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Fulton Street Transit Center Project: 3D/4D Model Application Report

By

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Executive Summary

Within this report we describe the 3D/4D model implementation and application on the Fulton Street Transit Center (FSTC) project during July 2004 to July 2005. The Fulton Street Transit Center is one of the major subway reconstruction projects in New York City. With a budgeted project value of $750 Million the New York City Transit Authority (TA) plans to refurbish the seven subway lines around Fulton Street [Figure 1]. Furthermore, the TA plans to build a new above ground Transit Terminal. On this project a joint venture between Parsons Brinckerhoff and Bovis Lendlease formed the consultant construction management team to support the TA with the tasks of constructability review, bid packaging and site supervision.

Figure 1: Subway Lines around Fulton Street in Lower Manhattan

Early on in the project the CCM team decided to build a 3D/4D model of the project to visually support the necessary engineering decision making. CAD operators spent more than 2000 hours to create a 3D computer model of the existing and proposed conditions of the site. We believe that this 3D model the CCM team created for the FSTC project is one of the largest models ever used on construction projects. To support construction sequencing and schedule review tasks the CCM team created a 4D model by linking the 3D model to various construction schedules. In this way the CCM team was able to simulate these construction sequences and schedules and visually evaluate the planned construction.

In the main part of this report we first explain the applications of the model for the main FSTC project challenges. In particular, we generally describe how construction managers on the project used the 3D/4D model to engage the challenges of the FSTC project. Table 1 shows a chart displaying the project challenges and the various applications of the model.

In the second part of the main report we then focus on several specific case examples from various areas of the projects describing the 3D model creation and the how the model was used to engage specific challenges that occurred for a respective project area. The main part of the report finishes with an evaluation of the creation and use processes of the 3D/4D model. In particular, we identify possible improvements with respect to the extent by which the construction engineers on the project used the model. Furthermore, we elevate on a number of problems encountered during the 3D/4D modeling process.

		project challenges						
		Complex Design	GO schedule	Passenger Flow	Road Traffic	Public Concerns	Tight Site Conditions	Multiple Contractors
Applications of 3D/4D Model	Understanding Design	X						
	Constructability Review	X	X	X	X	X	X	
	Construction Sequencing		X	X	X	X	X	
	Support of Master Schedule Review		X				X	X
	Support of Contractor Schedule Review		X		X			
	Team Communication	X		X	X	X	X	X
	Visualization support for client and public	X		X	X	X		X

Table 1 - Project Challenges and Application of the 3D/4D Model

Finally, we close this report with an appendix formulizing 3D/4D modeling guidelines with respect to data acquisition, 3D modeling and the linking process of the 3D model with construction schedules according to the experiences we gained on the FSTC project. Project Managers who intend to implement 3D/4D modeling on their project can use these guidelines as a starting point for their implementation.

Preface

The Fulton Street Transit Center (FSTC) construction project is currently the largest subway reconstruction project in New York City and therefore possibly one of the largest in the world. Covering underground work below 21 blocks in lower Manhattan and with the construction of an above-ground transit station the overall project value is estimated at $750 Million. Construction managers working on the project will need to manage a number of challenges during the construction. For example, due to the tight site conditions in lower Manhattan it will be important to impact car and subway traffic as little as possible. Additionally, construction managers need to coordinate the various different contractors and sub-contractors that will work concurrently on the tight site.

Various different parties are working together on the project. The client is the New York Transit Agency (TA). The designer of the project, ARUP, submitted three design drawing addenda for each of the various parts of the project to the TA, the first preliminary design submission, the second preliminary design submission and the final design submission. Furthermore, the TA hired a consultant construction management (CCM) team that is mainly responsible for constructability review of the design and the overall construction packaging strategy. This packaging strategy distributes the project into different bid packages. At the time of the writing of this report only one of the overall bid package had been awarded.

