Feasibility Study of 4D CAD in Commercial Construction

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Abstract: This paper concludes that 4D models are a useful alternative to project scheduling tools like CPM networks and bar charts. They enable more people to understand a schedule quickly and identify potential problems. By developing a 4D model for a commercial construction project, we were able to detect the incompleteness of the original schedule, find inconsistencies in the level of detail among the schedule activities, and discover an impossible schedule sequence. We were also able to anticipate potential time-space conflicts and accessibility problems. The results of the case study show that 4D models are effective in evaluating the executability of a construction schedule. The case study also highlighted the need for improvements to 4D tools. 4D tools should include bar charts, component lists, and annotation tools in their graphical user interface. Automating schedule data preparation and 4D model generation in the design stages of a project can expedite 4D model development and use. Users need to be able to generate 4D models at multiple levels of detail and generate and evaluate alternative scenarios rapidly.

INTRODUCTION

Construction planners typically use CPM-based networks and bar charts to describe the proposed schedule of a project. The CPM schedule helps coordinate the activities of all project team members. Construction activities are associated with one or more components that make up a project. The associations are made explicit in the CPM schedule by delineating each activity with an action/component pair (e.g., install formwork). However, the CPM schedule does not provide any information pertaining to the spatial context and complexities of the project components. Therefore, to identify the spatial aspects of a project, users must look at 2D drawings and conceptually associate the components with the related activities. Because CPM networks are an abstract representation of the project schedule, users need to interpret the activities to comprehend the sequence they convey. This presents two practical limitations of the CPM schedule. First, interpreting the schedule can sometimes be cumbersome as typical schedules have hundreds or thousands of activities, and the assumptions for the precedence relationships are not represented in the CPM schedule. This can make identifying mistakes (e.g., checking the schedule for its completeness and correctness of logic) in the CPM schedule difficult. Second, different project members may develop inconsistent interpretations of the schedule when viewing the CPM schedule. This in turn makes effective communication among project participants difficult.

Such shortcomings of conventional CPM/bar chart schedules have spawned research and development efforts to combine project planning tools with 3D CAD (computer-assisted design) models to convey the sequence of construction visually. Whereas previous visual simulations using computer graphics have been confined mainly to enhancing the product design, recent research has incorporated graphical illustrations to assist planners in the process design. For example, Cleveland et al. (1989) developed the ''Walkthru'' system, which animated 3D computer models in real time to view the construction process. Retik et al. (1993) have used nonimmersive desktop VR (virtual reality) techniques and projection VR presentations to simulate the construction process.

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At the Center for Integrated Facility Engineering (CIFE) laboratory at Stanford University, research is being conducted for the development of a *4D CAD* model. A 4D CAD model results from the linking of 3D graphic images to the fourth dimension of time. In the 4D model the temporal and spatial aspects of the project are inextricably linked, as they are during the actual construction process (Fischer 1995). Such a model allows planners of the construction process to visualize the construction process as it would be actually built.

Together with a group of M.S. students, we conducted a retrospective case study to substantiate the effectiveness of the 4D model in conveying a construction schedule. We first studied the 2D drawings and an as-planned schedule of a commercial building project to identify any potential problems in the proposed schedule. We then created the 4D model using the initial schedule so that the 4D model would visually show the same project sequence. Viewing the 4D model, we found several problems we had previously overlooked in the CPM schedule. Finally we verified whether any of these problems were encountered by the project managers during actual construction. The results of the comparative analysis showed that 4D models increase the comprehensibility of the project schedule, thereby allowing users to detect mistakes or potential problems prior to construction.

Based on the experiences from the case study, we were able to extrapolate the main benefits 4D models provide as a visualization tool, analysis tool, and integration medium. We also identified improvements to current 4D tools necessary for the more widespread adoption of 4D modeling.

MOTIVATION—CASE EXAMPLE

Overview of Case Study

We used a commercial two-story office building project as the basis for our case study. Three identical buildings have been contracted to be built. At the time of our research, the first of the three buildings was already completed. During construction, the project managers encountered several problems that they had not anticipated while planning the project. While we knew that the original schedule presented to us was not executable, we did not know the specific problems at the start of this retrospective case study. By analyzing the 4D model of the first building, we would try to detect these problems and provide recommendations to improve constructibility for the two remaining buildings.

We generated a 4D model using the project documents (i.e., CPM-based bar chart schedule of master plan, 2D drawings, pictures of specific stages of construction) provided by the general contractor. Fig. 1 shows the overall system architecture for generating the 4D model. We used a 4D-simulation appli-

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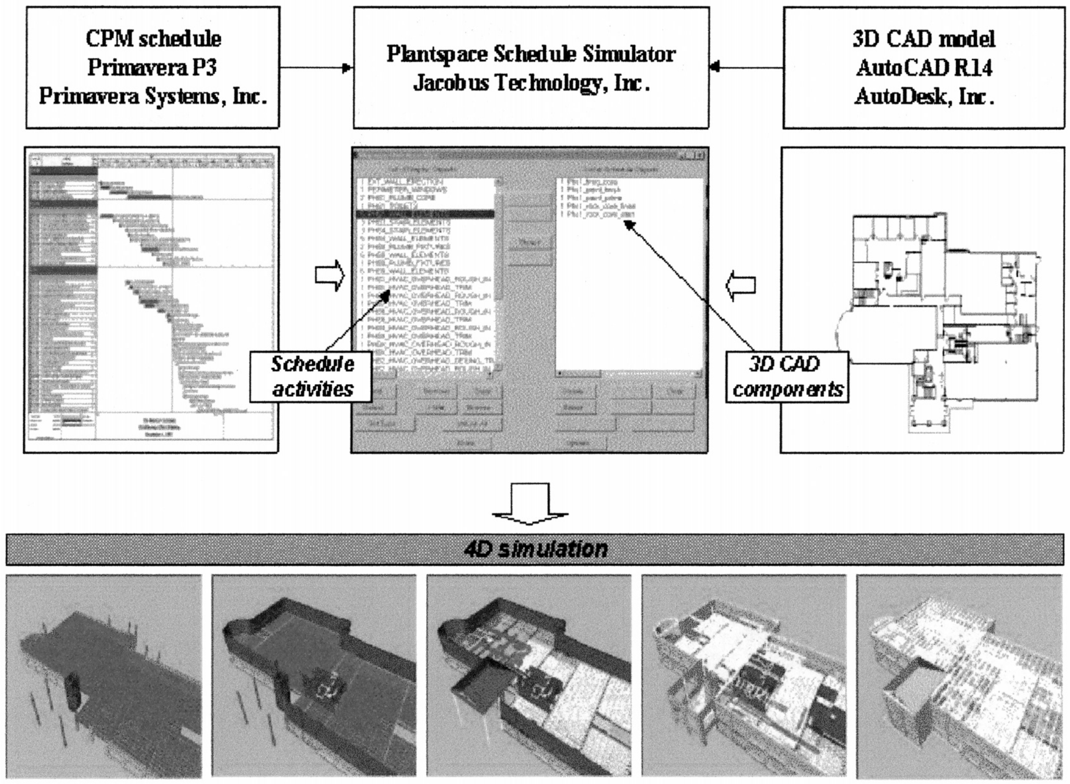

