none
4	14.50	8.00	3.00	0.00	0.00	0.00	2.00	1.50	none
5	31.00	8.50	10.25	0.00	0.00	0.00	9.75	2.50	none
6	44.50	18.00	10.00	0.00	3.25	0.00	12.00	1.25	none
7	44.50	16.25	22.25	0.00	0.00	0.00	6.00	0.00	none
8	38.00	13.25	18.00	0.00	0.00	0.00	3.00	3.75	none
9	16.00	10.00	3.75	0.00	0.00	0.00	0.00	2.25	none
10	22.50	9.00	6.25	0.00	0.00	0.00	4.25	3.00	none
11	29.00	12.00	7.00	4.00	0.00	0.00	4.75	1.25	none
12	54.00	18.50	24.50	0.00	0.00	0.00	4.50	6.50	none
13	30.00	9.00	6.50	4.00	0.00	0.00	8.00	2.50	none
14	29.00	7.50	9.00	0.00	0.00	0.00	10.00	2.50	none
15	33.50	3.00	19.00	8.00	0.00	0.00	0.00	3.50	none
16	39.00	21.00	15.25	0.00	0.00	0.00	1.00	1.75	none
17	28.00	13.00	9.00	0.00	0.00	0.00	3.50	2.50	none

Meetings	Percentage of time spent on each category of communication (%)						
	Descriptive	Explainative	Evaluative	Predictive	Decision making	Problem solving discussions	Others
1	19.28	31.93	0.00	5.42	0.00	36.14	7.23
2	40.63	34.38	7.03	0.00	0.00	14.06	3.91
3	57.76	26.72	0.00	0.00	0.00	6.90	8.62
4	55.17	`	0.00	0.00	0.00	13.79	10.34
5	27.42	33.06	0.00	0.00	0.00	31.45	8.06
6	40.45	22.47	0.00	7.30	0.00	26.97	2.81
7	36.52	50.00	0.00	0.00	0.00	13.48	0.00
8	34.87	47.37	0.00	0.00	0.00	7.89	9.87
9	62.50	23.44	0.00	0.00	0.00	0.00	14.06
10	40.00	27.78	0.00	0.00	0.00	18.89	13.33
11	41.38	24.14	13.79	0.00	0.00	16.38	4.31
12	34.26	45.37	0.00	0.00	0.00	8.33	12.04
13	30.00	21.67	13.33	0.00	0.00	26.67	8.33
14	25.86	31.03	0.00	0.00	0.00	34.48	8.62
15	8.96	56.72	23.88	0.00	0.00	0.00	10.45
16	53.85	39.10	0.00	0.00	0.00	2.56	4.49
17	46.43	32.14	0.00	0.00	0.00	12.50	8.93
Average percentage of time spent:							
	39	33	3	1	0	16	8

APPENDIX E

Human Subjects Approval

PENNSTATE

Vice President for Research
Office for Research Protections

The Pennsylvania State University
212 Kern Graduate Building
University Park, PA 16802-3301

(814) 865-1775
Fax: (814) 863-8699
www.research.psu.edu/orp/

Date: June 10, 2004

From: Mary B. Becker, IRB Administrator

To: Rajitha Gopinath

Subject: Results of Review of Proposal - Exemption **(IRB #18767)**
Approval Expiration Date: June 9, 2005
"Assessing the Use of Virtual Facility Prototypes in Plan Communication and Knowledge Extraction"

The Office for Research Protections (ORP) has reviewed and approved your application for the use of human participants in your research. By accepting this decision, you agree to obtain prior approval from the ORP for any changes to your study. Unanticipated participant events that are encountered during the conduct of this research must be reported in a timely fashion.

Enclosed is/are the dated, ORP-approved informed consent(s) to be used when enrolling participants for this research. Participants must receive a **copy** of the approved informed consent form to keep for their records.

The principal investigator is expected to maintain the original signed consent forms along with the research records for at least three (3) years after termination of ORP approval. The principal investigator must determine and adhere to additional requirements established by any outside sponsors.

If your study will extend beyond the above noted approval expiration date, the principal investigator must submit a completed Continuing Progress Report to the ORP to request renewed approval for this research.

On behalf of the ORP and the University, thank you for your efforts to conduct research in compliance with the federal regulations that have been established for the protection of human participants.

MBB/slk
Enclosure
cc: John I. Messner

Please Note: The ORP encourages you to subscribe to the ORP listserv for protocol and research-related information. Send a blank email to: L-ORP-Research-L-subscribe-request@lists.psu.edu <mailto:L-ORP-Research-L-subscribe-request@lists.psu.edu>.