To improve the engineering decision making the CCM team of the FSTC project created a comprehensive 3D model of the whole existing and proposed structural conditions of the project. The CCM team developed this geometric 3D model using 2D CAD drawings supplied by the designer. The CCM team then created corresponding 4D models by linking relevant construction schedules to these 3D models. By combining project scope and schedule information that would usually be represented in various different information sources, 3D/4D models serve as a construction planning, coordination and communication tool [Figure 2].
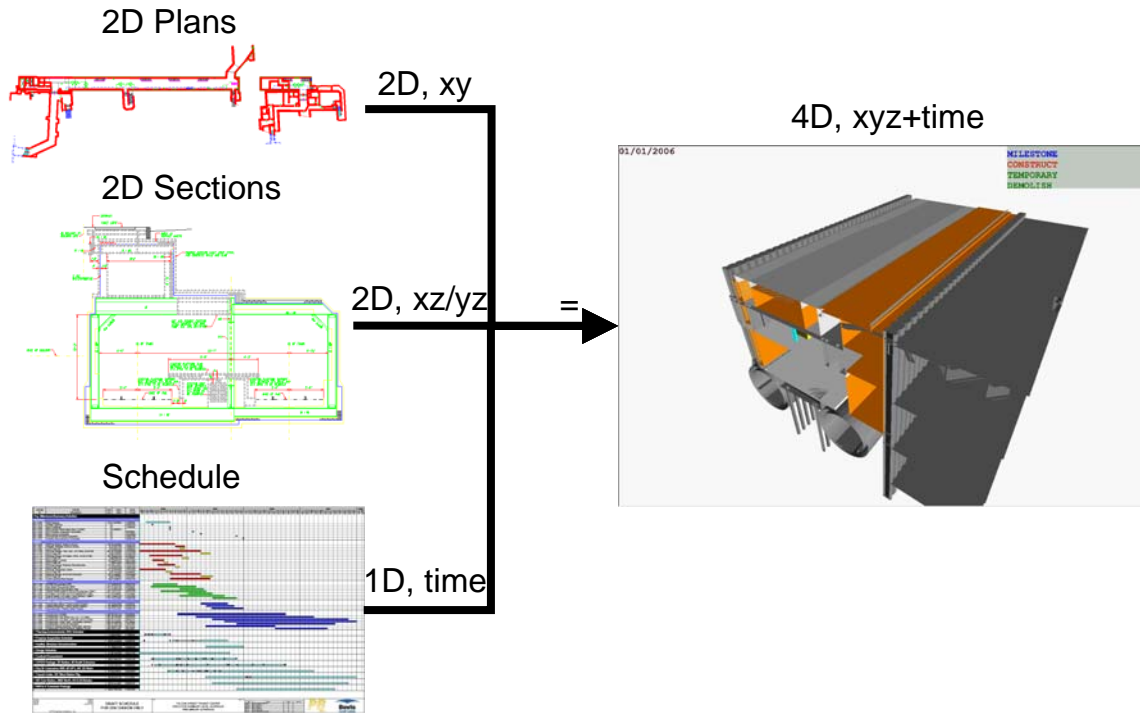
Figure 2: Information contained within a 3D/4D model

The overall 3D model consists of
- 228 3D-CAD model files,
- 25,253 3D objects with 1,366,292 polygons representing existing conditions and
- 19,458 3D objects with 1,596,041 polygons representing proposed conditions.

Overall 3D modelers spent more than 2,000 hours to model the project. In summary, we believe that the 3D/4D model the CCM team has developed on the FSTC project is one of the largest used on construction projects so far.