FIG. 1. Overall System Architecture for 4D CAD Model Development

TABLE 1. Hours Input in Developing 4D Model for Case Project

Development stages (1)	Hours of work input (2)
Preparing the schedule data (component breakdown)	12 h
3D CAD model drafting (24,360 3D CAD entities): see Table 2 for details	69 h
Plantspace 4D Visualization Toolkit	
• Comprehending the simulation application	8 h
• Setting up classes and libraries	5 h
• Converting external files (CAD and schedule files) into JSM files	7 h
• Establishing relationships between CAD objects and schedule objects	3 h
4D model analysis	15 h
Total hours	119 man-hours

cation, the PlantSpace Schedule Simulator (Jacobus Technology, Inc.). We converted the 2D CAD drawings into a 3D CAD model using AutoCAD R14. The schedule of the project was represented with Primavera's P3 scheduling software. The Schedule Simulator imports the schedule and CAD data and allows users to link the activities with their related components. The resulting 4D model displays the construction sequence by showing consecutive 3D CAD drawings as time progresses.

Converting the 2D drawings into 3D CAD models (24,360 3D CAD entities) took about 70 man-hours. Preparing the schedule data took about 12 man-hours. Learning to use the Schedule Simulator and establishing relationships between CAD objects and schedule objects took 23 man-hours. Once the 4D model was built, we evaluated the project plan with the 4D model. While reviewing the 4D model, we focused our efforts on detecting possible problems due to spatial restraints or other constructibility issues. We then compared these problems to the actual problems the project managers encountered during construction. Including the analysis of the 4D model, the execution of the test case took about 120 man-hours of work (Tables 1 and 2).

Project Description

Building Configuration

Fig. 2 shows the configuration of the office building. The building consists of four office spaces for each floor with a core structure in the center including bathrooms and a single elevator shaft. The two-story lobby is situated on the South side, providing access to the building via the elevator and a staircase. Two perimeter staircases are located at the West and East wing of the building. The site cast panels, roof screen system, and the gable roof of the lobby were prefabricated adjacent to the site and erected with a single crane.

Schedule Description

The level of detail shown in the master schedule was appropriate in conveying the overall progression of the project (approximately 300 activities). The master schedule showed activities representing exterior components in the first section and the activities for interior systems (Mechanical, Electrical, Plumbing, and Finishes) in the following sections. The project managers organized the activities for the interior MEP systems into their appropriate phases (Fig. 3). However, a notable disparity existed between the level of detail with respect to the exterior and interior work. The activities representing the exterior components were not detailed enough to represent the sequence of work for the foundation and exterior framing of the building. On the other hand, the schedule went into much more detail in describing the interior installations.

During interior work, several subcontractors typically have to work concurrently in the same or adjacent workspaces to shorten the overall project schedule. To minimize the potential conflicts among the subcontractors while still providing them with a continuous flow of work throughout the project, the

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TABLE 2. Hours of Input Required in Drafting 3D CAD Models from 2D Drawings

3D CAD files (1)	Square meter (sq. ft) of each floor area (2)	File size (AutoCAD r14 file) (3)	Number of 3D CAD entities (4)	Man-hours of work for input (5)
1. First-floor exterior walls and inner partitions	2,126 (22,875)	771 kb	1,893	11 h
2. Second-floor exterior walls and inner partitions	2,126 (22,875)	710 kb	1,142	10 h
3. Second-floor slab, frames, and trusses	2,126 (22,875)	690 kb	2,798	13 h
4. Roof floor slab, frames, and trusses	2,126 (22,875)	320 kb	1,136	8 h
5. First-floor MEP systems (HVAC + Electrical + Plumbing)	4,369 (47,006) (2,126 + 2,126 + 117)	1,365 kb (521 + 624 + 220)	1,092 (854 + 228 + 10)	7 h
6. Second-floor MEP systems (HVAC + Electrical + Plumbing)	4,369 (47,006) (2,126 + 2,126 + 117)	1,827 kb (898 + 724 + 205)	3,138 (1,354 + 1,770 + 14)	13 h
7. Roof equipment (RTU's, mechanical screen)	340 (3,675)	591 kb	608	4 h
8. Lobby walls, staircase, and elevator	121 (1,301)	2,426 kb	3,853	15 h
Total	26,207 (373,470)	8,700 kb	24,360	69 man-hours

