Leveraging the Power of 4D Models for Analyzing and Presenting CPM Schedule Delay Analyses

Mr. Kevin Coyne, PE PSP

This paper explores the use of 4D models, which provide a virtual construction simulation by linking a 3D model and project schedule, in support of CPM schedule delay analyses. Traditional delay analysis methodologies rely on bar charts or similar graphics for analyzing and conveying the results of complex schedule analyses. This paper supports the fact that the use of 4D models allows scheduling and claims personnel to perform and present more efficient and effective CPM schedule delay analyses during negotiations, alternative dispute resolution, or litigation. The author shares findings from case studies that used 4D models to visually analyze and present as-planned versus as-built CPM schedule delay analyses and time impact analyses. The paper also discusses the benefits and shortcomings of the use of 4D models, as well as additional topics for research.

INTRODUCTION

The architecture, engineering, and construction ("AEC") industry has made significant strides in the implementation and use of new virtual design and construction ("VDC") tools. Building projects in virtual reality during planning, pre-construction, and construction phases of a project can improve a project team's efficiency and assist in the resolution of problems before they become a reality in the field, when the solutions have a higher cost and risk. VDC tools have been used for the early resolution of many problems, such as field conditions that were impossible to describe fully in traditional 2D drawings; unanticipated physical interferences among mechanical, electrical, and plumbing ("MEP") designs; and constructability issues resulting from project phasing issues. However, VDC tools have seen little use in assisting project teams when analyzing project delays and presenting the results of schedule delay analyses. This paper explores how a 4D model, one of many VDC tools, can be used in this capacity during both the construction and post-construction phases.

4D Modeling Overview

Project schedules alone are not detailed enough for performing certain process analyses. Some parameters used for planning are lost once a schedule is created and some schedules are not conducive to considering "what-if" scenarios. 4D modeling solves many of these problems by enabling project teams to simulate the virtual construction of a project. The following sections will provide an overview of 4D modeling and its typical uses.

Standalone 4D Models

Figure 1 depicts the components of a standalone 4D model. These components include a 3D model of the project design, representative of the product, and the project schedule, representative of the process and plan. "Virtual" project models can also incorporate other parameters, such as cost and resources, and are referred to as XD models, where X represents the number of additional parameters included beyond the product and process.
Comparative 4D Models

Comparative 4D models involve the simultaneous review of multiple, yet related 4D models in adjacent computer screen “windows.” The playback of such 4D models is synchronized through the use of internal or external software links. For the most part, the current use of 4D modeling is limited to the review of a standalone 4D model, incorporating a single 3D model and its associated project schedule in a single window. This method of 4D modeling does not allow the user to efficiently and effectively review and compare multiple 4D models related to the same project.

Figure 2 depicts the components related to a comparative 4D modeling scenario that allows the user to perform a visual comparison of a single 3D model and two schedules. This scenario uses one 3D model that is linked to two schedules. This type of comparative 4D model is well suited for use in schedule delay analyses that involve the comparison of schedules, such as an as-planned schedule versus an as-built schedule. This use highlights the benefits of such a tool during all project phases and as a demonstrative aid or graphic in negotiations, alternative dispute resolution, or litigation.
Figure 3 depicts the components related to a comparative 4D modeling scenario that allows the user to perform a visual comparison of two 3D models and their respective schedules. This type of comparative 4D model is best suited for performing “what-if” schedule comparisons during the pre-construction and construction phases, especially when substantiating time entitlement for potential scope growth or design changes. Similar to the first scenario, this scenario is beneficial for use in schedule delay analyses that involve the comparison of schedules, such as an unimpacted schedule versus an impacted schedule.

Figure 3 - Comparative 4D Model Components: Scenario #2 (2 3D Models/2 Schedules)

Uses and Documented Benefits

4D modeling has been used on a myriad of project types, including transportation, general commercial, office and retail complexes, biotechnology, new and retrofitted hospitals, theaters and museums, industrial, manufacturing, heavy civil, and financial facility asset modeling. 4D modeling has been used during all project phases, from pre-construction through post-construction. 4D models have also been created at varying levels of detail, from high-level models used for tenant move management to complex 4D models of MEP systems, such as those found on biotechnology projects.

