EFFECTIVENESS OF 4D CONSTRUCTION MODELING IN DETECTING TIME-SPACE CONFLICTS ON CONSTRUCTION SITES

A Thesis

by

NARENDRA S. NIGUDKAR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2005

Major Subject: Construction Management

EFFECTIVENESS OF 4D CONSTRUCTION MODELING IN DETECTING TIME-SPACE CONFLICTS ON CONSTRUCTION SITES

A Thesis

by

NARENDRA S. NIGUDKAR

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Co-Chairs of Committee,	Julian H. Kang
	Kenneth F. Reinschmidt
Committee Member,	Neil N. Eldin
Head of Department,	James W. Craig

August 2005

Major Subject: Construction Management

ABSTRACT

Effectiveness of 4D Construction Modeling in Detecting Time-Space Conflicts on Construction Sites. (August 2005)

Narendra S. Nigudkar, B.E., Pune University

Co-Chairs of Advisory Committee: Dr. Julian Kang
Dr. Kenneth F. Reinschmidt

This research investigated whether 4D construction model effectively helps project participants on construction sites in detecting time-space conflicts in the schedule. Previous researchers on construction space management typically modeled space requirements for equipment and paths for material and focused primarily on static or dynamic layout planning. Some researchers regarded time-space conflicts as an essential aspect of construction space management. They demonstrated the use of 4D modules in time-space conflict analysis. Although these 4D prototypes have been successful in tackling time-space conflict analysis, they have been validated with only post-hoc analysis of construction projects. Also, various currently commercially available 4D visualization softwares do not take into account the workspace required during the construction of a component unless space is modeled as a separate component into the CAD application. Therefore, without modeling space as a component in the 3D model it is necessary to assess whether 4D visualization can be effectively used on construction sites to detect time-space conflicts in the schedule.

In order to fulfill the research goal an experiment was conducted. A 4D construction model of an ongoing project was developed.

Project participants were introduced to two different graphic representations of the schedule; namely, an overlay drawing - the conventional method used on site to detect conflicts and the 4D construction model. Analysis of the results compared the performance of the participants in detecting time-space conflicts in the schedule using the two methods.

The experiment produced empirical evidence that a 4D construction model may be effective on construction sites in detecting time-space conflicts in the schedule.

Dedicated to…

Family and Friends

ACKNOWLEDGEMENTS

I would like to express my gratitude to all those without whose help this thesis would not have been possible. I would like to thank Mr. James Barrett and Mr. Andy Tandon of Turner Construction Company and Mr. John Robertson of RWS Architects for allowing me to conduct this research on their construction project.

I am thankful to my family and friends from whom I received strong support and encouragement.

I am deeply indebted to my committee members for their valuable guidance. Dr. Kang introduced me to the 4D world and taught me the method of research. Dr. Reinschmidt showed me the pitfalls and gave direction to my research. Dr. Eldin showed me how to organize and plan my research.

And last, but not the least, I would like to thank my friend Mr. Jong Kwon Min, who helped me develop the 4D model for my research.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

In construction scheduling, a project is broken down into identifiable work packages to build a logical network among these work packages. By studying drawings, planned resources, site conditions etc., the scheduler identifies activities and develops their sequence relations. The entire complex information of the building cycle is illustrated using Critical Path Method (CPM) networks (McKinney et al. 1996). While determining the project schedule, the planner also has to take into account the workspace logistics and how the space will be utilized by labor, material, and equipment (Chau et al. 2004). But CPM networks represent the project schedule abstractly and do not convey the assumptions for the precedence relationships between activities (Koo and Fischer, 2000). Space requirements for labor, material, and equipment are addressed separately by preparing site layout plans (Chau et al. 2004). Thus, CPM networks are self-explanatory in describing only the temporal relationships between activities, but inherently discrepant in describing the spatial relationships between activities. This inconsistency in CPM networks is likely to cause spatial conflicts in construction schedules. The process for detecting such conflicts within the construction schedule may demand sound experience and judgment from a constructor in reading two-dimensional drawings, visualizing the structure in mind, and linking that with the schedule information provided by the CPM network (Kang 2001).

This thesis follows the style of the *Journal of Construction Engineering and Management.*

Novice constructors, in comparison with experienced constructors, may find it difficult to interpret the construction schedule by this method and hence are more likely to allow spatial conflicts pass undetected in construction schedules.

The latitude for errors in the schedule might be reduced if the construction sequence can be depicted visually. Four-dimensional (4D) visualization in which 3D components are linked to corresponding activities in the schedule may be an effective tool in communicating the schedule visually to project participants. Researchers have demonstrated the impact of 4D visualization in early detection of problems in layout planning of site facilities or spatial conflicts in the project schedule (Chau et al. 2004, Koo and Fischer 2000, Collier and Fischer 1995, and McKinney et al. 1996).

Time-space conflicts are commonly occurring problems on construction sites. They are caused due to the interference of spaces required by activities (Akinci 2000). On construction sites, various subcontractors work in a constrained area with each subcontractor requiring specific workspace, equipment space, material storage, travel paths and protected areas to complete the tasks (Guo 2002). Moreover, due to increasing pressure for shorter delivery schedules, general contractors have to increase the amount of work per unit time by increasing the resources utilized by activities and by scheduling more activities concurrently (Akinci et al. 2002c). This requires an increase in space for the activities. But space is limited on construction sites and increasing concurrency intensifies the work in a given space.

As a result, time-space conflicts may frequently occur on construction sites. Akinci et al. (1997) state, “if time-space conflicts between activities are not identified during planning, project managers can face constructability and productivity issues when implementing CPM schedules, and face cost overruns at the end of a project due to unrealistic cost estimates.”

Conventionally, space requirements on construction sites are addressed by managers by drawing site plans at the beginning of a project to allocate and manage space for material deliveries, staging areas, crane locations, and material hoists (Riley and Sanvido 1995). Even though the site plans are updated at specific time intervals, construction managers may find it difficult to manage a site if time-space conflicts are not anticipated during the planning phases.

Previous researchers have addressed time-space conflicts in various ways; Riley and Sanvido (1995), by studying space usage patterns on sites, Zouein and Tommelein (1999), by modeling equipment and material space requirements in constructing dynamic layouts, Zouein and Tommelein (2001) combined space planning and activity scheduling, while Riley (1994), Akinci (2000), Akinci et al. (2002a), and Guo (2002) used 4D modules to model various space requirements for time-space conflict analysis.

In this research also, a 4D construction model was developed to investigate whether 4D visualization is effective on construction sites in detecting time-space conflicts in the construction schedule.

1.2 Problems

Researchers have dealt with time-space conflict issues using 4D visualization by developing 4D modules. These modules were validated in post-hoc analysis of construction projects; thus having no interaction with the project participants during construction. This research investigates whether project participants on construction sites will find a 4D construction model to be effective in detecting time-space conflicts in the project schedule during construction.

Moreover, 4D visualization is perceived by many in the construction industry as a pre-construction and presentation tool. Hence it is necessary to assess whether 4D construction models can be used for managing space issues during the construction phase.

Various 4D softwares that are currently available commercially, which include Bechtel Corporation's 4D Workplanner®, Bentley Systems' Schedule Simulator®, Intergraph Inc's SmartPlant® Review, VirtualSTEP Inc's Project Navigator®, BALFOUR Technologies LLC's FourDviz®, and Common Point Technologies' Common Point 4D®, do not take into account the workspace required during the construction of a component unless space is modeled as a separate component into the CAD application (Heesom and Mahdjoubi 2001). Hence, it is also necessary to assess what impact a 4D construction model has as a visualization tool to detect time-space conflicts in the schedule if various spaces required by equipment, material, and labor during execution of activities are not modeled.

1.3 Research Objectives

The objective of this research is to investigate whether a 4D construction model is effective as compared to methods used on sites in detecting time-space conflicts. Another objective is to suggest the required level of details of schedule elements and 3D components to be modeled for increasing the accuracy of the 4D construction model in detecting time-space conflicts. In order to accomplish the goals of the research, a 4D construction model of an ongoing project was developed.

An experiment was conducted on the project participants to test the effectiveness of the 4D construction model in detecting time-space conflicts and suggest the level of details required to model the schedule elements and 3D components.

1.4 Organization of the Thesis

Section 2 provides a literature review of previous research on construction space management, 4D visualization, and time-space conflicts. Section 3 presents research methodology, description of the project and development of the 4D model.

The qualitative experiment designed to achieve the research goal is presented in Section 4. Experiment outcome and analysis and results are presented in Section 5. And, conclusions of this study and recommendations for future research are presented in Section 6.