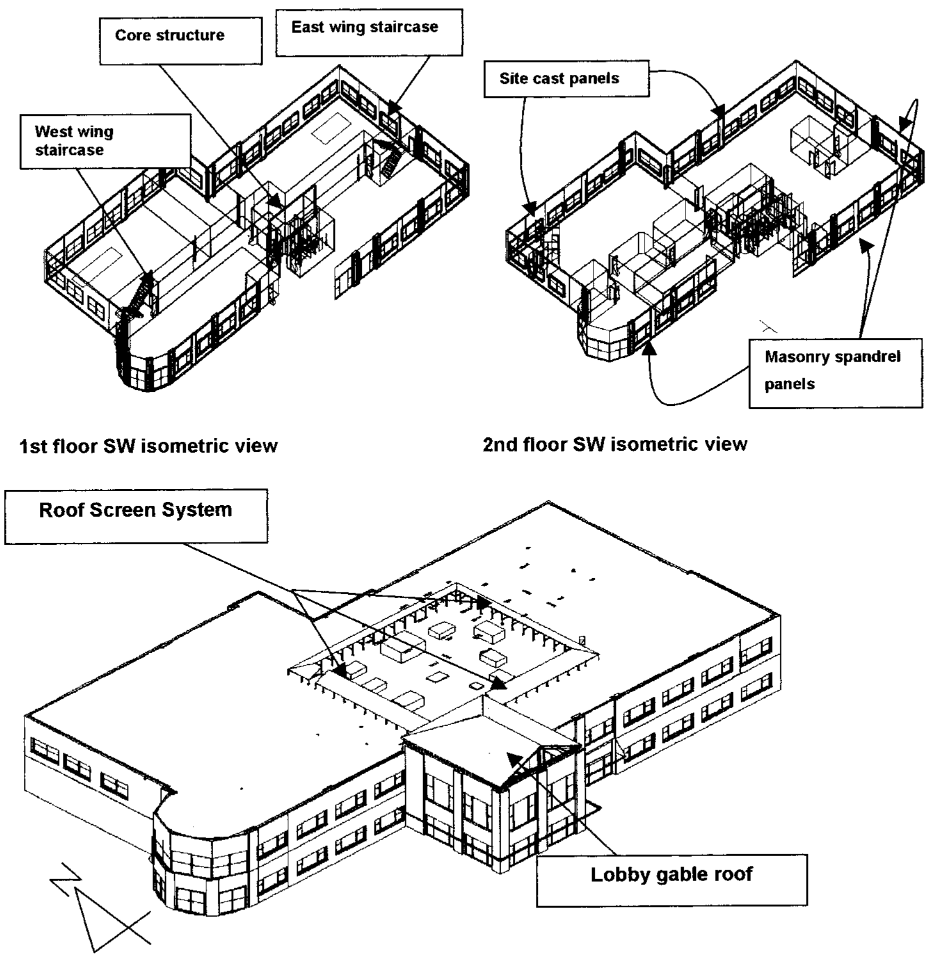

FIG. 2. Building Configuration of Office Building

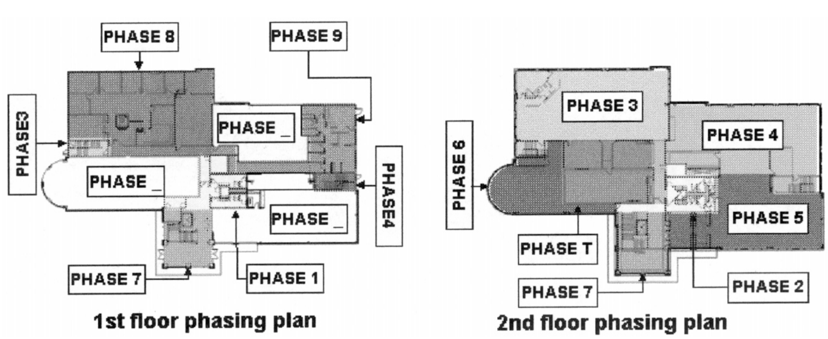

FIG. 3. 1st- and 2nd-Floor Phasing Plan

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project managers divided the workspace into several sections on each floor. As shown in the floor phasing plans (Fig. 3), the building was partitioned into 11 separate sections (phases 1 to 9 plus phases T and C). (Note: The phases with no numbers assigned are sections of the building that have not been leased to customers; Therefore these sections have not been scheduled for interior finishes.) The project managers organized the schedule to reflect these subdivisions. They also coordinated all the subcontractors so that the minimum number of subcontractors would be working in a phase at the same time.

Difficulties in Detecting Problems through CPM Schedule

Our research team first looked at the master schedule of the project to determine whether we could identify potential problems. We were not able to detect any problems. Maybe because of the students' limited construction experiences, we found it difficult to conceptualize the construction process by viewing the CPM schedule alone. We found it cumbersome to associate each component in the 2D drawing with its related activity or activities in the schedule. Another problem was that each student had slight variations in the interpretation of the schedule. This made it difficult to communicate and discuss whether a certain problem actually existed or not.

Problems Detected through 4D Model

The following sections describe the problems we discovered through the analysis of the original schedule with the 4D model. We were able to discover inconsistencies in the level of detail among activities in the schedule and identified missing activities. We also identified errors in the logic of the schedule, potential time-space conflicts, and accessibility problems. For each problem we suggest how to adjust the original schedule.

Consistency in Level of Detail of Schedule

We believe that it is important for a schedule to have a consistent level of detail for its activities. A master schedule does not need to and in most cases should not describe every small activity that occurs on a project. Instead it should have primary activities encompassing a set of other secondary activities that represent that primary activity in more detail. The master schedule should have activities that properly represent the work breakdown hierarchy so that the schedule's activities can be elaborated once more detail is required. Such consistency in a CPM schedule is important for users to be able to understand the logic of the schedule. However, it can be difficult to determine whether all activities in the schedule represent appropriate level of detail (i.e., whether they are on the same level in the breakdown hierarchy) from a CPM schedule alone. When we studied the master schedule for the project in the CPM format, we realized that the level of detail between the activities associated with the building's exterior elements was different from those associated with its interior elements. However, we could not decide which of the levels of detail was appropriate in conveying the overall flow of work. When we viewed the schedule in the 4D model, we were able to identify the inconsistencies in the level of detail among the schedule's activities quickly and were able to determine what level of detail was appropriate. The 4D model showed that the level of detail for the exterior elements was not sufficient to show a clear view of how these elements were actually built. The activity *erect structural steel* provides a good example. This single activity represented the erection of structural beams and columns of the entire building, the frames and trusses of the second floor and the roof. All of these components were associated with a single activity with a duration of 15 days. The situation was similar for the *site cast panels* and the *masonry spandrel panels* (Fig. 3). The site cast panels were cast on top of the foundation so that once fully cured, they could be tilted up into their position.

This was an innovative method incorporated by the project manager to reduce the transport and installation time of the site cast panels. In the schedule, casting the site cast panels was again associated with a single activity (site cast panels) with a duration of nine days, and their installation was represented by another activity (erect site cast panels) with three days of duration. The erection of all masonry spandrel panels was also represented as a single activity with a duration of 10 days. As a result, the 4D model did not convey the installation of the exterior components of the building in a sequential fashion, but rather these components were grouped together and appeared on the screen at the same time.

In summary, the 4D model made it easy to verify the consistency and appropriateness in the level of detail of the construction activities. More detail is required to convey the construction of the exterior components. The erection of the structural steel frame, trusses, and frames of the second floor and roof should be represented by separate activities. The installation sequence of the site cast panels and the masonry spandrel panels should also be represented by more detailed activities. The current level of detail is not sufficient in describing the sequence of how these exterior components were actually built.

Omission of Activities in Schedule

It is critical for construction planners to create a schedule so that all components of the project have related activities. However, confirming that all associations exist can be a time-consuming process because of the sheer number of components and related activities in a project. We could not determine whether the schedule was complete by viewing the CPM schedule. However, when we viewed the 4D model we could immediately see which components did not have related activities in the schedule.

Fig. 4 shows a screen shot of the 4D simulation at the start of the project. Normally, no components should appear on the screen. However, several components are still displayed. This means that these components have not been linked to an activity, i.e., no activity exists to build them. The doors of the interior partitions and portions of the electrical fixtures (furns, fix-strips, cable trays) were not given activities in the schedule although they were shown in the 2D drawings. The 4D model is a good way to check that everything in the design (i.e., 3D CAD model) is related to at least one activity. This provides an easy visual check that the schedule does indeed include activities for the whole scope of the project as represented in the 2D and 3D CAD models.

