4D CAD FOR HIGHWAY CONSTRUCTION PROJECTS

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Abstract

Computer technology has become integrated into every facet of modern day life, providing innovative solutions to a multitude of today's problems. This is true in the architectural, engineering, and construction industry, where new technologies have been changing the way facilities are designed and constructed around the world. One emerging technology is 4D CAD modeling, where a 3D CAD model is linked to a construction schedule. This 4D CAD technology has been proven to be beneficial in construction applications by several academic and industry professionals, showing improved project planning, scheduling, and communication capabilities. However, the majority of 4D CAD research has focused on building and industrial construction applications, and has not explored highway construction applications. Therefore, this research investigates the applications of 4D CAD for highway construction projects.

The primary research question identified in this thesis is *"what are the best applications of 4D CAD for highway construction projects"* This question is investigated using a case study application of 4D CAD for a highway construction project. The 4D model was shown to three groups of highway construction professionals from different companies. Once each group views the 4D CAD model, their thoughts and opinions are collected to determine the best applications of 4D CAD for highway construction projects.

The results of this research show that in the opinions of highway construction professionals, 4D CAD is beneficial for planning, scheduling and communication applications in highway construction projects. The best applications of 4D CAD for highway construction are for developing traffic plans and for communicating the construction plan to the public. There was a prevailing optimism for 4D CAD among the highway construction professionals, and was seen as "the next logical step" in planning, scheduling, and it communication tools for the highway construction industry.

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Chapter 1

Introduction

1.1 Introduction

Over the past fifteen years, 4D CAD has gained significant attention in the architecture, engineering, and construction (AEC) industry. 4D CAD is the result of linking a 3D CAD model with a construction project schedule in a virtual computer environment (Koo and Fischer, 2000). The idea behind 4D CAD was first developed in the mid 1980's, when Bechtel and Hitachi collaborated to develop 4D Planner software (Cleveland, 1989). Over the years, 4D CAD has developed into a tool used by planners, designers, and engineers, to analyze and visualize several phases of a project, from design related decisions, to construction planning, to cost and resources available (McKinney and Fischer, 1998). 4D CAD has also shown to improve communication throughout the use of improved visualization of a facility product and process via shared reference to interactive virtual prototypes (Otto et al., 2005).

4D CAD technology has risen in response to increased project complexity, shorter project delivery times, and a general need for better planning techniques. Typical 2D plans alone do not adequately communicate the 3D geometry of the structure, and rarely provide the details of the various components indicated in the design and in the accompanying construction schedule to be used by the construction personnel (Kunz and Fisher, 2005). Due to the difficulties in understanding and visualizing the different phases of the construction schedule, unexpected delays or conflicts that undermine the success of the project often occur (Liapi, 2003).

Therefore, 4D CAD has emerged as a powerful tool that can help engineers and constructors better plan and anticipate construction conflicts before they occur in the field.

1.1.1 Current 4D CAD Research

Current 4D CAD research has focused almost solely on building construction applications [Messner and Lynch (2002), Gopinath (2004), Hu et al. (2005)]. Research programs, such as Penn State's Computer Integrated Construction program and Stanford's CIFE institute have published a plethora of reports and thesis detailing the benefits of 4D construction simulation in building construction. These publications have shown benefits ranging from educational construction applications (Messner et al., 2003) (Messner et al., 2005), to space utilization and site planning applications (Chau et al., 2004) (Tan et al., 2005). The benefits shown in these reports have driven the continued interest and popularity of 4D CAD in construction, and helped create new methods of construction project modeling, such as building information modeling, or BIM.

The primary focus of the 4D CAD research, as discussed above, has revolved around building construction. Yet, there has been little investigation into the benefits of 4D CAD for highway construction applications. Transportation projects often involve complex geometric configurations which render the communication of project information between interesting parties very difficult and prone to errors (Liapi, 2003). Complex highway interchanges and constantly changing traffic patterns make highway construction projects increasingly difficult to plan and coordinate before and throughout the construction process. Due to this complexity, it would be beneficial to apply 4D CAD technologies in highway construction projects for planning, scheduling and other construction tasks.

This thesis investigates the research question *"what are the best use applications of 4D CAD for highway construction projects and why"*. This question is investigated using several research methods, including a case study, surveys, and focus group discussion, then suggests improvements and lessons learned throughout the 4D CAD development process.

1.2 Description of Research Study

This section gives an introduction to the research problem, then describes the goals, objectives, and other reasons that provided motivation for this research.

1.2.1 Introduction to Research Problem

The applications of 4D CAD for highway construction projects have not been adequately researched or defined in academic or industry research. 4D CAD has proven an effective tool for construction planning, scheduling and communication in building construction, but has not received the same research effort for highway construction applications. Therefore, this research initiative will investigate and define what the best use applications of 4D CAD for highway construction projects are and why. This research will help determine where future research efforts should be expended, and serve as the groundwork for future 4D CAD research for highway construction projects.

1.2.2 Goal

The goal of this thesis is to determine what the best use applications of 4D CAD for highway construction projects are and why. This will help focus future research and industry efforts while utilizing 4D CAD technology in highway construction applications. The research also aims to describe and suggest lessons learned from the 4D CAD development process.

1.2.3 Objectives

1. The primary objective of this research is ***to investigate what the best applications of 4D CAD for highway construction projects are and why.***

   There has been little investigation into the applications of 4D CAD for highway construction projects, with no clear definitions of the benefits and drawbacks of this technology. This thesis investigates numerous applications of 4D CAD for highway construction, and defines what the most valuable applications are and why.

2. The second objective of this research is ***to develop a 4D CAD model of a highway construction project by linking a 3D CAD model with the project schedule in the Navisworks environment.***

   This 4D CAD model serves as the primary example used to illustrate the concepts and ideas expressed in this thesis. It has been presented as the case study example used to determine both the best use applications and define the general model development process.

3. The third objective of this research is to ***document and suggest improvements and lessons learned during the 4D CAD development process.***

   It is important to document the challenges and pitfalls throughout the 4D CAD development process so that future researchers can anticipate similar problems in future research and implementation. It is also valuable to discuss the solutions to these problems so that they may be improved and solved in future 4D CAD applications for highway construction.

1.2.4 Research Approach

The research approach that was taken to investigate the applications of 4D CAD for highway construction used exploratory research methods to investigate this topic. These methods aimed to collect the opinions and views of highway construction professionals who work in the highway construction industry on a daily basis, and offer the best insight and perspective into this topic. Exploratory research methods are common in social science applications, and were used because 4D CAD for highway construction is a poorly understood topic that requires better definition for future research efforts. The exploratory methods aimed to gather qualitative and quantitative data from three research groups of highway contractors about their views of 4D CAD for highway construction, then present their ideas in a logical fashion.

1.2.5 Research Steps

The nature of this research requires that exploratory research methods be employed throughout the investigation of this topic. The exploratory research methods draw on social science research tools, such as surveys, questionnaires, and open forum discussion. These methods yield results of both qualitative and quantitative data, and give valuable insight into previously unexplored topics. The research steps followed include:

1. ***Literature Review:*** A literature review was performed to investigate and understand topics such as 4D CAD, construction process visualization, highway construction techniques, and virtual facility prototyping. The literature review is presented in Chapter 3.

2. ***Gather Case Study Information:*** The research case study used a highway interchange construction project located in Fairfax County, Virginia, USA. The project included the removal of a signaled intersection between Route 28 and McLearen Road, and the construction of a grade separated interchange. The project was completed in the Summer of 2006, at a cost of $15 million. A full description of this project is found in Chapter 4.

3. ***Develop 3D and 4D CAD Models:*** 3D and 4D CAD models were developed using the original 2D construction documents prepared for this interchange project. The 2D contract drawings were modeled in 3D using Autodesk Civil 3D. The 4D construction simulation was developed using Navisworks Jetstream V5 with timeliner, by linking the 3D model with the project schedule.

4. ***Develop Case Study Evaluation Tools:*** A number of evaluation tools were developed to assess the opinions and reactions of the case study project after viewing the 4D CAD visualization/simulation. These tools employed social science research methods, such as surveys, open-ended questions, and focus group discussions. These methods yielded both qualitative and quantitative data results used to develop the recommendations presented in this thesis.

5. ***Perform Survey Questionnaire and Focus Group Discussion:*** The survey and focus group discussion were performed at three different contractor locations in the mid-Atlantic region of the United States. The research included a total of 17 participants from three separate highway construction contractors. The data was collected using survey questionnaires, open-ended questions, focus group discussions, and content analysis. The research was performed over a three week period in Spring 2007.

6. ***Review and Analysis of Data:*** The data collected during the survey questionnaire and focus group discussion was reviewed and analyzed using several common research techniques. The results of this research are presented and discussed in Chapter 5.

7. ***Discussion and Recommendations for 4D CAD for Highway Construction Projects:*** A discussion and recommendations are described for 4D CAD for highway construction projects. This expressed improvements based on the researchers experiences while developing the 3D and 4D CAD models for the case study project. The lessons learned will also be discussed in order for future researchers and professionals to avoid the same complications encountered in this project. These ideas and discussions are presented in Chapter 6.

8. ***Document Conclusions from Case Study:*** The conclusions presented in this thesis are based on the data collected throughout this research. These conclusions address the primary research goals and objectives, and are the primary contribution of this thesis work. These conclusions are presented in Chapter 7.

1.2.6 Research Contributions

The research contributions from the work performed in this thesis are as follows:

1. A definition and description of the best applications of 4D CAD for highway construction projects.

2. Insights and opinions of highway construction professionals about the applications of 4D CAD for highway construction.

3. An illustrative case study detailing the 3D and 4D CAD development process.

4. Discussions, suggestions, and improvements of 4D CAD for highway construction projects.

1.3 Relevance and Justification

The effectiveness of 4D CAD for building applications has been well documented in both academic and industry applications over the past decade. This research has caused significant shifts in building construction trends, and has helped modernize a traditionally low-tech industry. The ideas and research presented in this thesis may help a similar movement in the highway construction industry, and further implement the benefits of technology into the future. This section presents the relevance of this research, then gives a few reasons that justify the efforts of this thesis.

1.3.1 Relevance

This research is relevant to three particular groups of people.

- ***Highway Construction Contractors:*** This research is relevant to highway contractors because it is defining what the best uses of 4D CAD are for highway construction projects, and describing why. This is valuable because in the competitive industry of highway construction, new technology can separate one contractor from the rest of the crowd, helping them to be more successful on projects and ultimately winning more business. Some contractors who are interested in 4D CAD can study this research and understand what the best application of 4D CAD are for highway construction and why. This removes the trial and error process that might have been taken to explore this technology, and helps focus future applications on the best uses of 4D CAD for highway construction.

- ***Academic and Industry Researchers:*** This research is relevant for future academic and industry researchers because it serves as a foundation for future research of 4D CAD for highway construction projects. This research is a base for 4D CAD research for highway construction projects, and defines specific areas that must be researched in future efforts. This will help future researchers focus their research efforts to collect the most relevant and effective information possible related to this topic.

- ***Software Developers:*** This research is relevant to software developers because it describes numerous software problems that were encountered while developing a 4D CAD model for a highway construction project. Currently, there are no adequate softwares that exist on the market to efficiently and effectively develop 3D CAD models that can be used in 4D CAD applications. Therefore, a software company can use the information presented in this thesis as a starting point to create or improve software.

1.3.2 Research Justification

There are numerous justifications that support this research at this point in history. These are the motivating factors for pursuing this research effort, and writing this thesis.

1.3.2.1 Software Developments

One of the most significant problems affecting the widespread use of 4D CAD is the predominant use of 2D CAD design softwares. Today, the majority of construction projects, both building and highway, are designed and presented in a 2D format (Kang et al., 2007). This is restraining because 4D CAD relies on a 3D CAD model, which must be independently developed by a construction company using the 2D drawings as shown in figure 1.1. This intermediary step of redeveloping the 2D design documents into a 3D product model is extremely time consuming and difficult to leverage in the fast-paced AEC industry. In a cost competitive industry, the time and cost cannot be leveraged by the owner, designer, or construction company, and they fall back on traditional methods of project planning and visualization (Kunz and Fisher, 2005). Another problem is the question of who's responsibility is it for developing the 3D model. The construction company believes it is the responsibility of the designer, and the designer believes the opposite. This finger-pointing consistently results in a standstill, and no progress is made (Kunz and Fisher, 2005).

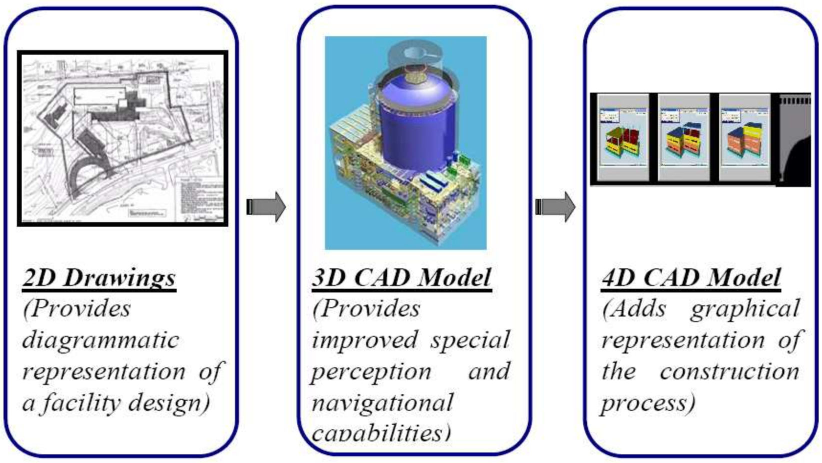

Figure 1.1. Typical 4D CAD Development Process

Image adapted from Messner et al. (2005)

Fortunately, new design software packages, such as Autodesk Civil 3D, are facilitating engineers and designers to create plans in 3D as the default design method. The result of the 3D design process is a functional product model that can be used in 4D CAD applications. This streamlines the 4D CAD development process by removing the most time consuming step in the overall development process. The 3D CAD model is available with the design, and does not have to be developed as previously described and shown in figure 1.1. Instead, the process now looks like figure 1.2, where the 3D development phase has been mostly eliminated. This is important because although the 3D design models are not perfectly ready to build a 4D CAD model, they serve as a solid foundation for the development of these simulations. This also solves the problem of responsibility for creating a 3D model, since the model is created as a default during the design process.

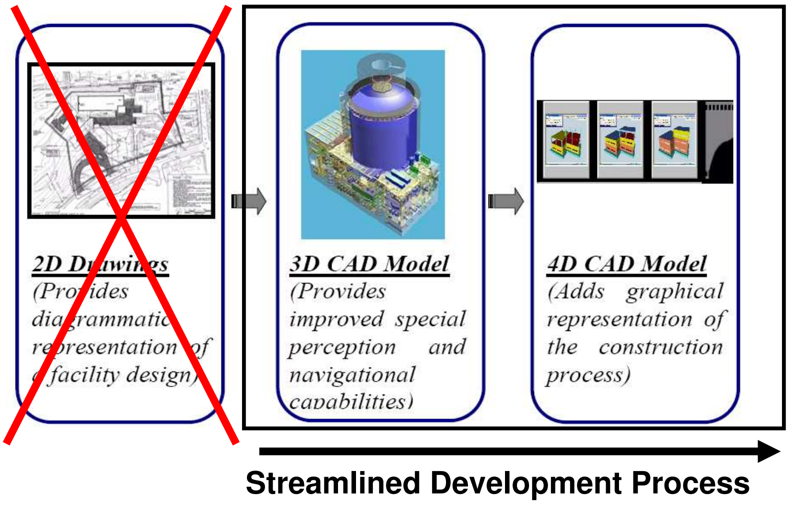

Figure 1.2. Streamlined 4D CAD Development Process

Image adapted from Messner et al. (2005)

1.3.2.2 Government Implementation

A second justification for investigating what the best use applications of 4D CAD are for highway construction projects are that industry implementation may be streamlined with the help of the US government. If 3D and 4D CAD models are equally beneficial in the engineering, procurement and construction of highways as in buildings, the US Federal Highway Administration could enact a similar mandate to the US General Services Agency. In 2005 the GSA realized the benefits of building information models (BIM's), which are object oriented 3D CAD models that are equivalent to the 3D models generated in Autodesk Civil 3D. The GSA announced that:

"For all major projects (prospectus-level) receiving design funding in Fiscal Year 2007 and beyond, GSA requires spatial program BIMs be the minimum requirements for submission to the Office of the Chief Architect for Final Concept approvals by the PBS Commissioner."

United State General Services Agency, Matta (2005)

This edict propelled the development of BIM among government designers and contractors, forcing them to choose between learning and adopting BIM or losing the largest facility owner in the world as a client. The project logic follows that if similar events were to take place in the Federal Highway Administration, 3D highway CAD models could see implementation within the near future.

1.3.2.3 Fewer Design and Construction Players

A third justification for investigating what the best applications of 4D CAD are for highway construction is that implementation may be easier in the highway construction industry compared with the building construction industry. Building design and construction requires numerous different design parties, including architects, structural engineers, civil engineers, MEP engineers, lighting designers, other consultants. This large number of design parties makes it extremely difficult to manage and coordinate one accurate 3D BIM because each party may use different design and analysis softwares that may not be able to communicate their design information within a BIM program. This jumbling of parties and design information can get frustrating, leading the designers all to revert back to the traditional approach for communicating design information.

Highway engineering and construction, on the other hand, has significantly less design and construction parties trying to communicate design information to one model. A typical highway design is developed by a single highway engineering firm, and they do not have to coordinate design data with numerous other engineers, such as in buildings. This makes it easier to maintain a 3D model throughout the design phase of a project. The project contractor can easily communicate with the design professional when questioning aspects of the model, and does not have to do as much coordination as a building contractor.

1.4 Scope and Limitations

The scope of this research focuses on investigating the best applications of 4D CAD for highway construction projects. It is believed that the best use applications defined in this research applies to all facets of highway construction, including complex geometric design, overpass bridges and structures, retaining walls, underground utilities and earthwork. Although, all of these features were not included in the case study, and therefore cannot be entirely supported with measured data. The suggestions for improvement and lessons learned expressed in this thesis are that of the author, and are supported only by personal insights gained throughout this project.

1.5 Thesis Organization

This thesis is divided into three main sections. The first section includes chapters 1, 2, and 3. Chapter 1 gives an introduction to the research and thesis layout. Chapter 2 gives a description of the research methodology used in this thesis, and Chapter 3 gives a summary of past research efforts in topics related to this thesis.

The second section consists of chapters 4, 5, and 6. Chapter 4 gives an in-depth description of the case study project that was used for this research. Chapter 5 presents the results of the research, and a discussion of these results. Chapter 6 gives discussions, suggestions, and improvements that can be made for 4D CAD for highway construction projects.

The third section consists of Chapter 7, which consolidates the conclusions drawn from this research work. Chapter 7 describes the conclusions, research contributions, and limitations of this research, then presents future research ideas that can be explored in future research efforts.

Chapter 2

Research Methodology

Proper research methodology aims to develop a systematic method for data collection to facilitate more trustworthy information from research (Singleton and Straits, 2005). This is important because a flawed research methodology can lead to biased and misleading results, negating the legitimacy of the research performed. This chapter describes the research methodologies that were used in this thesis. First, the case study methodology is described and justified using accepted research practices defined by Robert Yin and others. Then, the survey research methods are described, including the questionnaire, open-ended questions, and focus group discussion.

2.1 Introduction

The first and most important condition for selecting a research strategy is to identify the type of research question being asked. These types of research questions can be categorized into five basic groups, "who", "what", "why", "where", and "how" (Yin, 1994). In this research, the question was *"what are the best applications of 4D CAD for highway construction and why"*. Therefore, this research would be categorized into the "what" and "why" groups. Knowing this research question and category, the research strategies selected were case study and survey methods, as shown in table 2.1. It is acceptable to use more than one strategy in a given study, such as a survey within a case study or a case study within a survey (Yin, 1994).

Table 2.1. Relevant Situations for Different Research Strategies

Table adapted from Yin (1994)

Strategy	Form of Research Question
Experiment	How, Why
Survey	Who, What, Where, How Many, How Much
Archival Analysis	Who, What, Where, How Many, How Much
History	How, Why
Case Study	How, Why

It is also important to define the purpose of a research study. This can be defined into four general categories, exploratory, explanatory, descriptive, and emancipatory (Marshall, 1999). The purpose of a study tells the reader what the results of the research are likely to accomplish, and describes the intent of the research. The purpose of this study, as defined by Marshall, is exploratory because the research aims to:

1. Investigate poorly understood phenomena,
2. Identify/discover important variables, and
3. Generate hypotheses for further research.

2.2 Research Methods

The exploratory research strategy draws on several social science research methods used to collect information from human subjects. These methods include questionnaires, surveys, focus group discussions, content analysis and a case study. The information collected reflects the opinions of construction engineers and professionals, and serves as a foundation for future research.

2.2.1 Case Study Research Method

A case study is a valuable research method which draws on actual events that can be used to illustrate or determine a concept or theory. This method is preferred in examining contemporary events when relevant behaviors cannot be manipulated

(Yin, 1994). This is the situation presented in this research, and therefore is useful to examine using a case study.

Case study research must be evaluated using four widely used tests to determine the quality of a case study. These tests are common to all social science methods, and are defined below (Yin, 1994).

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

These tests were used to establish the quality of the case study examined in this research. The case study looked at a highway interchange project that was built between Summer 2005 and Summer 2006. The project highlighted one application of 4D CAD for a highway construction project to the research participants, and gave a better understanding of the benefits of 4D CAD for these applications. The case study is fully described in Chapter 4.

2.2.1.1 Test 1 - Construct Validity

Several tactics were suggested by Yin (1994) to construct validity for a case study project. These tactics, as discussed below, include using multiple sources of evidence, establishing a chain of evidence, and having key informants review a draft of the case study project.

1. ***Use Multiple Sources of Evidence:*** Several sources of evidence were collected in this research, including survey questionnaires, open ended questions, and focus group discussions. These sources of evidence were collected and analyzed to draw conclusions about the research topic.

2. ***Establish a Chain of Evidence:*** A significant chain of evidence was established using the multiple sources of evidence collected throughout this research. The chain of evidence was established using both qualitative and quantitative data that shows consistant results throughout this thesis.

3. ***Review and Draft the Case Study:***

   The case study was reviewed with three separate teams of highway construction professionals. These research participants gave significant feedback, which was used to develop the conclusions put forth in this thesis.

2.2.1.2 Test 2 - Internal Validity

Proving the internal validity is only for explanatory or casual studies, and not for descriptive or exploratory studies (Yin, 1994). Therefore, this test is not applicable in this research because it is exploratory in nature.

2.2.1.3 Test 3 - External Validity

External validity is established through replication of the results of the case study. This replication logic is the same as in scientific experimentation, allowing scientists to generalize from one experiment to another (Yin, 1994). This case study used three separate research groups to prove external validity, showing replication between groups tested. However, this still requires further testing to fully prove external validity.

2.2.1.4 Test 4 - Reliability

Reliability states that if a later investigator followed exactly the same procedures as described by an earlier investigator and conducted the same case study all over again, the later investigator should arrive at the same findings and conclusions (Yin, 1994). The procedures of this research are closely documented for future replication.

The reliability of this research should be tested in future research. Using the same procedure, it is believed that a future researcher would reach the same findings and conclusions.

2.2.2 Survey Methods

Numerous survey methods were used for this research, such as questionnaires, open ended questions, and focus group discussions. Survey methods measure a relatively small sample of a population to gain insight into the population in general (Czaja and Blair, 2005). This can save time and effort because it does not require the entire population to gain an understanding of their views, but relies on a small group of people representing the population as a whole.

Surveys are used to address four broad classes of questions (Weisberg et al., 1996):

1. The prevalence of attitudes, beliefs, and behavior;

2. Changes in them over time;

3. Differences between groups of people in their attitudes, beliefs and behavior; and

4. Casual propositions about these attitudes, beliefs, and behaviors.

The main focus of the survey methods in this research are to measure the prevalence and casual propositions of attitudes, beliefs, and behaviors of highway construction professionals in regard to 4D CAD for highway construction.

It is also important to define how the survey will be administered, to gain a better understanding of the results (Czaja and Blair, 2005). Surveys can be administered using several methods, including mailed questionnaires, internet surveys, telephone interviews, and face-to-face interviews. This research uses face-to-face interviews because this method achieves the best return from the research participants (Czaja and Blair, 2005).

2.2.2.1 Survey Questionnaire

The information that can be collected using a survey questionnaire can be gathered using two methods of questioning (Czaja and Blair, 2005). The first type of question is an open-ended question, which allows the survey respondent to answer in their own words. This is advantageous because it lets the researcher see what the respondents actually think about the topic, instead of just choosing a response that the researcher has provided (Weisberg et al., 1996). The second type of question is a close-ended question, which forces the respondent to choose one response from a list of choices. This method of survey question is valuable because a researcher can gain quantitative insight into numerous issues without using too much time during the research.