Early on in the project the CCM team realized that a controlled process for creating and managing a 3D/4D model of this size needed to be introduced. Therefore, the CCM team developed guidelines and standards while implementing the 3D/4D process. Furthermore the CCM team established a 3D/4D modeling team, consisting of a 3D/4D modeling manager and a number of 3D modelers. The CCM team has integrated the 3D/4D modeling team into its organizational hierarchy [Figure 3].
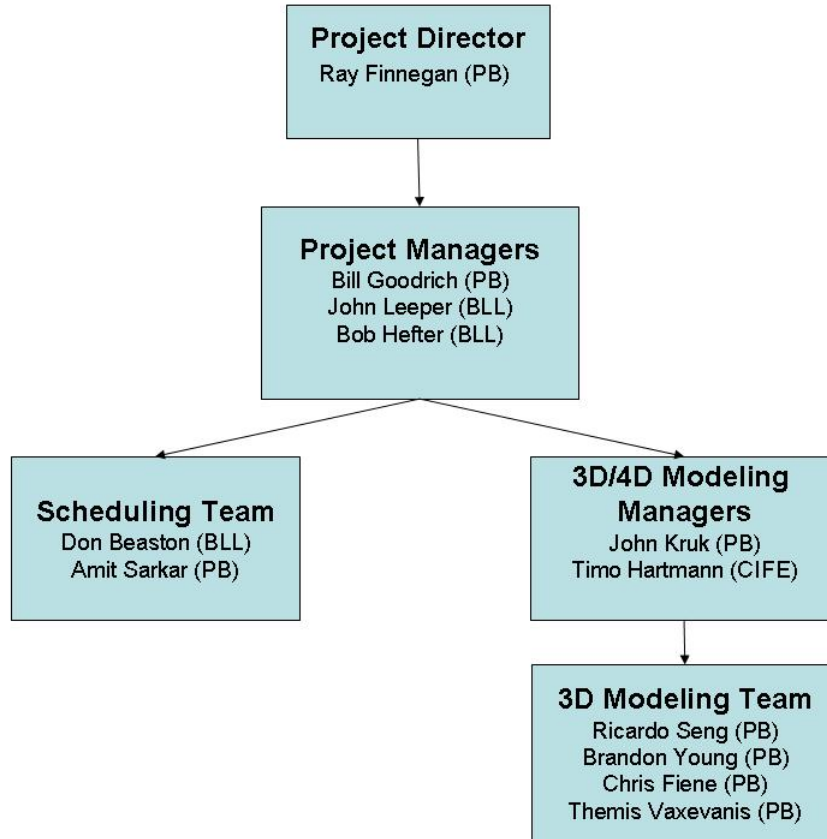
Figure 3: CCM team organizational chart

The authors describe the so far developed guidelines and standards within the appendix of this report. The main part of this report focuses on the various areas of application of the 3D/4D model during the construction planning and coordination process by the CCM team for the FSTC project from July 2004 until July 2005. During this period the project was still mainly in the conceptual design phase.

In the first part of this report the authors describe the various uses of a 3D/4D model on the FSTC project. The second part of the report describes various detailed examples of the 3D/4D model application. Finally the report suggests future uses of the created models and describes various encountered problems.

General project challenges and 4D model application

Table 2 shows how the CCM team applied the 3D/4D model resolving the various project challenges. Within this chapter the authors will describe these specific challenges. Furthermore, the authors will describe how 3D/4D models can be used to improve the decision making process that deals with these challenges. The following chapter illustrates the application of the 3D/4D model using examples from the FSTC project.

Project Challenges

By creating the 4D model the CCM team planned to address the following coordination challenges of the FSTC project shown in Table 2.

Applications of 3D/4D Model	project challenges						
	Complex Design	GO schedule	Passenger Flow	Road Traffic	Public Concerns	Tight Site Conditions	Multiple Contractors
Understanding Design	X						
Constructability Review	X	X	X	X	X	X	
Construction Sequencing		X	X	X	X	X	
Support of Master Schedule Review		X				X	X
Support of Contractor Schedule Review		X		X			
Team Communication	X		X	X	X	X	X
Visualization support for client and public	X		X	X	X		X

Table 2 - Scope of Coordination on FSTC: Main project challenges and uses of 3D/4D models. Applications on the FSTC project are marked with a cross