The activities for these components need to be added to the master schedule. The project managers acknowledged these omissions in the schedule and notified us of when the components had actually been installed. The doors were installed after each phase of the MEP systems was completed. The electrical fixtures were installed at the same time the electrical overhead components were being installed for each phase.

Problems Related to Logic of Schedule

It can often be difficult to identify activities that are out of sequence in the CPM schedule. This is because activities with mutual dependencies (i.e., predecessor and successor relationships) may be located in different parts of the schedule. As the 4D model displays components when and where they are built,

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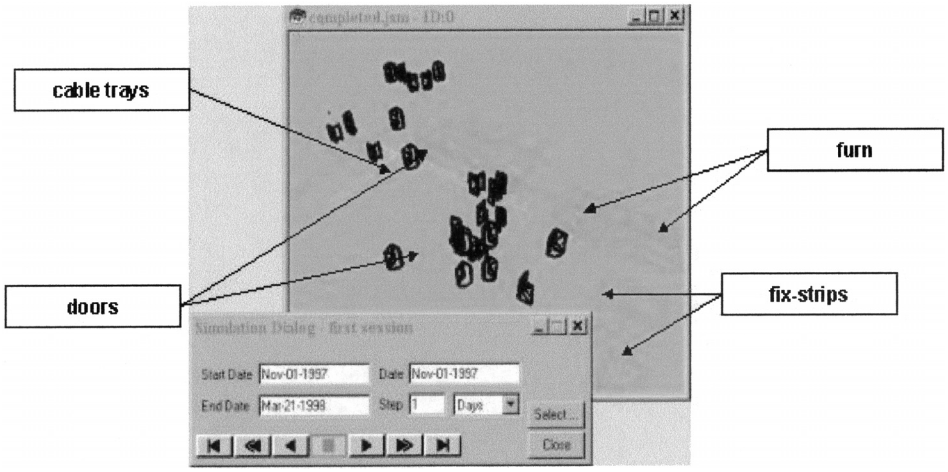

FIG. 4. 4D Model Showing Components Not Related to Activities in Master Schedule

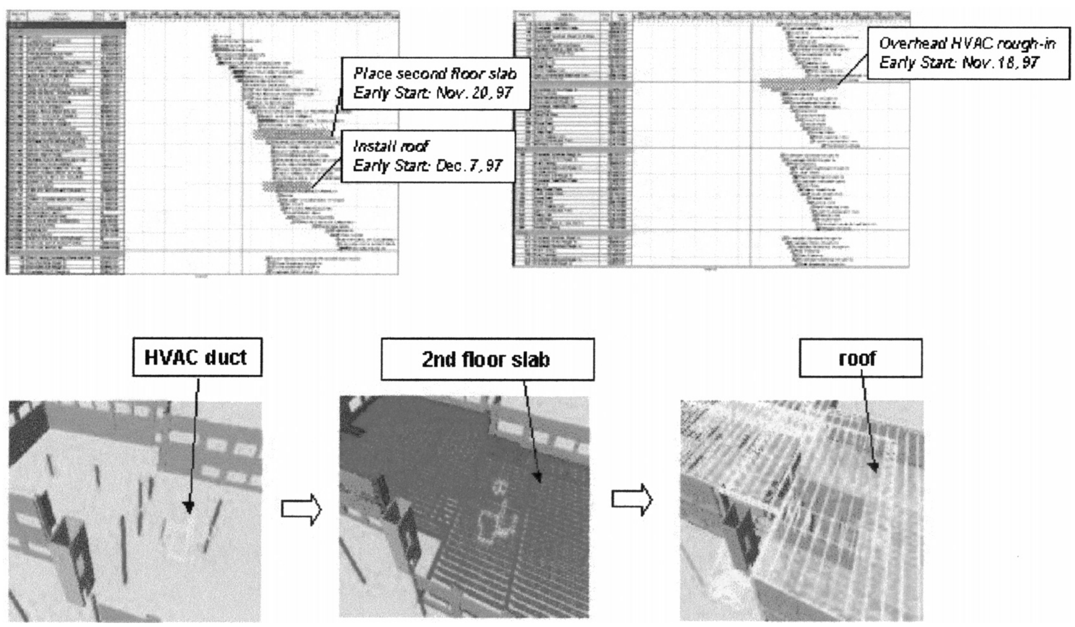

FIG. 5. 4D Model Showing HVAC Ducts Being Installed prior to 2nd-Floor Frame and Truss and Roof

it clearly shows whether the activities in the schedule have been properly sequenced. The following are descriptions of two problems in the logic of the schedule identified by viewing the 4D model:

1. The overhead HVAC system for phase 2 was scheduled to be installed before the second floor slab and truss frame were completed (Fig. 5). There would not have been a platform on which the workers could have worked. Furthermore, as the roof frame had not been installed, there would not have been support from which to hang the HVAC ducts. This is an obvious oversight in the logic of the schedule. Activity *phs2_hvac_overhead* needs to be delayed until the second floor slab, truss frames, and roof frames are installed.
2. The HVAC and electrical subcontractors are working on phase T of the second floor while the roof is still being installed. Because roof installation is not completed, there is no protection for phase T work from the weather even though the execution dates are in the winter season (December 8–15). Since the site is located in Colorado, it is crucial for the work to have weather protection. Conversely, while installing the roof slab and truss frames, no other work is done in other phases apart from the lobby (phase 7) and phase T of the second floor. No work is scheduled on the first floor, which would have coverage from the weather. The schedule could be adjusted so that the HVAC and electrical subcontractors can work on the first floor instead of phase T of the second floor.

Problems Related to Time-Space Conflicts

When generating or evaluating the schedule, construction planners must ensure that work crews have sufficient workspace. Multiple crews working in a limited workspace may decrease each other's productivity rates, which can lead to delays of the entire project. CPM schedules do not convey whether time-space conflicts may exist, because they do not convey the spatial aspects of the project.

The 4D model can be used to predict possible spatial interference of crews. The master schedule showed three activities (*electrical rough in*, *overhead HVAC rough in*, and *plumbing rough in*) executed at the same time. By viewing the schedule alone, we could not determine whether such a sequence would create congestion among the workers. In the 4D model, we could forsee that three different crews would have to work concurrently in a limited space; therefore conflicts might exist in this area (Fig. 6).