2. REVIEW OF LITERATURE

2.1 4D Visualization in Construction Scheduling

In the architecture, engineering and construction (AEC) industry, 2D drawings have been the most popular means to express ideas to the project participants (Kang, 2001). 2D drawings are merely projections of 3D objects in a single plane. Hence, interpreting 2D drawings is difficult as the complexity of 3D objects increases. Developing construction schedule from 2D drawings is even more difficult as one has to visualize the entire sequence of construction of a 3D object that never existed. Architects have been making miniature 3D models to convey their design easily to customers (Kang, 2001). However, miniature 3D models have limitations on size, and scale and consume a lot of time to make. (Collier and Fischer, 1995)

As 3D CAD became popular in the AEC industry, architects realized that they can make more accurate 3D models and in less amount of time. They also noticed that they could combine additional engineering information with the 3D model. Engineering, Procurement, and Construction (EPC) firms were leaders in development and implementation of 3D CAD to support their design and construction efforts. Stone & Webster developed 3D modeling environment for construction planning, scheduling, progress monitoring, and reporting called Construction Management Display System COMANDS. Fluor Daniel designed the CALMA Plant Design System (PDS), and Black &Veatch developed POWERTRAK. (Mahoney et al. 1990).

Bechtel Corporation has also developed 4D-Planner that integrates 3D CAD model with construction sequence into a 4D model that can be reviewed interactively (Heesom and Mahdjoubi 2001).

4D Planner imports CAD components and schedule from commercially available applications such as AutoCAD, Primavera Project Planner, MicroStation etc. 4D planner is reported to help project managers, construction planners, and field engineers plan and manage their projects effectively. (Williams, 1996).

In research conducted at CIFE, 3D CAD objects were connected with construction schedule to demonstrate the construction sequence visually. (Collier and Fischer 1995). CIFE also showed in the San Mateo County Rehabilitation Center campus expansion project that 4D CAD helped people understand the construction sequence effectively. (Collier and Fischer, 1996). The 4D CAD tool used at CIFE was further modified and developed as CPT4D, by Common Point Technologies, Inc. CPT4D was used as a tool for visualization, communication, and coordination, for the construction of the Walt Disney Concert Hall in Los Angeles, designed by Frank O. Gehry. (Hastings et al. 2003). In another research to study the effect of 4D model on construction planning, Common Point 4D Inc.'s CPT4D was used for construction planning of the Ray and Maria Stata Center project on the campus of Massachusetts Institute of Technology (MIT). The 4D model demonstrated effectiveness in schedule visualization and communication among the project's participants. (Hastings et al. 2003). Communication was so clear that "the general contractor was able to resolve certain conflicts in the virtual model before they became real problems" (Hastings et al. 2003).

Researchers Chau et al. (2004) demonstrated that 4D visualization with a visual interface of layout of site facilities and allocation of resources along with the installed components can facilitate site planning and help construction managers streamline the site management practices.

According to Koo and Fischer, 4D model can reduce costs to the projects by supporting the early detection of problems, such as time-space conflicts, safety issues, and site workspace restrictions. It also allows the construction planner to decide upon the most appropriate construction method by generating alternative scenarios (2000).

Koo and Fischer (2000) summarize the advantages 4D models have over the traditional CPM based schedules: visualizing and interpreting construction sequence, anticipating time-space conflicts and other issues on the site, promoting interaction among project participants, and conveying the impact of changes.

2.2 4D Visualization and Time-Space Conflicts

Project schedules are developed by construction managers by taking into consideration the practical construction sequence, workspace logistics, resource allocation and use of site space. (Chau et al. 2004). Koo and Fischer (2000), assert that different project participants may develop inconsistent interpretations of CPM based schedules since typical schedules can have hundreds of activities making it cumbersome to read them and the assumptions for the precedence relationships are not presented in them. Moreover, CPM based schedules do not provide any information regarding the spatial aspects and complexities of the project components (Mckinney et. al 1996).

As a result, it is very difficult for construction managers to update site layout drawings with respect to schedules as the construction progresses; thus they can only gather information from design documents and internally conceptualize new facility arrangements as conditions evolve. (Chau et al. 2004).

Space management involves three primary aspects of research – site layout planning, path planning, and space scheduling Guo (2002). Previous research attempts on site layout mainly focused on static and dynamic layout planning. In Static layout models objects have predetermined space and proximity constraints and the possibility of reuse of space to accommodate different resources at different times is ignored, as against dynamic layout models in which layouts change over time as construction progresses (Zouein and Tommelein 1999). However, the site layout approach considers mainly the temporary facilities and most of the studies did not consider time factor in space availability (Akinci et al. 2000b).

Guo (2002) argues that path-planning studies mainly focus on determining the shortest route for equipment and generally do not include labor and material, and hence are not significant for space conflict resolution. However, space scheduling considers all working elements that change over time and hence suitable for space conflict resolution.

Zouein and Tommelein (2001) presented an algorithmic time-space trade-off model by characterizing resource space requirements over time and establishing a time-space relationship for each activity in the schedule.

The space scheduling algorithm changes activity durations or their start times depending upon the resource space requirements for activities and the availability of space on site, while minimizing the increase in project schedule.

Akinci et al. (2000a) argue that the algorithms developed in space scheduling studies can eliminate all work space conflicts in the construction schedule, however the user has to define the geometric as well as the time attributes of all types of work spaces required by all construction activities; a time consuming and tedious process.

Staub and Fischer (1998) enumerate the requirements to identify time-space conflicts: spatial information – location of a building component and the space it identifies. Temporal information – activity start and finish times and activity duration. Relational information – logic information including preceding and succeeding activities, and the relationships between activities and 3D CAD objects, and the Geometric attributes – length, area, volume etc. depending upon the type of analysis required.

Research on time-space conflicts in the construction schedule is focused mainly on material usage space (Riley 1994, Zouein and Tommelein 1999), and the space required for execution of activities (Akinci 2000, Akinci et al. 2002b, Akinci et al. 2002c and Guo 2002).

Riley and Sanvido (1995) defined 12 construction space types required to complete work elements. These are layout area, unloading area, material path, staging area, personnel path, storage area, work area, tool and equipment area, debris path, hazard area, and protected area.

Akinci et al. (2002a) classified these spaces into three categories namely, macrolevel spaces, micro level spaces and paths and attempted to represent workspaces generically in construction method models. They developed a prototype system, 4D Work Planner Space Generator (4D SpaceGen) to model construction methods and space requirements for activities. The research concludes that automated generation of workspaces enables the user to visualize the space usage on site and to detect spatial conflicts between activities prior to construction.

Akinci et al. (2002c) enumerated six different types of spaces required by construction activities.

These are: building component space, labor crew space, equipment space, hazard space, protected space, and temporary structure space. They developed a prototype system, 4D WorkPlanner Time-Space Conflict Analyzer (4D TSConAn) to automate time-space conflict analysis process. This prototype system takes a space-loaded 4D production model and the six different types of activity space requirements as input. The 4D TSConAn detects spatial conflicts between activities and categorizes them according to the taxonomy developed by the researchers.

Although this research concludes that time-space conflict analysis can be formalized as a classification task, the taxonomy used in the time-space conflicts analysis is limited to specific activities only, and hence the research has a limited application on sites.

3. METHODOLOGY

3.1 Overview

In this research, the effectiveness of a 4D construction model in detecting time-space conflicts on construction sites is investigated through comparison of the data gathered from the experiment when participants used two methods to detect space management issues on the site. The participants first used an overlay drawing and schedule, and then the 4D model to detect time-space conflicts in the schedule and provided solution for resolving the conflicts detected. The data were collected through interviews with the project participants. Data gathered from the experiment is analyzed and results are presented.

3.2 Qualitative Empirical Study

This research investigates whether a 4D construction model effectively aids site level project participants in detecting time-space conflicts in the construction schedule. To fulfill the research objective, the following research process is followed: 1) A 4D construction model of an ongoing construction project is developed. 2) Project participants are recruited for the experiment. These consist of the sub-contractors from the mechanical, electrical, plumbing, and fire protection (MEPF) trades and the project superintendent. 3) Two sessions of interviews with each participant are conducted. In each session, a different graphic representation of the construction schedule is shown to the participants and asked to detect time-space conflicts in the schedule.

The graphic representations consisted of; a) CPM based project schedule and sub-contractor coordination drawing (or overlay drawing), which was developed by combining the MEPF drawings, and b) the 4D construction model. All participants were interviewed individually and each interview session lasted for about one hour.