The survey questionnaire in this research used both open-ended and close-ended question formats to collect information from the research participants. There were thirteen close-ended questions that used a rating scale to collect quantitative data to measure the attitudes and beliefs of the survey participants. The rating scale was based on a 0 - 10 rating system, where the 0 was no benefit and 10 was high benefit. There were seven open-ended questions that allowed the research participants to give further insight into their responses from the close-ended questions. These questions focused on similar issues that were surveyed in the close-ended questions, but allowed for a written response investigating "why" on certain topics.

2.2.2.2 Focus Group Discussion

A focus group is a group of people, usually with the same characteristics, assembled for a guided discussion of a topic or issue (Czaja and Blair, 2005). The discussion is moderated by a facilitator, who creates a supportive environment, asking focused questions, to encourage discussion and the expression of differing opinions and points of view (Marshall, 1999). The questions should not be raised sequentially, but relative to the topic because topics tend to be interwoven and to reappear, sometimes with very different implications (Templeton, 1994). A focus group can be classified into three types of categories: full groups, minigroups, and telephone groups. A full group consists of eight to ten people discussing a topic that is moderated by a facilitator. A minigroup consists of four to six people, and a telephone group is individuals participating in a conference call (Greenbaum, 1993).

The focus groups used for this research were three separate groups of highway construction professionals. The three groups were all minigroups, consisting of four to six people. The focus discussion topics investigated the question "what are the best uses of 4D CAD for highway construction and why." The meetings were facilitated by the researcher.

2.2.2.3 Content Analysis

Content analysis is a research technique for making replicable and valid inferences from data to their context. As a research technique, content analysis involves specialized procedures for processing scientific data to provide knowledge, new insights, and representation of facts (Krippendorf, 1980). Also, when other researchers, at different points in time and perhaps under different circumstances, apply the same technique to the same data, the results must be the same. This is the requirement of a content analysis to be replicable (Krippendorf, 1980).

A content analysis was done to organize the focus group discussions performed in this research. The objective was to systematically evaluate the discussions, and find common content among the three focus groups that could be used as evidence for this thesis. The results from the content analysis were consistent among the groups, and were proven to be replicable by identifying common content among the three research groups.

2.3 Experimenter Expectancy and Bias

Experimenter expectancy is a conscious or unconscious influence on the attitudes of the research group from the researcher that can persuade the group to reflect the experimenters desired outcome in their results. This can have a powerful effect in the research environment, and negate the quality and generalizability of research results (Crano and Brewer, 2002). This is similar to bias, which is a tendency to observe the phenomenon in a manner that differs from the "true" observation in some consistent fashion (Simon and Burstein, 1985).

The solution to expectancy bias can be controlled using three methods, monitoring, blind procedures, and mechanized procedures (Crano and Brewer, 2002). The method that was used for this research was monitoring, which uses a second researcher to monitor the presentation of the primary researcher to ensure objectivity throughout the research. The primary researcher was monitored by a second researcher with significant academic research experience, who ensured objectivity and consistency throughout the research. Other bias was controlled using systematic forms of content evaluation, such as content analysis.

2.4 Summary

This chapter described numerous research methods that were used throughout this thesis. These research methods were selected because they were viewed as the most applicable forms of data collection methodologies for this exploratory research. Also, by using several research methods, consistency was ensured because each research method and exercise provided similar results. Overall, these methodologies provided qualitative and quantitative data supporting the conclusion of this thesis.

Chapter 3

Literature Review

This chapter presents the literature review performed prior to and throughout this research. The review investigates topics such as 4D CAD, visualization practices, and highway construction because this research aims to bring these three disciplines together for one purpose. The review focused on recent academic and industry research because this science is relatively new, and continually changing as more people begin to experiment and implement 4D CAD in their research and business practices.

3.1 Concepts in 4D Construction Practices

4D CAD can be defined as 3D CAD linked to the construction schedule (Koo and Fischer, 2000). The resulting 4D model of a project allows project stakeholders to view the planned construction of a facility overtime on a computer screen and to review the planned or actual status of a project in the context of a 3D CAD model for any day, week, or month of interest (Fisher and Kunz, 2004).

The benefits of 4D CAD have been proven in numerous case studies and journal papers, and are accurately summarized in the following statement:

"4D models enable a diverse team of project participants to understand and comment on the project scope and corresponding schedules in a proactive and timely manner. They enable the exploration and improvement of project executing strategy, facilitate improvements in constructibility with corresponding gains in on-site productivity, and make possible the rapid identification and resolution of time-space conflicts. 4D CAD models have proven particularity helpful in projects that involve many stakeholders, in projects undergoing renovation during operation, and in projects with tight, urban site conditions." (Fisher and Kunz, 2004)

3.1.1 Product-Process Structure

An important concept in understanding 4D CAD is recognizing the difference between the product and the process in a construction project. These two elements, which are mutually dependent, represent the building blocks required for a 4D model and must both be planned accordingly (Kunz and Fisher, 2005). The break down and definition of these components are described below.

- Product: defines the physical building elements required to construct a facility. Product examples include beams, columns, slabs, etc.
- Process: describes the order of schedule activities required to construct a facility. A process example for a concrete foundation would be:

    1. Excavate foundation,
    2. Set and tie rebar,
    3. Erect formwork,
    4. Pour concrete,
    5. Strip formwork, and
    6. Backfill foundation.

Before 4D construction simulation, both process and product areas had been well defined in academic research and industry practice. An Integrated Building Process Model, developed in the late 1980's, defined a process model of the activities required to provide a facility. The model included managing, planning, design, construction and operations of a facility. In addition to the processes, it identified the inputs, outputs, constraints, and mechanisms associated with each function (Sanvido et al., 1990). These models are helpful in understanding 4D construction simulation because they give an in-depth perspective of activity process flow in construction.

3.1.2 4D CAD Development Process

The 4D CAD development process has been defined by numerous researchers over the past decade. Stanford's CIFE and Penn State's CIC research programs along with others, have each published detailed process models describing the 4D CAD development process, and have been reviewed for applicability to this research. The most appropriate process definition is described by Yerrapathruni (2003), in Using 4D CAD and Immersive Virtual Environments to Improve Construction Planning. In this report, the author proposes a logical process for assisting construction planners as well as future researchers to develop construction plans using an Immersive Virtual Environment (IVE). It describes the processes and the various steps involved for developing a 4D construction plan. The model was developed using the $IDEF_O$ modeling method, which provides engineering methods for analyzing and designing complex systems.

One initial concern with this process model was that it was intended for 4D construction plans in immersive virtual environments. The consideration of viewing environments is outside of the scope of this research, but after review of the process model, it still can be accurately applied to 4D highway construction research. Instead, a computer monitor will be substituted for an IVE. This should have little effect on the overall process model and is sufficient for this research.

This model breaks the 4D development process into three levels: Level 0, 1, and 2. Level 0, shown in Figure 3.1 on page 25 gives a general description of "Develop 4D Construction Plan in the IVE". This is defined by inputs, controls, mechanisms, and outputs for the process. The overall input is the 3D design model, and the controls are the construction methods. This is broken down in level 1.

Level 1 is divided into four sub processes, as shown in Figure 3.2 on page 26. These sub processes are:

1. Develop 3D facility model,
2. Organize model by construction assemblies,
3. Develop 4D construction plan, and
4. Review and communicate 4D construction plan.

The 3D facility model is developed using 3D CAD software, and is controlled by design parameters, project objectives and regulations as specified in Hetrick and Khayyal (1989). The second step is to organize the 3D models by construction assemblies. The construction assemblies are determined by construction methods and site conditions, and should be assembled using the 3D design software from the original 3D model. This will avoid interoperability issues common during data exchange between software programs, such as loss of geometry, color, texture, and other information described in the design. The third step is to develop the 4D construction plan with the construction team. This construction plan is determined by site conditions, resource availability and temporary facility interactions.

Level 2 sub-processes represent node 3 from Figure 3.2 on page 26, and break the development of a 4D construction plan down further into 5 processes, shown in Figure 3.3 on page 27. The subprocess are:

1. Define construction methods,
2. Define activities and durations,
3. Assign resources,
4. Sequence activities, and
5. Plan space utilization.

The process of defining construction methods are controlled by site conditions, resource availability, cost and the clearances and tolerances provided by the design (Yerrapathruni, 2003). The output of this process is a 3D model with proper assemblies. The second process is to define the activities and durations of each activity. These are defined by construction methods, site conditions, and resource information. The resultant output of this sub process is the work breakdown structure of the construction project. The third sub process assigns project resources, such as crew, materials and equipment. The resources are a function of materials, crews, equipment availability, site conditions and temporary facilities. The output of this sub process is a 3D model with resource information. The fourth sub process is the sequencing of activities, which the construction planners define the order in which activities should occur. This process is controlled by resource information,

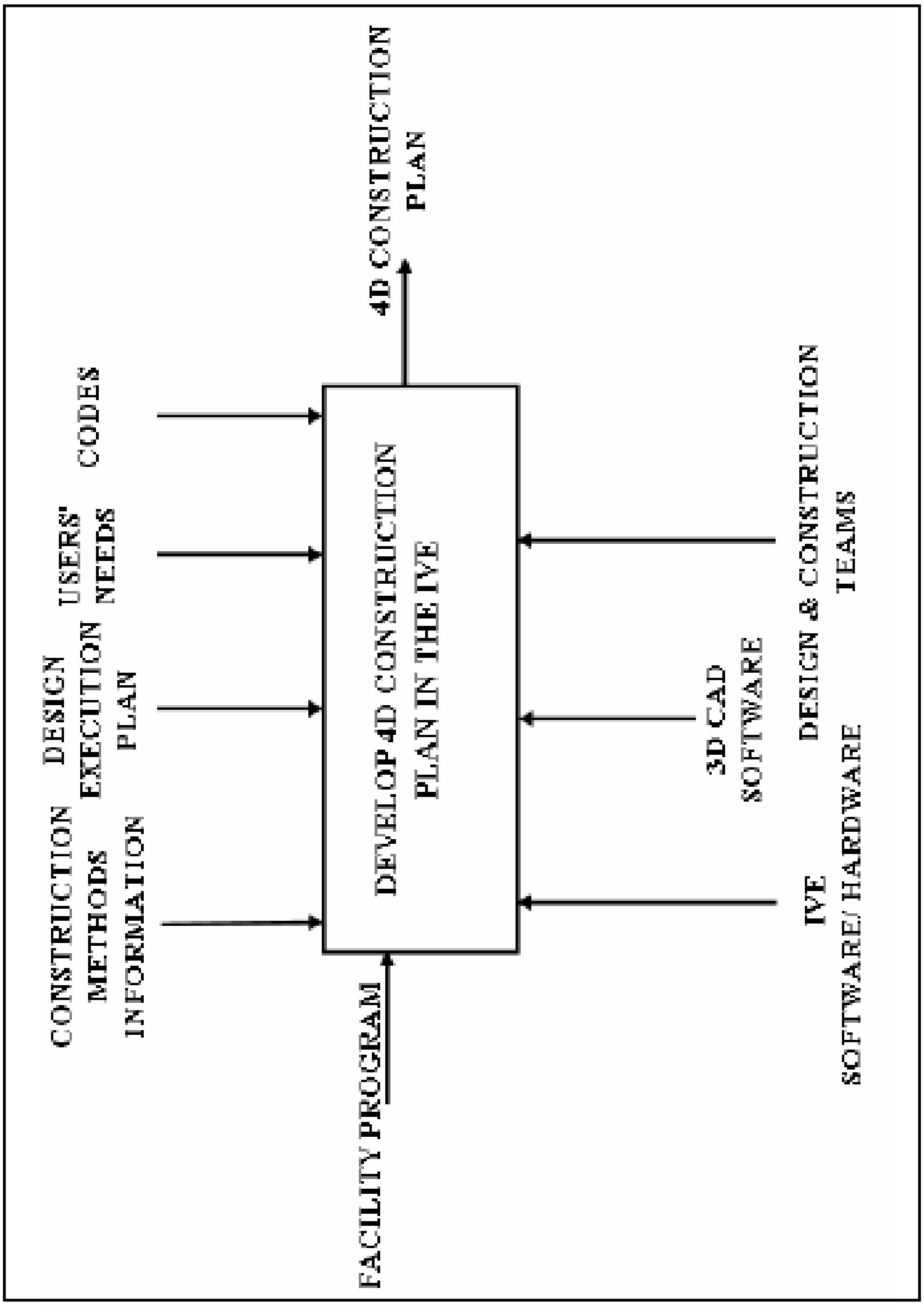

Figure 3.1. Level 0: Developing a 4D Construction Plan

Image adapted from Yerrapathruni (2003)

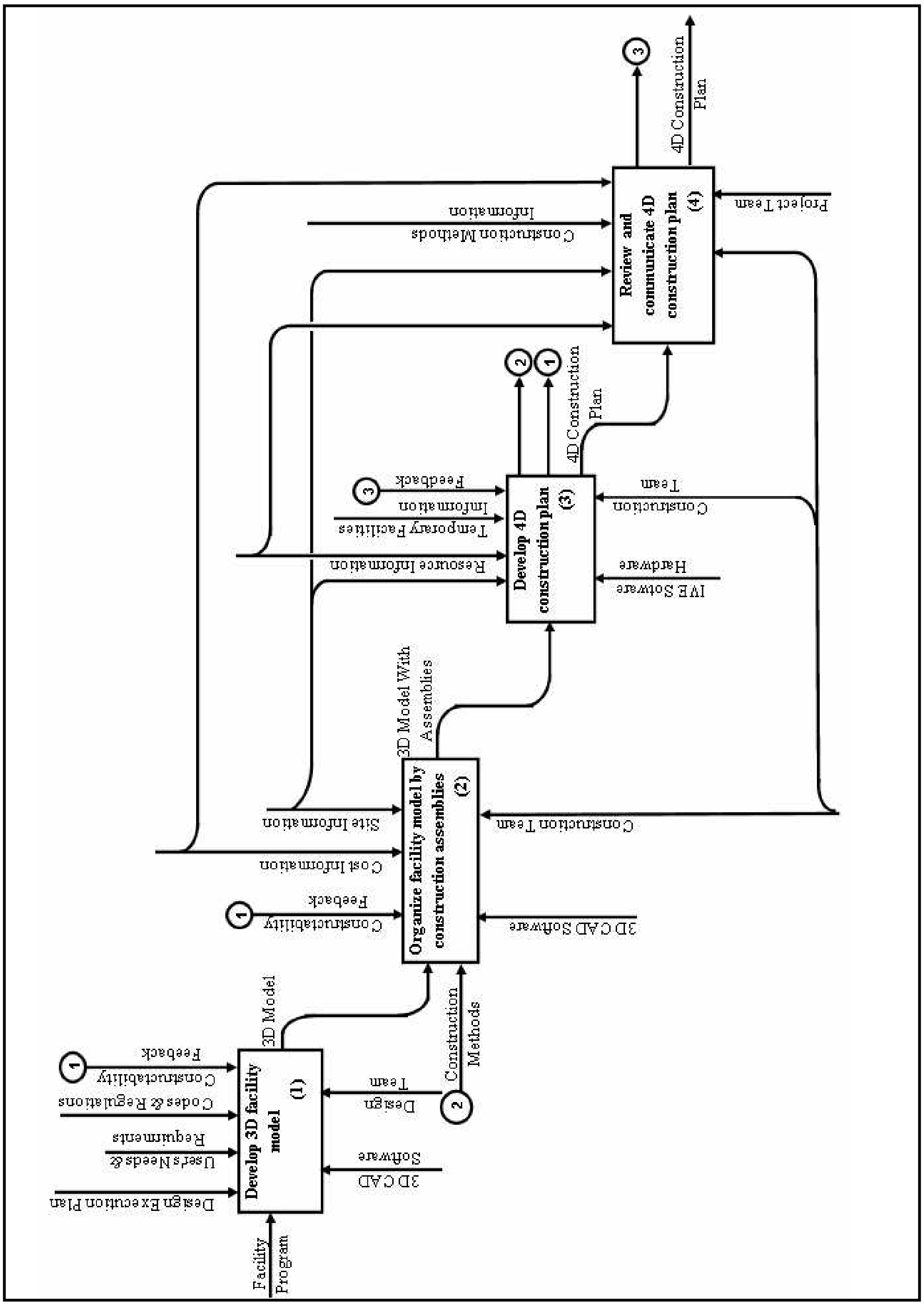

Figure 3.2. Level 1: Developing a 4D Construction Plan

Image adapted from Yerrapathruni (2003)

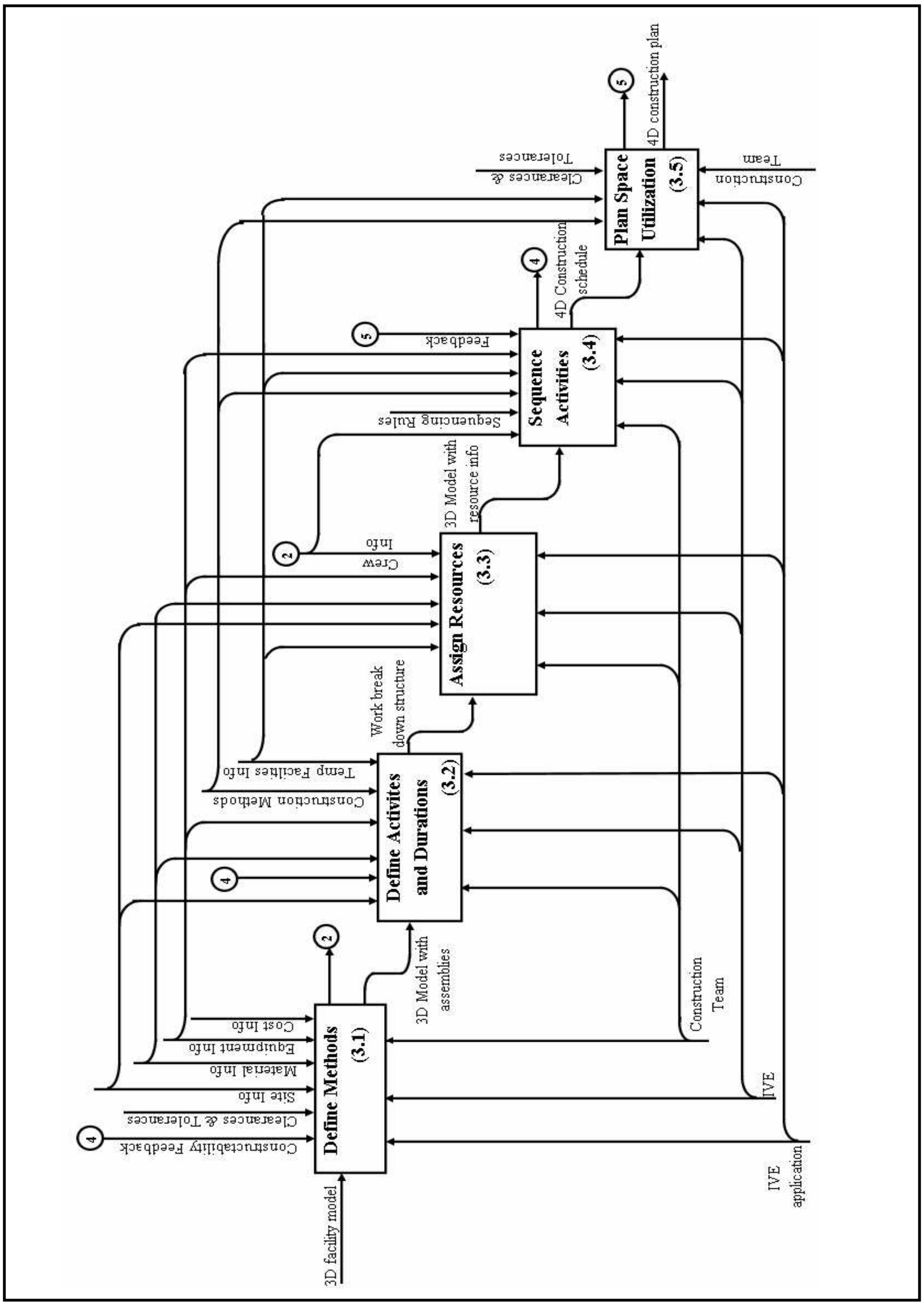

Figure 3.3. Level 2: Developing a 4D Construction Plan

Image adapted from Yerrapathruni (2003)

construction methods and sequencing rules. The output of this process is a 4D construction schedule. This final sub process is to plan the space utilization for project coordination. This is controlled by crew, equipment and site conditions. The output is a complete 4D construction plan.

This process for developing a 4D construction plan has been applied for the development of the 4D highway construction simulation in this research.

3.1.3 4D CAD in Highway Construction

There has been little published research on the topic of 4D CAD for highway construction projects. The literature review revealed only one major publication related to this topic, titled *4D Visualization of Highway Construction Projects* by Katherine Liapi (2003). This paper discusses how 4D CAD visualization can be used in the construction phase of a highway project, and suggests a framework for developing then applying these techniques. The research also focuses on the benefits of 4D CAD for traffic planning.

Liapi points out that *"transportation projects often involve complex geometric configurations which render the communication of project information between interested parties very difficult and prone to errors."* Therefore, she suggests that 4D visualization can provide a better understanding of the aspects and spatial constraints of a project when compared with traditional 2D data. This hypothesis was tested in a case study project on the high five interchange in Dallas, Texas.

The process for developing 4D CAD models begins with a 3D graphical model of the project. The 3D graphical model should be constructed using a geometric database, which should be the basic feature of any 4D CAD system (Liapi, 2003). According to Liapi (2003), the 3D model should include the following parameters to effectively communicate the design and construction of a project.

1. ***Site Modeling***
   The site model represents the terrain contours and existing highway features in the proposed project area. This digital terrain model (DTM), should also include the surrounding area, including building footprints and other relevant structures important for construction. This data may be retrieved from a GIS database, or a topographical survey of the project site.

2. ***Existing and Proposed Highway Structures***
   These structures include all aspects of the geometric configuration before, during, and after construction. This includes the modeling of the existing structures, temporary structures during construction, and the finished structures upon completion. These objects should be modeled as 3D parametric solids.

3. ***Highway Context*** The highway context represents the surrounding highway elements that make the model appear in its natural environment. This includes 3D buildings in both close and far ranges, trees, telephone poles, and horizon.

4. ***Library of Highway Elements***
   The library of highway elements is composed of common highway components that are used and installed throughout the construction process. This includes railings, barriers, medians, curbs, etc. These should be hosted in a digital library, and be placed in necessary locations for construction by the designer.

5. ***Library of Traffic Elements*** The library of traffic elements is composed of common traffic control structures and signs. This database must include both permanent and temporary traffic signage, and be hosted in a digital library similar to the Highway elements.

Liapi has defined these five characteristics as the necessary elements for developing the 3D graphical model to be used for 4D CAD applications.

Once the 3D graphical framework has been defined, Liapi suggests visualization applications for the 3D and 4D model. The visualizations are most useful for the effective communication of project planning and scheduling information for visual evaluation (Liapi, 2003). This applies in two separate categories:

- 4D CAD based animations that involve linking geometry with construction schedule and traffic planning.

- 4D digital animations that simulate the perception of the traveling public.

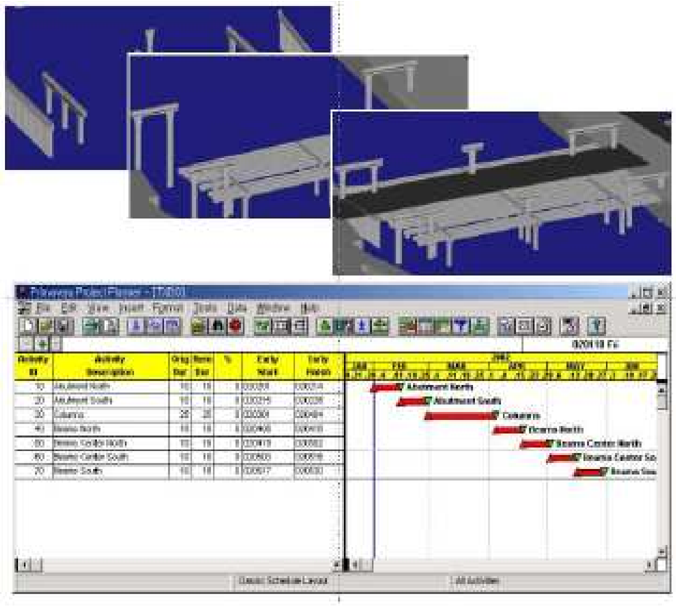

Figure 3.4. Linking 3D CAD with Construction Schedule

Image adapted from Liapi (2003)

The first category is for traffic engineers and construction contractors. The 4D CAD visualizations are useful because interchange construction is a function of traffic planning, and must be considered during the construction scheduling process. The 4D CAD model helps integrate traffic planning with construction sequencing and scheduling, and lets engineers and contractors optimize these activities. Since this use is for the engineers and contractor, it is not necessary to include surrounding buildings and other irrelevant environmental features. Figures 3.4 and 3.5 show screenshots of the 4D visualization used for planning during the high five interchange project in Dallas, Texas.