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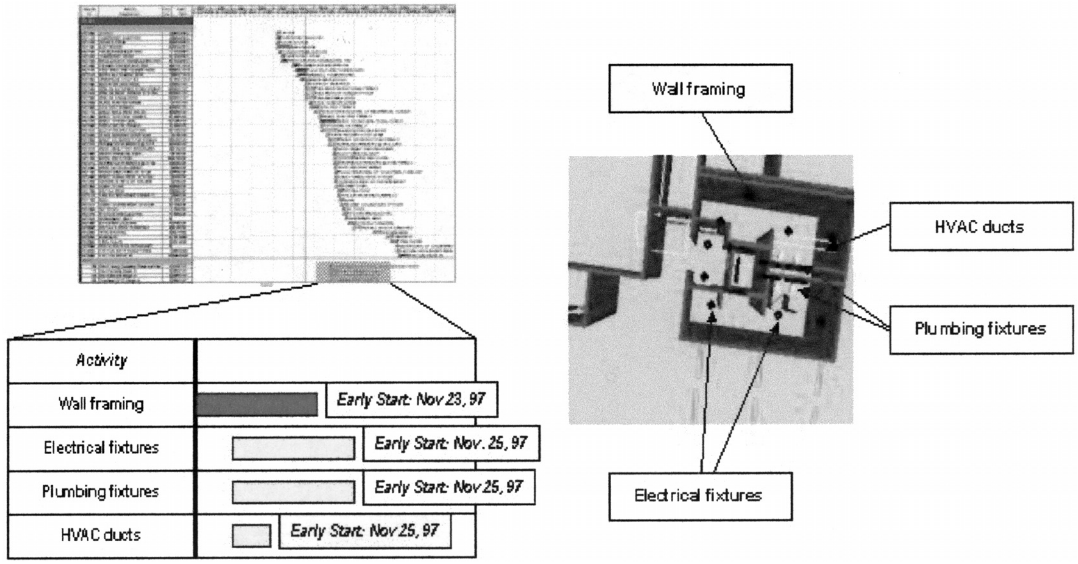

FIG. 6. 4D Model Showing Concurrent Activities Being Installed within Restricted Workspace

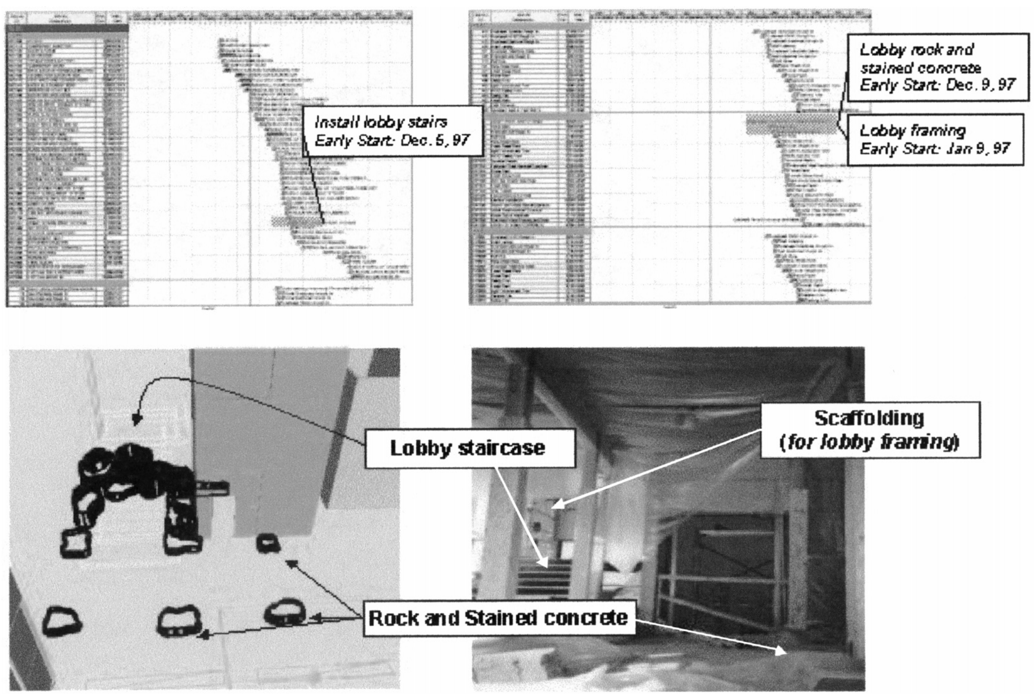

FIG. 7. Snapshot of 4D Model and Picture Showing Possible Accessibility Problems Due to Early Installation of Stained Concrete

Accessibility Problems

We detected a possible accessibility problem in the lobby area. The lobby stairs were installed during the early stages of construction, most probably to provide access for construction of the second floor. However, the subcontractors could not access the second floor through the lobby stairs while the activity *lobby stained concrete* was performed (Fig. 7). This conflict could cause delays for the second floor subcontractors and the workers installing the stained concrete in the lobby.

A possible solution would be to reroute the second floor workers so that they may use the perimeter staircases. In the original schedule, the perimeter staircases are installed after most of the lobby components are installed. Therefore, a solution would be to install the perimeter staircases at the East and West wing earlier than shown in the original schedule and before the second floor work begins.

Actual Problems Encountered during Construction

After viewing the 4D models to evaluate the schedule and detect potential problems in the schedule sequence, we consulted the project managers and asked them about the actual problems they faced during construction. The two major problems were the congestion in the lobby area and the imbalance of work for the interior phases of the project.

Congestion in Lobby Work Area

One of the problems was the congestion in the lobby area. The project managers installed the lobby stairs early in the project to provide access for the subcontractors working on the second floor. However, the subcontractors could not use the stairways while the stained concrete in the lobby was being installed. Scaffolding erected in the lobby area for the paint subcontractors further compounded the problem. Specifically,

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the drywall frame, rock, and finish subcontractors kept well on schedule through phases 3, 4, and 5. However, the installation of rock, stained concrete, and scaffolding for the lobby interior construction delayed the drywall subcontractors from moving on to phase 6.

Imbalance of Work for Interior Phases

Another problem was the imbalance of work scheduled for each phase. The project managers had tried to size the work areas so that the installation time for all the subcontractors would be similar for each phase of the project. However, the amount of time required for each phase turned out to be quite different for each subcontractor. The working space for each section of the building was derived from the space requirements of the MEP, wall frame, rock, and finish subcontractors. The project managers assumed that the allotted spaces would be sufficient for all other subcontractors to work at their expected productivity rates and scheduled the activities accordingly. However, the finish crews working in a horizontal plane (carpet, ceiling grid, and tile subcontractors) required approximately twice the allotted space of each phase to work at the expected productivity level. The limited space decreased the productivity level of these subcontractors, which in turn prolonged their time to install their work for each phase.