1. **Design complexity due to the integration of a new modern architecture into the existing conditions of lower Manhattan**
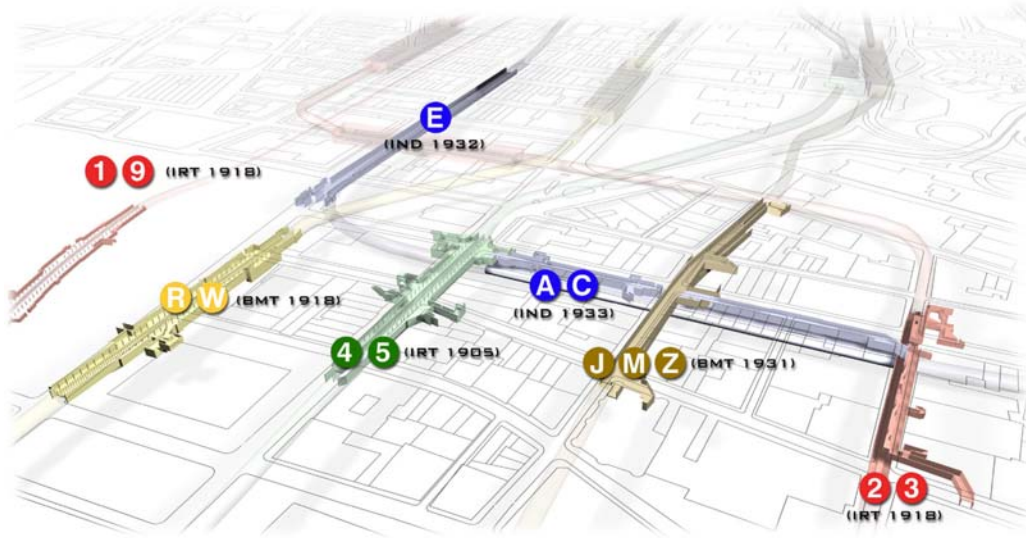

Figure 4: Existing subway infrastructure of the FSTC project

One major challenge of the project is the renovation of the existing subway structures that have been built between 1905 and 1932 [Figure 4]. No major refurbishment activity has taken place since then. The proposed design scope of the project includes linking all of the existing subway lines of the project's area below the street. On top of these existing lines New York City Transit (NYCT) plans to construct a modern dome structure out of structural steel and glass that incorporates various shops and restaurants. All of these design issues lead to a complicated design that is reflected in the numerous 2D drawing submissions and addenda. Other design related problems are, for example, that the design needs to integrate the existing buildings including basements and sidewalk vaults into the new design of the FSTC. Another example of a design challenge is the rerouting of the existing subsurface utilities serving the FSTC.

2. **Construction constraints due to general outages of the active subway lines**

The Fulton street subway lines are a major transportation hub for lower Manhattan. Thus, it is of extreme importance that the construction activities disturb the subway traffic as little as possible. Therefore, NYCT is only granting a limited number of general outages (GO) when no trains are running and therefore work on or near the subway tracks can be performed. The NYCT incorporates these GOs into a GO schedule that the schedulers of the construction teams will have to incorporate into their construction schedule.

3. **Construction constraints due to passenger flow**

The existing subway lines are frequented by more than 250,000 passengers each day. Thus, in addition to considering the GO schedule, it is also important for the contractors to maintain passage for subway riders from one line to another during construction. Construction activities should only affect the passenger flow to a minimal extent. Therefore, construction teams have to plan additional means for the maintenance of the passenger routes like, for example, the construction of temporary stairs.

4. Construction constraints due to road traffic

It is important to impact road traffic as little as possible during construction. Most of the streets in the construction area need to maintain multiple lanes for local traffic, emergency and delivery vehicles at all times. As New York subways are typically constructed from the street level and not with underground tunneling methods, this is another major constraint construction teams need to consider during the scheduling and construction sequencing.

5. Construction constraints due to public concerns

Construction work within lower Manhattan has to be extremely sensitive to public concerns. It is important to affect residential and commercial abutters as little as possible. Thus, project teams need to consider environmental issues like noise or exhaust discharge. Furthermore, construction managers need to maintain access to buildings, stores and streets during construction planning.