The second application of a 4D animation is for the traveling public. This animation can be used to disseminate changing traffic control measures to drivers during the construction process (Liapi, 2003). This information should be displayed as a photo-realistic animation along the drivers path, showing changing traffic conditions and construction activity along the route. This animation will alert drivers of the conditions before they travel the work zone, and help them anticipate changes in the traffic patterns along their route. Figure 3.6 on page 32 shows a photo-realistic traffic animation used to communicate changing traffic

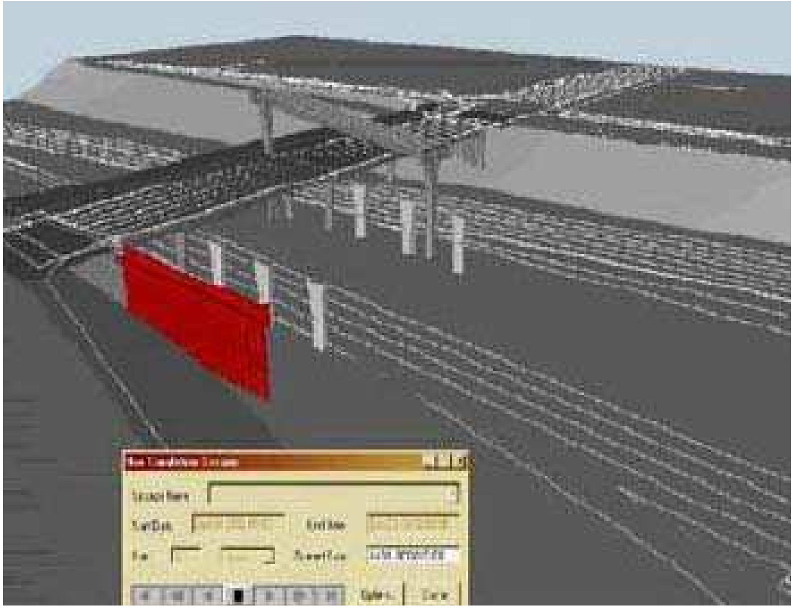

Figure 3.5. Screenshot of 4D Construction Visualization

Image adapted from Liapi (2003)

measures to drivers.

Overall, Liapi concluded that 4D CAD is a useful tool for two groups of people: Traffic engineers/construction contractors and the traveling public. The engineers/contractors can use it for traffic planning and construction sequencing, and the traveling public can use it for communication of traffic changes. The 4D CAD facilitates collaborative decision making and improves construction project communication for both the engineer/contractor and the public.

3.2 Visualization Practices

Graphic representations have been one of the main forms of communications for thousands of years (Luzadder and Duff, 1989). From the earliest prehistoric drawings to current drafting standards, graphical illustrations are a natural means for communicating ideas, concepts or actions (Cory, 2001). Today, the primary form of graphical communication in engineering and construction is 2D CAD drawings developed by an architect or engineer. The purpose of these drawings are to communicate design information and specifications to a construction team using visual

Figure 3.6. Photo-Realistic Animation of Traffic Measures

Image adapted from Liapi (2003)

representations. The problem is that 2D drawings are often hard to visualize in the 3D world we live in, and takes significant practice to learn how to read proficiently. The importance of visual understanding is paramount in human comprehension, as described in a letter by Albert Einstein.

"Words and language, whether written or spoken, do not seem to play any part in my thought processes. The psychological entities that serve as building blocks for my thought are certain signs or images, more or less clear, that I can reproduce and recombine at will. The elements that I have mentioned are, in my case, visual and sometimes motor."

Einstein in a letter to fellow mathematician Hadamard (1945)

Visualization of data makes it possible for researchers, analysts, engineers, and the lay audience to obtain insight into data in an efficient and effective way, thanks to the unique capabilities of the human visual system, which enables us to detect interesting features and patterns in short time (Wijk, 2005). Therefore, visualization is a valuable tool for evaluating large data sets that otherwise might be difficult to understand, such as a large scale construction project. A generalized model of visualization has been proposed by Wijk (2005), that logically expresses a visualization as a function of data, specification, and time, as shown in equation (3.1).

$$I(t) = V(D, S, t) \tag{3.1}$$

The central process in this formula is visualization, V. The data, D, is transformed according to a specification S into a time varying image I(t). In a 4D CAD visualization example, the D would be 2D design drawings, project schedule, and construction plan. The S would be the 4D CAD algorithm from the software, and the image I(t) would change as a function of time t. This is a logical method of viewing 4D CAD visualization and understanding the general function of how it works.

3.2.1 Visualization in Highway Applications

Visualization techniques in the highway transportation industry have been used for many years for highway project development, planning, engineering, and public communications. These methods include illustrations, photo simulation, photorealistic 3D CAD, multimedia animations, and GIS (Keister and Moreno, 2002). Yet, today the highway transportation industry is still years behind its counterparts in aerospace, architecture, plant facilities, automotive, shipping, and others, when it comes to fully embracing visualization tools and the corresponding mindsets (Manore, 2006). This may be because engineers and contractors, especially in the highway construction industry, have a culture and method to minimize costs and maximize profits on a project. This process of minimizing costs works efficiently, making it difficult to justify new processes that are not yet proven in the field (Kunz and Fisher, 2005). It may also be because applications of computer visualization technology in transportation projects are limited due to the widespread perception that it is an expensive technology and the total hardware and software expenses combined with necessary manpower to perform visualization far outweigh the benefits (Jha, 2006). No matter the reason why the highway construction industry has been slow to embrace visualization technology, the future looks bright for applications.

Today, new visualization technologies, such as 4D CAD, Google Earth, lidar scanning, and others are offering the highway construction industry the opportunity to modernize and take full advantage of the benefits of visualization technologies. Research organizations such as the Transportation Research Board, have shown examples of how visualization can improve the highway transportation industry, and help it move into the future. One good example of visualization in the highway transportation industry discusses the feasibility of computer visualization in highway development, and is further discussed in section 3.2.1.1.

3.2.1.1 Computer Visualization for Highway Development

The feasibility of computer visualization in highway development has been shown to be an effective method for developing highway projects. In this research, the author used a fuzzy logic based approach to accurately define the feasibility of computer visualization in highway development. The objectives of this study were to first develop a Microstation-based efficient batch process to automate repetitive procedures resulting in efficient visualization production, and second to apply fuzzy logic to calculate benefits and costs of visualization that may allow us to calculate the benefit-cost (B/C) ratio (Jha, 2006). According to the researcher, this is beneficial for two reasons:

1. "Better representation of future improvements resulting in enhanced public and political support and,
2. early identification of adverse environmental and land impacts as well as detail design requirements resulting in fewer scope changes."

The researcher first proposes a flowchart detailing the application of computer visualizations for highway projects. This chart, shown in figure 3.7, gives a good framework for understanding the decisions and thought process required before developing a visualization.

Next, the researcher developed a Microstation-based efficient batch process to automate repetitive procedures resulting in efficient visualization production (Jha, 2006). This was done by automating tasks with repetitive procedures linked to a database of reusable components. This is valuable because instead of hard-coding tasks manually, the program could do this automatically, saving significant computing time, and in turn visualization costs. Once the automated batch processor

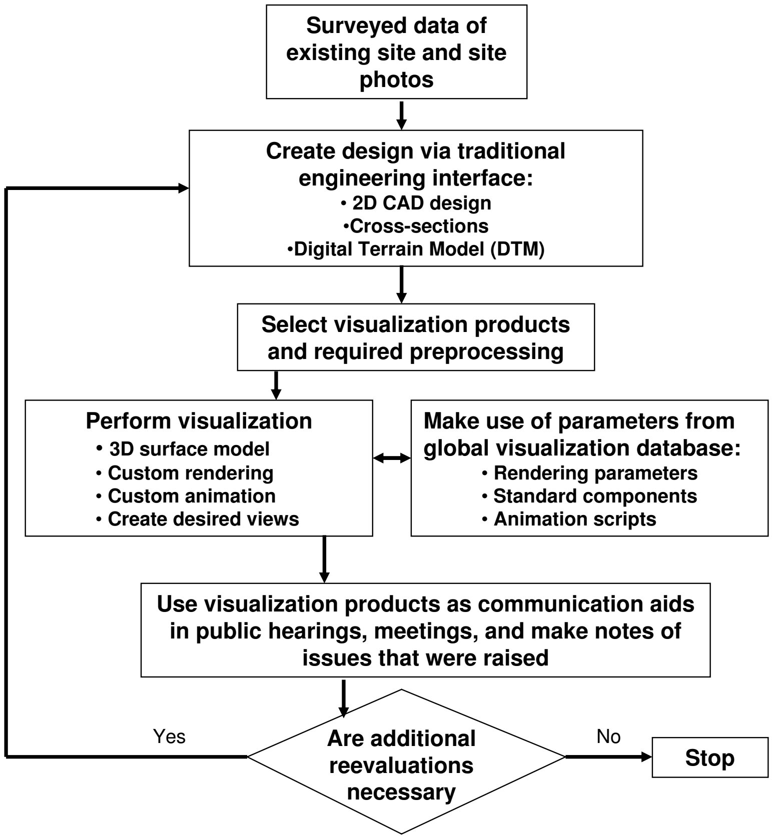

Figure 3.7. Flowchart for Visualization Application in Highway Projects

Image adapted from Jha (2005)

was developed, a benefit-cost analysis was performed. This analysis aimed to measure the visualization costs vs. the realized savings from avoided approval delay and reduced frequency of scope changes using a fuzzy logic based approach.

The results from this research showed that the benefits from using the automated batch process for developing visualizations can far outweigh the costs of developing a visualization. The research also showed that visualizations may or may not be cost effective depending on the level of visualization details to be performed (Jha, 2006).

3.3 Summary of Literature Review

There has been a considerable amount of research in the areas 4D CAD and visualization. The benefits of these two sciences have been well documented in research over the past fifteen years, such as in Koo and Fischer (2000) and Jha (2006). However, there has been little research investigating the applications of 4D CAD for highway construction applications. The only significant paper found on this topic was by Katherine Liapi (2003), where she investigated the use of 4D CAD for a highway interchange in Dallas, TX. In this paper, Liapi lays out a general framework for developing 4D CAD models for highway construction projects, but does not define how they can be used and why they are beneficial. Therefore, this researcher aimed to investigate the research question of "what are the best uses of 4D CAD for highway construction and why".

The 4D CAD modeling process was defined by Yerrapathruni (2003), using a three level process model detailing the important actions and decisions required to create a 4D model. This model has been proven to be effective for developing 4D CAD models for buildings, and is believed to be suitable for highway construction applications.

The literature review revealed an academic and industry wide interest in 4D CAD and visualization, proving the relevance of the research performed for this thesis.

Chapter 4

Case Study: Route 28 - McLearen Road Interchange

This chapter presents an in-depth description of the case study chosen for this research. The chapter will discuss the background information related to the case study and the development process employed to construct the 4D CAD model.

4.1 Case Study Introduction

The case study chosen for this research was a highway interchange project intended to alleviate traffic congestion on Route 28 in Fairfax County, Virginia. Route 28 carries traffic between Route 7 and Interstate 66 through Northern Virginia, providing access to Dulles International Airport, the Smithsonian's Air and Space Museum, AOL Time Warner Headquarters and other regional businesses (VDOT, 2002). Route 28 carries traffic via three northbound lanes and three southbound lanes, separated by a jersey barrier. McLearen Road had previously intersected Route 28 from the east with a signaled intersection, as shown in figure 4.1. This caused significant traffic disruptions along the corridor, impeding traffic flow along Rt. 28. Therefore, the signaled intersection between Route 28 and McLearen Road was replaced with a high-capacity, grade-separated overpass that could accommodate future traffic loads and allow economic growth in the future. Figure 4.1 on page 38 shows the existing conditions and Figure 4.2 on page 39 shows the interchange design.

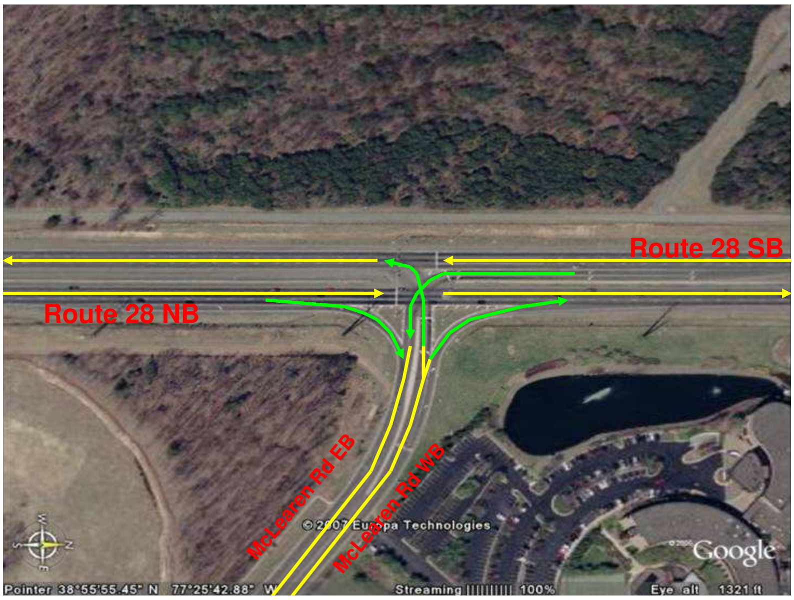

Figure 4.1. Existing Rt. 28 - McLearen Road Intersection

The project was commissioned as a public/private partnership to perform "improvements to the corridor which are vital to the continued economic development of the fast-growing area that is home to Dulles International Airport, AOL Time Warner Headquarters and the Smithsonian's new Air and Space Museum." (VDOT, 2002)

4.1.1 Case Study Objective

The objective of this case study was to investigate what the best use applications of 4D CAD are for highway construction in the opinion of highway construction professionals. The research groups used for the case study consisted of the management team whom originally constructed this interchange, and other highway construction professionals from different highway construction companies.

4.1.2 Project Statistics

The major project statistics are described in sections 4.1.2.1 and 4.1.2.2. This includes general project statistics and a description of the project team.

Figure 4.2. Conceptual Rt. 28 - Mclearen Road Interchange

4.1.2.1 General Statistics

The general project statistics are as follows:

- Location: 38°55'53.43" N Latitude 77°25'47.66" W Longitude
  Intersection of Route 28 and McLearen Road, Fairfax County, Virginia
- Project Budget: $15 Million
- Funding Source: Private
- Schedule Duration: 450 Days (Summer 2005 - Summer 2006)
- Contract Type: Lump Sum
- Delivery Method: Design-Build

4.1.2.2 Project Team

The project team consisted of the following stakeholders:

- Owner: Virginia Department of Transportation
- Developer: Route 28 Corridor Improvements, LLC

- Development Manager: Clark Construction Group Inc.
- Contractor: Shirley Contracting Company, LLC
- Designer: Dewberry and Davis, LLC

4.2 Project Description

The Route 28 - McLearen Road interchange project required the construction of a high capacity, grade-separated trumpet-style interchange between Route 28 and McLearen Road in Fairfax County, VA. The project scope included the construction of four interchange ramps and an overpass bridge carrying traffic between Route 28 and McLearen Road. The new interchange ramps were identified as ramps A, B, C, and D. Ramp A carries McLearen Road west bound traffic to Rt. 28 north bound. Ramp B carries McLearen Road west bound traffic to Rt. 28 south bound. Ramp C carries Rt. 28 south bound traffic to McLearen Road east bound. Ramp D carries Rt. 28 north bound traffic to McLearen Road east bound. The scope of work also included the construction of a perimeter access road for Dulles Airport. Since the west portion of the project enters into Dulles Airport property, an access road must be constructed per FAA requirements to allow vehicle access to the airport perimeter for security and other maintenance purposes (FAA, 2007). Figure 4.3 shows the western area of the project, including the locations of the airport access road and ramps B, D, and C.

The project also included the demolition of the existing McLearen Road intersection, then reconstruction of McLearen Road connecting it to the overpass bridge. Figure 4.4 shows the eastern portion of the construction area, including the new McLearen Road construction and ramp A and D. Figure 4.5 shows the demolition of existing McLearen Road.

4.2.1 Bridge Description

The overpass bridge is a three span structure carrying traffic between McLearen Road and Route 28. The primary bridge elements include abutments, piers, foundations, and deck. The bridge abutments employ a mechanically stabilized earth

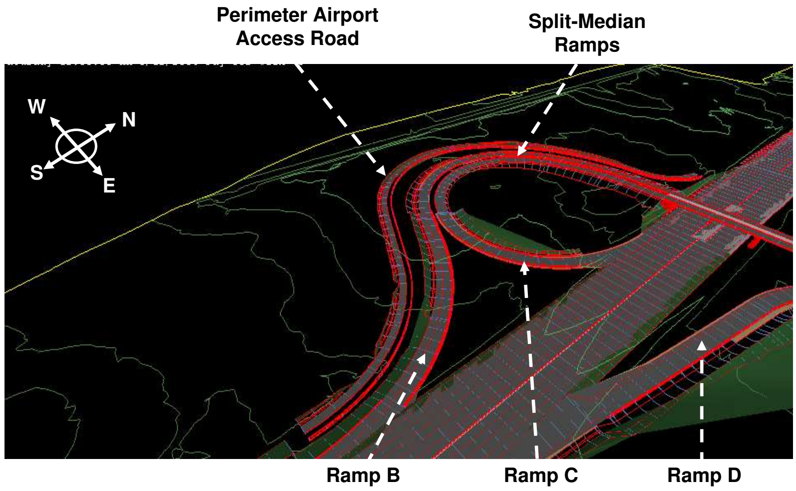

Figure 4.3. Western Portion of Interchange

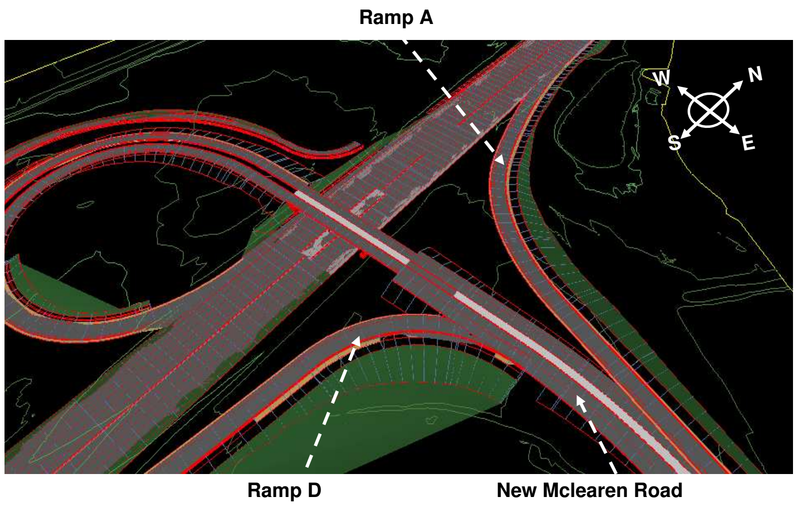

Figure 4.4. Eastern Portion of Interchange

wall (MSE) system. The system is composed of precast concrete panels that fit together modularly to form the abutment walls. The system also includes steel H piles encased in concrete cylinders for foundation stability behind the precast wall panels. The two bridge piers are cast-in-place (CIP), reinforced structural concrete. Each pier is composed of three columns and three corresponding foun-

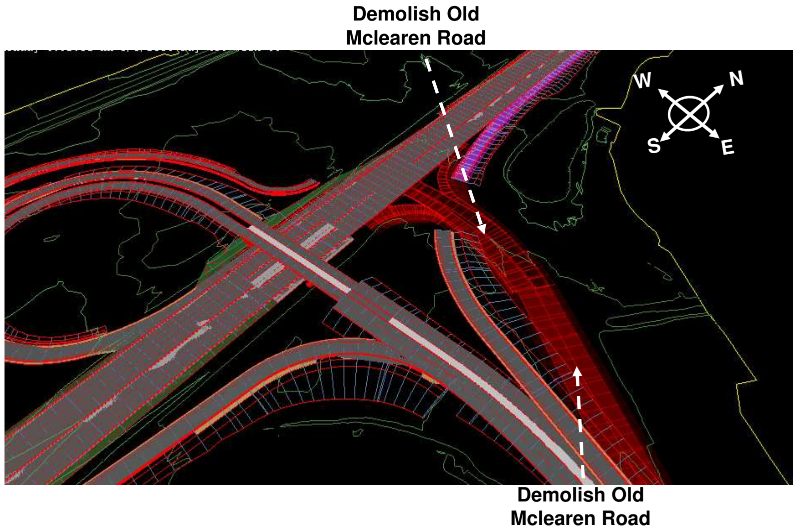

Figure 4.5. Western Portion of Interchange

dations. The columns are connected with a precast concrete piercap. Figure 4.6 details a number of the bridge elements.

The bridge spans are composed of five steel I beams for each span, as shown in figure 4.7. The bridge deck and parapet is CIP reinforced concrete, with a slip-formed concrete median separating the eastbound and westbound lanes. The surface of the bridge lanes are paved asphalt. Figure 4.8 details bridge deck, asphalt pavement, and the center median.

4.2.2 Traffic Control Plan

The traffic control plan for the Rt. 28 - McLearen Road interchange project was divided into two phases. Phase I included the construction of the airport access road, bridge structure, and ramps B, C, D, and partially ramp A . Since ramp A crossed the existing McLearen Road, a portion of this ramp had to be postponed until the road was closed to traffic. Throughout phase I of the traffic plan, the existing Rt. 28 - McLearen Road signaled interchange remained open to traffic. Figure 4.9 shows phase I of the traffic plan.

The Rt. 28 traffic controls during phase I closed both the north bound and south bound shoulders of Rt 28. Jersey barriers were placed at the edges of the

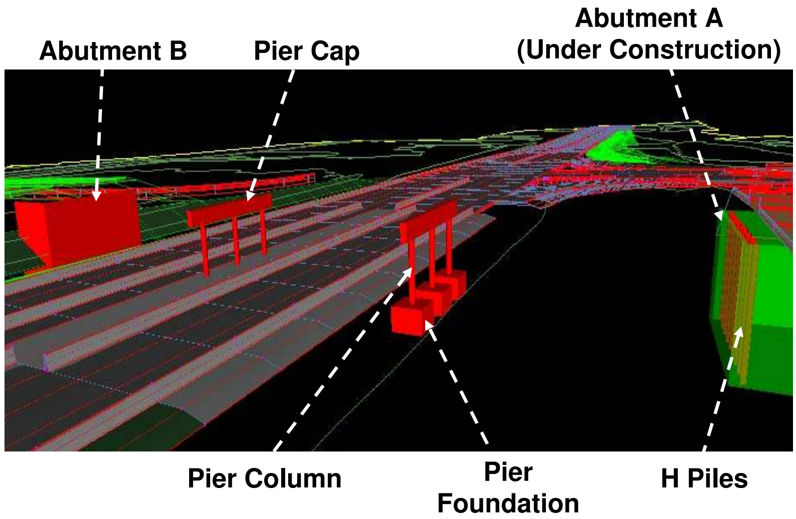

Figure 4.6. Bridge Elements

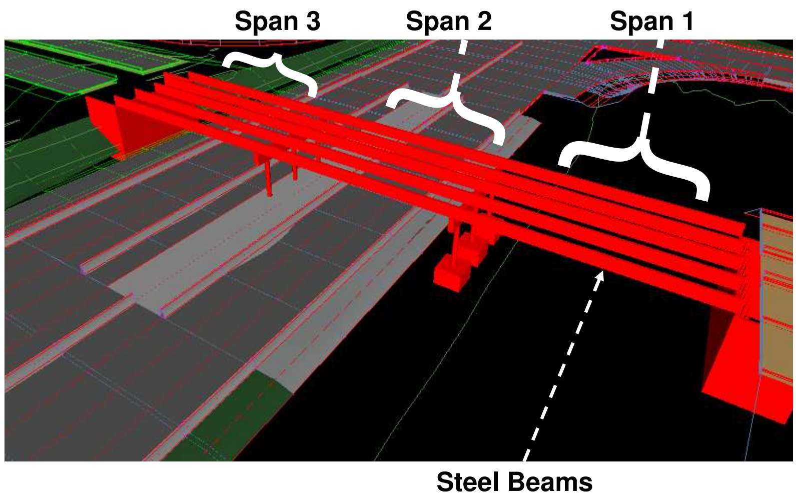

Figure 4.7. Span Detail

travel ways to provide protection for construction operations throughout ramp construction. Also, a central island was constructed around the bridge pier construction area using jersey barriers. Figure 4.10 details the traffic control measures for Rt. 28 during phase I.