The use of a 4D model to assess and validate a schedule’s durations, sequencing, or critical path has proven successful. This is due in large part because the 4D model allows the user to visualize many of the parameters that are not easily discernible when reviewing a Gantt chart or critical path method (“CPM”) diagram. It has been documented that the use of 4D modeling has contributed to projects completing on time and within budget, as compared to similar projects without 4D models [2]. The following list provides some of the typical uses and benefits resulting from the use of 4D models during the pre-construction and construction phases:

- **Increase scheduling efficiency and reliability:** The use of a 4D model enables a project team to easily visualize schedule constraints and opportunities for improving the project schedule, as well as recognizing where the major project risks will manifest themselves. In addition, a 4D model enables the project team to rapidly compare alternative “what-if” scenarios.

- **Optimize site use and safety:** The use of a 4D model allows the user to more easily understand and improve the use of work, access, and staging areas over time, as well as to visually assess and review safety plans, erection plans, traffic rerouting plans, and testing plans.
Increase constructability: 4D models assist in analyzing the schedule and visualizing conflicts that are not apparent in Gantt charts and CPM diagrams.

Improve coordination and communication: The construction phase can introduce spatial conflicts that are very difficult to identify when coordination is performed using 2D overlays. The use of 3D and 4D models greatly improves this coordination process. In addition, the overall communication of project scope, sequencing, and construction scenarios is greatly improved through the use of 4D models.

Optimize resource use: The use of a 4D model allows for the optimization of labor and equipment use through the analysis of spatial conflicts among crews and other production elements.

While 4D models have seen increased use in the areas of project planning and coordination, they have seen limited use in the analysis of schedule delays and the presentation of the resulting findings. The subsequent sections of this paper address this area and elaborate on some of the potential uses of 4D models as analytical tools and visual aids for negotiations, alternative dispute resolution, or litigation proceedings.

**CPM Schedule Delay Analysis Methodologies**

The use of CPM schedules has become the accepted standard in the construction industry and courts have recognized their use in assigning causation and in quantifying delays and disruptions on projects:

Today, CPM schedule analysis is an integral part of a claimant’s burden of proof when asserting a delay claim. In a construction delay claim, the claimant bears the burden to show delay and how that delay affected planned performance. Failure to establish both responsibility for and the duration of delays can be fatal to the successful prosecution of a delay claim. In establishing the requisite proof, courts have typically held that an ordinary bar chart is insufficient to identify the project critical path, and as a result, is ineffective to show the cause and impact of the delay [3].

Many scheduling contract specifications identify a particular schedule delay analysis methodology required for analyzing project delays and preparing time extension requests. Regardless of the methodology specified, all recognized schedule delay analysis methodologies share the same common steps (not necessarily in the same order) as the following:

- quantify delays’ identify and analyze issues;
- relate causes and effects; and,
- determine responsibility for delays.

The following sections will address two commonly-used schedule delay analysis methodologies and the ways in which these methodologies and the presentation of their results can be augmented through the use of 4D modeling tools.

**Prospective Time Impact Analysis**

A prospective time impact analysis (TIA) is a methodology used to assess project delays contemporaneously. Prospective TIAs are often the contractually-required means for quantifying the impact due to delays and changes that occur during the life of a project and are a necessary component for ensuring that the project schedule is kept up-to-date. A typical TIA contract provision is as follows:

When change orders or delays are experienced by the contractor and the contractor requests an extension of time under one or more of the contract clauses, the contractor shall submit a written time impact analysis (TIA) illustrating the influence of each change or delay on the contract completion date or milestones, using the current updated project schedule. Each TIA shall include a fragnet demonstrating how the contractor proposes to incorporate the change order or delay into the project schedule. A fragnet is defined as a sequence of new activities and/or activity revisions that are proposed to be added to the existing schedule to demonstrate the influence of delay and the method for incorporating delays and impacts into the schedule as they are encountered [1].
The analysis should also be based on the pertinent facts associated with added or changed work and with the proofs required to support the delay issue: availability of workers, crew size, productivity factors, equipment, and materials [3]. Some of the advantages of this methodology include the provision of a disciplined approach to evaluate the impact of delays or changes, the ability to measure and quantify concurrent delays and cumulative impacts, and the provision of a realistic forecast of project completion dates based on delays or changes.

A typical TIA includes the following steps:

- Update the schedule at the time the change order or unexpected event occurs without considering the change order or unexpected event’s impact on the current schedule update.
- Study the scope of the change or unexpected event.
- Review all contract reference material.
- Prepare an accurate description of the changed condition or the unexpected event encountered.
- Review the current unimpacted schedule update to determine which activities are affected by the change order or unexpected event and how they are affected.
- Prepare a fragnet illustrating the change or unexpected event and define its relationship to the current unimpacted schedule update.
- Insert the fragnet into the current unimpacted schedule update and recalculate the schedule with the change or unexpected event incorporated.
- Compare the current unimpacted schedule update with the impacted schedule update to determine the effect the change or unexpected event has on the schedule update.
- Determine whether any alternatives for mitigating the impact of the change or unexpected event exist.
- If more than one change or unexpected event occurs during the same period, determine and document on a chronological and cumulative basis the time impact caused by each change or unexpected event.
- Prepare a written report and/or presentation of the overall schedule analysis.