During our analysis of the 4D model, we were able to detect that congestion may exist in the lobby area, but could not identify whether an imbalance of work existed for the work crews for the interior phases of the project. This indicates that the 4D model is useful in conveying which components are being built at a certain time and location. However, the 4D model does not convey all the planning information that is required to evaluate all aspects of the construction process. It does not show the workspaces required for each activity nor the relationship between production rates among subcontractors. Furthermore, unless the contractor adds scaffolding and other temporary structures to the 3D model, the 4D model does not show the space needs and corresponding potential congestion of temporary works.

Assessment of Case Study

Based on the results of the case study, we can conclude that the 4D model enables even relatively inexperienced users to identify problems previously overlooked in the original schedule. The 4D model was effective in verifying the correctness of a schedule, i.e., verifying the completeness of the schedule, the consistency in the level of detail of the schedule, and the logic of the schedule activities. The 4D model clearly conveyed the spatial complexities of the project. Therefore, it allowed us to verify whether a component can be physically placed or whether crews can work in a certain location. We were able to identify a time-space conflict and anticipate an accessibility problem because the 4D model conveyed the spatial implications of a component being installed at a certain time and location.

Through the case study, we also discovered limitations in the development and analysis stages of the 4D model. Developing the 4D model involved categorizing the activities of the original schedule, creating 3D CAD models from 2D drawings, and creating relationships between the activities with the 3D CAD model components in a 4D-simulation application. This process was quite labor-intensive (Tables 1 and 2).

While analyzing the 4D model, we needed to step through the simulation with the CPM schedule to comprehend the construction process. Viewing the 4D model alone made it difficult to comprehend the current status of the project (i.e., which components were being installed, which activities were being executed).

As mentioned, the 4D model does not convey all the information required to evaluate the schedule. When evaluating a schedule, users need to know *why* activities have been sequenced in a certain way. Activities are sequenced because of physical or nonphysical constraints. Users can infer the physical constraints in a 4D model (e.g., they can infer why a column has been sequenced before a beam by viewing the spatial implications in the 4D model). However, other activities are sequenced because of nonphysical constraints. For example, activities may be sequenced in a certain order because of resource availability or a specific construction method. 4D models do not inform the viewer of such constraints.

Furthermore, the 4D model does not convey all the planning information represented in the CPM schedule. The 4D model does not alert users to the availability of float for the activities in the schedule. The 4D model does not show activities that do not have corresponding components. For example, there is no effective way of conveying the activity *Inspection* in the 4D model. One can use a particular color to show all the components or areas under inspection at a given time, but it quickly becomes difficult to remember the meaning of all the colors. The 4D model becomes ''cluttered'' quite rapidly if each action on a component is shown with a different color.

Current 4D models convey only one perspective of the project and can only be viewed at a single level of detail. This makes it difficult for multiple participants of a project to use the model for their purposes.

Developing alternative scenarios enables project members to simulate different sequences so that they can view which solution is most adequate for a given situation. However, current 4D tools do not support the rapid generation of alternative scenarios. When users wish to make a change to the 3D CAD model or schedule, they need to refer back to the schedule and the 3D CAD models in their separate applications. This limitation restricted our ability to view and investigate multiple options to resolve the detected problems.

ADVANTAGES OF USING 4D CAD AS PROJECT PLANNING TOOL

Based on the experience gained from the case study, the following section discusses the advantages of using a 4D model for construction planning. The discussion is presented with respect to the 4D model's ability to convey planning information (*visualization tool*), enhance collaboration among project participants (*integration tool*), and support users to conduct additional analyses (*analysis tool*).

Using 4D Model as Visualization Tool

The 4D model obviates the need to conceptualize the association between components and activities to comprehend the schedule. The 4D model also shows the spatial constraints between components, enabling users to detect space-related conflicts.

Visualizing and Interpreting Construction Sequence

Although bar charts and CPM networks are the most prevalent method in conveying sequences of activities in the construction industry, there are several alternative scheduling methods in use in different sectors of the industry. The variety of scheduling methods indicates that some methods are better at conveying the sequence than others for particular projects. For example, the time space scheduling method, or vertical production method (VPM), is often used for scheduling projects that consist of repetitive activities and for scheduling the work in sections (Stradal et al. 1982). The reason for the specific use of a scheduling method for certain projects is simple:

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it conveys the information more clearly for the participants involved (i.e., owner, architect, engineer, general contractor, subcontractors, vendors, etc.). Put in another way, a particular scheduling method makes it relatively easier to ''visualize'' or ''conceptualize'' the sequence of activities for certain situations.

Regardless of the nature of the project, however, most scheduling software used in the AEC industry (Primavera P3, Microsoft Project, etc.) generates CPM-based bar charts. Such schedules force users to visualize and interpret the activity sequence in their minds. Therefore, multiple participants of a project must individually conceptualize the sequence by associating the activities with the components shown in 2D drawings. The interpretation of the schedule can vary according to the level of experience, knowledge, and individual perspective of the participants. The problem is compounded because schedules do not convey the thought processes that went into developing them. Inconsistencies in the interpretation of a schedule can create miscommunication among the participants. As the 4D model displays the actual project being built, there is no need to select a particular scheduling method that will best represent the construction sequence. Nor is there a further need to use to 2D drawings and the schedule to conceptualize the sequence of activities. The 4D model obviates much of this interpretation process and allows users to view the two separate documents through a single medium.

As all the participants are now working on and communicating with the same model, the disparity in their experience or knowledge of the project is less important, as it is less likely to lead to varying interpretations. Better perception of the schedule can improve collaboration between project members and make it more likely that potential problems are detected prior to construction.

Conveying Spatial Constraints of a Project

Although spatial constraints between activities are important, today's stand-alone CPM scheduling tools do not model these relationships effectively. CPM schedules model the temporal dependencies between activities explicitly. However, interferences that might occur between activities due to the sharing of common workspace are not represented and cannot be detected (Akinci et al. 1997). This is achieved only through the conceptualization of the schedule by construction managers, who rely on their experience to anticipate time-space conflicts and incorporate them into the schedule. Accordingly, CPM schedules can represent spatial constraints only as logical relationships and do not communicate the specific nature of, or reason for, such relationships. If space-related conflicts are not identified during planning, it is likely that an optimistic schedule will be developed that is not workable in reality. If these conflicts are left to be resolved during the construction stages, the project managers may be faced with time and cost overruns.