The following information was collected through the experiment:

- Additional number of time-space conflicts detected by using the 4D construction model
- Identification of different spaces required for various installations
- Various alternatives suggested for resolving time-space conflicts
- Feedback on utilization of the 4D construction model on sites for day-to-day planning

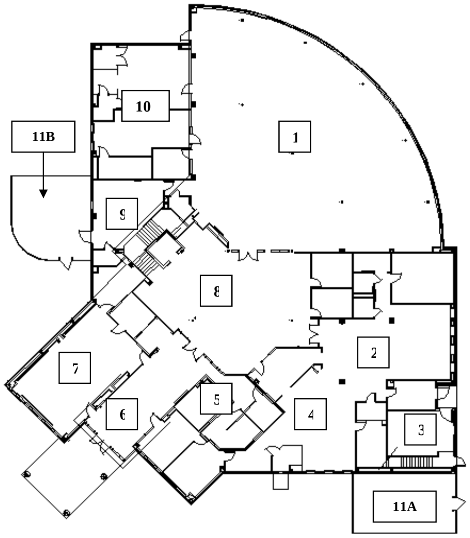
3.3 Research Logic

The research process was carried out in the following steps:

- Review previous work to develop a theoretical basis of this research
- Develop a 4D construction model of an ongoing construction project
- Update the 4D construction model as the project progresses
- Develop an experiment protocol to collect data required for the research
- Recruit project participants and conduct the experiment

3.4 Overview of the Project

For the research, the Precinct 3 Montgomery County Library construction project being built by Turner Construction Company (TCC), Houston, Texas and RWS Architects (RWS), Houston, Texas is selected. This 30,000 sqft., two-storey structure is located in the Woodlands, Texas. Construction of the library began in June 2004 and is scheduled to be complete by the end of April 2005. Figures 3.1a and 3.1b show the first floor and second floor plans.



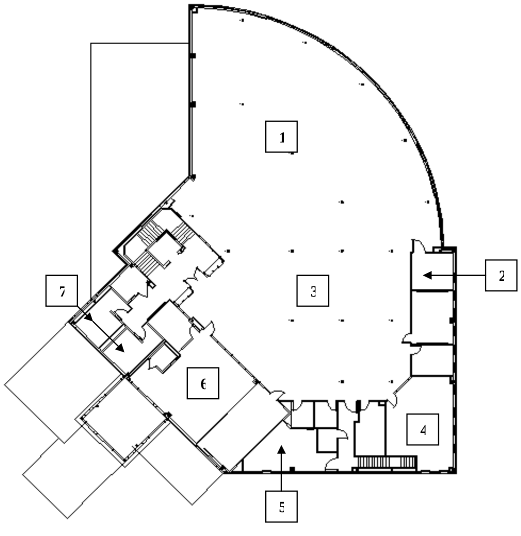


Figure 3.1a First floor plan

Figure 3.1b Second floor plan

1. CHILDRENS'S CENTER
2. STAFF AREA
3. MECH ROOM 2
4. SHELVING AREA
5. REST ROOMS
6. LOBBY

7. CONFERENCE ROOMS
8. CIRCULATION AREA
9. MECH ROOM 1
10. CHILDREN'S AREA
11A & 11B. MECH YARDS

1. GENERAL ADULT AREA
2. MECH ROOM 4
3. REF INFO CENTER
4. YOUNG ADULT AREA & SHELVING

5. MECH ROOM 3
6. ADULT SERVICES
7. REST ROOMS

3.5 Schedule Description

On this construction project, the project superintendent was responsible for developing the construction schedule. The master schedule was in the form of a CPM network that only outlined all the major construction activities and certain sub-activities (approximately 55). The master schedule was divided into two parts. The first part covered all exterior activities while the second part covered all the interior activities for the first floor and second floor levels. Although the schedule seemed simple and gave an overall idea of the progression of the project, the level of details for all activities was not consistent. Some activities were divided into sub-activities and described in a greater detail than others. For example, activity ‘structural steel erection’, scheduled for 20 days, was designated as a single activity with no description of the sequence of the sub-activities, whereas the activity ‘wall installation’, scheduled for 25 days, was divided into three sub-activities, *viz.* frame walls, rough-in walls, and close walls/tape and float.

It was expected from the subcontractors to develop their own schedule, based upon the master schedule at a suitable level of detail and complete their work by the date specified in the superintendent’s schedule.

The project superintendent had designated specific locations on the site for material unloading, material staging, debris etc., generally, for all exterior activities. However, for all interior activities, area 1 (refer to Figs. 3.1a, 3.1 b, and 3.2) in the first and second floor was considered as the space for material unloading, handling, and debris.

Hence, for all interior activities that were concurrently scheduled in the project, space management issues such as temporary material staging, pathways for crews etc. were to be addressed and resolved by the subcontractors among themselves during installation. Thus, time-space conflicts were highly likely for some interior activities.

According to the project superintendent, the usual procedure followed on the site to resolve any conflicts is to discuss the conflicts in sub-contractor coordination meetings. Sub-contractor coordination meetings are conducted on the site regularly by the project superintendent to discuss various issues on the site, such as design coordination, schedule coordination, conflict resolution etc. For sub-contractors that are scheduled to work concurrently, space related problems are addressed in the following manner: one sub-contractor who requires the maximum space and/or time to install a component is identified by the superintendent as the ‘lead’ sub-contractor. Detailed plans of all other sub-contractors are superimposed on the lead sub-contractor’s drawing to form an overlay drawing that depicts all the components to be installed concurrently on the site. In the sub-contractor coordination meetings, all issues are discussed based upon the overlay drawing. A preliminary sub-contractor coordination meeting is a requirement on the site before all concurrently scheduled sub-contractors are mobilized on the site. However, additional coordination meetings are held only if conflicts are not resolved by the sub-contractors among themselves.

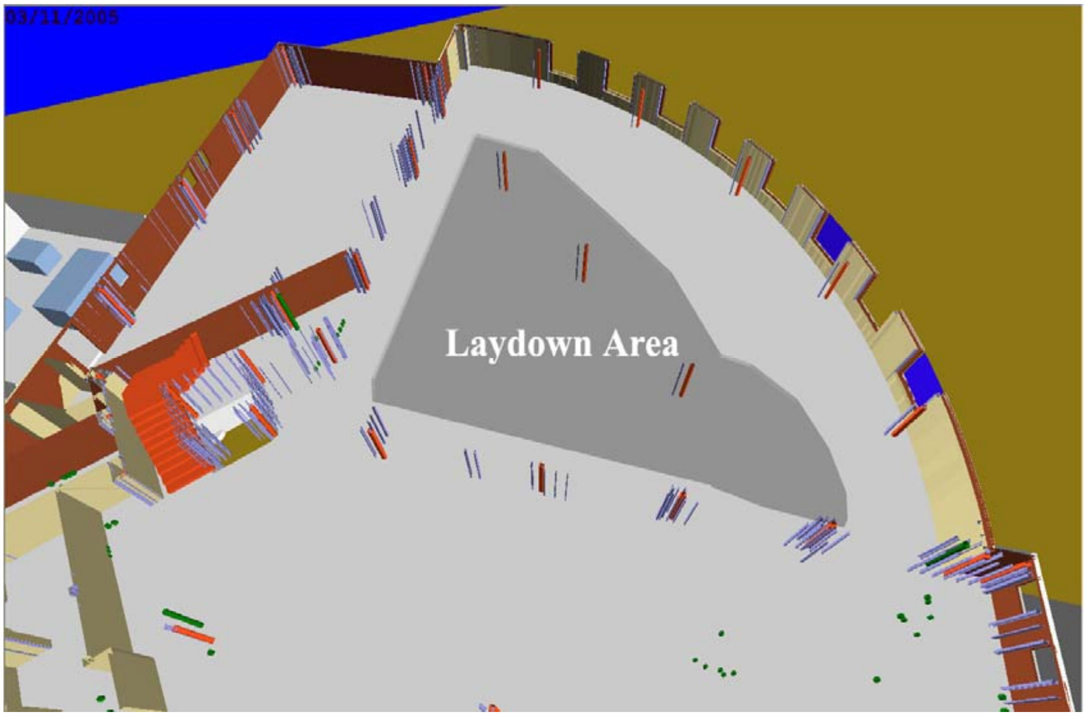


Figure 3.2 Laydown area on first floor and second floor for material unloading and staging and debris

3.6 Development of 4D Construction Model

The 4D construction model was developed as follows:

After procuring CAD drawings from the Architect, a 3D model was developed using AutoCAD. The model comprised only of building components, which include structural steel components – columns, beams and joists, concrete slabs, roof decks, external and internal metal studs, dry walls, sheathing, external walls, pavement, plumbing system – domestic, sewer and storm water pipes, mechanical system – sheet metal ducts, air handling units and other equipment, electrical system – conduits and cable trays, and fire protection system – sprinkler pipes. Figure 3.3 shows a perspective view of the 3D model.