Integration of 4D Modeling Tools

This section details the steps from the above list that can benefit from the integration of 4D modeling.

Step 1 involves updating the schedule at the time the change order or unexpected event occurs, without considering the change order or unexpected event’s impact on the current schedule update. A 4D model can be updated throughout the course of construction using a process similar to the one used in developing project schedule updates. As a project schedule is updated, a dynamic link between the schedule and the 3D model allows for the automatic updating of the 4D model. As a result, the 4D model accurately depicts updates to the project schedule that pertain to actual progress, logic, activity durations, and resource allocation.

Step 5 involves the review of the current unimpacted schedule update to determine which activities are affected by the change order or unexpected event and how they are affected. The use of a 4D model during this step allows the user to evaluate, using the 4D visual interface, the physical constraints associated with the change or unexpected event. Many construction contracts require that the contractor’s project schedule be resource-loaded. If such a schedule is incorporated into a 4D model, the resource component of the schedule can be visualized in the 4D model, making it a 5D model. This type of model allows the user to visualize resource information, such as crew size and resource density, associated with the change or unexpected event.

In Step 6 a fragnet illustrating the change or unexpected event is prepared and its relationship to the current unimpacted schedule update is defined. TIAs are often prepared to assess the impact of delays or unexpected events that are not attributable to added scope or design changes. However, when added scope or design changes are involved, the creation of a “3D fragnet” is necessary. This 3D model of the CPM schedule fragnet should reflect the added scope or design changes and be created at the same level of detail as the CPM schedule fragnet. This 3D fragnet offers the user a means to visualize the fragnet and gain a better understanding of how this fragnet will interact with and impact activities in the project schedule.

Figure 4 depicts a 3D fragnet representing a change, in the form of additional piping scope, for an industrial project.
In Step 7 the fragnet is inserted into the current unimpacted schedule update and this schedule update is recalculated with the change or unexpected event incorporated. In the case that a 3D fragnet is created, it is inserted into the 4D model and the 4D model is recalculated with the 3D representation of the change or unexpected event incorporated. In the case that a 3D fragnet is not necessary, due to the scope of the change or unexpected event, the 4D model is recalculated based on the insertion of the schedule fragnet into the current schedule update.

Figure 5 depicts the 3D fragnet, as shown in Figure 4, after insertion into the current 4D model of the project.

Step 8 compares the current unimpacted schedule update with the impacted schedule update to determine the effect the change or unexpected event has on the schedule update. Figure 6 shows a theoretical example of a comparative 4D model used to review the results of a TIA. This 4D model incorporates one 3D model and two project schedules, the unimpacted schedule update and an impacted schedule update. The impact associated with this TIA is a forecasted delay to the delivery of structural steel. This type of comparative 4D model allows the user the option to make visible only the critical path activities, thus focusing on only those activities and 3D model components affected by the impact or impacts. This function is useful for analyzing critical path shifts and changes in float values.
Step 9 involves determining if any alternatives for mitigating the impact of the change or unexpected event exist. In this step, a comparative 4D model provides the user an efficient means by which to analyze multiple “what-if” schedules for mitigating impact and recovering delay, thus allowing for the creation and review of more schedule iterations in the same amount of time as that of a traditional CPM scheduling process. Through the use of a comparative 4D model, the user has the opportunity to compare and visually filter many parameters, such as specific work groups, critical paths, or resource allocation variances, between the schedule alternatives.

Step 11 involves preparing a written report and/or presentation of the overall schedule analysis. One of the greatest documented benefits of the use of a 4D model is the tool’s ability to communicate complex issues through a simple visual interface. Written reports and presentations communicating the results of a TIA are augmented by the incorporation of pictures or videos showing a 4D visual comparison of the unimpacted critical path versus the impacted critical path and the subsequent extension to the contract completion date.