Phase II of the traffic control plan included the demolition of the McLearen

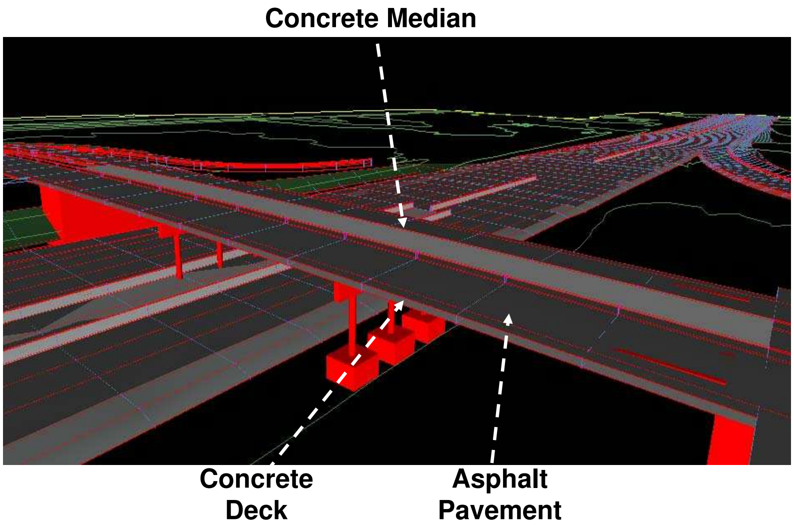

Figure 4.8. Deck Detail

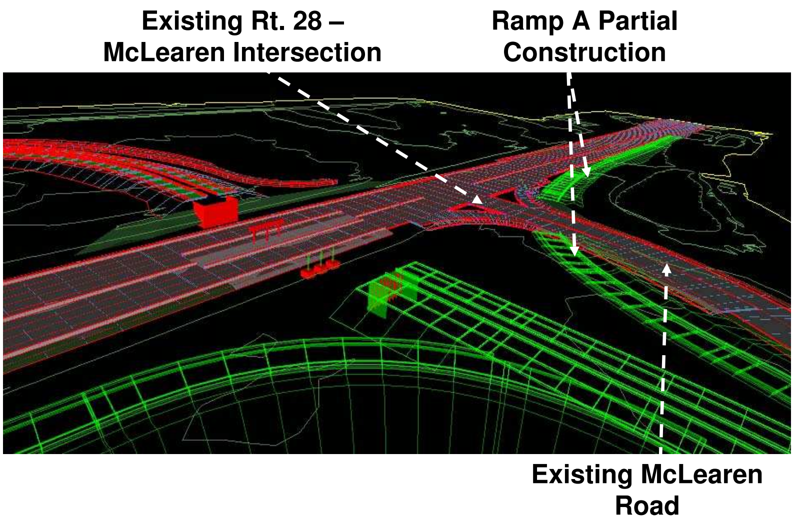

Figure 4.9. Traffic Plan: Phase I

Road - Rt. 28 intersection, completion of ramp A, and the tie in between new and existing McLearen Road. During this phase, the Rt. 28 - McLearen Road intersection was shut down, while traffic was diverted to different entry and exit points along Rt. 28. Phase II of the traffic plan lasted thirty days. Figure 4.11 and figure 4.12 detail the detour routes for Rt. 28 - McLearen road traffic.

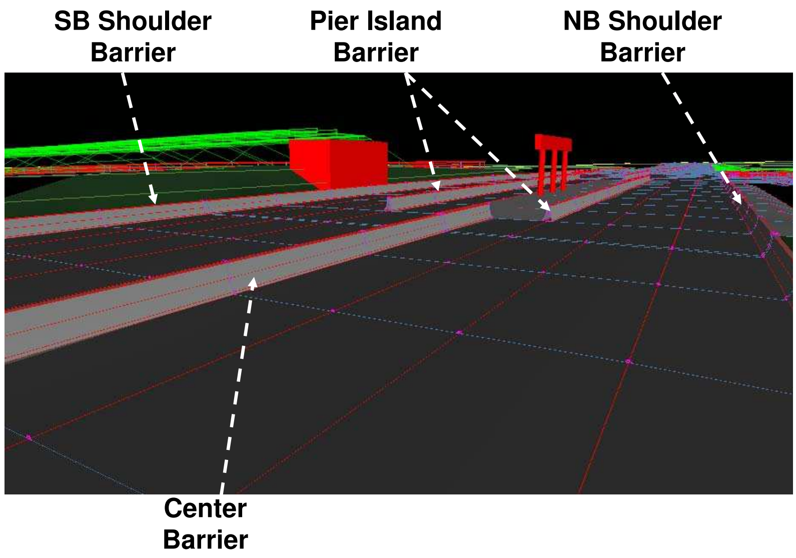

Figure 4.10. Deck Detail

Figure 4.11. Rt. 28 - McLearen Road Detour A

Once phase II of the traffic plan was completed, the Rt. 28 - McLearen Road interchange reopened using the design traffic pattern. Rt. 28 - McLearen Road traffic now moves between two carriage ways via the new interchange. The jersey barriers along Rt. 28 shoulders were removed and the road is fully operational.

Figure 4.12. Rt. 28 - McLearen Road Detour B

4.3 Model Development

There were numerous tools and processes required to develop the 4D CAD model used for this research. This section gives a detailed explanation the software and hardware used to develop the 4D CAD model, and then describes this process performed throughout the development.

4.3.1 3D CAD Model

The 3D CAD model was created using Autodesk Civil 3D 2007. Civil 3D (C3D) is a 3D civil design application introduced by Autodesk in 2005. This software was intended to replace the older version of Autodesk's civil engineering software, Land Development Desktop (LDD), offering a 3D parametric modeling environment opposed to LDD's 2D environment. According to Autodesk, C3D represents a significant advancement in software technology, moving away from a 2D design environment into a 3D environment.

The C3D CAD model was developed using the original project drawings developed by Dewberry engineers and per VDOT specifications. These drawings were designed using Bentley Microstation software, and were obtained in the Microstation file format (.dgn). Therefore, the files were converted into AutoCAD file format (.dwg) using the export function in Microstation V.8 so they could be opened in C3D. This allowed the manipulation and redevelopment of the 2D design into a 3D model.

The first feature that was required in the C3D CAD model was a 3D surface model, representing the existing land conditions within the project limits. This surface model, also referred to as a digital terrain model (DTM), contained topographical information detailing the contours and drainage patterns of the existing land. The surface model was generated using 3D point data collected during an existing condition site survey performed by a Dewberry survey crew. The survey information was imported to C3D as 3D polylines from the .dgn file, then converted into a triangular irregular network (TIN) using the "create surface" tool in the surfaces tab. Figure 4.13 shows the 3D TIN.

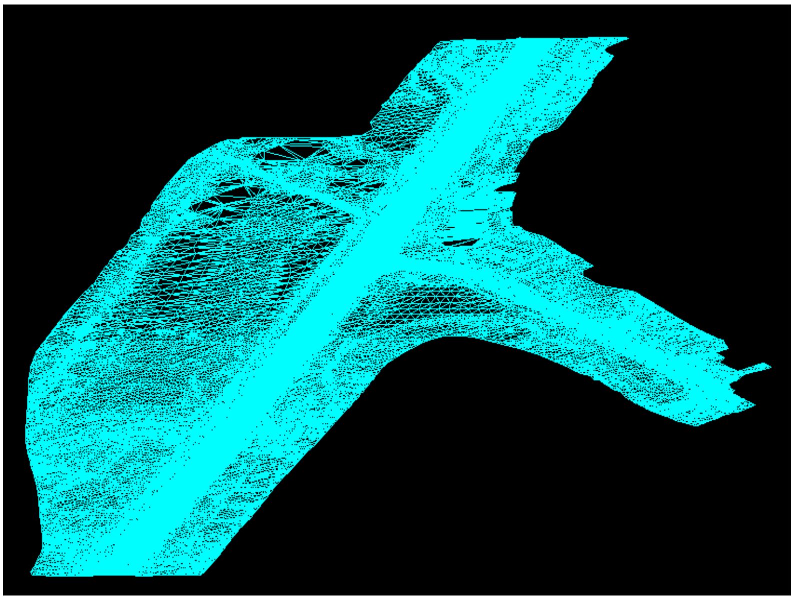

Figure 4.13. Triangular Irregular Network in C3D

Once the existing ground surface had been created in C3D, the interchange design was overlayed on the surface using the "xref" command in C3D. Using the 2D interchange design drawing, horizontal alignments were placed on the 3D surface model. To ensure model accuracy, the C3D tangent and curve values were compared to the values in the construction documents. Figure 4.14 shows the horizontal alignments overlayed on the existing ground surface.

The next step in developing the C3D model was to create the design profiles

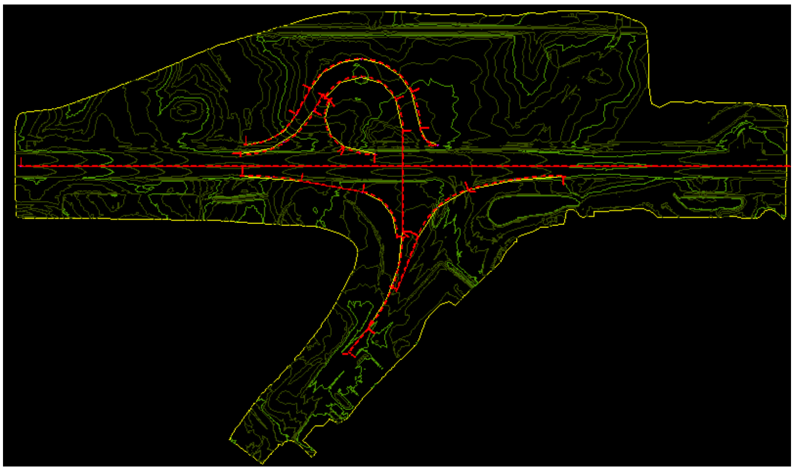

Figure 4.14. Horizontal Alignments

for the project. These were created using the "profiles" tab in C3D. The profiles were drawn identically to the original design profiles, and confirmed numerically in C3D. Figure 4.15 gives an example of the ramp A profile.

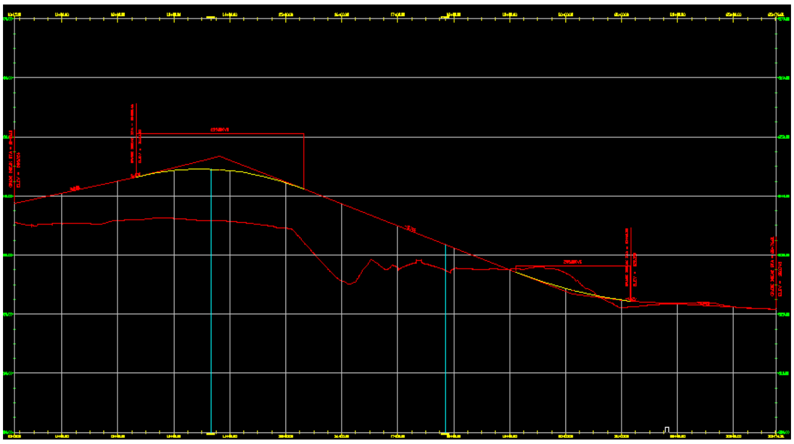

Figure 4.15. Ramp A Profile View

After the horizonal and vertical alignments had been drawn in the model, the interchange cross sections were defined in accordance with the original design cross sections. The cross sections, termed assemblies in C3D, were constructed using the

C3D assemblies catalog. This catalog contains generic highway elements, called sub-assemblies, such as lane outside superelevated and curb. These sub-assemblies are combined to make an assembly, which represents the cross sectional structure of a corridor. Figure 4.16 gives an example of a ramp assembly used in the model.

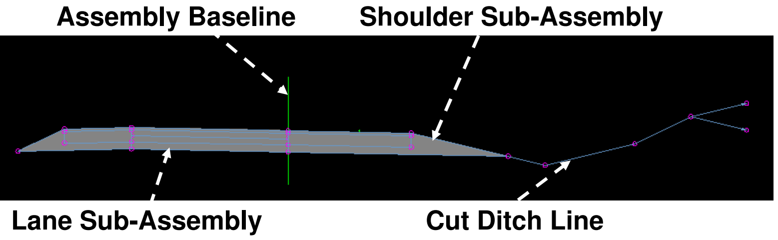

Figure 4.16. Ramp Assembly

The 3D corridors were then built using the horizontal and vertical alignments, roadway assemblies, and the existing ground surface. The 3D corridors were built in small sections that represented one portion of work in the field, such as individual ramps and small pieces of road. This was necessary because each section would need to be linked individually to a schedule activity in the 4D model, and needed to be organized properly in the 3D model. This issue is further discussed in Chapter 6. The corridors were built using the "create corridor" option under the corridors tab. The corridors were displayed in C3D as sections and 3D feature lines. This is a efficent method of displaying 3D information because it does not create extraneous design data that would require large amounts of RAM to rotate in 3D. Figure 4.17 shows a 3D corridor in C3D.

After the 3D corridors had been modeled, 3D surfaces were built to represent roadway surfaces in the model. These surfaces served to visually represent layers in the roadway construction. Surfaces were built for the barriers, sub-base, gravel base, base asphalt, intermediate asphalts, and surface asphalt. The surfaces were created using the "surfaces" tab in the corridor properties, and were displayed as TIN's in the model. Each surface was placed on its own unique layer for interoperability with the 4D CAD program, which is further discussed in Chapter 6. Figure 4.18 shows how the surfaces were created using the corridor properties in C3D, and Figure 4.19 shows the TIN's created in the model. Each different color

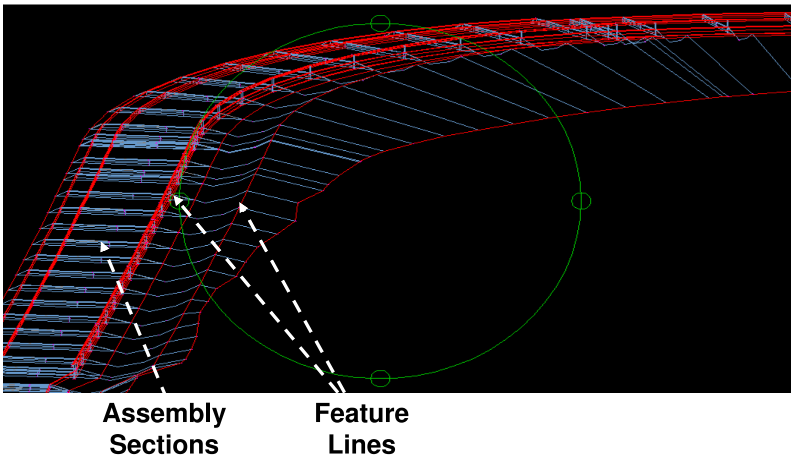

Figure 4.17. 3D Corridor

TIN represents a separate surface in C3D.

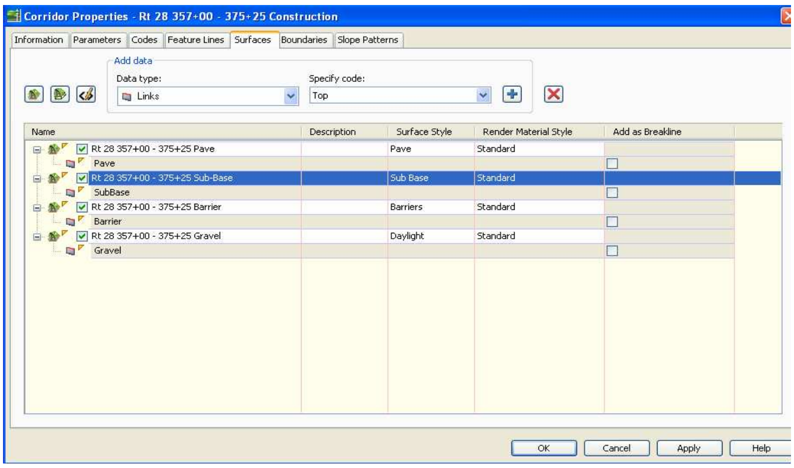

Figure 4.18. Surfaces Tab in Corridor Properties

Once the surfaces were completed, the model needed a 3D bridge placed in the appropriate section of highway. The development of the 3D bridge is described in section 4.3.1.1.

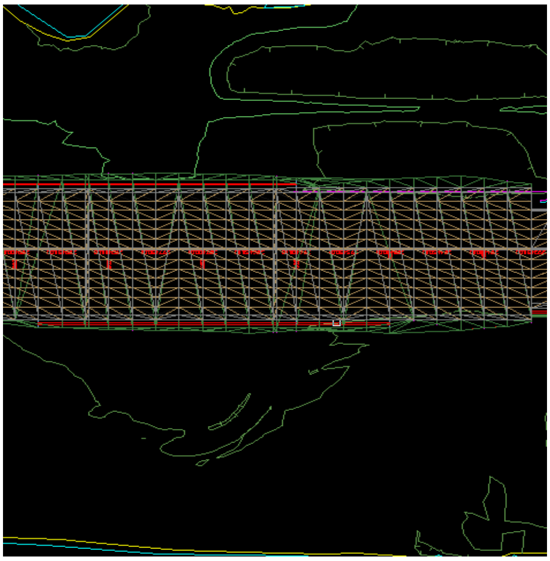

Figure 4.19. 3D TIN Surfaces

4.3.1.1 3D Highway Bridge

The 3D highway bridge was developed using 3D Autocad objects. Autocad objects are simple 3D blocks that can be used to make structures such as the bridge used in this research. The bridge was made of simple shapes, such as cubes, rectangles, and cylinders. The abutments, piles, pier caps, and beams were 3D rectangles. The pier foundations were made of cubes and the piers were made of cylinders. The bridge deck was part of the highway design, and was built using the C3D methods previously described. Figure 4.20 shows the 3D CAD drawing of the bridge used for this project.

The bridge was meant to represent only the bare minimum of elements required to portray a bridge. The bridge was not built to scale, and unlike the rest of the highway design, was not based on the design drawings. The bridge serves only to give a general idea of what it would look like and how it fits into the entire project on a macro scale. Smaller bridge elements such as rebar cages and connections were excluded from the design since they are short duration activities with little effect on the overall project schedule.

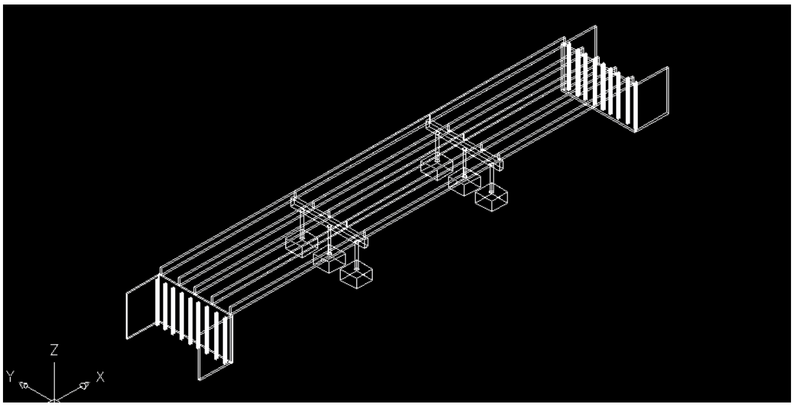

Figure 4.20. 3D Highway Bridge

4.3.2 Scheduling

The construction schedule was developed by the general contractor, Shirley Contracting Company, using Primavera Suretrak software. The schedule was exported to .mpx format so it could be imported into the 4D CAD software. Figure 4.21 shows a preview of the project schedule.

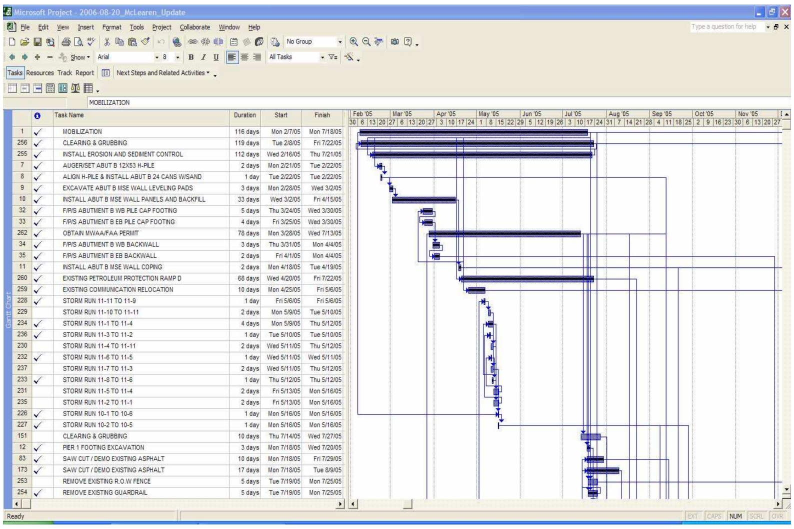

Figure 4.21. CPM Schedule in Microsoft Project

4.3.3 4D CAD Model

The 4D CAD model was developed using Navisworks JetStream V.5, by linking the C3D CAD model with the construction schedule. Navisworks JetStream is a collaborative 3D/4D design review software intended to improve productivity and quality in the project lifecycle (Navisworks, 2007)

The C3D model was opened as a .dwg file in Navisworks, then saved in the Navisworks file format, .nwd. The schedule was imported as a .mpx file using the Timeliner plug-in, and saved as part of the .nwd file. The 3D model was linked to the schedule activities manually by selecting the 3D objects in the model, then selecting the corresponding schedule activity and attaching the selection. Once all the relevant objects and tasks were linked, the 4D CAD simulation was complete. Figure 4.22 shows how a 3D object is link to its corresponding schedule activity.

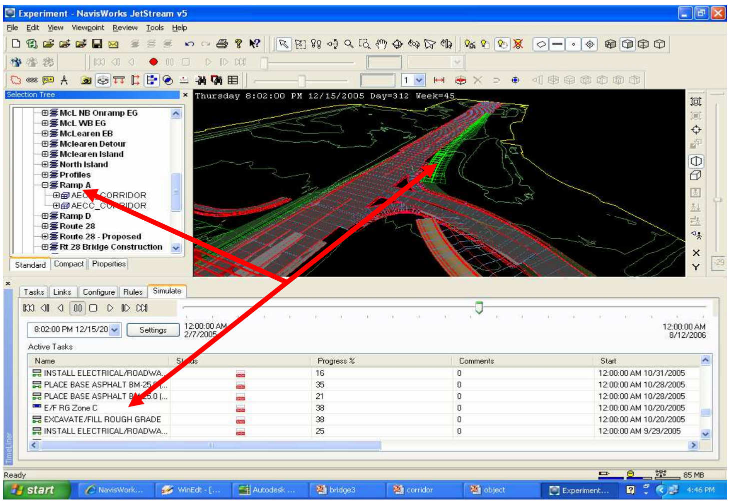

Figure 4.22. Linking Model and Schedule in Navisworks with Timeliner

4.3.3.1 Navisworks Navigation

The 4D CAD model was navigated using several tools found in the Navisworks JetStream software. The navigation capability of this software is important because it provides users with the ability to move through and around the model for inspection throughout the construction process.

The primary form of navigation used to view the 4D model was the “walk” tool. The “walk” tool enables users to walk around the model in a scaled view, giving the user a more realistic sense of the physical characteristics of the site. Figure 4.23 shows the “walk” tool in use, and gives a realistic scale to the size of the project.

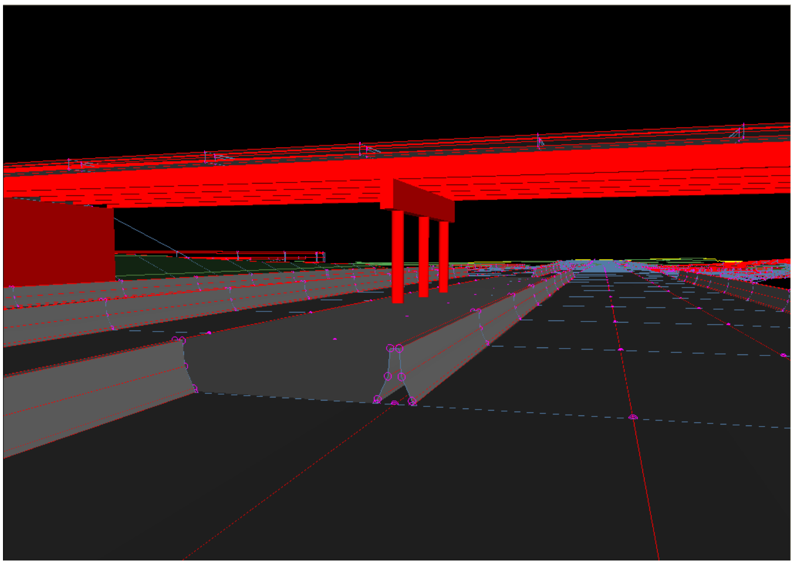

Figure 4.23. Walking View of the Overpass Bridge

The secondary tool that was useful for the navigation of the 4D model was the orbit tool. Orbit allows the user to rotate the model in any direction, slowly or quickly, allowing rapid movement across different areas of the model. This is especially useful during the construction simulation process, where numerous activities are occurring rapidly in different areas of the model and must be traversed quickly to see all aspects of construction.

4.3.4 Hardware

The computer console used for the development of the 4D CAD model used in this research was a Dell Optiplex GX 620 running on Windows XP Professional V. 2002 SP. 2. The graphics card was a 256 MB ATI Radeon X600. The processor was an Intel Pentium 300 GHz, with 3.50 GB RAM.