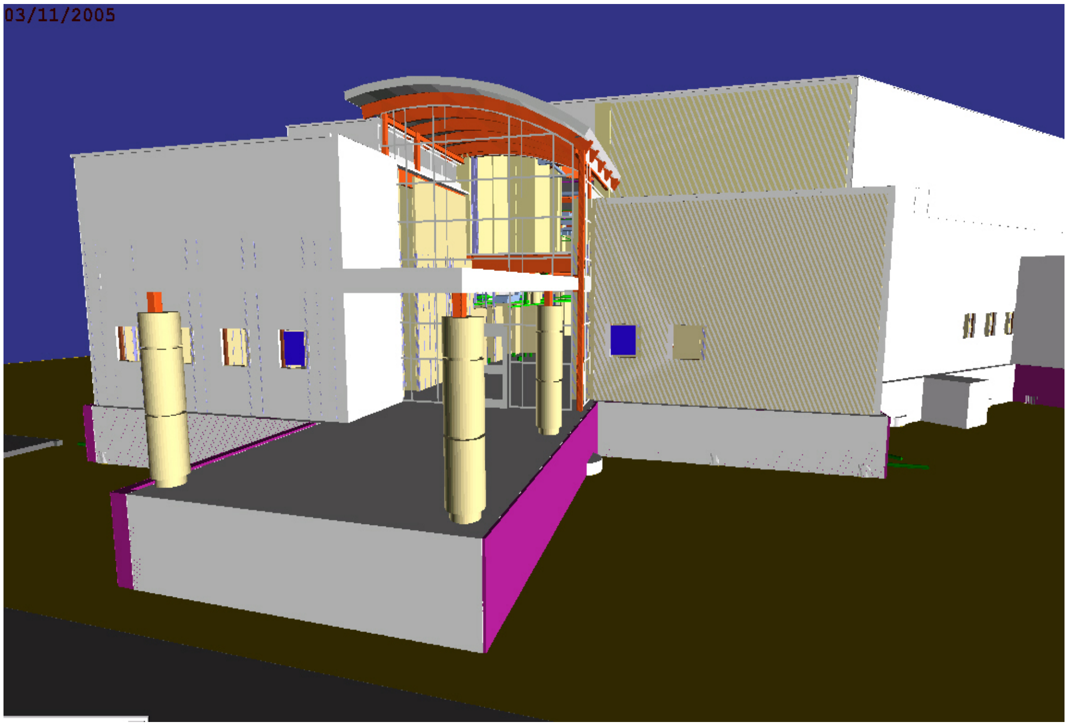


Figure 3.3 Perspective view of the 3D model

Schedule was provided by the project superintendent. As discussed in Section (3.5) the schedule was improvised to facilitate the development of the 4D construction model. 3D components were further divided into individual units such that, one unit represented the parts of a component installed per day (or week) depending upon the size of the component.

In the visualization software, Common Point 4D, the 3D components were linked to corresponding activities in the schedule. Figure 3.4 illustrates the system architecture of the 4D construction model. Table 3.1 shows activities in the schedule and corresponding 3D components. Figure 3.5 shows the MEPF systems in plan view.

TABLE 3.1 Activities in the Schedule and Corresponding 3D Components

ACTIVITIES	3D COMPONENTS
Mobilization, site fence, erosion control	No component
Clear Site/Establish Building Corners	Default site area
Earthwork -cut/fill/stabilize pad	Formwork foundation, Default site area
Sitework - grading/ utilities	Formwork foundation, Default site area
Concrete Piers	Footing excavation, Footing concreting
Underslab MEP	Underslab plumbing
F/R/P Slab on Grade	Formwork foundation, Reinforcement, Level 1 slab
Erect Structural Steel	Columns, Beams, Joists, Staircase
Metal Deck, Reinforce, pour level 2	Level 2 slab
Exterior Metal Studs / Sheathing L1	Exterior metal studs and Sheathing for Level 1
Metal Deck -Roof	Roof deck
Exterior Metal Studs / Sheathing L2	Exterior metal studs and Sheathing for Level 2
Damproof Exterior	Sheathing Level 1, Level 2
Masonry	Brickwork
Glass & Glazing	Main entrance structure, Window openings
Roofing	Roof deck
Set AHU's and RTU's	Mechanical equipment
Bump ACC's and AHU's	Mechanical equipment
Elevator Installation	No component
Level 1	
Overhead MEP Rough-in	Electrical conduits, HVAC ducts, Plumbing pipes, Sprinkler system
Layout	Electrical conduits, HVAC ducts, Plumbing pipes, Sprinkler system
Frame Walls	Internal studs
Rough-In Walls	Inside walls
In- Wall Inspections	Inside walls
Close Walls/ Tape and Float	Inside walls
Frame ACT/Sheetrock Ceilings - Level 1	No component
Set Light Fixtures and HVAC	No component for light fixtures, Air handling units for HVAC
Ceiling Inspections	No component
Close ACT/Sheetrock Ceilings	No component
Casework	No component
MEP Trim	Electrical conduits, HVAC ducts, Plumbing pipes, Sprinkler system
Floorcovering/Finishes	Level 1 slab

TABLE 3.1 cont'd

Level 2	
Overhead MEP Rough-in	Electrical conduits, HVAC ducts, Plumbing pipes, Sprinkler system
Layout	Electrical conduits, HVAC ducts, Plumbing pipes, Sprinkler system
Frame Walls	Internal studs
Rough-In Walls	Inside walls
In- Wall Inspections	Inside walls
Close Walls/Tape and Float	Inside walls
Frame ACT/Sheetrock Ceilings - Level 1	No component
Set Light Fixtures and HVAC	No component for light fixtures, Air handling units for HVAC
Ceiling Inspections	No component
Close ACT/Sheetrock Ceilings	No component
Casework	No component
MEP Trim	Electrical conduits, HVAC ducts, Plumbing pipes, Sprinkler system
Floorcovering/Finishes	Level 2 slab
Miscellaneous	
Final Clean / TCCO Punch	No component
Final Inspections/Testing	No component
Certificate of Occupancy	No component
Site Paving	
Electrical/Light Pole Bases	No component
Underground Sprinkler/Irrigation	No component
Lime/Fly Ash Stabilization	No component
Paving	Pavement
Landscaping	Default site area

The following factors were critical for the development of the 4D construction model:

The master schedule developed by the project superintendent had disparity in the level of details for various activities. Hence some activities were modified to maintain consistency in the schedule. Spaces for equipment etc. could not be modeled since the construction methods, and equipment used by the sub-contractors were not known until each sub contractor mobilized on the site. As a result, the level of details for workspace required for installing a building component depended on the gross space surrounding the building component.

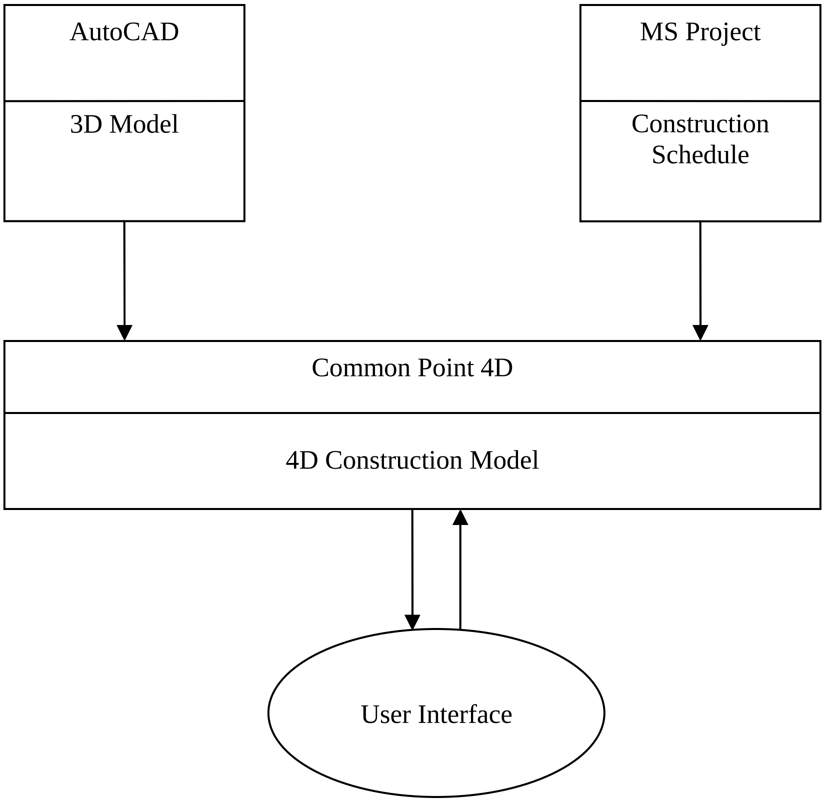


Figure 3.4 System architecture of the 4D construction model

Figure 3.5 Plan view of the 4D model: MEPF systems

4. EXPERIMENT DESIGN

This section presents how the experiment was designed to fulfill the research objective. Development of the instrument to conduct the research and the resources provided in the experiment are also presented.

4.1 Participants

As discussed in the earlier section, the project superintendent had designated the semi-circular open area inside the building as the material unloading, temporary storage, and debris area combined for all interior activities. Moreover, for interior work, many sub-contractors were scheduled to work concurrently; sharing workspaces in a constrained area. As a result, time-space conflicts were more likely to occur in the interior than the exterior of the building. Hence this research primarily concentrated on the interior activities.

Participants in the research comprised of the project superintendent, sub-contractors of the mechanical, electrical, plumbing, and fire-protection (MEPF) trades

4.2 Experiment Setup

The objective of the experiment was to assess how effectively a 4D construction model can be used on construction sites to detect time-space conflicts in the construction schedule. In order to determine the effectiveness of the 4D construction model over the conventional methods used on sites to manage spatial issues, the experiment was designed to provide two levels of graphic representation; a 2D overlay drawing depicting building components that had potential workspace interference during installation and the 4D construction model. A questionnaire was designed for both the graphical methods to gather information from the participants during the experiment.