In addition to displaying the logic (temporal dependencies) among activities of a schedule, the 4D model shows spatial constraints on the site and in the building. Whereas CPM schedules can only convey *what* is built *when*, the 4D model shows *what* is being built *when* and *where*. It therefore allows users to verify whether a component can be physically placed or whether crews can work in a certain location. Detecting a time-space conflict or anticipating an accessibility problem is made possible because the 4D model conveys the spatial implications of a component being placed at a certain time and location.

For example, in the case study we were able to anticipate a simple time-space conflict. Time-space conflicts occur when work crews of different specialties working on concurrent activities have to share a common workspace and therefore interfere with each other. This can decrease their productivity as well as prevent the execution of one or more affected activities (Akinci et al. 1997; Thabet and Beliveau 1997).

The 4D model allows users to view the temporal, spatial, and logical information through a single medium on the screen. With CPM schedules, construction planners must keep track of the spatial implications between activities and components in their heads only. The 4D model can clearly manifest problems relating to space restrictions.

Using 4D Model as Integration Tool

The traditional building process and the medium through which information is exchanged restricts collaboration among the designers and builders of the AEC industry. The building sector of the construction industry relies heavily on subcontracting work to specialty contractors. Therefore clarity in communication among the multiple participants involved is critical for the success of the project. However, the typical facility delivery process is sequential in nature. Designers produce a design that is input for construction managers, who produce schedules that are then used during construction. Such a process results in a fragmented and linear facility delivery process with minimum feedback between the design and construction entities. This is the classic construction problem where early design decisions have a large impact on cost of construction, but these decisions have to be made in a phase in which it is still unknown how and by whom the building will be constructed (Ahuja and Walsh 1983; Ferry and Brandon 1992).

Recent research has focused on the application of information technology (IT) as a way to facilitate the integration process of all parties involved in the planning process. Visualization was recognized as one of the most important tools for achieving this goal (Fischer 1997). As clients demand faster delivery and higher quality, the requirement for better integration of design and construction, also called Design for Construction (DfC), is growing (Luiten and Fischer 1995). Integration of design and construction is achieved by formalizing and standardizing the information exchanged between project participants, and by promoting interaction among them. The following section discusses how project members can use the 4D model to exchange design and planning information, and how the 4D model encourages collaboration among project members.

Formalizing Design and Construction Information

There is a lack of standardization in the information used by designers and the builders. Different professionals interpret 2D drawings differently and therefore do not necessarily discover inconsistencies. To make matters worse, designers and builders often use different sets of drawings (i.e., design drawings versus shop drawings). Whereas design drawings are structurally oriented, shop drawings are more construction oriented. Although effective planning of the construction sequence is critical for the project to save costs, designers do not always notice how their design will affect the building sequence. They are also not as familiar with CPM schedules as their construction counterparts and can find it difficult to comprehend the logic of the schedule sequences.

Project members can use 4D models to escape from the limitations of the 2D drawing and paper document paradigm deeply embedded in the AEC industry. The designer and builder can and must both work with the same models when viewing the 4D model, which eliminates the use of separate drawings. Because the geometric and planning information is conveyed through a single medium, both entities can benefit from viewing the other's perspective.

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Promoting Interaction among Project Participants

Because many issues that are not always addressed during today's planning process must be resolved when building the 4D model, this naturally encourages interaction between the designer, planner, and builder. Luiten and Fischer (1995) state that 4D models are especially useful providing feedback on a building design from the construction perspective. If the 4D model is built in the early planning stages of the project, the construction planner can review alternative scenarios to decide upon the best construction method that is most cost effective and time saving. On the other hand, the construction planner can provide feedback to the designer by performing feasibility studies and determine which design is most appropriate for the selected construction method.

By building the 4D model, users can evaluate the schedule but also detect design restrictions that force the schedule to be sequenced in a certain way. Construction planners can alert designers of the problems by showing the 4D model and the problems they will face because of the design. In this respect, the 4D model increases communication between the design and construction entities and serves as a collaboration tool.

Using 4D Model as Analysis Tool

Generating the 4D model involves significant work-hours and also creates additional up-front costs to the project. The 4D model must be able to convey issues to the construction planner that can save time and ultimately lower the total cost of construction. The 4D model can reduce costs to the project by supporting the early detection of problems, such as time-space conflicts, safety issues, and site workspace restrictions. As a result, planners can formulate more realistic schedules and cost estimates. It also allows the construction planner to decide upon the most appropriate construction method by generating alternative construction scenarios.

Anticipating Safety Hazard Situations

Safety hazards at the construction site can be one of the main causes of unanticipated additional costs. Indeed, the slim profit margins with which general contractors often work can quickly disappear with a single accident on site. Many construction companies stress safety to be the prime objective of a project. As all construction projects are unique in nature and many accidents occur due to unforseeable human errors, it can be difficult for project managers to anticipate all the hazard areas existing on the site. By viewing the 4D model, project managers can detect areas where accidents may occur and execute prevention measures (such as placing warning signs, restricting access, or providing safety guards, etc.). But more importantly, by viewing the time and location of the work through the 4D model, project managers can perceive how separate crews may affect one another and therefore inadvertently create hazardous situations. By showing the 4D model to the crews, the project managers can inform them better of their work and the work of other crews.

Once these problems have been found, project managers can incorporate these findings into the schedule by resequencing concurrent activities into subsequent activities or by adding activities that represent the installation of safety equipment or prevention measures.

Allocating Resources and Equipment Relative to Site Workspace

One of the restrictions project managers face when allocating resources and equipment is the availability of site workspace. Most site workspaces are occupied by trailers, large equipment, and building materials that can clog up the site and hamper maneuverability of the equipment and their related crews. Therefore, using limited workspace economically and effectively can create a significant difference in project time and costs.

Management of site workspace becomes increasingly important when projects are located in urban areas. In some of these projects, project managers can only work on the actual area the building will occupy. In these situations, the project managers need to divide the site into sections so that, while constructing the building for one section, other sections can be used for cranes, backfill, or material storage. The 4D model can make it clear to all affected parties what materials should arrive when, and where they will be stored.

Project managers must also manage material delivery times. Materials should be delivered at the nearest time of installation to minimize delays to other work and to quickly relinquish the space it occupies.

The 4D model can be used to manage site workspace and schedule material delivery times. Project managers can view when and where workspace will be available or occupied, and appropriate the site area accordingly. In this sense, the 4D model can be used as a *spatial timetable*.

Running Constructibility Reviews

As discussed, the 4D model provides a basis for analyzing time-space conflicts, safety issues, and site workspace management. When conducting constructibility reviews, project managers cannot isolate a specific issue but must consider all of these factors together. All of these issues are interdependent. For example, a change in the schedule to resolve a time-space conflict may result in reducing the workspace available for other workers or equipment. The true value of the 4D model lies in the availability to consider all of these factors through a single medium. This is possible because the 4D model shows the logical, temporal, and spatial information of the construction project.