Chapter 5

Data Collection and Results: Identifying the Best Applications of 4D CAD for Highway Construction Projects

This chapter presents the research methods and results performed in this thesis to determine the best applications of 4D CAD for highway construction. The scaled questionnaire, open ended questions, and focus group discussions are first described, then the results are presented. The data is then analyzed and discussed in-depth, representing the views and opinions expressed by the research groups used for the research.

5.1 Research Groups

This research was performed using three separate groups of highway construction professionals. Each group was from a different construction company, and for the remainder of this thesis are referred to as Contractor 1, Contractor 2, and Contractor 3. The contractors all have significant highway construction experience on complex construction projects, and served as the primary resource for data collected in this thesis.

Contractors 1 and 3 were located in Northern Virginia, and worked primarily in the greater Washington D.C. area. Contractor 2 was located in Central Pennsylvania, and worked on projects throughout the state. The experience range of the professionals in the groups was from one year to thirty years, representing entry level engineers to a President/CEO. This wide range of construction professionals is valuable for research purposes because it represents a broad perspective of highway construction experts, and does not limit the research data to a specific age or experience level. The opinions expressed in this thesis are based on the thoughts and suggestions of the highway construction professionals surveyed, and represent their opinions regarding 4D CAD in highway construction.

5.2 Research Meeting Procedure

The data collection was performed at the offices of the contracting companies participating in the research studies. The presentation and data collection were done in the offices conference room, by projecting the presentation and 4D CAD model on a screen in the front of the room. Research participants viewed the presentation from their seats, as the slide show and model were presented by the researcher. The research meetings typically lasted ninety minutes.

The research meetings began with an introductory slide show giving an overview and background to the research topic. The slide show described the purpose and objective of the study, and how the participants relate to research being performed. Then, a definition and example of 4D CAD was given to familiarize the group with 4D CAD technology. This helped define a baseline of understanding among the research participants, since most were not familiar with 4D CAD technology. The 4D CAD example showed the erection of a twelve story apartment building, conveying the essential concepts of 4D CAD and giving the group a general idea of what a 4D CAD model looks like. Next, the case study project was introduced. The introduction defined the goals and objectives of the case study, then outlined project details such as the work requirements, schedule, and project team. Once the case study had been introduced, the 4D CAD model of the project was shown. The model was first shown at full speed, without any comments through the visualization. This gave the research group their first ideas and impressions of the 4D highway model. Then, the visualization was played a second time, slowly moving step by step through the progression of work with an explanation of each activity occurring in the visualization. This gave the research team a more detailed look at the 4D CAD model, and a better understanding of the project simulation. The 4D CAD visualization was then removed from the screen and the research exercises were performed. These exercises included a scaled questionnaire, open ended questions, and a focus group discussion, and are discussed in detail in sections 5.3, 5.4, and 5.5. Once the exercises were completed, the research meeting was concluded.

5.3 Exercise 1 - Scaled Questionnaire

The objective of scaled questionnaire was to collect quantitative data from the research participants that could be used to determine the best applications of 4D CAD for highway construction projects. The questionnaire asked participants to rank their ***perception*** of the benefits of 4D CAD in numerous different highway construction applications on a scale of 0 - 10, 0 being no benefit and 10 being high benefit. The survey consisted of thirteen questions divided into two general categories, I. Planning and Scheduling (PS) and II. Communication (C). These two categories were chosen because previous 4D CAD research had shown them to be the most beneficial areas for 4D CAD applications in building construction. Table 5.1 summarizes these publications, and describes the benefits shown in each paper.

Table 5.1. Summary of Publications Documenting 4D CAD Benefits

Name	Publication	Results
Messner and Lynch (2002)	A Construction Simulation Model for Production Planning at the Pentagon Renovation Project	Improved Production Plan
Yerrapathruni (2003)	Using 4D CAD and Immersive Virtual Environments to Improve Construction Planning	Improved Sequencing
Koo and Fisher (2000)	Feasibility Study of 4D CAD in Commercial Construction	Better Understanding of Schedule, Improved Schedule Communication
Fisher and Kunz (2004)	The Scope and Role of Information Technology in Construction	Gain Better Visual Understanding of Facility
Otto et al. (2005)	Expanding the Boundaries of Virtual Reality for Building Design and Construction	Importance of Visualization for Communication

Table 5.2. Survey Questions

Question #	Category	Question
1	C	Communicating the design and construction plan to the public
2	C	Communicating the design and construction plan to the owner/DOT
3	C	Gaining public approval and acceptance
4	C	Gaining permit approvals from government/ transportation advisory board
5	C	Conceptualizing the 3D geometric layout
6	C	Identifying 3D design data irregularities
7	PS	Developing the construction process plan/workflow plan
8	PS	Reviewing and improving construction schedule sequencing
9	PS	Developing the traffic phasing and detour scheduling
10	PS	Planning the equipment locations
11	PS	Optimizing the paving schedule
12	PS	Developing the work zone plan
13	C/PS	Communicating the schedule for subcontractor coordination

The thirteen survey questions were divided equally into the two groups, with six questions related to planning and scheduling and six questions related to communication. One question fell into both categories, since it related to both scheduling and communication. Each question investigated a specific area of its general category, further defining the best applications of 4D CAD for highway construction. Table 5.2 lists the survey questions, and notes whether they are planning and scheduling questions (PS) or communication questions (C). The research participants did not know the question categories.

5.3.1 Scaled Questionnaire Results

The results are presented in several different formats to give both a macro view of the data, along with more specific insight into the data collected from each different contractor. First, the results are presented as a combination of the contractors in section 5.3.1.1. This gives a better overall understanding of the data collected, and is used to determine what the best use applications of 4D CAD are for highway construction. Then, to further understand the data and its relationship to each contractor, the results are presented individually by contractor. This is presented since each contractor had slightly different business strategies and organizational hierarchies, giving each a slightly different perspective that was reflective of their company. This also gives insight into the opinions of different levels of experience and employment positions within a group. It is valuable to understand the different perspectives of highway construction professionals relative to their age and experience because opinions and insights change drastically over an individuals career. For example, high level management may see certain benefits of 4D CAD for highway construction that lower level employees may not. This is because upper management deals with different problems and issues in their job, giving them a wider perspective into applications of the model. This data is presented in section 5.3.1.2.

5.3.1.1 Overall Results

The overall results present the combined data from each of the contractors. This gives quantitative insight into the overall opinions and viewpoints of the contractors that participated in this research.

The results of the scaled questionnaire show that in the opinion of highway construction professionals, 4D CAD for highway construction projects was beneficial for both communication applications and planning and scheduling activities. The results indicate that participants viewed the communication applications as slightly more useful than the planning and scheduling applications, with the C questions scoring an average of 7.5 and the PS questions scoring an average of 6.5. Figure 5.1 shows a comparison of the average ranking of the two question types from the data collected from contractors 1, 2 and 3. The overall results are presented in table 5.3.

Table 5.3. Summary of Results

	Question Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Contractor 1	7.8	7.3	6.5	4.8	7.7	8.0	7.7	7.3	7.8	3.8	5.5	7.8	6.2
Contractor 2	8.4	7.6	8.0	7.2	7.6	8.4	6.4	6.6	6.8	6.4	5.6	7.0	7.0
Contractor 3	9.1	9.3	7.9	7.8	7.8	7.8	6.6	7.0	7.6	5.8	5.4	7.0	5.4
Weighted Average	8.4	8.0	7.4	6.5	7.7	8.1	6.9	7.0	7.4	5.3	5.5	7.3	6.2
Std. Dev.	1.3	1.6	1.5	2.0	1.7	1.4	1.7	1.5	1.3	1.8	2.1	1.2	1.6

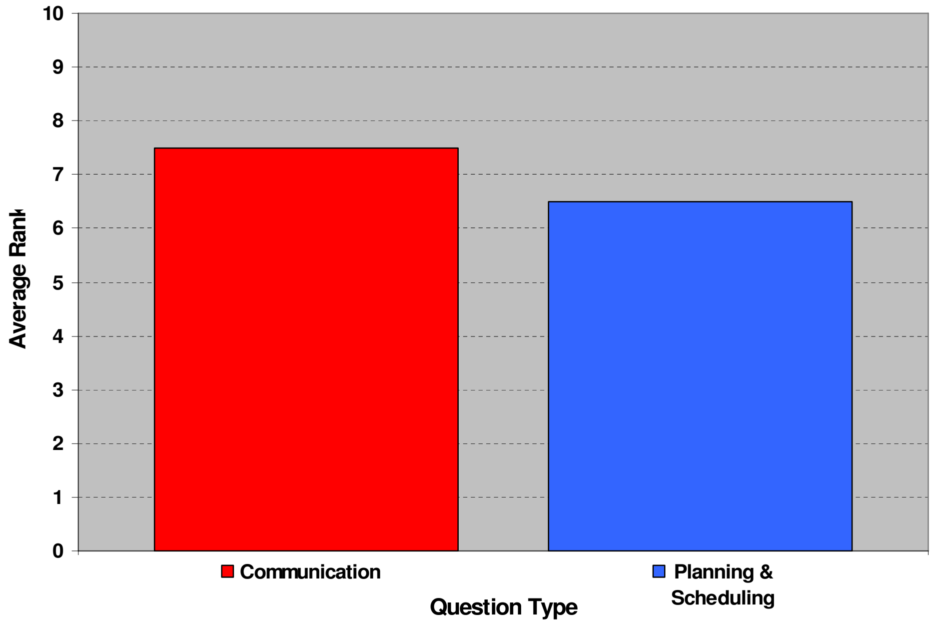

Figure 5.1. Average Rank of Question Types

The results show that the most beneficial application of 4D CAD in highway construction was for communicating the design and construction plan to the public. This question scored an average of 8.4 on the survey. The second most beneficial application was for identifying 3D data design irregularities before field construction, scoring 8.1 on the survey. The least beneficial application based on the participant opinions was for planning equipment locations on the job site, scoring a 5.3 overall. The second least beneficial application was for optimizing the paving schedule, scoring a 5.5.

The most beneficial application of 4D CAD in highway construction related to planning and scheduling was for developing the traffic phasing and detour scheduling. This question scored 7.4 on the survey. The least beneficial application of 4D CAD relative to communication was for gaining permit approvals from government/transportation advisory boards. These results are fully discussed in section 5.6.

5.3.1.2 Individual Results

The individual results present an in-depth view of the data collected from each contractor. This gives insight into the responses from each company, and provides further understanding of the data related to individuals experience and job title.

The results are presented in tabular format, summarizing each individuals current job title, total years experience, years of highway construction experience, and responses to each question. The responses are averaged and standard deviation calculated at the bottom of each table. Table 5.4 gives the full title of the acronyms used for position titles in the survey results. Tables 5.5, 5.6, and 5.7 on pages 62 and 62 present the results of contractors 1, 2, and 3 respectively.

Table 5.4. Positions Key

Acronym	Full Title
CEO	Chief Executive Officer
VP	Vice President
S PM	Senior Project Manager
PM	Project Manager
S PE	Senior Project Engineer
PE	Project Engineer

The results show that highway contractors 1 and 2 both believed the best application of 4D CAD for highway construction was for identifying 3D design data irregularities. Contractor 2 also believed that there was an equal benefit in communicating the design and construction plan to the public, with an average score of 8.4 for each. Contractor 3 believed that the most beneficial use of 4D CAD was for communicating the design and construction plan to the owner/DOT.

The results show that highway contractor 1 believes the least beneficial application of 4D CAD for highway construction projects was for planning equipment location. Contractors 2 and 3 both believed the least benefit was in optimizing paving schedules. Contractor 3 also believed the least benefit was for communicating the schedule for subcontractor coordination.

Table 5.5. Survey Results from Highway Contractor 1

Position	Total Exp. (Years)	Hwy. Ind. Exp. (Years)	Question Number												
			1	2	3	4	5	6	7	8	9	10	11	12	13
VP	18	15	8	8	7	6	7	7	9	9	9	5	6	8	8
S PM	22	18	5	10	5	8	10	10	10	10	10	5	10	10	7
PM	16	16	8	6	8	3	10	10	10	7	7	2	2	6	6
S PM	7	7	8	6	7	5	6	7	7	7	8	4	6	7	6
PE/PM	6.5	2.5	8	6	7	5	4	5	5	4	5	3	3	7	7
PE	5.5	4.5	10	8	5	2	9	9	5	7	8	4	6	9	3
Average			7.8	7.3	6.5	4.8	7.7	8.0	7.7	7.3	7.8	3.8	5.5	7.8	6.2
Std. Dev.			1.6	1.6	1.2	2.1	2.4	2.0	2.3	2.1	1.7	1.2	2.8	1.5	1.7

Table 5.6. Survey Results from Highway Contractor 2

Position	Total Exp. (Years)	Hwy. Ind. Exp. (Years)	Question Number												
			1	2	3	4	5	6	7	8	9	10	11	12	13
CEO	37	37	9	7	8	8	6	7	5	6	5	5	4	7	9
VP	23	23	8	6	8	5	7	8	5	4	6	4	3	7	4
PM	16	10	9	9	10	8	9	10	7	8	8	8	8	7	8
PE	3	1	9	9	5	7	9	9	8	8	8	6	5	7	7
PE	1	1	7	7	9	8	7	8	7	7	7	9	8	7	7
Average			8.4	7.6	8.0	7.2	7.6	8.4	6.4	6.6	6.8	6.4	5.6	7.0	7.0
Std. Dev.			0.9	1.3	1.9	1.3	1.3	1.1	1.3	1.7	1.3	2.1	2.3	0.0	1.9

The most optimistic perception of 4D CAD for highway construction projects was from contractor 3, with an average score of 7.3. The least optimistic perception was from contractor 1, with an average score of 6.8. Contractor 2's average score fell just slightly below contractor 3, at 7.2. These results are discussed in section 5.6.

Table 5.7. Survey Results from Highway Contractor 3

Position	Total Exp. (Years)	Hwy. Ind. Exp. (Years)	Question Number												
			1	2	3	4	5	6	7	8	9	10	11	12	13
VP	28	28	8	10	7	7	10	8	7	8	8	6	6	5	4
PM	30	30	10	10	7	7	7	8	8	7	7	7	5	7	7
PM	28	28	10	10	8	8	7	9	7	7	8	7	7	9	6
PM	20	20	8.5	8.5	8.5	8	8	7	5	7	8	5	5	7	5
S PE	33	33	9	8	9	9	7	7	6	6	7	4	4	7	5
Average			9.1	9.3	7.9	7.8	7.8	7.8	6.6	7.0	7.6	5.8	5.4	7.0	5.4
Std. Dev.			0.9	1.0	0.9	0.8	1.3	0.8	1.1	0.7	0.5	1.3	1.1	1.4	1.1

5.4 Exercise 2 - Open Ended Questions

The objective of the open ended questions was to gather qualitative data from the research participants about specific applications of 4D CAD for highway construction using open ended questions. This portion of the research allowed the participants to explain their perspective of 4D CAD for highway construction by describing their opinions in writing. The open ended questions gave the participants an opportunity to elaborate on their responses given in the scaled questionnaire, providing insight into the quantitative data gathered in exercise 1. The open ended questions investigated ***why*** each application of 4D CAD for highway construction was beneficial.

The open ended questions consisted up of seven questions that encouraged written explanations about the best applications of 4D CAD for highway construction projects. Table 5.8 on page 64 shows the questions asked in the open ended portion of the survey.

5.4.1 Open Ended Question Results

The results for the open ended questions are presented in a tabular format, and summarized to consolidate repeat answers within each research group. The responses are broken down by individual contractor so they can be easily compared

Table 5.8. Open Ended Questions

Question #	Question
1	Are there other applications in which 4D CAD could be used as a beneficial tool?
2	What additional information would be valuable to represent in the 4D CAD visualization?
3	What disadvantages might a 4D CAD visualization have related to a project?
4	Do you believe a 4D CAD visualization can accurately describe and communicate a construction strategy? Please explain.
5	What is the most important aspect visually in a 4D construction model? (Traffic Diversion, Pipe layout/storm water, grading and earthwork, equipment, etc.)
6	Does a 4D construction model provide better insight into the general construction strategy? Please explain.
7	Does 4D construction visualization environment helps in producing a better AS-BUILT and Information Model for Owner?

and contrasted for data analysis. Each question showed numerous reoccurring responses from each individual contractor, leading to concrete conclusions about 4D CAD for highway construction projects. The results from contractors 1, 2, and 3 are presented respectively in figures 5.2, 5.3 and, 5.4 on pages 65, 66, and 67.

The results from the open ended questions give several specific suggestions about applications of 4D CAD for highway construction projects. Each question posed in this portion of the survey shows specific trends in the responses from each contractor. Common suggestions appeared throughout the surveys for each question, independent of the contractor participating at the time. Often, a suggestion would appear in 2 out of 3 contractors, suggesting a strong correlation between responses. The most convincing responses appeared across all three contractors, and represent the best suggestions for each question. These common suggestions, where all three contractors responded identically, served as the primary evidence used to support the findings in this research, and represented the most important issues in the opinions of highway construction professionals. Figure 5.5 shows the common suggestions given by the highway construction contractors.

Question #	Contractor 1
1	• Utility conflicts, overhead and underground. • Phased takeoff
2	• Drainage • Existing utilities • Mapping • Traffic analysis
3	• Too complex • Confuse less technically savvy staff • Time consuming to develop and update • Need high level of detail
4	• See design/ scheduling conflicts • Identify errors in plans • Helps buy-in • Good overview of project & schedule • Complex projects w/ many stages & traffic shifts
5	• Maintenance of traffic to ensure sufficient area for construction • Identify conflicts • Maintain traffic • Maintain drainage • Grading/earthwork
6	• Visually depict how project is constructed • Reinforce a construction schedule • Show alternative sequences of work to find best option
7	• Visual flow of work • Would be difficult and lot of work

Figure 5.2. Open Ended Questions Results from Contractor 1

Question #	Contractor 2
1	• Constructability evaluation • Defense of Claims • Adjust structures, access, block outs for sequencing • Balancing earthwork • Utility locations • Resource equipment to activities to know what you need on site • Logistical control for ordering materials • Virtual traffic simulation • On-screen milestone display • GPS schedule updates
2	• Underground elements and conflicts (existing and new) • Overhead obstructions • Traffic • Equipment in use diagrams
3	• Requires effort for in house utilization • Need 2, 1 for early start and 1 for late start • Might allow for false expectations and changes • Just because it looks good doesn't mean it will work in the field • May lead to improper planning if model leaves elements of construction out • May be used by inexperienced to make an inferior plan look good
4	• Helps present construction process in a manner understandable to any non construction oriented groups • If the design is adequate, a picture is worth a thousand words for those who can't visualize. • Helps identify potential schedule problems so to lose less time in field • Must include all aspects of construction process • Everyone takes a virtual walkthrough of each stage of the job
5	• ID possible conflicts in plans or between construction operations and traveling public • Traffic maintenance • Earthwork balancing • Existing structures and utilities • Anything that deals with the public
6	• Provides focus to encourage discussion between individuals with different levels of construction experience • Would improve and add to strategy, but still based on same information • Visual 3D plans are great for sharing ideas and concepts that 2D cannot • Can show how a project will come together • Can show strengths and weaknesses of plan and ID conflicts • Can get everyone on the same page quickly
7	• Would be OK, but not enough detail for historical document • No, just visual • Probably will be better in future when owners are more computer literate • Would be good if updated with field GPS data

Figure 5.3. Open Ended Questions Results from Contractor 2

Question #	Contractor 3
1	• Any construction project – Runways, dams • Claims and court cases/ dispute resolution • GPS modeling excavation
2	• A timing study of traffic flow before, during and after construction • Needs more detail shown, but helpful to show all phases • Representations need to be clearer, need to depict surfaces • Traffic phasing • Earthwork balancing • Good for heavy civil jobs like dams, tunnels
3	• Used on site as a planning tool • Time to complete • Bad plans leads to a bad visualization • May cause micromanagement by the owner • Hard to view linear activities
4	• Should be shared with customer, subs, suppliers • May be limited to audience it reaches • Visuals can depict 3D progression very well • Very dependent on an accurate model • Can help for construction phasing and strategy of attack
5	• Bridge structures • Grading • Traffic diversions • Sequencing of portions of work • Resource constraints • Intersection of activities • Sequence of structural work
6	• Gives anyone interested a visual display of overall construction program • Sequencing is all important • It is more of an outcome of a plan than a planning tool • Better on complicated projects w/ intense phasing • Provides better visual for layman on how a job is built • Still needs work for value in the field
7	• Yes if showed the actual progression of events in 3D • Current schedule data isn't compelling when not visual • Good for claims and disputes • Depends on accurate schedule data • Relates time and date

Figure 5.4. Open Ended Questions Results from Contractor 3

Question #	Suggestion Frequency	
	3 out of 3	**2 out of 3**
1	• None	• Defense of claims • GPS modeling • Utility conflicts/locations
2	• Traffic phasing/analysis	• Underground and overhead utilities
3	• Time to complete/level of detail	• None
4	• Scheduling/phasing	• Need an accurate model
5	• Traffic maintenance • Earthwork applications • Identify schedule conflicts	• None
6	• Sequencing • Good visual depiction of construction	• None
7	• Would be difficult	• Require a lot of work

Figure 5.5. Common Suggestions to Open Ended Questions

5.5 Exercise 3: Focus Group Discussions

The objective of the focus group discussions was to facilitate a group discussion among highway construction professionals about the best applications of 4D CAD for highway construction projects. The discussion was organized in a semi-structured format, with the researcher posing several pertinent questions to encourage group discussion. If the discussion came to a halt, then a new topic was introduced to the group. The researcher/facilitator of the discussion did not participate in the discussions, except for posing the questions. The conversation was recorded using a digital audio recorder, then reviewed and transcribed by the researcher. A content analysis of the conversation was performed, then organized individual ideas into a logical structure for presentation.

The motivation for the group discussion was to openly discuss ideas about 4D CAD in highway construction, letting individuals express ideas that encouraged new and unconventional thinking amongst the group. Often, an individual left alone may not see all applications of a certain idea until another person has suggested something the open forum. This can start someone else's train of thought, and generate ideas that would not have been suggested unless piqued by the discussion. The discussion topics often changed sporadically as new ideas were suggested, encouraging participants to offer new ideas to the group. When the discussion slowed down, questions posed by the researcher began new lines of thought. Table 5.9 shows the questions posed for this focus group discussion.

Table 5.9. Focus Group Discussion Questions

Question #	Question
1	What are the benefits, drawbacks, and major issues associated with using 4D CAD in scheduling and schedule review?
2	What are the benefits, drawbacks, and major issues associated with using 4D CAD for construction plan communication?
3	What are the benefits, drawbacks, and major issues associated with using 4D CAD for contractor/subcontractor coordination?
4	What are some other benefits or drawbacks to using 4D CAD for highway construction project and why?
5	Any other comments and/or suggestions you would like to provide related to this research project?

5.5.1 Focus Group Discussions Results

The focus group discussions results are presented using a content analysis that systematically analyzed the discussions performed with contractors 2 and 3. The content analysis aimed to logically classify the conversations between the highway construction professionals to develop concrete messages within their discussion. This is important because these ideas serve as the primary data used to support the claims put forth in this research. The content analysis also aimed to identify common instances of discussion content independent of the research group. These common discussion instances are identified in the content analysis maps using a color coding system described in figure 5.6. The blue highlighted text represents content taken from contractor 2's focus group discussion. The red highlighted text represents contractor 3's discussion. The green highlighted text represents common content that was discussed by both contractors who participated in the focus group discussions. Contractor 1 did not participate in a focus group discussion, and is therefore not represented in this data.

The content analysis consisted of three common categories that the discussion could be classified into. These categories were scheduling and schedule review, planning and phasing, and communications. These are similar to those categories defined in the scaled questionnaire and open ended questions, but have separated the planning and scheduling group (PS) into two separate groups to gain further insight into the applications of 4D CAD in highway construction. The content was further classified into four sub-categories once placed into the general category. These sub-categories were positive, negative, issues, and other.