SURVEY CONSENT FORM
The Pennsylvania State University

Title of Project: Assessing the Use of Virtual Facility Prototypes in Plan Communication and Knowledge Extraction (IRB # 18767)

Principal Investigator: Rajitha Gopinath
Faculty Advisor: Dr. John Messner

1. Purpose of the Study: This study is a part of ongoing research at the Architectural Engineering Department at the Penn State University, in assessing the value of utilizing advanced visualization technologies in the Architecture Engineering Construction (AEC) Industry. The objective of this study is to assess the potential for using Virtual Facility Prototypes (VFPs) on the School of Architecture and Landscape Architecture (SALA) building project located at Penn State University. The intent of this survey is to gain a better understanding of the participant's view of using VFPs in visualizing the facility in the design and construction phases.

2. Procedures to be followed: To participate in this research the participants will have to view the models of SALA building in the Immersive Environments Lab located at 306 Engineering Unit C. A survey will be handed out to the participants after they have viewed the models and returned to the Principal Investigator.

3. Criteria for participation: The participants should have construction experience of at least 2 years. Construction professionals related to on going project of the School of Architecture and Landscape Architecture building project or construction professionals visiting Penn State can participate in this study. All the collected data will be destroyed by the year 2008.

4. Discomforts and Risks: None

5. Benefits:
   a. The participants will have an opportunity to gain more knowledge related to the value of visualization in the AEC industry.

6. Duration/Time: 15-20 minutes

7. Statement of Confidentiality: The survey answers are recorded anonymously and do not require the participants to share any personal information (like name, name of employer, age, sex etc.) with the investigators.

8. Right to Ask Questions: Participants have the right to ask questions and have those questions answered. If you have questions about your rights as a research participant, contact Penn State's Office for Research Protections at (814) 865-1775.

9. Compensation: There are no compensations involved in participating in the survey.

10. Voluntary Participation: Participation is voluntary. Participants can skip any questions or withdraw from the study at any time.

You must be 18 years of age or older to consent to participate in this research study. Return of the survey will be considered as consent for the participation in the study. You will be given a copy of this consent form to keep for your records. Please feel free to contact the Principal Investigator or the Office for Research Protection for any queries.
Sincerely,

Rajitha Gopinath
MS Graduate Student
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The Pennsylvania State University
University Park, PA 16802
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Dr. John I. Messner
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ORP USE ONLY:
The Pennsylvania State University
Office for Research Protections

Approval Date: 06/10/04 M. Becker

Expiration Date: 06/09/05 M. Becker

INTERVIEW CONSENT FORM
The Pennsylvania State University

Title of Project: Assessing the Use of Virtual Facility Prototypes in Plan Communication and Knowledge Extraction (IRB # 18767)

Principal Investigator: Rajitha Gopinath
Faculty Advisor: Dr. John Messner

1. Purpose of the Study: This study is a part of ongoing research at the Architectural Engineering Department at the Penn State University, in assessing the value of utilizing advanced visualization technologies in the Architecture Engineering Construction (AEC) Industry. The objective of this study is to assess the potential for using Virtual Facility Prototypes (VFPs) on the School of Architecture and Landscape Architecture (SALA) building project located at Penn State University. The intent of this interview is to gain an in depth understanding of the participant's view of using VFPs in visualizing the facility in the design and construction phases.

2. Procedures to be followed: To participate in this research the participants will have to view the models of SALA building in the Immersive Environments Lab located at 306 Engineering Unit C. After which the participant can volunteer to take an interview with the Principal Investigator. If permitted by the participants, the conversation during the interview will be tape recorded for content analysis and will be destroyed after the research is completed by the year 2008. The principal investigator and the faculty advisor will have the access to the recorded information and will be kept in the faculty advisor's office.

3. Criteria for participation: The participants should be construction professionals with an experience of at least 2 years. Construction professionals related to on going project of the School of Architecture and Landscape Architecture building project or construction professionals visiting Penn State can participate in this study as interviewees.

4. Discomforts and Risks: None

5. Benefits:
   a. The participants will have an opportunity to gain more knowledge related to the value of visualization in the AEC industry.

6. Duration/Time: 15-20 minutes

7. Statement of Confidentiality: The participants name, position, name of employer or any such personal information will not be associated with any comments made by them. However, for research purposes, the comments or quotes made by the participants may be used but will not be associated with them.

8. Right to Ask Questions: Participants have the right to ask questions and have those questions answered. If you have questions about your rights as a research participant, contact Penn State's Office for Research Protections at (814) 865-1775.

9. Compensation: There are no compensations involved in participating in the interview.

10. Voluntary Participation: Participation is voluntary. Participants can withdraw from the study at any time by notifying the principal investigator. Participants can decline to answer specific questions.

You must be 18 years of age or older to consent to participate in this research study. Your participation in the interview will be considered as consent. You will be given a copy of this consent form to keep for your records. Please feel free to contact the Principal Investigator or the Office for Research Protection for any queries.

Sincerely,

Rajitha Gopinath
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