Users can reinforce their analysis by generating and viewing multiple scenarios to determine the best possible approach in alleviating a given situation. This allows project managers to actually view the implications of their decisions, instead of mentally conceptualizing the changes in their minds and speculating whether they will actually work or not.

FUTURE IMPROVEMENTS TO 4D CAD

Through the case study, we discovered several limitations of 4D models and current 4D tools. In response to these limitations, we propose possible solutions and introduce several applications that are being investigated by the CIFE community.

Efficient schedule data preparation and acceleration of 3D CAD model generation are the two major aspects that require the most improvement to expedite the development of the 4D model. Initial decisions concerning the purpose of the 4D model determine the level of detail of the 4D model. Therefore, methods must be developed to assist users in making the appropriate decisions and automating schedule data preparation. To expedite 3D CAD model generation, better CAD tools need to be developed that can automate the repetitive steps involved in creating 3D CAD models.

Network schedules and component lists should be shown together with the 4D model to make comprehension of the project sequence easier. Furthermore, annotation tools are needed to improve the analysis of the 4D model by emphasizing points of import and describing the assumptions that were made in developing the original schedule.

To allow easier and faster generation of alternative scenarios, a research prototype CIFE 4D CAD (McKinney et al.

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1996) has been developed at CIFE. CIFE 4D CAD allows users to manipulate the schedule and CAD data in a single environment, which in turn facilitates the rapid generation of alternative 4D scenarios. The construction method modeler (Aalami et al. 1996), can generate schedules at different levels of detail and subsequently generate multileveled 4D models. To support computer-based analyses of 4D models, semantic 4D models must be developed. These models will support knowledge-based systems that infer potential problems and relay the information to users. The 4D Work Planner (Akinci et al. 1997) is one example of such an application. The 4D Work Planner identifies time-space conflicts, quantifies their impact, and updates the original schedule and cost estimate.

The realization of these improvements will not only allow users to visualize the construction sequence, but also allow them to create, evaluate, and analyze schedules while considering multiple planning information through a single application.

SUMMARY

CPM-based bar chart schedules do not effectively convey the thought processes and assumptions made in generating them. Users must conceptualize the association between components and related activities to comprehend the construction process. The 4D model reduces the need for this conceptualization as it conveys the temporal and spatial aspects of planning information. The 4D model allows easier comprehension of the project plan and allows users to detect possible problems in the schedule. Through the case study, we discovered that the 4D model was particularly effective in determining the correctness of the schedule and in conveying the spatial implications and constraints of project components and their related activities.

By integrating and displaying design and construction information, the 4D model can promote interaction and collaboration between project team members. The 4D model allows designers and builders of a project to evaluate the geometric and planning information through a common medium. The 4D model also supports additional analyses concerning cost, productivity, safety, and resource allocation, which can lead to more realistic schedules and cost estimates.

Developing the 4D model involved categorizing the activities of the original schedule, creating 3D CAD models from 2D drawings, and creating relationships between the activities with the 3D CAD model components in a 4D-simulation application.

Improvements to current 4D models and 4D tools must be made to expedite the generation of 4D models and to aid users in conducting 4D model analyses. Automating schedule data preparation and building the 4D model in the design stages can expedite 4D model development. Functional improvements, such as the insertion of schedule charts, component lists, and annotation tools can aid users in viewing the project sequence and detecting potential problems or conflicts.

The realization of these improvements will allow 4D CAD to evolve into a more economically viable and technically user-friendly tool. This in turn can reduce the reluctance industry members may have toward using 4D models and warrant the 4D model's use as a project planning tool in future construction projects.

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APPENDIX. REFERENCES

Aalami, F., Fischer, M., and Kunz, J. (1998). ''AEC production model: Definition and automated generation.'' *Working Paper 53*, Ctr. for Integrated Facility Engrg., Stanford University, Stanford, Calif.

Ajuha, H., and Walsh, M. (1983). *Successful methods in cost engineering*, Wiley, New York.

Akinci, B., Staub, S., and Fischer, M. (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.

Cleveland, A. B. Jr. (1989). ''Real-time animation of construction activities.'' *Proc., Constr. Congr. I—excellence in the constructed project*, ASCE, New York, 238–243.

Collier, E., and Fischer, M. (1996). ''Visual-based scheduling: 4D modeling on the San Mateo County Health Center.'' *Proc., 3rd Congr. on Comp. in Civ. Engrg.*, ASCE, New York, 800–805.

Ferry, D., and Brandon, P. (1992). *Cost planning of buildings*, BSP Books, London.

Fischer, M., and Aalami, F. (1996). ''Computer-interpretable construction method models.'' *J. Constr. Engrg. and Mgmt.*, ASCE, 122(4), 337–347.

Fischer, M. (1997). ''Visualization technologies.'' *Proc., Global Constr. IT Futures*, P. Brandon and M. Betts, eds., Armathwaite Hall, U.K., 80–84.

Jacobus Technology, Inc. (1997). *Plantspace enterprise navigator: User's guide*, Gainsburg, Md., www.jacobus.com

Koo, B., and Fischer, M. (1998). ''Feasibility study of 4D CAD in commercial construction.'' Master of Engineering thesis, Stanford University, Stanford, Calif.

Kunz, J., Luiten, G., Fischer, M., Jin, Y., and Levitt, R. (1995). ''CE4: Concurrent engineering of product, process, facility and organization.'' *Tech. Rep. 104*, Ctr. for Integrated Facility Engineering, Stanford University, Stanford, Calif.

Luiten, G., and Fischer, M. (1995). ''Opportunities for computer aided design for construction.'' *Tech. Rep. 39*, Ctr. for Integrated Facility Engineering, Stanford University, Stanford, Calif.

McKinney, K., Kim, J., Fischer, M., and Howard, C. (1996). ''Interactive 4D-CAD.'' *Proc., 3rd Congr. in Comp. in Civ. Engrg.*, Jorge Vanegas and Paul Chinowsky, eds., ASCE, New York, 383–389.

Retik, A. (1993). ''Visualization for decision making in construction planning.'' *Visualization and intelligent design in engineering and architecture*, J. J. Connor et al., eds., Elsevier Science, New York, 587–599.

Stradal, O., and Cacha, J. (1982). ''Time space scheduling method.'' *J. Constr. Engrg. and Mgmt.*, ASCE, 108(3), 445–457.

Thabet, W. Y., and Beliveau, Y. J. (1997). ''SCaRC: Space-constrained resource-constrained scheduling system.'' *J. Comp. in Civ. Engrg.*, ASCE, 11(1), 48–59.

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