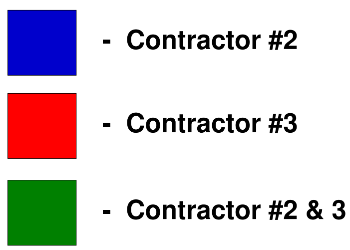

Figure 5.6. Text Color Key for Content Analysis

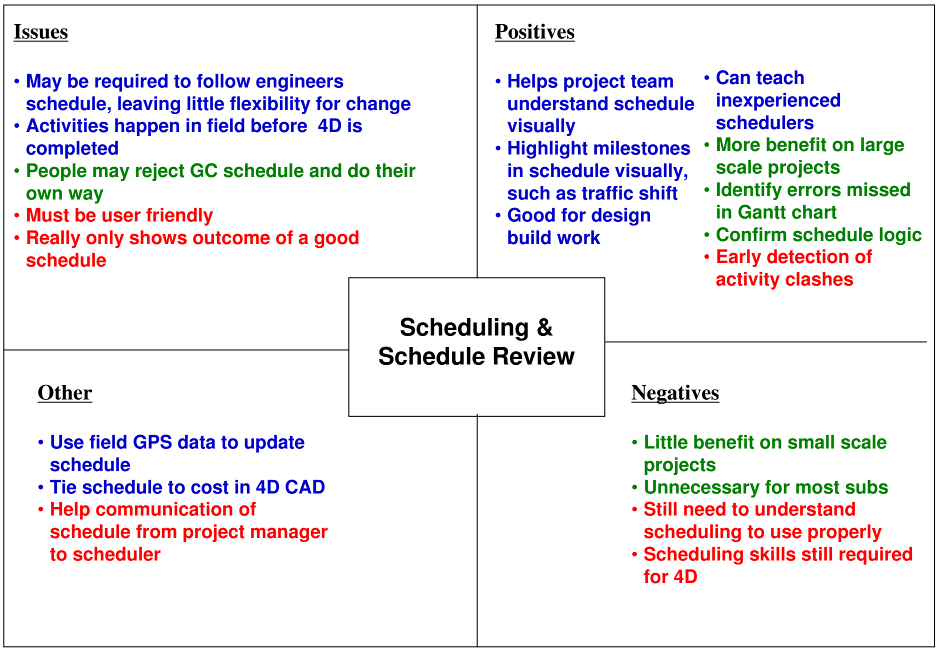

Figure 5.7. Scheduling and Schedule Review Content Analysis

The results of the focus group discussions give numerous valuable insights and suggestions about the opinions of highway construction professionals regarding applications of 4D CAD for highway construction projects. Each contractor presented both unique and common ideas throughout their discussions, and introduced additional research topics that had not been considered throughout this research.

Some common ideas presented regarding scheduling and schedule review were that 4D CAD can help identify errors and omissions missed in the Gantt chart representation of the schedule. Another common idea was that people, both internal or external, may reject the 4D CAD technology and follow their traditional methods of scheduling. One unique opinion presented regarding scheduling and schedule review was that the schedule could be tied to GPS earthwork systems in order to update the schedule automatically.

One common idea expressed by both contractors regarding planning and phasing was that 4D CAD could be a valuable tool for developing a site safety plan. One unique opinion presented by contractor 3 regarding planning and phasing was that 4D CAD is much more valuable if applied to large scale, heavily phased

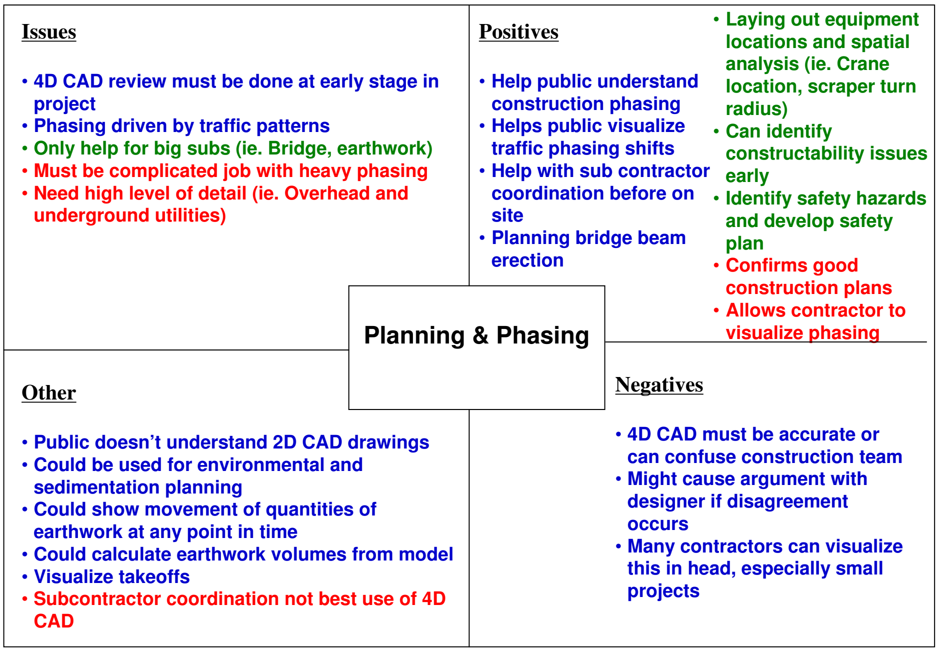

Figure 5.8. Planning and Phasing Content Analysis

highway construction projects.

One common idea found amongst both contractors regarding communication was that 4D CAD would be useful for communicating traffic plans to affected business and land owners in proximity of the project. One unique opinion presented by contractor 2 was that communicating 4D CAD to internal and external people may lead to false expectations of the field construction.

A number of ideas that were suggested by the contractors did not fit into the categories defined in this analysis, but are worth mentioning. The first idea was suggested by both contractors, that 4D CAD could be a valuable tool in legal claims and dispute resolution. Another issue that was expressed by contractor 2 was that software interoperability issues would make it difficult for 4D CAD models to reach their full potential. A detailed discussion of the results of the focus group discussions are presented in section 5.6.

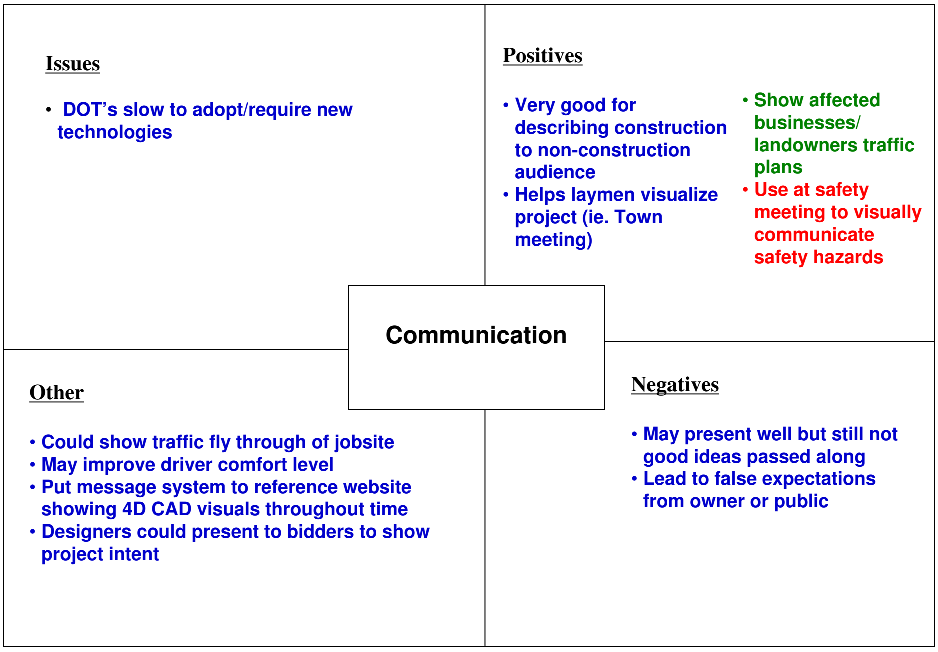

Figure 5.9. Communication Content Analysis

5.6 Discussion of Results

The discussion of the results aims to consolidate common ideas and opinions expressed by the highway construction professionals throughout the scaled questionnaire, open ended questions, and focus group discussions. These common themes collected throughout the research are supported by both the qualitative and quantitative data, and serve as a foundation for the conclusions put forth in this thesis. This section also includes other specific examples and quotations collected during the open ended question and focus group discussion that give valuable insight into 4D CAD for highway construction.

The discussion is broken down into four separate categories to maintain structure throughout this section. Section 5.6.1, starts by giving an overview of the general findings collected in this research, and offers insight into the overall opinions of the researcher and research participants. Section 5.6.2 discusses results related to planning and scheduling, section 5.6.3 discusses communication applications of 4D CAD, and section 5.6.4 discusses other miscellaneous results that do not fit into the prior categories.

5.6.1 General Discussion

The results gathered in this research suggest an overall optimistic view of 4D CAD for highway construction projects in the opinion of highway construction professionals. For example, the scaled questionnaire asked each participant to rank their perception of the benefit of 4D CAD for highway construction on a scale of 0 - 10, where 0 was no benefit and 10 was high benefit. The lowest average score returned on this questionnaire was 5.3, which shows that although this is not the best application of 4D CAD, there still is moderate benefit. No individual gave a zero response for any of the applications in question, showing that in all instances surveyed, the person saw at least some benefit in 4D CAD for highway construction.

The highway construction professionals all gave enthusiastic responses throughout the data collection and discussions in this research, and suggested many new applications and ideas that are worth exploration in future research. Much of the professional outlook was slightly skeptical of 4D CAD in the highway construction industry today, but could see the bigger picture of how this technology will apply to the future of their industry. All three contractors noted that the 4D models needed substantial improvement from the case study shown, but could be widely adopted once improvements are made. One research participant commented that *"4D CAD models are the next logical step"* in the progression of planning, scheduling and communication technology in the highway construction industry. This slightly skeptical, but positive outlook embodies the views expressed by all three contractors.

5.6.2 Planning and Scheduling

The data collected throughout this research shows that 4D CAD is beneficial for numerous planning and scheduling activities for highway construction projects. Specific examples and instances are discussed, and have definitive evidence of their importance in this research.

The results from the scaled questionnaire identified traffic phasing and detour scheduling as the most beneficial applications 4D CAD for planning and scheduling activities. This idea was supported throughout exercises 1, 2, and 3, and was reinforced in a quote from a focus group discussion where the vice president of contractor 2 says

"I see huge benefit any time you get a complex traffic control plan, it's usually because you have a complex phased construction. That's were I see this having the most benefit"

Contractor 2 points out that 4D CAD is extremely valuable in highway construction because often times the construction phasing plans are driven by the traffic patterns required throughout the construction project. Highways must maintain a consistent flow of traffic throughout construction to enable transportation across the area. This requires detailed traffic control planning to ensure the project operates smoothly and safely for both the contractor and traveling public. Several traffic control suggestions were also made in the open ended questions. In question 2, all three contractors suggested that traffic phasing would be valuable additional information that could be included into the 4D CAD model, and would help traffic planning and scheduling before the construction process. Also, in question 5, all three contractors responded that the most important aspect visually in a 4D CAD model was traffic maintenance. The importance of traffic modeling and sequencing in 4D CAD for highway construction is paramount to developing a beneficial 4D model. Suggestions throughout the data collection shows that this aspect of highway construction should be closely considered and included when developing a 4D CAD model for highway construction projects.

The scaled questionnaire ranks "developing a work zone plan" as the second most beneficial aspect of 4D CAD for highway construction projects, and "developing a construction process/workflow plan" as third. These ideas are similar, and are both supported by common comments expressed in the open ended questions and the focus group discussions. Contractor 3 stated in the focus group discussion that 4D CAD allows contractors to develop and confirm construction plans and work zone phasing visually, which can help identify problems that were omitted on the 2D drawings and Gantt chart. This is valuable because field work zone conflicts occurring cause delays in work, ultimately costing the contractors time and money. If these issues had been identified in a 4D CAD review, these conflicts may have been prevented. In the open ended questions, one participant noted that

*"If the 4D model shows **visually** a flaw in the sequence one time per project, it is successful."*

This quote sums up the importance of developing accurate construction plans and work zones, and highlights the value a 4D CAD model can offer for work zone planning.

Another benefit of 4D CAD in highway construction projects is in scheduling and schedule review. Highway construction professionals identified several applications of scheduling benefits in all three of the exercises, including superior understanding of scheduling logic, and easy detection of activity clashes. The focus group discussions suggested that 4D CAD can help the project team understand the schedule visually, and can get the everyone on the same page quickly. This is important for the general contractor because it is critical that he understand construction schedule intimately for each project. If 4D CAD can increase schedule understanding, it will improve the overall team performance and improve the project as a whole. Contractor 2 suggested in that this would be especially beneficial in design-build work because projects require careful scheduling for maximum performance. The tighter schedule deadlines and stricter penalties make 4D CAD ideal for planning and scheduling when working under these conditions.

The results of the focus group discussions also suggests some drawbacks and issues associated with using 4D CAD for scheduling and schedule review. Both contractors said that one drawback was that people such as subcontractors, owners, and internal personnel may reject the schedule shown in the 4D CAD simulation and prefer to do the work their own way. This is a difficult problem for the general contractor because the success of a project is highly dependent on proper execution of the schedule. If people do not agree with the 4D CAD schedule, it would not be valuable because it wouldn't represent the true field construction. This illustrates the need to get subcontractors and other parties involved in early schedule reviews of the model. This would improve the schedule quality and encourage long term planning before the project begins. Another drawback suggested by contractor 3 was that a 4D CAD model still requires a good schedule by a person with competent scheduling skills. The participant noted that a 4D CAD model was an outcome of a good schedule, and could not make a good schedule itself. This is an important point because the 4D CAD model is highly dependent on the project schedule. If the schedule is not logical for construction, than the 4D CAD model will not be valuable for schedule and schedule review. One participant from contractor 2 summarized this problem saying "garbage in, garbage out." This shows that a 4D CAD model should not be relied on for initial schedule development, but should be used as a tool to review and improve the original project schedule.

Other benefits of 4D CAD for highway construction when applied to planning and scheduling were in planning on-site equipment locations. Although equipment planning scored relatively low in the scaled questionnaire, several suggestions during the focus group discussions identified valuable situations in which 4D CAD could be used for planning equipment locations. One comment from contractor 2 was that a 4D CAD model would be valuable in selecting crane locations for bridge erection. This is a vital task in the success of any project requiring overpass bridge construction, and could be used to plan crane pad locations at different periods throughout the project. Contractor 2 also suggested that a spatial analysis could be done in the 4D CAD environment where the project team could determine how many cranes would be needed for a certain activity, and how close they would be at different points in construction. This could reduce cost by possibly eliminating one crane on the project. Another example of using 4D CAD for equipment planning was suggested by contractor 3, where using a model, the project team could test if certain machines could operate in different areas on the project. In some cases, grading cannot be done by a scraper because their is not enough space for the machine to turn around. Therefore, bulldozers are used to grade the area and the scrapers left idle, costing the contractor money. The project team could spatially test certain areas on the project and evaluate if a machine could or could not be used in that phase of the project.

The results from the scaled questionnaire shows that using 4D CAD for optimizing paving schedules was not one of the better applications of 4D CAD relative to the others surveyed. This is explained in a focus group discussion, where both contractors said that small, individual activities such as paving are not worthwhile to show because of their short duration. Often, paving crews come in on short notice, and can finish their work quickly without disturbing other trades. This means that scheduling around the paving crew is not as important as other larger crews. Longer duration activities, such as earthwork, where much of the project is dependent on that crew are much more beneficial to model in a 4D CAD simulation.

5.6.3 Communication

The research shows that 4D CAD is beneficial in numerous communication applications related to highway construction projects. In general, the highway construction professionals viewed these applications as more beneficial than the planning and scheduling applications surveyed throughout this research. In the scaled questionnaire, the communications questions scored an average 7.5, while the planning and scheduling questions scored a 6.5. The open ended questions and focus group discussions offer an explanation for why the communication applications are so beneficial, and how they can be used in the future of 4D CAD for highway construction.

The scaled questionnaire shows that highway construction professionals believed the most beneficial application of 4D CAD was for "communicating the design and construction plan to the public." This claim is supported in the open ended questions and focus group discussions, where substantial qualitative data exists to support this idea. In a focus group discussion, a quote from the president and vice president of contractor 2 describes their opinion of the communication applications of 4D CAD for highway construction.

President: *"I think [4D CAD] would be helpful for describing what your doing to a non construction audience. You could go to a town meeting, or some other people who don't understand construction, and visualize what your going to do."*

VP: "That's absolutely one of the biggest benefits."

This quote shows that in the opinion of a president and vice president of a highway contractor, with a combined 60 years of construction experience, how beneficial a 4D CAD model can be for communication. The open ended questions reiterated this idea when contractor 3 said that 4D CAD is a valuable tool to visually communicate how a job is built to a layman, such as the public.

The reason that communicating the design and construction plan to the public is so important is because highway construction projects directly effect the daily lives of the public. They are effected in several ways, each giving substantial reason why they should be cognisant of highway construction projects in their area. The first way that the public is effected by highway construction is that the highway facilities being built are for their use, and will be funded with their tax dollars. Highway construction projects are extremely expensive, and it is important for every construction project to be justified in the public eye. The public must believe that each project is going to improve their transportation system, and that each project is a worthwhile investment of their tax dollars.

This research shows that highway construction professionals believe that a 4D CAD model would be valuable for communicating a construction project to the public, and would ultimately give them a better understanding of the design and construction plan that they are paying for. In the open ended questions and focus group discussion, contractor 2 notes that the majority of the public does not clearly understand 2D drawings, making it difficult to communicate the construction plan. He says that

"I think it [4D CAD] would work very well...because it would lend great credibility to public input. People who don't understand construction phasing and can't just visualize how this is going to work...but if you take people out and you show them 2D plans then they can't understand it. If you just fly them through that [4D CAD model], they can say, oh you have to go do this, and this, and you show them where traffic goes so they can understand it."

This quote emphasizes how 4D CAD can give the public a "visual advantage" in understanding a project, and ultimately a superior understanding of the work when compared with the 2D design documents.

A second instance in which the public is effected by highway construction is when they must wait in traffic created during the construction phase of the project. This costs the traveling public time, money, and frustration, because they must wait in their car through lane closures and other traffic control measures. A 4D CAD model would be valuable in this situation because the traffic control plan could be communicated to drivers before they begin their travel. One suggestion from contractor 2 was that a message system could be put up as drivers approached a highway construction project that referred them to a specific website. This website would show a video of the 4D CAD model and alert drivers to upcoming traffic shifts in the road. This would give the public an increased awareness of shifting traffic patterns, and improve driver comfort through construction zones.

There were also some problems expressed by the contractors relating to the communication of construction plans using 4D CAD. Contractor 2 suggested that using a 4D CAD for a public or DOT presentation might lead to false expectations about the delivery of the project. Since highway construction projects are dependent on numerous external factors such as weather and permitting, it can never be guaranteed that a project will progress exactly how it is planned in the beginning of the job. Change order requests and other field issues during construction can effect start and completion dates of different phases of a project, and might differ from the 4D CAD model shown in the beginning of the project. This could cause confusion and anger from the public, and adversely effect the completion of a project. Another negative expressed by contractor 2 was that just because a 4D CAD plan looks good, doesn't mean that it is the best plan for a project. The contractor suggested that people may get easily convinced from a 4D CAD model because it presents well in a meeting, and looks impressive as a communication tool. This may cause people to be complacent in their constructibility review because they think it looks good, so it should work well.

One of the common issues identified by the research participants was that the 4D CAD model would have to be improved significantly to include more detail to communicate the construction plan. In the open ended questions, two out of three contractors said that utilities would need to be included in the model to better communicate a construction plan using 4D CAD. Underground and overhead utilities are extremely important factors in highway construction, and require thorough planning and communication between utility companies and contractors to be installed correctly. Contractor 3 also said that more surfaces must be shown in the 4D CAD model to make the presentations clearer. This is important because the 4D CAD model aims to communicate the field, design and construction conditions throughout a project, and should be as realistic as possible. The clearer and more realistic the 4D CAD model, the more effective it is as a communication tool.

5.6.4 Miscellaneous

This section discusses the miscellaneous ideas and comments collected throughout this research that give insight into 4D CAD for highway construction. There were several common ideas that were suggested by all three contractors, but did not fit into the previous two categories. This section discusses those ideas and why they were important in the opinion of the highway construction professionals.

The most common opinion expressed throughout this research was that 4D CAD technology is more useful for large scale highway construction projects, rather than smaller construction applications. In a focus group discussion, a quote from highway contractor 2 accurately summarizes this opinion.

"[4D CAD] depends on the project size though. I don't see a lot of benefit on a smaller scale...because you better have worked through in your mind the constructibility issues and your sequencing and your phasing. Now on a larger scale project, obviously you can get more benefit from it because there's a lot of longer duration processes. Usually as the contractor you have the flexibility that you can jump back and fourth, and determine your own sequencing."

This quote is valuable because it explains why 4D CAD is better for larger scale projects in comparison with smaller projects. The larger projects offer more flexibility to the contractor in developing their own construction plan, and require extensive critical thinking to lay out the project correctly. The larger projects are also typically unique, and do not have a standard construction plan that has been done countless times by the contractor.

The opposite of these large, unique highway construction projects are smaller construction applications, where a contractor may have done the same type of job hundreds of times. These smaller projects do not require intense planning because the contractors have extensive experience building them, and can be completed easily. This was the case in the Rt. 28 - McLearen Road interchange example presented in this research. Highway interchange projects are standard jobs for highway contractors, and may not need the planning, scheduling and communication benefits offered from a 4D CAD model. This opinion was expressed in a quote from contractor 2.

"For the job like you've shown, I couldn't see much benefit in it at all, it's a two half season job. For the end of the first year you know what your end paving date

is. From VDOT you know what phase you have to be completed by and a certain date. You have to be on that schedule, so it's already mapped out for you."

This makes an important point about the applicability of 4D CAD for highway construction. It shows that 4D CAD is much more beneficial in large scale highway construction applications, and should be used to plan unique, multi-phased construction projects.

The highway construction contractors suggested that a 4D CAD model would be a valuable tool for legal issues and dispute resolution. In the open ended questions, this idea was expressed by two thirds of the contractors when asked if they could think of any other beneficial applications of 4D CAD in highway construction. In a focus group discussion, the president of highway contractor 2 said:

"I think the area of litigation would be well served by this, whether your going to defend a claim or present a claim. If you laid out a plan and showed what interrupted your goal, you could present that pretty easily. Or if you were being brought into a claim, you could defend yourself."

Highway construction projects often encounter numerous problems on the jobsite that were unforseen in the beginning of the project. One common problem encountered in the field is differing site conditions, where the contractor finds something different on site than what was reported in the contract documents. This can halt field construction if the conditions pose an on-site danger, such as an unaccounted for gas line, meaning lost schedule time and unproductive man-hours that cost the contractor money. If the contractor cannot reach an agreement on who is going to take responsibility for the error, the dispute may end up in court. This is where the contractor could use a 4D CAD model to communicate the location, schedule impact, and overall effects of the problem encountered. This visual means of display would help the contractor communicate their problem with the judge and others who are not construction experts, giving everyone a better understanding of the dispute in question. This application of 4D CAD would be an valuable topic to explore in future research.

There were numerous drawbacks and logistical issues that were pointed out by the construction professionals surveyed in this research. These issues are important to discuss because they can help avoid pitfalls and false applications of 4D CAD in the future. The most common drawbacks identified by the highway construction professionals were directly related to each other, and are therefore discussed together. These issues were:

A. The amount of time required to develop a 4D CAD model, and

B. The level of detail required in a 4D CAD model.

These two issues are directly related because the higher the level of detail in the 4D CAD model, the more time must be spent while developing it. These two characteristics work opposite of each other in real world business, and may be difficult to balance in daily operations.

The first issue of time required to develop the model is important because highway construction companies are extremely critical of how their employees spend their time. The highway construction industry is fiercely competitive, and often driven by low bid project procurement. This means that each employee on a project must complete their work in a timely manner to stay competitive in the market, and any time wasted is money lost for the company. This means that anything that is not directly related to core project necessities is categorized as a secondary activity in day to day work, and does not get full attention. In order for a contractor to derive the full benefits from 4D CAD, they must make a significant commitment that model development is a project priority. This means that at least one person must be dedicated to model development, and construction teams must use the model to assist in their planning and scheduling of the job. If this is not the case, than the models will never reach their full potential within the company.

The second question regarding the level of detail of the 4D CAD model be made is important because it directly correlates with time spent on developing the model. The theoretical goal of a 4D CAD model is to show as high of a level of detail as is sufficient for the project. Although, this goal may be unrealistic in real world applications because of the time constraints placed on projects. Sometimes, a certain level of detail must be sacrificed for development efficiency. Finding the balance between these two factors is important, and will pose a challenge in the future.

5.7 Summary of Results

This chapter presented the results of the research performed for this theis, then discussed those results in detail. The results showed that in the opinions of highway construction professionals, 4D CAD was beneficial for both planning and scheduling applications, as well as communication applications. The research participants believed the communication applications were slightly more beneficial than the planning and scheduling applications, but overall were both helpful for highway construction.

Chapter 6

Discussion, Suggestions, and Improvements of 4D CAD in Highway Construction

This chapter discusses a number of the issues encountered throughout the 4D model development process. Each problem is identified, categorized, and described in order to effectively communicate each issue. Then, solutions and improvements are suggested on how these problems may be solved or avoided in future research applications.

6.1 Logical Issues

This section describes a number of the logical issues that were encountered throughout the 4D modeling process. These issues deal with problems related to the overall process of 4D CAD modeling, and the unique challenges posed by highway construction. Previous research has identified many of the logical issues of 4D modeling for buildings, but highway construction presents different challenges that must be addressed while developing a 4D model.