6. Construction constraints due to tight site conditions

Spatial constraints are another major problem for construction work in lower Manhattan. Logistics like material delivery and storage as well as positioning of construction machinery such as fixed cranes are a major issue that requires thorough sequencing and scheduling of construction activities. Other problems due to the tight site conditions are introduced, for example, by the need to reroute and maintain the under-street utilities serving the residential and commercial facilities adjacent to the construction area.

7. Coordination of multiple contractors

The client plans to distribute the overall work of the FSTC project into various bid packages. This reduces the overall project duration as multiple contractors can perform more work concurrently. The CCM team needs to develop a sound packaging plan that provides that qualified contractors are bidding for the different types of construction like subway refurbishment, building demolition or steel and curtain wall erection. The CCM team has to coordinate the various contractors on the tight site. To do so the CCM team is developing a master schedule that considers the various interfaces between the different contracts. Also the CCM team establishes Milestones within the schedule to further coordinate the construction work between the packages.

3D/4D Model Application

In order to meet these project challenges the CCM team has applied the 3D/4D models for the following evaluation tasks:

1. Design Understanding

Project managers used 3D models to facilitate the understanding of the design as it integrates information that is usually distributed over numerous 2D drawings. Engineers used the navigation features of the 3D/4D viewing applications to display additional elevations and cross sections that were not submitted within the sets of 2D drawings.

Furthermore, 3D models integrated designs of the various disciplines and engineers can use these models to detect conflicts and interferences between systems and components.

2. Constructability Review

Construction managers used the 3D/4D model to determine how trouble-free the facility can be constructed according to the given design. The 3D model supported engineers in detecting problems within the design. Furthermore, planners created various 4D models by linking the 3D models to preliminary schedules. In this way the project engineers evaluated the overall constructability of the design by simulating alternative construction sequences.

3. Construction Sequencing

3D/4D models were helpful in determining feasible construction sequences. The visualization capabilities of the 4D model enabled engineers to step through a construction sequence represented within a schedule. In this way schedulers were easily able to verify whether all necessary activities are present in the schedule and if the created relationships between activities are logical.

4. Master Schedule Review

After the schedulers had determined the sequence of the activities with their relationships, they attached the date constraints to the milestone activities. This can lead to conflicts regarding spatial constraints or resource use. Thus the schedulers used the 4D model to simulate the schedule and in this way could easily detect these conflicts. Then either the scheduler had to change the activity sequencing, or the scheduler had to re-evaluate the milestones within the schedule.

5. Contractor's Schedule Review

As multiple contractors will be responsible for the construction of the FSTC project the 4D model can be valuable to detect conflicts between their schedules. Each contractor typically creates a schedule only taking his contractually defined milestones into account. This may lead to spatial or resource conflicts among the different contractors. By using a 4D model that integrates the different contractor schedules engineers can easily detect and visualize these conflicts.

6. Team Communication

Another important application of 3D/4D models is to support the communication amongst all team members. Engineers visualized planning ideas by incorporating them in 3D/4D models. Therefore, other participants within the planning process could understand ideas of other individuals or groups faster. The use of 3D/4D models as a communication medium has proven to be very beneficial on the FSTC project.

7. Visualization Support for Clients and Public

Clients needed to make accurate and understandable presentations that communicated complex information to a variety of technical and non-technical audiences. In particular when dealing with the public and other agencies, these presentations must communicate the right information in the most effective manner. These presentations usually apply a

variety of visualization techniques ranging from marked-up 2D drawings and plans to sophisticated 3D photorealistic renderings and animations. While 3D photorealistic renderings and animations are very expensive to create, they are usually the most effective way to communicate engineering issues to non-engineers. As a 3D/4D model was available the project team could create impressive and effective visualizations without the usually long lead-time and the high expense.