The experiment was conducted in two parts through interviews with the participants: In the first part, the 2D overlay drawing and project schedule was given to each participant. The participants were asked to detect time-space conflicts in the project schedule, describe the nature of conflicts, describe the effects of the conflicts on their individual schedules, and finally suggest means to resolve the conflicts. This information was gathered through the questionnaire.

In the second part, the 4D model was introduced to each participant. Again, the participants were asked to detect time-space conflicts, describe the nature of time-space conflicts, describe the effects of the conflicts, and suggest means to resolve the conflicts.

5. EXPERIMENT OUTCOME AND ANALYSIS

This section presents the data gathered both the parts of the experiment and analysis of the results. An overview of the schedule is also presented.

5.1 Schedule Overview

The sequence of MEPF activities was as follows:

MEPF rough-in was scheduled for 29 days. The rough-in was to start just after the installation of exterior metal studs and sheathing. The original sequence was: Plumbing rough-in –> electrical rough-in –> mechanical rough-in –> fire proofing rough-in. However, certain changes were made in the sequence of these activities because of two factors that were previously unaccounted for; Architect's late decision in selecting and conveying the appropriate brick color and the job site had to be closed for about seven days because of rain in early November.

Considering that the exterior work was delayed and brickwork would not start until the Architect's decision, the superintendent re-scheduled the electrical work ahead of other MEPF activities to ensure smooth progress. Consequently, the new sequence was Electrical rough-in –> plumbing rough-in –> mechanical rough-in –> fire proofing rough-in.

5.2 Outcome of Part I: Overlay Drawing and Schedule

As discussed in the previous section, the superintendent developed the master schedule that depicted only the major activities and some sub-activities, and designated a space inside the building as the laydown zone for all activities combined. Consequently, it was the sub-contractors’ responsibility to develop individual detailed schedules and space management plans to ensure smooth progress of the project.

The experiment focused on the interior activities, primarily on the MEPF trades. In all, four sub-contractors, one each from the mechanical, electrical, plumbing, and fire protection trades and the project superintendent participated in the research.

As a thumb rule, the Mechanical sub-contractor was designated as the lead subcontractor since he consumed the maximum component space, workspace for installation and material, and required more time on the site than other sub-contractors. Consequently, the overlay drawing was developed by superimposing the electrical, plumbing, and fire protection drawings on the mechanical drawing.

The overlay drawing consisted of all components and systems to be installed by these sub-contractors that included: HVAC ducts, air handling units, sanitary and storm water pipes, electrical panels and conduits, and the sprinkler system. However, the overlay drawing did not illustrate the workspace, material space etc. requirements during installation.

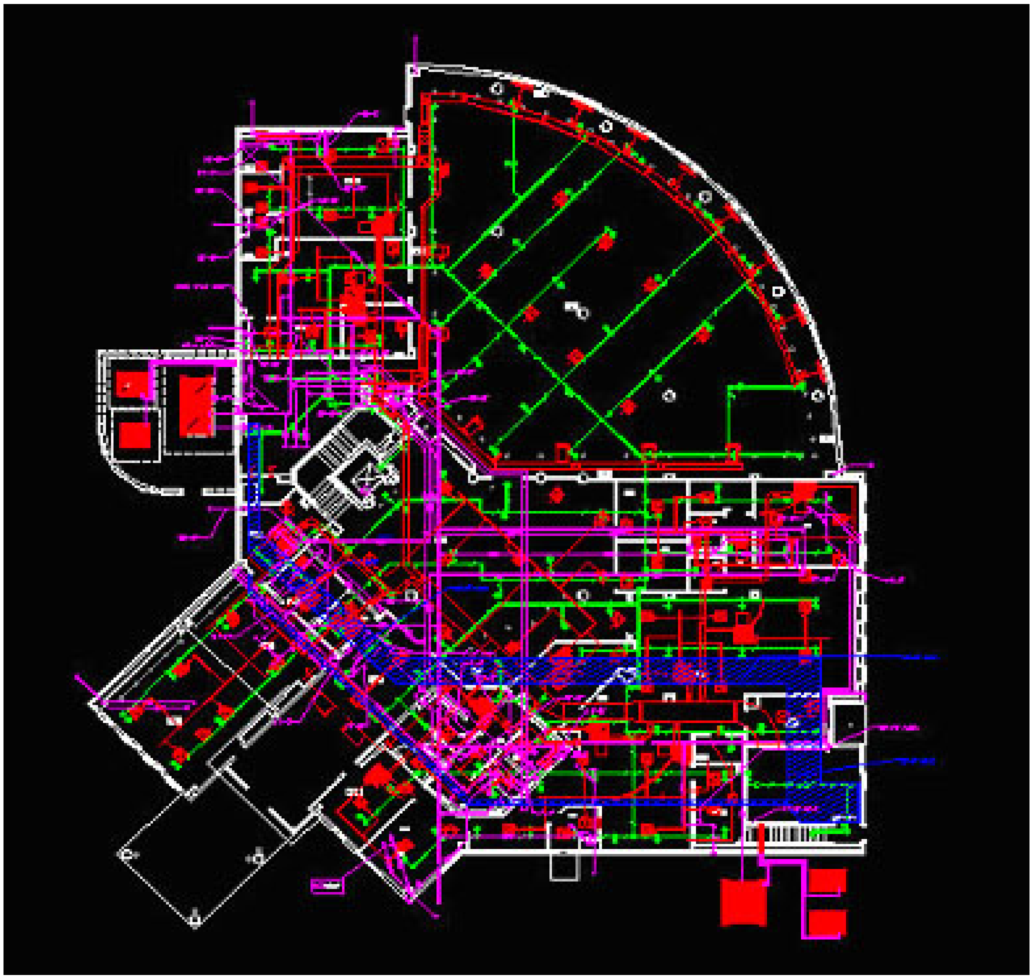


Figure 5.1a Overlay drawing first floor

BLUE	ELECTRICAL CONDUITS
GREEN	SPRINKLER SYSTEM
MAGENTA	HVAC DUCTS
RED	PLUMBING SYSTEM

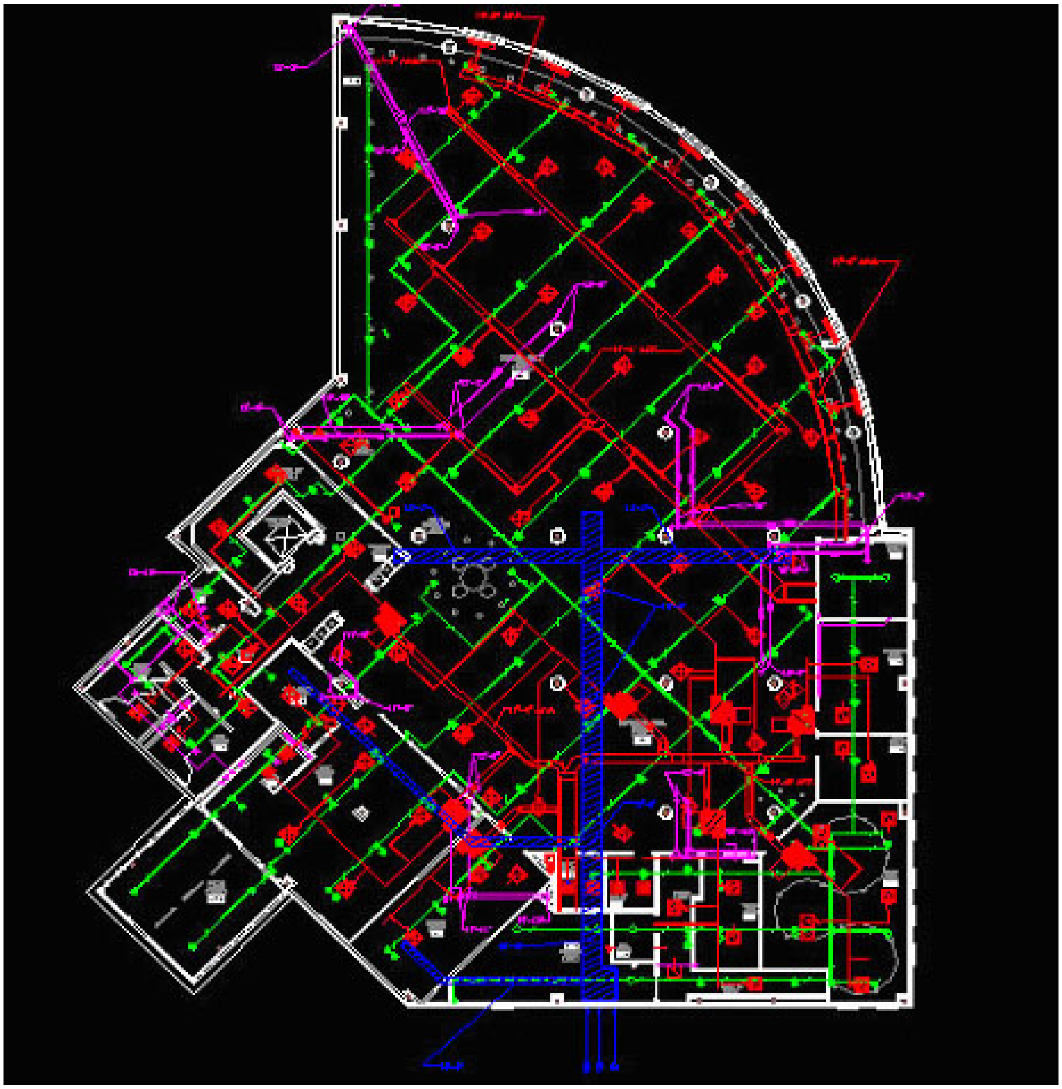


Figure 5.1b Overlay drawing second floor

BLUE	ELECTRICAL CONDUITS
GREEN	SPRINKLER SYSTEM
MAGENTA	HVAC DUCTS
RED	PLUMBING SYSTEM

5.2.1 Conflicts Identified

Conflicts identified in the Mechanical and Electrical activities:

Since electrical rough-in was scheduled ahead of mechanical schedule, possibility of any time-space conflicts during the rough-in activities was ruled out. However, one spatial conflict was detected – in the area between the Mechanical Room 2 and the Lobby, cable trays clashed with the air-handling units. This conflict was classified as a design conflict.

Time-space conflicts in the mechanical rooms:

It was anticipated before the experiment that the mechanical rooms would be congested during the installation of electrical panels and mechanical equipment, and activity ‘pull wires’. According to the electrical contractor, start of the activity ‘pull wires’ may be delayed by 1 or 2 days if the activity is scheduled during the installation of mechanical equipment. In that case he may have to relocate 1 or 2 electricians at some different location on the site to avoid congestion.

Time-space conflicts during installation of air handling units and electrical fixtures: these activities had an overlap period of 5 days. Although both the electrical and mechanical sub-contractors anticipated time-space conflicts, they could not pinpoint the exact location of the conflicts since each had no knowledge of the other’s schedule. Hence according to them, the best way to deal with the problem is to make changes in the schedule as and when conflicts arise.

Conflicts identified in the Mechanical and Drywall installation activities:

Activities ‘installation of internal studs’, and ‘mechanical rough-in’, were scheduled simultaneously on the site. According to the mechanical sub-contractor, congestion was possible in the area at the boundary of the mechanical rooms because of crew and equipment space interference.

Conflicts identified in the Mechanical and Fire-protection activities:

No time-space conflicts detected. However, one spatial conflict in the area near mechanical room 1 was detected. Bottom of the HVAC duct in the area clashed with the fire protection piping system. This conflict was reported as a design conflict.

Table 5.1 shows all the conflicts identified by the participants between various trades

TABLE 5.1 Conflicts Identified in the First Part of the Experiment

	Mechanical	Electrical	Plumbing	Fire protection	Drywall
Mechanical		2	0	1	1
Electrical	2		0	0	0
Plumbing	0	0		0	0
Fire protection	1	0	0		0
Drywall	1	0	0	0	

5.3 Outcome of Part II: 4D Construction Model

Components modeled relevant for the experiment comprised of the following –

- Mechanical components – HVAC ducts, air-handling units (AHU's), air cooled condensing units (ACCU's), and refrigeration pipes.
- Electrical components: conduits and cable trays.
- Plumbing components: Storm water, domestic water, and sewage pipes.
- Fire protection components: sprinkler system pipes.
- Dry wall systems: External and internal metal studs, and sheathing.

Modeling for labor workspace and staging area for material was not required. However, equipment space could not be modeled because information on the construction methods as well as equipment to be used by the sub-contractors was not available when the model was developed.

5.3.1 Conflicts Identified

Conflicts identified in the Mechanical and Electrical activities:

In addition to the design conflict that was detected in the first part of the experiment - In the area between the Mechanical Room 2 and the Lobby, cable trays clashed with the air-handling units, another conflict was detected. Refer to Figure 5.2

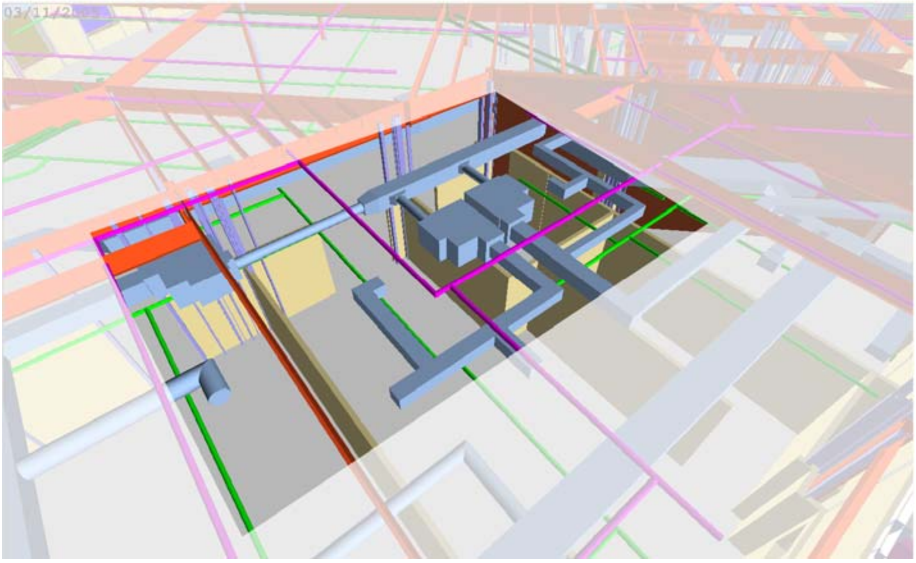


Figure 5.2 Potential time-space conflict during installation of cable trays and AHUs near Mechanical Room 2

Time-space conflicts in the mechanical rooms: According to the electrical contractor, start of the activity ‘pull wires’ may be delayed by exactly 1 day if the activity is scheduled during the installation of mechanical equipment. As opposed to the previous case he may not have to relocate 1 or 2 electricians. On the contrary, 3 electricians can work in the mechanical room 2, while the mechanical technicians can work at a different elevation in the same place. Here, according to the mechanical contractor, the workspace will be congested and will affect his crew. Further, the activities ‘mechanical equipment installation’ and ‘pull wires’ can have an overlap of exactly 1 day, which may cause only 1 day of congestion.

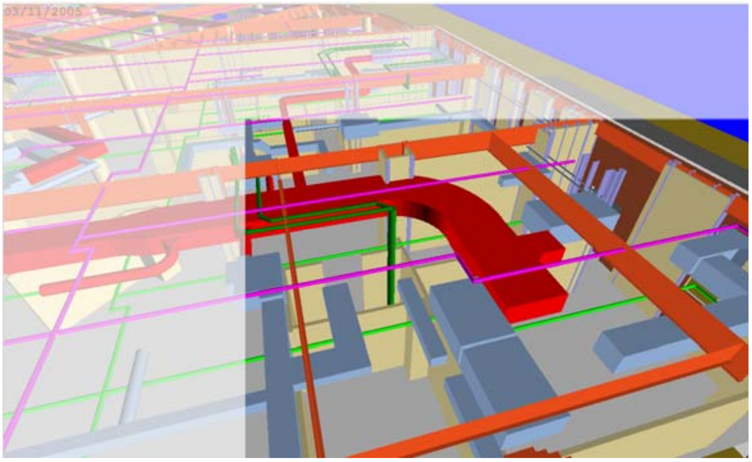


Figure 5.3 Potential time-space conflict during installation of cable trays and AHUs in Mechanical Room 1

Time-space conflicts during installation of air handling units and electrical fixtures: these activities had an overlap period of 5 days. As opposed to the previous case, both the electrical and mechanical sub-contractors detected at least 2 potential time-space conflicts. These time-space conflicts can cause delay of exactly 2 days in installing electrical fixtures or a delay of 1 day in the installation of the AHU's, if they are scheduled simultaneously. According to them, these conflicts can be avoided if, either the installation of AHU's starts 2 days later than the installation of electrical fixtures or 1 day late but starting from a different point.