6.1.1 Linear Construction

Highway construction is a continuous linear process, which is characterized by a geometrically linear layout and no clearly identifiable units (Liu, W., and Flood, I., and Issa, R., 2005). This characteristic separates highway construction from other types of construction, and creates challenging problems in 4D CAD modeling for highway construction projects.

The problems presented in modeling 4D CAD for highway construction are rooted in the differing characteristics between highway construction and 4D CAD technology. Highway construction relies on continuous processes where no clearly identifiable units exist, such as earthwork. The implementation of 4D CAD technology in software applications, on the other hand, relies on showing discrete processes linked with clearly identifiable objects over time. This 4D time and object linking process corresponds well for building construction because buildings are composed of clearly identifiable units, such as columns and slabs. This is not the case in highway construction, because many of the objects cannot be clearly identified, and therefore cannot be linked with discrete schedule activities. This creates a conflict at basic foundations of 4D CAD modeling for highway construction projects, an poses significant challenges in future modeling applications.

To accommodate this issue, the underlying implementation of 4D CAD must be revised to represent highway construction projects. The 4D CAD model must use surfaces and objects together, instead of just objects as in building applications, to represent a highway construction project. The surfaces are used to represent the changing terrain of the project, and while the objects are used to show bridge structures and other clearly identifiable units. The surfaces must separated into small pieces representing discrete portions of work, such as in earthwork. These pieces of the project can then be linked to the construction schedule and simulated in the 4D CAD environment. This approach has been shown in a simple application for managing small cut and fill earthwork jobs (Yabuki and Shitani, 2005), but has not been applied in larger scale 4D CAD applications.

The solution of breaking the 4D CAD model into smaller pieces simulate continuous activities brings a new set of problems that must be discussed to properly model highway construction. These issues are best discussed in the context of a highway construction example, and are applied to an earthwork discussion below.

Modeling earthwork is a useful example for illustrating the conflicting characteristics of highway construction and 4D CAD technology. The problem is that earthwork is a continuous process of cutting, filling, and temporarily storing soil throughout the project duration. This continuous process of sculpting the land results in daily terrain changes in the project landscape, creating infinite scenarios that could be shown in a 4D CAD model. This would be extremely time consuming, and not possible for any real large scale application of 4D CAD. The solution to this, as suggested above, is to break down the work into quantifiable portions that can be linked to a schedule activity. This raises the next question of how can earthwork be broken down into manageable proportions, and still maintain visual fidelity in the 4D CAD model.

There are two approaches that can be considered when breaking down earthwork for a 4D CAD application. The first approach breaks the earthwork down by volumes, with corresponding schedule activities for each volume. The duration of the schedule activity would be calculated using the earthwork productivity rates from a particular company, by multiplying the volume (Cubic Yards) by the productivity rate (hr/CY or day/CY). This method gives the contractor the flexibility to choose volumes that they see fit to move together on a project, and allows them to separate the earthwork however he pleases. The second approach would be to separate the earthwork in terms of time. This means that volumes of earth would be separated by how much could be moved per unit time. For example, if the contractor wanted to show the progression of earthwork every five days in the 4D CAD model, the volume of earth could be calculated and shown on a week to week basis. This approach makes for a more schedule driven separation of earthwork in the 4D model because the volumes reflect unit times throughout construction. This is a more rigid method of separating the earthwork, and may not allow for the desired level of detail when separating the earthwork.

After modeling 4D CAD for highway construction, the better approach to separating earthwork in the researcher's opinion is by breaking the earthwork down by volumes. This method is better than breaking the work down by time because of the increased flexibility gained while working within the model. Separating the earthwork by volumes allows for a greater level of detail to be shown when needed, and less detail when not needed. This is valuable because some sections of a project may require intense planning in order to properly execute the activity, while other sections of the project may require little planning. This way, the modeler can spend more time focusing on the complex sections, and less time on the easier sections. The drawback to this method is that the modeler drives the schedule because the activities reflect how the the portions of earthwork are separated in the model. This is opposite in typical highway construction, where the modeler would have to show earthwork with respect to the schedule duration, and break up the work according to the activities detailed. Contractors would have to alter their method of scheduling, and work closely with the 4D CAD modeler to reach a functional medium.

6.2 Software

4D CAD modeling is highly dependent on the software applications used to develop the model. Each software application has unique features and challenges that must be considered throughout the model development process, making it difficult to coordinate functionality across software packages. Often times, challenging interoperability issues arise between programs, and must be solved to successfully develop a 4D model. This section describes the software issues encountered while developing the 4D CAD model used in this research, then gives some suggestions for each issue.

6.2.1 3D Model Development

A 3D CAD model is a vital ingredient for developing a 4D CAD model. The 3D model must be both geometrically and visually accurate to competently convey the design of a project. This requires the model to be developed under specific parameters to function properly in a 4D CAD model. The 3D model must account for how it will be linked with the schedule in the 4D CAD application, then separated accordingly. This requires careful planning throughout the 3D modeling process, and poses unique software challenges during its development.

The software used to develop the 3D model of the Rt. 28 - McLearen Road interchange case study was Autodesk Civil 3D 2007. Civil 3D (C3D) is an engineering design software intended for land development and highway design applications. In this research, C3D models were intended to stretch beyond their design capabilities to function in a 4D CAD environment. This was a challenging obstacle because C3D models were never intended to be used in 4D applications when developed by Autodesk. The underlying philosophies behind a C3D design model are very different than those of a 4D CAD model, and this made it difficult to adapt the C3D model for a 4D CAD application.

The difference between a typical C3D model and a C3D model that is being used in a 4D CAD application is that a typical C3D model is used for design management purposes while the C3D model being used in a 4D CAD model is for visual analysis and review. The objective of a standard C3D model is to facilitate dynamic design documents that are a function of the 3D model (Autodesk, 2007). This allows drawing modifications to be automatically updated in the contract documents, saving the designer time and effort because it eliminates manually updating each drawing. The visual appearance of the 3D model is not as important, and only needs to communicate the most basic parameters of a design project in the CAD environment. Figure 6.1 shows a typical C3D model, where visual fidelity is not emphasized.

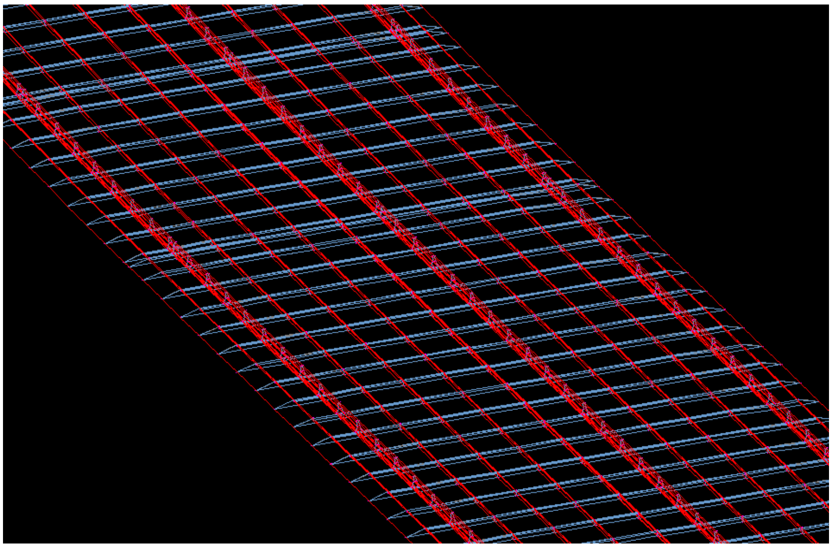

Figure 6.1. Typical Civil 3D Model

The objective of a 4D CAD model, on the other hand, is for planning, visual analysis and communication of a project with the project team and other related parties. The visual appearance of the 4D CAD model is extremely important because it is ***showing*** what is happening at a certain point in time on the project. This means that a 4D CAD model should include the maximum amount of detail possible to increase visual comprehension of the project. This disparity between visual appearance of a typical C3D model and a C3D model being used for a 4D CAD applications caused numerous problems that were critical to solve during the 4D CAD development process.

6.2.1.1 Segmenting Corridors

The most difficult problem encountered while developing the C3D model was that 3D corridor models could not be separated into smaller segments in the 3D CAD application. This is a problem because the corridors needed to be split up and placed on different layers to function properly in the 4D CAD model. A 4D CAD model relies on linking schedule activities with corresponding layers to simulate a construction schedule. Each layer has a specific piece of geometry assigned to it in the 3D CAD model, then is linked with its schedule activity in the 4D CAD program. The program runs the schedule from start to finish, turning the assigned layers on and off according to their linked activities to show the progression of construction. Therefore, the highway corridors must be separated in C3D and put on specific layers that will be linked with a schedule activity in the 4D CAD program. Unfortunately, this cannot be easily done in C3D. When a corridor is built in C3D, the ***entire corridor*** is placed on a single default layer that cannot be separated in Civil 3D. The corridor, including the cross sections, ditches, sidewalks, and any other features it may have are all placed on a single, permanent layer.

To illustrate this problem, lets use an example where a 1,000 ft corridor might need to be separated into 10 smaller parts to show a natural construction progression in the 4D CAD model. The 1000 ft corridor would be broken up into 100 ft stations (sta. 0+000 - sta. 0+100, sta. 0+101 - sta. 0+200, sta. 0+201 - sta. 0+300, etc.), then each 100 ft section would be placed on it's own separate layer in the 3D CAD model. These layers would then be linked with their corresponding schedule activity and simulated in the 4D CAD program. Although, this cannot be done because the 1,000 ft corridor built in C3D could not be separated into the smaller segments.

The solution to this problem is to build each highway segment as its own corridor. This makes it possible to assign different layers to each segment because each segment is now its own corridor, and separate corridors can be placed on separate layers. To illustrate this solution, lets refer back to the previous example where a 1000 ft corridor needed to be separated into 100 ft segments. In this example, each 100 ft segment would be built as its own corridor, instead of one large 1000 ft corridor. Each of these segments could be placed on their own layer, then linked with their corresponding schedule activity in the 4D CAD program.

Creating individual corridors for each segment does not appear to be the optimum solution for this problem, but it is the only way to do this in C3D 2007. Most notably, the biggest issue that this solution creates is that the C3D model becomes extremely segmented and difficult to keep organized throughout the model development. Single corridors might be broken down into 10 segments, each their own corridor. Therefore, it is important to label the corridor segments using a consistent method to keep the 3D model organized and understandable when it moves into the 4D CAD program. Another notable drawback to this solution is that it is extremely tedious and time consuming to create each segment as its own corridor. This requires patience and planning, which can become difficult throughout the modeling process. The best solution to this problem is to work with a powerful computer that can model corridors quickly and efficiently.

6.2.1.2 Managing Surfaces

Surfaces are an important feature in the 3D CAD model because they transform the appearance of the 3D model from simple lines and cross sections to actual 3D surfaces that can be used in a 4D model. These surfaces include construction barriers, pavement layers, ditches, curb and gutter, existing ground and other common attributes found in highway construction. The surfaces are also important because they act as the primary objects that are linked with the schedule activities in the 4D CAD model. The two biggest problems that the surfaces posed were the display properties required to function with the 4D CAD software, and the sheer number of surfaces contained in the model.

The most difficult problem dealing with the 3D surfaces was developing a method to maintain sufficient interoperability between the 3D CAD model and the 4D CAD program. The surfaces in the 3D model were of vital importance because they functioned as the primary geometric object that would be linked to the schedule activities in the 4D CAD program. Therefore, the surfaces needed to be organized and displayed so that they would appear consistently in the 4D CAD model, and could be linked with their corresponding schedule activities with ease. To do this, two specific measures were required to maintain interoperability between the programs.

The first measure required to maintain interoperability between the 3D CAD model and 4D CAD program was that each surface be a separate object on an identifiable layer that can be communicated to the 4D CAD program. This is important because when the 3D model is imported into the 4D CAD program, the surfaces must be identifiable in the selection tree so they can be linked to their schedule activity in the 4D model. The second measure required to maintain consistent interoperability between the models was that each surface appear as a solid object in the 4D CAD environment, instead of lines or contours. This is important because the surfaces must appear as realistic as possible to communicate the best portrayal of the project site. This allows the users of the 4D CAD model to gain the valuable insight and perspective while planning the job, giving them an accurate visualization of the project site.

These requirements were both met by developing original surface styles in Civil 3D. Surfaces styles are a feature in C3D that allows the user to define how each surface is displayed in the 3D model, such as major and minor contours, grids, triangles, points, elevations, flow arrows, etc. Different surface styles can be used for numerous engineering analysis purposes, and can be quickly changed to display different features of the model throughout the design process. In this application, surface styles were developed that placed the specified surface on an assigned layer and also made the surface appear as a solid when imported into the 4D CAD program. This solution worked extremely well, and easily organized surfaces to be imported into the 4D CAD program.

Original surface styles were created for many of the features in the 3D CAD model, such as barriers, curb and gutter, daylight, gravel, pavement, and others.

These original surface styles were created by right clicking the surface styles folder under drawing settings tab, and choosing new style, as shown in figure 6.2. The style was then assigned a name and description, and edited for display properties as shown in figure 6.3. Under the display tab, only the triangles were chosen to show the surface. This parameter made the surface appear as a solid when imported into the 4D CAD program, which is an important characteristic for visual purposes.

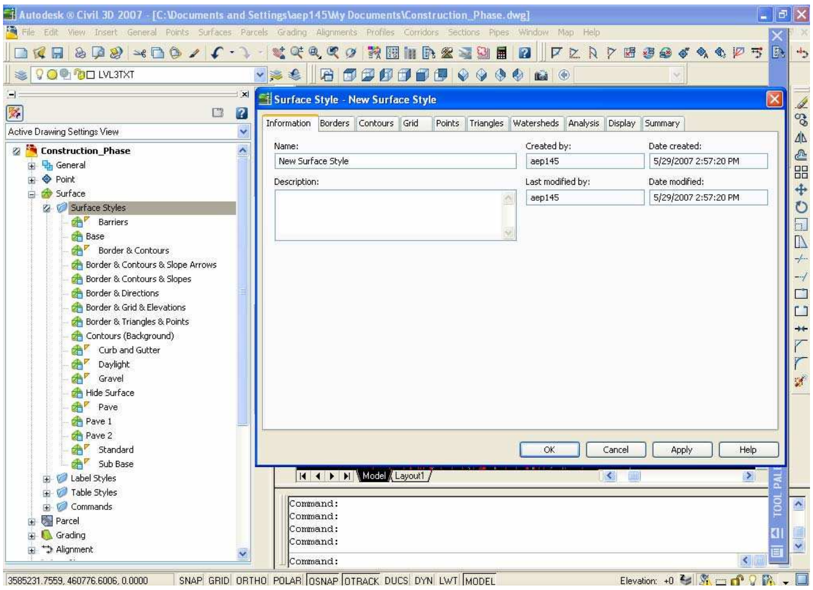

Figure 6.2. New Surface Style

Furthermore, the layer onto which the surface is placed is defined under the display tab. The layer that was selected was created specifically for this surface style, and was assigned the color that the surface will appear in the 4D CAD model, as shown in figure 6.4. Once surface styles were created for all features in the 3D CAD model, they were assigned to each surface via the surface properties of each surface, as shown in figure 6.5. Once each surface had been assigned the proper style, the 3D model was ready to be imported into the 4D CAD program.

Creating surface styles in C3D was an important development in the 3D modeling process, and significantly cut down on overall model development time. The surface styles streamlined the layering, coloring, and display processes required for interoperability with the 4D CAD program. If these parameters had not been defined in the surface styles, each surface would have had to be manually defined,

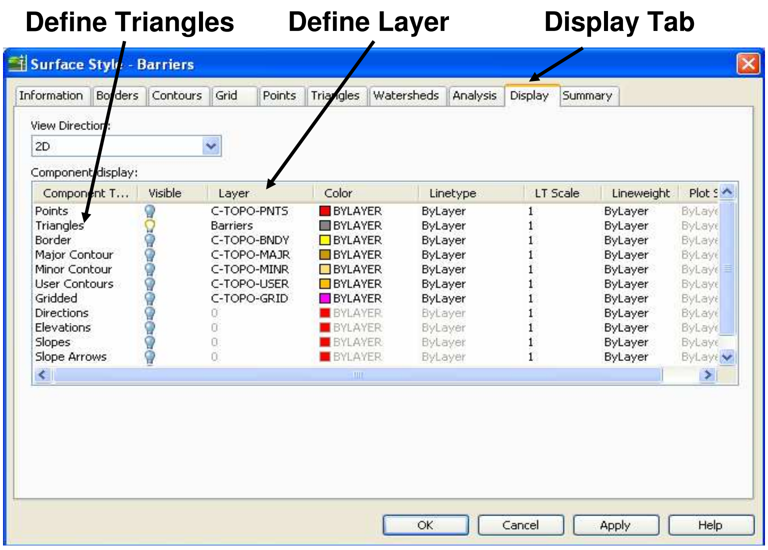

Figure 6.3. Display Properties Tab

which would have been a tedious and time consuming activity. The surface styles proved to be the biggest benefit in preparing the 3D CAD model to be imported into the 4D CAD program.

The second major problem with managing surfaces was that hundreds of surfaces were created to represent different highway attributes in the model. These surfaces made the model extremely large and difficult to manage, causing congestion in the 3D CAD model. The reason that so many surfaces were created was because each corridor required separate surfaces to be built for it individually, with each corridor needing at least 3 surfaces to represent its structure (sub-base, base, pave) in the CAD model. This problem was a result of the previous problem discussed, where larger corridors had to be separated into smaller sections by building smaller corridors. As the number of smaller sectioned corridors increased, the number of surfaces increased threefold. This caused excessive clutter in the model, making the surfaces difficult to track and maintain throughout the modeling process.

The solution to this problem was to maintain a strict methodology for naming the surfaces, and eliminating any unneeded surfaces in the model. This allowed the surfaces to be tracked by referencing their parent corridor and surface name,

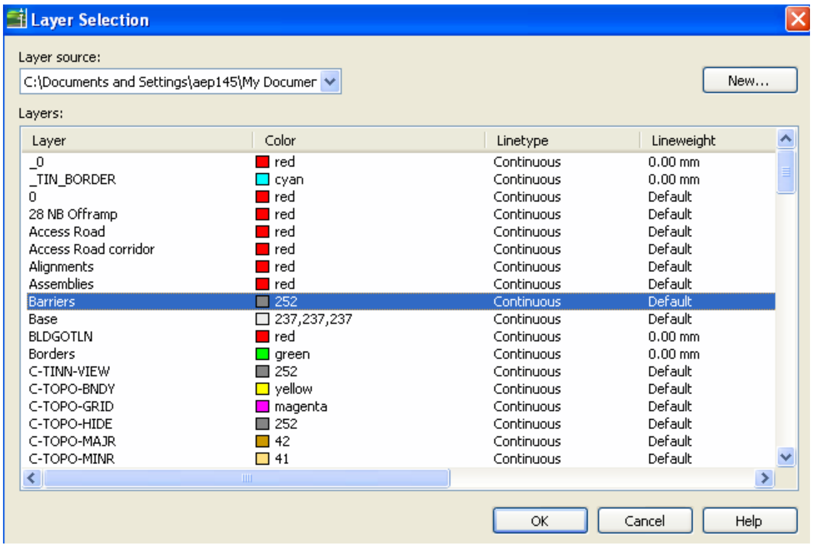

Figure 6.4. Display Properties Tab

and was the best method for maintaining organization within the model.

Other problems that were encountered with the 3D CAD surfaces also posed difficulties that could not be solved throughout the model development process, and must be more closely considered in future applications of 4D CAD in highway construction. One problem was that certain surfaces could not be created in the C3D model, such as the ditches and fill, as shown in figure 6.6. This is a significant drawback because it reduces the visual fidelity of the model, making it look less realistic in the 4D environment. Another problem was that for certain objects, such as curb and gutter, only the top surface would be built. The rest of the object, such as the sides and the bottom remained empty space, as shown in figure 6.7. These two issues presented challenges that could not be solved, which may be because of software bugs or operator error. In either case, future development will show improved tools that will hopefully decrease these types of problems.

Overall, the surfaces posed some difficult problems throughout the development of the 3D CAD model. These problems required time consuming solutions, and proved to be an extremely frustrating aspect of the 3D modeling process. Other issues proved to be too difficult to solve given the time constraints, and must be more closely considered in future applications of 4D CAD for highway construction.

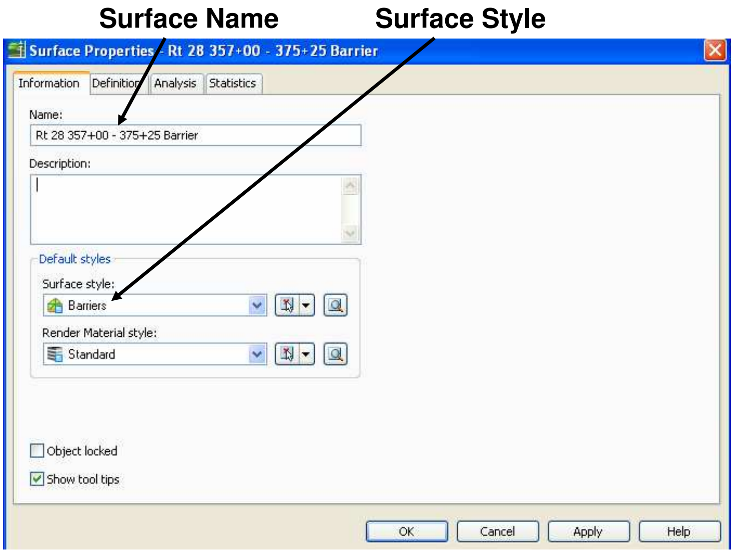

Figure 6.5. Defining Surface Style

6.2.2 4D Model Development

Developing the 4D model was one of the most important activities completed in this research. The model was used as the primary example of a 4D CAD application for a highway construction project, and was the focal point of the opinions expressed by the highway contractors surveyed in this research. The overall 4D development process was significantly easier than the 3D development process, and had only a few flaws that needed to be solved to realize a working model. It is also important to understand that Navisworks does not have any CAD functionality, and cannot be used to move or draw new objects in a 3D CAD model. This makes the software rigid in that the 3D CAD model must be formatted properly before it is imported into Navisworks, because the model cannot be edited once the files have been imported. This is the reason that the majority of software challenges were in the 3D modeling phase, because Navisworks has a specific format that information must be input, offering no flexibility in how this is done.

The software that was used to develop the 4D model was Navisworks Jetstream V.5 with timeliner. The primary function of this software was to provide an environment where the 3D CAD model could be linked with the project schedule, then simulated to show the construction progression. This software also provided

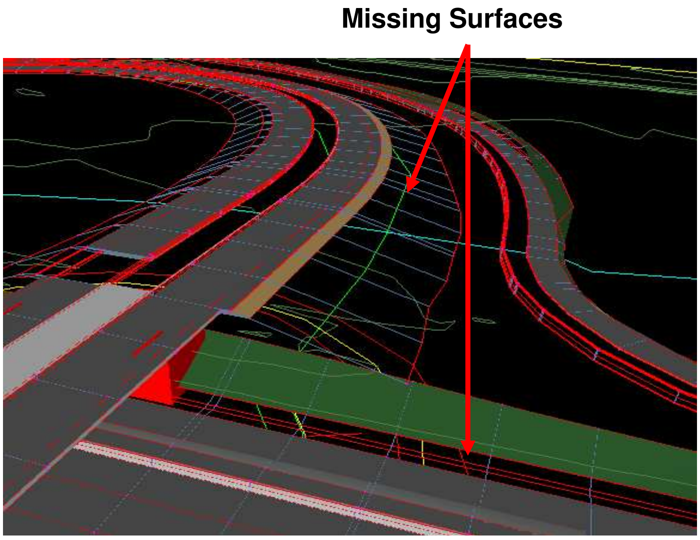

Figure 6.6. Missing Slope Surfaces

an environment to navigate the model, giving a good view of the project site while performing the research.

6.2.2.1 Surface Proximity Conflict

The only major problem encountered throughout the 4D development process was that surfaces that were in close proximity to each other in the 3D model visually conflicted once imported into the 4D environment. This visual conflict made the close surfaces appear as inconsistent colors, as shown in figure 6.8. The reason that some surfaces were so close to each other in the 3D CAD model was because of the pavement design of the Rt. 28 - McLearen Road interchange project. The cross-sectional structure of the road consisted of five layers of materials, including sub-base, base course aggregate, base pave, intermediate pave, and surface pave layers. Each layer was built as a surface in C3D so that each could be linked with its corresponding schedule activity in the 4D CAD model. This close proximity of the pavement layers caused a rendering conflict in the 4D CAD environment, and needed to be solved to develop a visually believable 4D model.