Project Examples

General Site Overview

Description:	General Site Overview
Scope of Work	• 2/3 Station Rehabilitation • 4/5 Southern Entrance • Transit Center – Deconstruction, Removal of Hazardous Material and Foundations • Underpinning of 4/5 and R/W Lines • Dey Street Concourse Structural Box • AC Mezzanine
Start of Construction	December, 04
Substantial Completion	December, 08
Application of 3D/4D Model	• Support of master schedule review • Visualization support for client and public
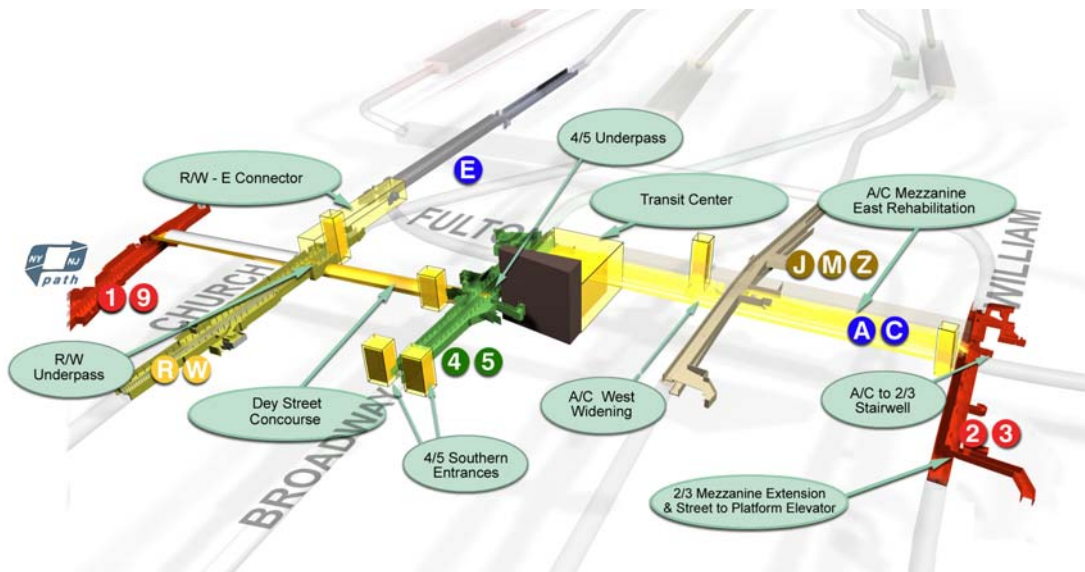
Figure 5: Main FSTC project components

Figure 5 gives an overview of the main components of the FSTC project. One of the main challenges for the CCM team is to distribute these components into various bid packages. During the development of the packaging plan the CCM team needed to effectively coordinate the work of the different contractors in order to minimize spatial conflicts on the tight site. Furthermore, the CCM team tried to package different kinds of construction

work, like for example, deconstruction work or subway renovation work, into different bid packages in order to attract specialized contractors.

To propose this project packaging plan to the client the 4D modeling team created a general site overview 3D/4D model. The 3D/4D model consisted of basic three-dimensional massing and building envelopes that were linked to a very high level Master schedule [Figure 6, Figure 7] containing around 20 activities. This 3D/4D model shows only the durations of the overall work of the various contractors. The general site overview model proved to be very useful to evaluate the interfaces between the various construction packages and to communicate the overall packaging strategy to the client.

Figure 6: Packaging Overview September 2006 – Highlighting the planned construction at this date