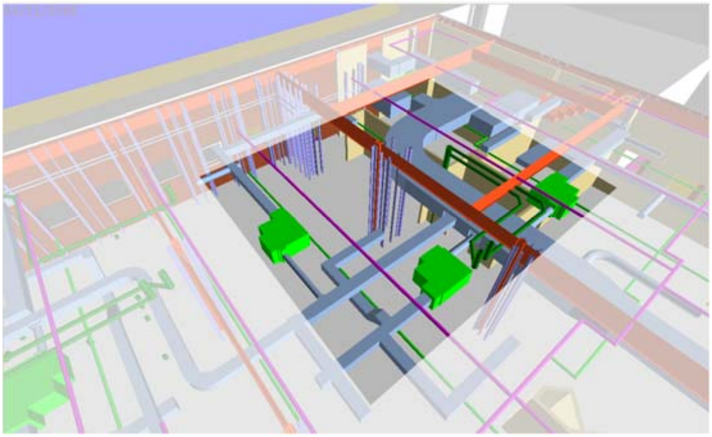


Figure 5.4 Potential time-space conflict during installation of cable trays and AHUs

Conflicts identified in the Mechanical and Dry wall activities:

As detected in the previous part of the experiment, time-space conflicts between activities ‘installation of internal studs’, and ‘mechanical rough-in’, was causing congestion in the area at the boundary of the mechanical rooms because of crew and equipment space interference. During the installation of studs at the boundary of the mechanical room, HVAC ducts cannot be installed in the area since a hazard space is formed in the mechanical room due to the possible falling of the studs. Hence, the mechanical contractor might have to delay work for at least 1 day.

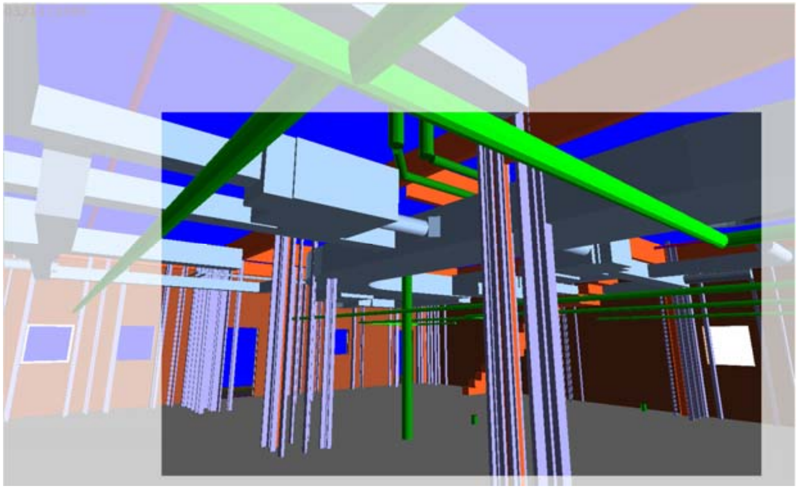


Figure 5.5 Potential time-space conflict during installation of ducts and metal studs

However, according to the mechanical sub-contractor, the conflicts can be avoided if the installation of studs in that part is delayed by 1 or 2 days. Moreover, he can also use equipment like ladders and scissor lifts from both sides of the mechanical room. Possible damage to the studs was also expected in the area, which may require rework.

Conflicts identified in the Mechanical and Fire-protection system activities:

No time-space conflicts detected. However, the same design conflict in the area near the mechanical room 1 was detected.

Table 5.2 shows all the additional conflicts identified by the participants between various trades when they used the 4D construction model.

TABLE 5.2 Additional Conflicts Identified in the Second Part of the Experiment

	Mechanical	Electrical	Plumbing	Fire protection	Drywall
Mechanical		1	0	1	1
Electrical	1		0	0	0
Plumbing	0	0		0	0
Fire protection	1	0	0		0
Drywall	1	0	0	0	

NB

The conflicts identified here are in addition to those identified using the overlay drawing and schedule

5.4 Results

In the first part of the experiment, when the participants used the overlay drawing along with the schedule, each participant was looking at the jobsite from his point of view. Hence time-space conflicts that were very obvious were identified. Non-obvious time-space conflicts were either overlooked or merely speculated on the basis of judgment. However, after the introduction of the 4D construction model, the exact number of time-space conflicts could be detected. Possible schedule alternatives were also given.

Results from the first part and second of the experiment are shown in Table 5.3 and Table 5.4, respectively.

Table 5.3 Results Table showing Outcome of the First Part of the Experiment

Conflict issue	Trades involved	Schedule affected (days), (trade)	Labor productivity (yes/no)	Loss due to delay (% of Scheduled* Value/day)	Require design changes (yes/no)	Rework (yes/no)	Comments
1 - Congestion in mechanical room	M and E	1or 2 – E	Yes	2%	-NA-	-NA-	-
2 - Component conflict	M and E	-NA-	-NA-	-NA-	Yes	-NA-	Design conflict
3- Congestion at multiple areas	M and E	1 or 2 – M, E	Yes	5%	-NA-	No	Multiple time-space conflicts
4- Congestion near mechanical rooms	M and W	1 - M	Yes	5%	-NA-	No	-
5- Component conflict	M and F	-NA-	-NA-	-NA-	Yes	-NA-	Design conflict

*Scheduled value as per *AIA Document G703* provided by the project superintendent
In the table (Loss due to delay - % of Scheduled Value/day) refers to the dollar amount lost per day on labor expressed as a percentage of the total labor value of an activity

Trades involved:
M – Mechanical, E – Electrical, F – Fire protection, W – Drywall

TABLE 5.4 Results Table showing Outcome of the Second Part of the Experiment

Conflict issue	Trades involved	Schedule affected (days), (trade)	Labor productivity (yes/no)	Loss due to delay (% of Scheduled* Value/day)	Require design changes (yes/no)	Rework (yes/no)	Comments
1- Congestion in mechanical room	M and E	1 - E	Yes	4%	-NA-	-NA-	Schedule alternatives suggested
2- Component conflict	M and E	-NA-	-NA-	-NA-	Yes	-NA-	Design conflict
3- Congestion at multiple areas	M and E	2 – M, E	Yes	5%	-NA-	No	Schedule alternatives suggested
4- Congestion near mechanical rooms	M and W	1 - M	Yes	10 - 15%	-NA-	Yes	Schedule alternatives suggested
5- Component conflict	M and F	-NA-	-NA-	-NA-	Yes	-NA-	Design conflict

*Scheduled value as per *AIA Document G703* provided by the project superintendent

In the table (Loss due to delay - % of Scheduled Value/day) refers to the dollar amount lost per day on labor expressed as a percentage of the total labor value of an activityTrades involved:

M – Mechanical, E – Electrical, F – Fire protection, W – Drywall

6. CONCLUSION

This section reviews the objectives of this research, presents the contributions, and discusses how a 4D construction model can be effectively used on sites by project participants. Limitations of the 4D construction model and recommendations for further research and are also presented.

6.1 Review of Research Objectives

The objective of this research was to investigate whether a 4D construction model is effective as compared to conventional methods in detecting time-space conflicts on construction sites.

6.2 Contributions

This research has produced empirical evidence to substantiate the research objectives. The contributions are: 1) A 4D construction model of an ongoing construction project was developed and 2) An experiment was conducted to produce evidence for effectiveness of the 4D construction model in detecting time-space conflicts

6.2.1 Development of the 4D Construction Model

4D construction model was developed by using a commercially available software, namely Common Point 4D. The development process was as follows: first, a 3D model of the facility was developed using AutoCAD. The 3D model comprised of the building components only.

Workspaces required for execution of activities, such as crew space, material space etc. were not modeled. The schedule was developed in Microsoft Project. The master schedule provided by the project superintendent contained only the major activities and some sub-activities. Consequently, some activities had to be sub-divided into various sub-activities in order to use it for the 4D model. Also, the modified schedule depicted the progress of activities on a day-by-day basis.

Finally, in the 4D software, 3D components were linked to corresponding activities in the schedule to form the 4D construction model.

6.2.2 Development of the Experiment

The objective of the research was to gather evidence of the effectiveness of the 4D construction model over the conventional methods used on sites to detect conflicts in the schedule. On construction sites, project participants typically conduct sub-contractor coordination meetings to discuss and resolve conflicts as and when conflicts arise. Before the meetings, an overlay drawing is developed by superimposing all crafts drawings on one main drawing. In coordination meetings, the participants discuss all conflicts and make resolution plans based upon overlay drawings and project schedules. However, this method has a distinct disadvantage in regards to the detection of time-space conflicts because overlay drawings convey the spatial requirements of building components only and space requirements for activities are not shown, while CPM schedules convey only the temporal aspect of activities.

Hence in order to fulfill the research objective, the experiment was designed to provide two different graphic representations of the construction schedule to the participants. Two sessions of structured interviews of each participant were conducted in which they were asked to detect time-space conflicts in the schedule, and describe how the conflicts affect the schedule. In the first session the overlay drawing and construction schedule was shown to the participants, while in the second session the 4D construction model was shown to the participants.

The experiment focused mainly on the interior activities because of the possibility of existence of time-space conflicts in congested area inside the building. In all, 4 sub-contractors and the project superintendent took part in the experiment.