The solution to this problem was to delete all of the pavement surfaces in C3D except the top pavement and sub-base layers. These two layers had significant sep-

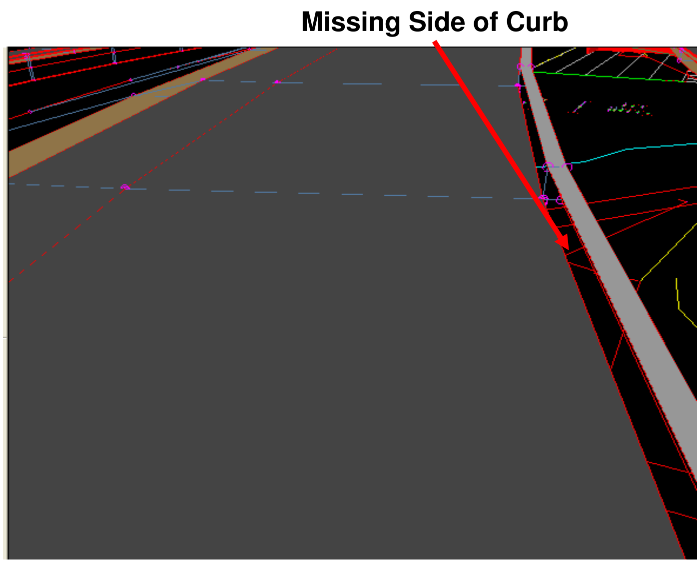

Figure 6.7. Missing Curb Surfaces

aration so that their colors did not conflict. Then, to show the different pavement layers in the 4D CAD model, the top pavement surface was highlighted different colors throughout the simulation to represent different pavement levels. For example, when the base pavement activity occurred, the surface turned dark red for the duration of the activity to symbolize that it was being performed. When the intermediate pavement activity occurred, the same surface turned pink, and when the surface pavement occurred, the surface turned yellow. Figures 6.9 and 6.10 give an example of the same surface showing different paving activities. This was a suitable solution because the viewers of the 4D CAD model could not distinguish the difference between layers in the model, so one surface turning different colors did not confuse them throughout the presentation of the 4D CAD model. This solution also worked because an object (i.e., the surface) was able to have more than one activity assigned to it in the 4D model, and did not create any problems within the software.

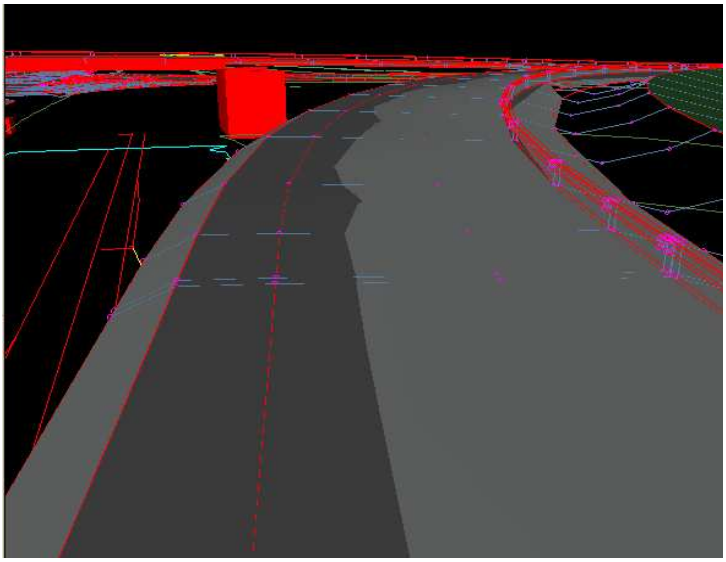

Figure 6.8. Close Surfaces Conflict in Navisworks

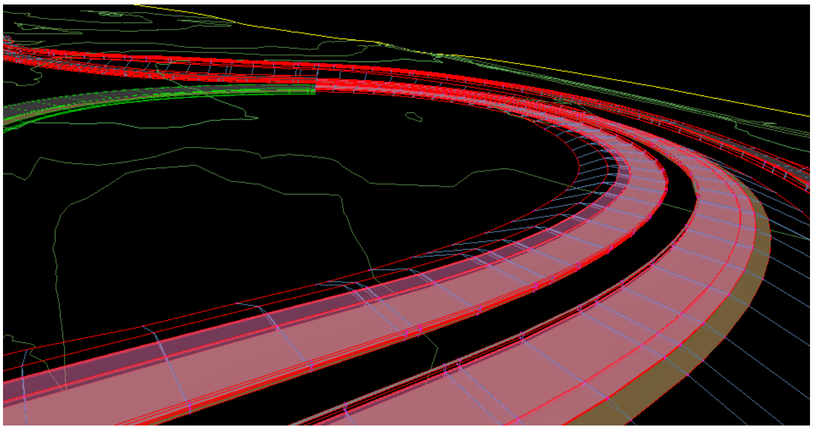

Figure 6.9. Intermediate Asphalt Paving

6.3 Miscellaneous

This section briefly discusses some of the other issues that were encountered throughout this research, but did not fit into the two previous categories of discussion. These issues are important to mention because each had a significant effect on the overall research, and should be considered in future research. This section will focus on the two most pertinent issues throughout this research, the

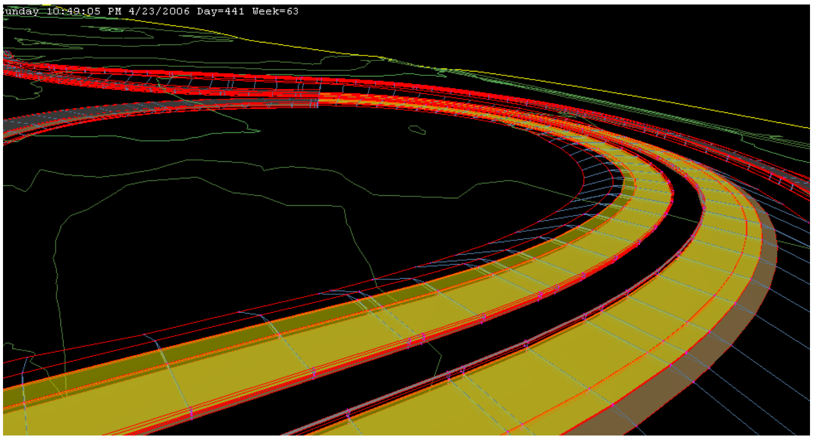

Figure 6.10. Top Asphalt Paving

construction schedule quality and the 4D CAD viewing environment.

6.3.1 Schedule Quality

The construction schedule is an extremely important ingredient required for developing a 4D CAD model. The schedule dictates how the construction activities will progress, and serves as the linking items that are associated with the 3D CAD model geometry. The schedule must be logical and precise, with the activity durations, start dates and completion dates clearly defined for the duration of the project. It is vital that the schedule clearly lay out an overall construction strategy that can be realized throughout the field construction process.

This was not the case with the construction schedule that was received for the Rt. 28 - McLearen Road case study project from the general contractor. The schedule for this project was extremely confusing, with numerous activities having 100+ day durations. The schedule did not convey any clear construction plan, and only gave general insight into the activity sequences and durations. The reason that this schedule was so confusing was because it had been developed for payment purposes between the general contractor and the DOT, and was not intended for detailed analysis in a 4D CAD model. Often times, a highway construction company will develop two separate schedules for a construction project. There will be one schedule that is given to the owner for payment purposes, and one schedule that is kept internally for the project team. The schedule that is given to the owner is typically very general, with long activity durations and extended float times. This allows the construction company increased flexibility throughout the construction process because the owner cannot exactly identify the site progress relative to the construction schedule activities. The construction company can then front-load the progress payments for work activities to ensure sufficient funds for any unexpected costs in the future of the project, and to receive the payment as early as possible. The internal construction schedule, on the other hand, is more detailed than the owner schedule because it is used by the project team to track activities on site throughout the construction project. This detailed schedule would have been much more useful for the 4D model development, but was not obtained for this project.

The solution to not having an understandable construction plan shown in the schedule was to talk to the project manager, and have him explain the construction schedule and site plan in more detail. In a phone call, the project manager gave valuable insight into the site phasing and schedule progression that was carried out in this project, and helped make sense of the otherwise confusing schedule. The 4D CAD model was developed using the phasing and progression described by the PM, along with the schedule activities and their durations given in the schedule. In the final 4D model, the schedule needed to be slightly reworked to accommodate the project managers description, but overall gave an accurate portrayal of the construction progression according to the general contractor.

The best solution to this problem would be to obtain the internal, more detailed construction schedule that was developed by the construction company for team use. This schedule would be much more insightful for developing the 4D CAD model, and would save time and effort in understanding the schedule. In future 4D CAD research applications, it should be a priority to obtain a detailed schedule, instead of a generalized owners schedule.

The second issue with the schedule was the long duration of numerous activities, especially the earthwork operations. The reason the earthwork operations were so long was because earthwork is a function of a cut/fill balance calculation that is done before a project is started. The objective of this calculation is to balance and optimize the usage of cut and fill on a project, and to minimize the haul distance of dirt around the site. Often times, earthwork requiring fill will be done slowly throughout the project, as cut materials accumulate from other areas of work. This is due to the earthwork balance of the project site, and is less a function of the schedule durations. This is especially true on flat sites, such as the Rt. 28 - McLearen Road site, where the cut/fill balance was extremely tight on the project. A ramp may have a 150 day slope work duration because it may take that long to create enough fill to finish the ramp. Even though actual work is not happening on that ramp for all 150 days, it will take that long to generate the required fill to build it.

The solution to this problem was to show the long duration earthwork activities as a green wire frame, as shown in figure 6.11, and alert the construction professionals to this issue before viewing the simulation. This solution was sufficient for this research because the construction professionals could empathize with this issue, and could therefore understand why this problem would occur. This would not be the case in future applications where a 4D model was presented to a non construction audience. Showing a green wire frame to represent earthwork would not be an optimal solution to this problem, and must be further investigated to determine a better approach in future applications.

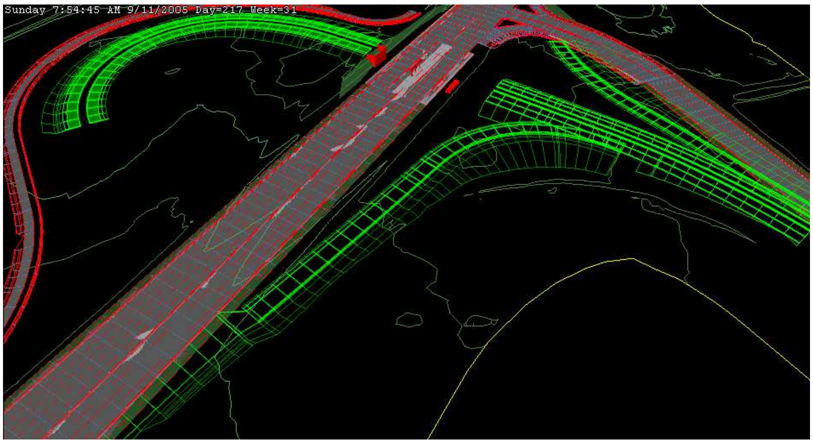

Figure 6.11. Green Wireframe Representing Earthwork in 4D CAD Model

6.3.2 Viewing Environment

The display technology used to present the 4D CAD model can have a significant impact on the research participants in the study, and therefore must be discussed in this thesis. The 4D CAD viewing environment is an important consideration because it is the primary interface between the 4D CAD model the research group (Otto et al., 2005). Since much of the benefit of 4D CAD is from the visual evaluation of the model, it must be presented using the best means possible to effectively communicate the model information. There are many different types of viewing environments that can be considered when displaying 4D CAD models, such as a computer monitor, a single projector, a three screen immersive virtual environment, and a cave automatic virtual environment. Typically, the larger, more lifelike immersive projection environments give an increased benefit in viewing 4D CAD models, and would be ideal for this research. Unfortunately, this was not possible due to logistical reasons throughout the research. Instead, the 4D CAD model was presented using a single screen projector linked to a laptop computer that hosted the 4D CAD model and accompanying software. The projector displayed the 4D CAD model on a pull down white screen in the front of the room, with the typical dimensions of 6 ft wide by 4 ft tall. The research participants each sat at a table and viewed the 4D model from their seats.

The reason that this research was performed using a single screen projector as the primary viewing environment was because the data collection had to be done on site at the highway contractors offices. This was the only way that enough people could be gathered for the research, considering the schedules of the highway construction contractors surveyed. These contractors were extremely busy with their day to day business, and could only give two hours for the exploratory research performed in this thesis. Ideally, the highway contractors would have traveled to Penn State for the data collection to be performed using a three screen immersive virtual environment. This would have been the best option for viewing the 4D CAD model, but was not logistically feasible due to the time restrictions of the participants.

In the future, it would be beneficial to use a better viewing environment for the 4D CAD research. A larger, immersive environment might improve the opinions of the highway construction professionals, and give them better insight into 4D CAD for highway construction.

6.4 Summary

This chapter discussed numerous issues that were encountered throughout the research performed for this thesis. These issues included logical conflicts between highway construction and 4D CAD, software interoperability problems, and other obstacles that posed challenging issues that had to be solved to complete this research. The best suggestions and solutions were presented to the problems faced throughout the research process, and reflected one method of how to solve these problems. These methods may not be the best solution to each problem, and should be further explored in future research. Overall, this chapter can help future researchers gain a perspective into 4D CAD modeling for highway applications, and avoid similar pitfalls that were stumbled upon in this research. There is still significant room for improvement, and future research is required to further the applications of 4D CAD for highway construction projects.

Chapter 7

Conclusion

This chapter presents the final conclusions that were determined from this research project. The chapter begins by giving a brief summary of the research performed for this thesis, then describes the significant research contributions put forth in this work. The limitations of the research methodologies are then discussed, and future research suggestions are made. The chapter concludes with some final observations and remarks about the research, and how it applies to future research efforts.

7.1 Research Summary

The research presented in this thesis investigated the best applications of 4D CAD for highway construction projects. This was investigated using exploratory research methods to collect the views and opinions of seventeen highway construction professionals from three different highway construction companies. Based on their insight, it was determined that 4D CAD is a beneficial tool for both planning and scheduling activities, and communication applications in highway construction projects.

The benefits of 4D CAD for highway construction projects were proven using two experiments performed in this research. The research was performed by first showing highway construction professionals a 4D CAD model that simulated the construction of a highway interchange project in Northern Virginia. After they were shown this model, a scaled questionnaire, open ended questions, and focus group discussions were performed to collect their reactions and opinions of 4D

CAD for highway construction. The scaled questionnaire collected the perceived benefits of different applications of 4D CAD for highway construction from highway construction professionals. The applications were categorized into two general categories that were identified as beneficial applications of 4D CAD in previous research. These categories were planning and scheduling uses and communications applications. The open ended questions and focus group discussions collected qualitative data that was used to support the research participants responses from the scaled questionnaires. These exercises gathered written and oral responses from the highway construction professionals that gave further insight and explanations of their opinions expressed into the scaled questionnaire. This was done in exercise 2 by asking open ended questions that encouraged written responses from the research participants. These open ended questions allowed the contractors to explain their opinions in writing, and gave better detail about their thoughts regarding the best applications of 4D CAD for highway construction. Qualitative data was collected in exercise 3 by recording focus group discussions between the highway construction professionals. This open exchange of ideas allowed the participants to express their views and ideas in an informal conversation format. These conversations were then transcribed and analyzed using the content analysis technique.

The results of the research performed in for this thesis produced data showing that 4D CAD is a beneficial tool for highway construction applications. The scaled questionnaire yielded quantitative data indicating that 4D CAD was beneficial in both planning and scheduling and communications applications for highway construction. The survey showed that in the opinions of the highway construction professionals, 4D CAD has slightly more benefit in communication applications than in planning and scheduling applications, but overall was good for both. The questionnaire also showed that out of the thirteen applications that were surveyed, all were perceived as at least moderately beneficial for highway construction. The results from the open ended questions and focus group discussions reinforced the the findings in the scaled questionnaire, provided quantitative data that further explained the findings. For planning and scheduling applications, the contractors highlighted the benefits of developing traffic plans using the 4D CAD model. This was important because highway construction is often constrained by the traffic control plan, making it vital to carefully plan and schedule the project so it coordinates with the traffic plan. They also were enthusiastic about the benefits of using 4D CAD for construction process and work zone planning. For communication applications, the contractors focused on the benefits of using a 4D CAD model to visually describe and communicate a construction plan to a non-construction audience. This was important because often times it is difficult to describe construction sequencing and traffic control measures to the general public, who are funding and driving through the project. The contractors also identified some miscellaneous applications and issues related to 4D CAD modeling for highway construction. One application that was suggested was using a 4D CAD model for legal cases and dispute resolution. This would be beneficial because it could ***show*** exactly where the contractor was at a specific time in the project, and visually describe the site condition to the judge or other decision making party in the dispute. The contractors also emphasized the importance of project size when using 4D CAD for highway construction. It is more beneficial to use a 4D CAD model for larger, more complex projects as opposed to smaller, more common projects because the larger projects require intense planning and scheduling to successfully execute the construction.

This research also investigated some of the challenging issues that were encountered in 4D CAD modeling for highway construction. These issues were divided into three general categories: logical issues, software issues, and miscellaneous. The logical issue that presented the biggest challenge was the divide between continuous linear construction used for highway applications and finite elemental construction used by 4D CAD programs. The solution to this problem was to divide highway construction into discrete objects that can be linked with the project schedule in a 4D CAD environment. The software issue that posed the biggest challenge was developing a 3D CAD model that could be imported into a 4D CAD application using Autodesk Civil 3D. This was difficult because Civil 3D was never intended to be used for developing 3D CAD models that could be used in a 4D application. The solution to this problem was to break up C3D corridors into smaller segments representing a single portion of work, and create surfaces to give the model a more realistic appearance. This allowed the 3D model to be linked to a project schedule in Navisworks using the corridor segments and surfaces as objects that were linked to the schedule activities. The miscellaneous issue that created the biggest problem while developing the 4D CAD model was the lack of quality in the schedule for the case study project. This problem highlighted the importance of a logical, quality schedule required to develop an effective 4D model. The short term solution to this problem was to talk to the project manager about the job sequencing and layout, then interpret his explanation and develop the schedule accordingly. The better, more long term solution was to emphasize the importance of a detailed project schedule that could be easily integrated into a 4D model. This would streamline the 4D development process and reduce confusion during model development.

7.2 Research Contributions

There has been little research that has studied the potential applications and benefits of 4D CAD for highway construction projects. Therefore, this thesis intended to investigate the best applications of 4D CAD for highway construction projects. This was done by surveying highway construction experts with an intimate knowledge of the highway construction industry, because they could offer the best insight into the value and possible benefits of 4D CAD in their industry. The research concluded that 4D CAD is a beneficial tool in highway construction projects, and should be further investigated in future research applications. This thesis serves as evidence that the topic of 4D CAD for highway construction should be further researched, and lays the groundwork for future efforts in this area.

This section discusses the research contributions that were developed in this thesis. These contributions are important because they provide a justification for future research in this area, and can be used as a starting point for future research projects. These findings define the current state of 4D CAD research today, and how it may be furthered in future research efforts.

7.2.1 Benefits of 4D CAD for Highway Construction Projects

The benefits of using 4D CAD for highway construction projects are described here.

- ***Communication Applications:*** 4D CAD is a beneficial tool for communication applications in highway construction. These applications scored an average of 7.5 out of 10 when ranked on their benefits for highway construction purposes. The best application of 4D CAD was for communicating construction information to a non-technical audience, such as the general public in a town meeting.

- ***Planning and Scheduling Applications:*** 4D CAD is a beneficial tool for planning and scheduling applications in highway construction. These applications scored an average of 6.5 out of 10 when ranked on their benefits for highway construction purposes. The best application of 4D CAD for planning and scheduling activities was for traffic planning and phasing.

- ***Other Applications:*** 4D CAD is a beneficial tool for other applications in highway construction, such as legal issues and dispute resolution. These applications were identified as additional benefits by the contractors surveyed in this research.

7.2.2 Issues in 4D CAD for Highway Construction Projects

Some of the issues and problems identified for 4D CAD for highway construction projects are listed here.

- ***Project Size:*** The most common issue identified throughout this research was that 4D CAD should be used for large scale, heavily phased highway construction projects, instead of smaller, more common projects.

- ***Logical Issues:*** The most difficult logical issue that must be accommodated in 4D CAD applications is the divide between continuous linear construction used to describe highway work and discrete object construction used by 4D CAD programs. This can be done by dividing highway construction into smaller, discrete objects that can be linked with their schedule activity.

- ***Software:*** The most difficult software issue identified in this research was the difficulties encountered in developing a 3D CAD model for a 4D CAD application. The 3D CAD software was not intended to develop 3D models that would be used in a 4D CAD application, and needed significant modifications to create a functional 4D prototype.

- ***Miscellaneous:*** The most important miscellaneous issue that was identified in this research was the importance of a quality construction schedule. The schedule used for the 4D application must accurately reflect the construction plan, and logically link with the 3D CAD model in the 4D environment.

7.3 Limitations

This section addresses a number of the limitations that apply to this research.

7.3.1 Case Study Limitations

Exploratory research methods were selected for this project because of the lack of knowledge on the topic of 4D CAD for highway construction projects. It was decided that a detailed look into a single example of 4D CAD for highway construction would give the most valuable insight into this topic, and serve best for future research efforts.

The case study presented in this research represented a single application of 4D CAD for highway construction projects. This does not sufficiently represent all types of highway construction, but indicates that similar results would be collected if a different application were shown. The case study excluded many important highway features and activities that play an important role in highway construction, such as the underground and overhead utilities, earthwork, and environmental and sediment control measures. Each of these items are necessary while shaping a construction strategy, and must be included in future 4D applications to gain a more complete understanding of this technologies role in highway construction.

The case study was a rudimentary application of 4D CAD for highway construction, and did not give the best example of how this technology might be leveraged in future applications. The model gave the research participants a basic example of what a 4D CAD model for highway construction might look like, but left them to speculate on the potential benefits of 4D CAD with an improved model.

7.3.2 Research Group

This research surveyed a total of seventeen highway construction professionals from three different companies on the east coast of the United States. This is a small group of people to represent the entire highway construction industry, and needs further investigation using more participants to gain better insight into the overall attitude of the industry towards 4D CAD for highway construction. The research participants views and opinions of 4D CAD for highway construction indicated that other highway construction professionals will express similar views, but this cannot be proven from this research. Future research should investigate these opinions on a national level, using a statistical approach to more accurately capture the opinion across the US.

7.3.3 Software Limitations

Many of the issues, discussions, and suggestions expressed in this thesis are specific to the software applications used during this research. This limits the applicability of some of the content presented throughout this thesis because it may only apply to these specific software applications. Other CAD packages may offer better options for creating 3D and 4D CAD models, and should be further investigated in future research efforts. This thesis describes one method to create a 4D CAD model for highway construction applications.

Some of the 3D software limitations were due to the 3D CAD program being slow and unstable throughout the modeling process. The 3D CAD model was slow because of the large amount of surface data contained in the model file. The corridor and surface data were large sets of TIN data that was difficult to move and rotate in the C3D environment. This often caused the computer program to crash, causing loss of work and frustration throughout the process. The 3D model was also limited by the features included in the C3D highway elements catalog. If the feature was not contained in the catalog, it could not be added to the 3D model, such as a fence.

One limitation of the 4D CAD software was that linking a 3D CAD model to the project schedule required a sufficient amount of manual labor. It would be better if this could be automated in a future software application.

7.4 Future Research

4D CAD for highway construction is still a largely unexplored subject that has many issues that should be investigated in future research. The following outlines a number of these research topics that would be valuable to clarify in future research efforts.

7.4.1 Further Define the Benefits of 4D CAD with Interactive Experiments

Future research should further define the benefits of 4D CAD for highway construction projects using measurable metrics for planning and scheduling and communication applications. This thesis defined numerous beneficial applications of 4D CAD for highway construction, but did not explore any interaction between the contractors and the 4D model. It would be valuable to perform experiments with the highway construction team interactively using a 4D CAD model for planning, scheduling, and communication before a project has begun in the field. This would quantify the measurable effects of where and how 4D CAD helped for planning, scheduling and communication, and would give more insight into the benefits of 4D CAD for highway construction.

7.4.2 Modeling Earthwork

Future research should investigate methods for modeling earthwork for 4D CAD applications. This idea presented a difficult dilemma in this research because the continuity of earthwork activities did not work with the finite object simulation of 4D CAD technology. A better solution than dividing the earthwork into discrete objects, as suggested in this thesis, must be developed to sufficiently model earthwork activities in future 4D applications.

7.5 Final Remarks

The future of 4D CAD in the highway construction industry looks promising as computers and technology play a more integral role in project delivery. New software and faster, more powerful computers will improve the capabilities of 4D CAD in the future, allowing this technology to reach its full potential in highway construction applications. Sometime in the future, a 4D CAD model will be an inexpendable asset for a highway construction project. The model will be used from the design development phase of a project, to the planning and scheduling phase, to the field construction of the highway facility. The model will serve as a centralized database for management and communication throughout the project life cycle, clearly and efficiently organizing project data into a single source stored in a database. It is vital that the highway construction industry continue to adapt and integrate new technology into their businesses, and fully realize the benefits of technology into the future.

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