Retrospective As-Planned versus As-Built

A retrospective as-planned versus as-built analysis is performed after delays have occurred, many times during the post-construction phase of a project. This type of schedule delay analysis addresses delays in a chronological and cumulative fashion by measuring planned versus actual performance to identify and quantify critical delays. Some of the advantages of this methodology include the ability to track “shifts” in the project’s critical path and determine concurrent delay.
Typical Analysis Steps

A typical as-planned versus as-built analysis includes the following steps:

- Identify the planned schedule to be used and assure that it is reasonable.
- Assemble an as-built schedule. Depending on the requirements of the schedule delay analysis, the level of detail of the as-built schedule can vary.
- Conduct an as-planned to as-built comparison in chronological order, finding start delays, start gains, production delays, and production gains, thus identifying the as-built critical path.
- Calculate the total delay by adjusting for concurrency and summing individual activity delays and gains.
- Allocate delays (gains) to the proper party based on the facts and contemporaneous project record. And,
- Prepare a written report and/or presentation of the overall schedule analysis.

Integration of 4D Modeling Tools

This section details the steps from the above list that can benefit from the integration of 4D modeling.

Step 1 involves the identification of the planned schedule to be used in the analysis. It is important that this planned schedule be assessed to ensure that it is reasonable. The use of a 4D model to assess and validate a planned schedule’s durations, sequencing, or critical path has proven successful. This is due in large part because the 4D model allows the user to visualize many of the parameters that are not easily discernible when reviewing a Gantt chart or CPM diagram.

In Step 3 an as-planned to as-built comparison is conducted in chronological order, finding start delays, start gains, production delays and production gains. This process involves performing these calculations on multiple float paths in the schedule, which can become onerous. Streamlining of this process can be achieved by utilizing a 4D model to color-code, and easily visualize, the activities on different planned float paths. Subsequently, the activities on different as-built near-critical paths can be color-coded to check for concurrent delay. In addition, if a resource-loaded schedule is incorporated into the 4D model, the 5D model can be used to isolate, through color-coding, the resource-driven critical paths.

Step 6 involves preparing a written report and/or presentation of the overall schedule analysis. One of the greatest documented benefits of the use of a 4D model is the tool’s ability to communicate complex issues through a simple visual interface. Written reports and presentations communicating the results of a schedule delay analysis are augmented by the incorporation of pictures or videos showing a 4D visual comparison of the as-planned critical path versus the as-built critical path.

Figure 7 depicts the components associated with a comparative 4D model that provides a 3D visual comparison of an as-planned schedule and an as-built schedule. This scenario uses one 3D model that is linked to the two schedules.
Figure 7 - As-Planned versus As-Built Comparative 4D Model Components

Figure 8 shows a theoretical example of a comparative 4D model that incorporates an as-planned schedule and an as-built schedule. In this particular example, the user is able to clearly visualize a critical delay to a section of the project’s structural steel erection.

Figure 8 - As-Planned versus As-Built Comparative 4D Model
Currently, a 4D model’s greatest contribution to the area of schedule delay analyses is in the tool’s ability to simplify complex issues associated with CPM networks into an easily understandable visual interface. Schedule delay analyses are an important component of project management and controls and can be a point of contention between project parties. Often, this contention is the result of a lack of a common communication tool that can be understood by all parties. The use of a 4D model assists in the resolution of this communication gap by allowing all parties to visualize project delays. In addition, a 4D model is an effective tool for presenting information during alternative dispute resolution or litigation in a way that can be easily understood and retained. 4D models have the potential to be used as demonstrative aids and trial graphics and are extremely effective when used in a comparative capacity.

Further research and software development is necessary to make 4D modeling a feasible tool for increasing the efficiency of schedule delay analyses. Many of the visualization and color-coding techniques mentioned in this paper are not fully-automated processes in the currently-available 4D software applications. In addition, many of the 5D modeling techniques mentioned in this paper, such as the ability to automatically color-code the activities on a resource-driven critical path, are not yet fully automated. If a user wishes to utilize these techniques today, a manual effort or the customization of off-the-shelf 4D software would be required. Further, only a small percentage of the available 4D software applications provide the capability to perform comparative 4D modeling as detailed in this paper. In addition to the availability of comparative 4D modeling software, the cost to implement 4D models can be a limiting factor, although the average cost to develop a 4D model is decreasing as improvements are made to the interoperability and the functionality of existing 3D and 4D software applications.

In the area of schedule delay analyses, the use of 4D models has seen very little use, mainly due to the relative immaturity of 4D modeling, but also as a result of reluctance by some parties to adopt new technologies for use in negotiations, alternative dispute resolution, or litigation. As 4D software applications evolve, the ease and efficiency of developing a 4D model will undoubtedly improve and will be met with more widespread use during all project phases.

REFERENCES

Mr. Kevin T. Coyne, PE PSP
Exponent
kcoyne@exponent.com