The effectiveness of 4D construction model over the conventional method in detecting time-space conflict was determined by the following factors:

- Number of time-space conflicts detected
- Effects of the identified time-space conflicts on the schedule
- Various alternatives suggested for resolving the time-space conflicts

6.3 Experiment Findings

- 4D model can be effective for updating schedules and space planning for activities during the construction phase

- Disparity in the level of details of activities and 3D components existed; between activities and 3D components, among activities, and among 3D components. However, if consistency in the level of details is maintained a priory, then a 4D model can be more beneficial.
- Various currently commercially available 4D visualization softwares do not take into account the workspace required during the construction of a component unless space is modeled as a separate component into the CAD application.
- Design conflicts were successfully identified by the participants by using both methods. However multiple design conflicts of similar nature were identifiable only in the 4D construction model
- Number of time-space conflicts detected by using the 4D construction model exceeded by those when using the overlay drawing
- Single schedule alternatives were suggested for each time-space conflict detected using the conventional method. Where as multiple schedule alternatives were suggested for some time-space conflicts detected using the 4D construction model
- Spaces created while installation of certain components such as Hazard Spaces were identifiable only by using the 4D construction model

The experiment produced enough empirical evidence in support of the research objective. Hence a 4D construction model may be effective in detecting time-space conflicts on construction sites.

6.4 Limitations

The 4D construction model did not model various workspaces required by crew, equipment and materials, and spaces like hazard space or protection space formed during installation of building components. Hence the model remains as a visualization tool rather than an integration tool.

The 4D model also does not take into consideration the methods used to install the building components. Consequently, visualization of schedule alternatives with respect to different methods of construction is not possible.

6.5 Recommendation for Future Research

The empirical evidence gathered by developing the 4D construction model and conducting the experiment to test its effectiveness is based on a single case study only. Conducting the experiment on multiple project sites can validate the methodology presented in this research.

Deficiencies in the 4D construction model can be eliminated if the following things are modeled: 1) workspace requirements for activities and 2) component and workspace requirements for alternative construction methods used to install the same building component.

REFERENCES

Akinci, B., Fischer, M., and Staub, S. (1997). "Productivity and cost analysis based on a 4D model", *IT support for construction process reengineering, publication 208*, Div. of Constr. Mgmt., James Cook University of North Queensland, Townsville, Queensland, Australia, 23-32.

Akinci, B. (2000). "Automatic generation of work spaces and analysis of time-space conflicts at construction sites." PhD dissertation, Dept. of Civil and Environmental Engineering, Stanford Univ., Stanford, CA.

Akinci, B., Fischer, M., and Kunz, J. (2002a). "Automated generation of work spaces required by construction activities", *Journal of Construction Engineering and Management*, ASCE, 128 (4), 306-315.

Akinci, B., Fischer, M., Kunz, J, and Levitt, R. (2002b). "Representing work spaces generically in construction method models", *Journal of Construction Engineering and Management*, ASCE, 128 (4), 296-305.

Akinci, B., Fischer, M., Levitt, R., and Carlson, R. (2002c). "Formalization and automation of time-space conflict analysis", *Journal of Computing in Civil Engineering,* ASCE, 16 (2), 124-134.

Chau, K. W., Anson, M., and Zhang, J. P. (2004). "Four-Dimensional visualization of construction scheduling and site utilization", *Journal of Construction Engineering and Management*, ASCE, 130 (4), 598-606.

Collier, E. and Fischer, M. (1995). "Four-Dimensional modeling in design and construction," *Technical Report*, *No. 101,* Center for Integrated Facility Engineering, Stanford, 1995.

Collier, E. and Fischer, M. (1996). "Visual based scheduling: 4D modeling on the San Mateo County Health Center," *Computing in Civil Engineering: Proceedings of the Third Congress Held in Conjunction with A/E/C Systems '96,* Ed. Jorge Vanegas and Paul Chinowski, ASCE, New York, pp. 800-805.

Guo, S.J., (2002). "Identification and resolution of work space conflicts in building construction", *Journal of Construction Engineering and Management,* ASCE, 128 (4) 287-295.

Hastings, J., Kibiloski, J., Fischer, M., Haymaker, J., and Liston, K. (2003). "Four-Dimensional modeling to support construction planning of the Stata Center Project", *Journal Leadership in Management,* ASCE, (3), .86-90.

Heesom, D., and Mahdjoubi, L. (2001). “Technology opportunities and potential for the virtual construction site” *umist.ac.uk*, <http://www2.umist.ac.uk/construction/research/management/vircon/publications/VIRCON_Task3_Report_Volume3.pdf> (March 24, 2005).

Kang, H. (2001). “Web-based 4D visualization for construction scheduling,” PhD Dissertation, Dept. of Civil Engineering, Texas A&M University, College Station, TX.

Koo, B., and Fisher, M. (2000). “Feasibility study of 4D CAD in commercial construction”, *Journal of Construction Engineering and Management,* ASCE, 126 (4), 251-260.

Mahoney, J.J., Tatum, C.B., and Kishi, K., “Construction site applications of CAD,” *Technical Report, No. 36,* Center for Integrated Facility Engineering, Stanford University, Stanford. 1990.

McKinney, K., Kim, J., Fischer, M., and Howard, C. (1996) “Interactive 4D-CAD,” *Computing in Civil Engineering: Proceedings of the Third Congress Held in Conjunction with A/E/C Systems ’96,* Ed. Jorge Vanegas and Paul Chinowski, ASCE, New York, pp. 383-389.

Riley, D. (1994). “Modeling the space behavior of construction activities,” PhD dissertation, Dept. of Architectural Engineering, Pennsylvania State Univ., State College, PA.

Riley, D. R., and Sanvido, V. E. (1995). “Patterns of construction-space use in multistory buildings”, *Journal of Construction Engineering and Management,* ASCE, 121 (4), 464-473.

Staub, S., and Fischer, M. (1998). “Constructibility reasoning based on a 4D facility model” *Structural Engineering World Wide*, T191-1 (CD ROM Proceedings), Elsevier Science Ltd.

Williams, M. (1996). “Graphical Simulation for Project Planning: 4D-PlannerTM,” *Computing in Civil Engineering: Proceedings of the Third Congress Held in Conjunction with A/E/C Systems ’96,* Ed. Jorge Vanegas and Paul Chinowski, ASCE, New York, pp. 404-409.

Zouein, P. P., and Tommelein, I. D. (1999). “Dynamic layout planning using a hybrid incremental solution method”, *Journal of Construction Engineering and Management,* ASCE, 125 (6), 400-408.

Zouein, P. P., and Tommelein, I. D. (2001). “Improvement algorithm for limited space scheduling”, *Journal of Construction Engineering and Management*, ASCE, 127 (2), 116-124.

APPENDIX A

INTERVIEW QUESTIONS

Identifying time-space conflict issues

Part 1 Introduction to the project

1. During what time/s would your crew be working on the site? Specify dates. Check the superintendent's schedule. This question is valid only if he does not provide the schedule.
    1. –
    2. –
    3. –
    4. –
    5. –

2. Do you make your own work schedule or use the one provided by the superintendent?
   Refer to Q2

3. List the different trades that will also be working on the site when you are working.

    1. –
    2. –
    3. –
    4. –
    5. –

4. Do you have any knowledge about CPM networks? If not, how do you schedule your work? Describe how do you use the shop drawings and the schedule provided by the superintendent to plan your work

Part 2 Identification of Space issues:

You are provided with the site drawing specific to your trade, overlay drawing, and the work schedule indicating the time you are/were working on the site. Use the drawing and schedule to answer the following questions. You can also use your own work schedule if needed.

1. Describe how are you going to use your work space? Can you divide your work space into parts from most crowded space to least crowded space?

2. List the activities in your trade that had direct interference from other trades working on the site at the same time
    1. –
    2. –
    3. –
    4. –
    5. –

3. List the time (date) of occurrence of all the above mentioned interferences. Also list the duration (hours) of each interference
    6. –
    7. –
    8. –
    9. –
    10. –

4. Describe how each interference (space conflict) affects/affected your work?

Space-conflict issue	Trades involved	Schedule affected (days)	Labor productivity (yes/no)	Extra Cost ($/day)	Require design changes (yes/no)	Rework (yes/no)	Other
1							
2							
3							

Part 3 Resolution plan for each space conflict issue

How are you going to manage the crowded spaces?

1. What adjustments would you do in your work space to accommodate other trades?
    1. –
    2. –
    3. -

2. Would you suggest any adjustments to the other trades? List those
    1. –
    2. –
    3. –

3. What suggestions do you have to the superintendent?

Space Conflict issue	Resolution Plan				
	Schedule change	Change in activity duration (+/- days)	Design change	Change in crew size (+/- number)	Rework plan
1					
2					
3					
4					

Part 4 Comments on the 4D Construction Model

-
-
-
-

Part 5 General Information of the Interviewee

Name:

Category: Project superintendent / Subcontractor

VITA

Name: Narendra S. Nigudkar

Address: 2255 Braeswood Park Drive, # 234,
Houston, Texas 77054

Email Address: narendra@neo.tamu.edu

Education: B.E., Civil Engineering, Pune University, 1998