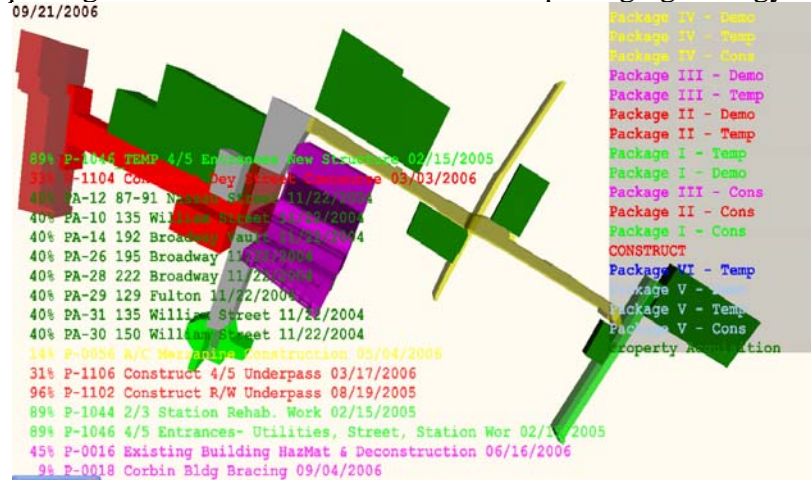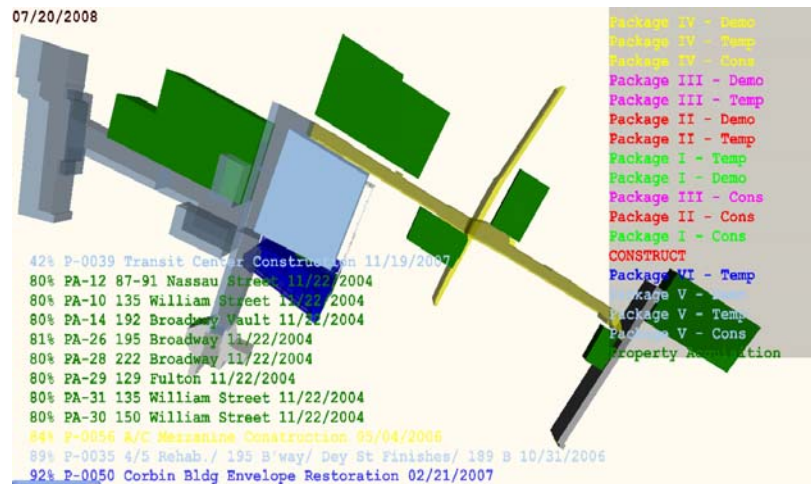**Figure 7: Packaging Overview July 2008 – Highlighting the planned construction at this date**

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2/3 Station Rehabilitation

Description:	2/3 Station Rehabilitation
Scope of Work	• Reprogramming/Rebuilding existing space in the 2/3 line Mezzanine • Subway Platform repair and partial replacement • Extension of Platform at North edge • Elevator installation
Start Construction	December, 04
Substantial Completion	November, 06
Application of 3D/4D Model	• Understanding Design • Support of Contractor Schedule Review

The 2/3 line station rehabilitation construction is a familiar project type for NYCT. Nevertheless, a fair amount of coordination between construction operations and ongoing subway traffic is necessary as parts of the existing passenger platform have to be demolished. As the subway line cannot be closed down during weekdays, the responsible construction contractor has to integrate its schedule into the prescribed weekend GO schedule. Furthermore, the construction team has to maintain the passenger flow and safety at all times. The CCM team used the 3D/4D model for this part of the project supporting the two tasks of understanding the design and reviewing the contractor's schedules.

Creation of the 3D Model

The CCM team first created a 3D model of the 2/3 line representing the second preliminary design submission. The 3D/4D modeling team did not need to remodel anything in order to update the 3D model according to the final design submission. However, after publishing the bid documents the design team introduced design changes due to newly discovered site conditions. The CCM team decided to incorporate these design changes into the 3D model.

Understanding Design

Before the necessary remodeling of the introduced design changes, the CCM team used the 3D model to brief the 3D modelers about the design changes. The responsible project manager of the team showed the important structural changes with the 3D model by marking-up the changes the designer made [Figure 8]. Altogether eight marked up 3D model screen shots were created during the meeting. The CCM team then used these mark-ups for informing other persons that had not been part of the initial meeting.

Review of Contractor schedule

After the contractor submitted the first version of the construction schedule the CCM team tried to link the schedule to the 3D model. Early during the linking process the team realized that the sequencing within the schedule was not logical. The contractor's scheduler scheduled activities for construction before the necessary deconstruction. In the end the client rejected the contractor's schedule based in part on the results of the linking process. The CCM team was unable to use the 3D/4D model linked to the schedule for

any visual evaluations. However, due to the systematic matching of geometry with construction activities during the linking process the CCM team was able to quickly understand that the sequence within the schedule was not feasible.
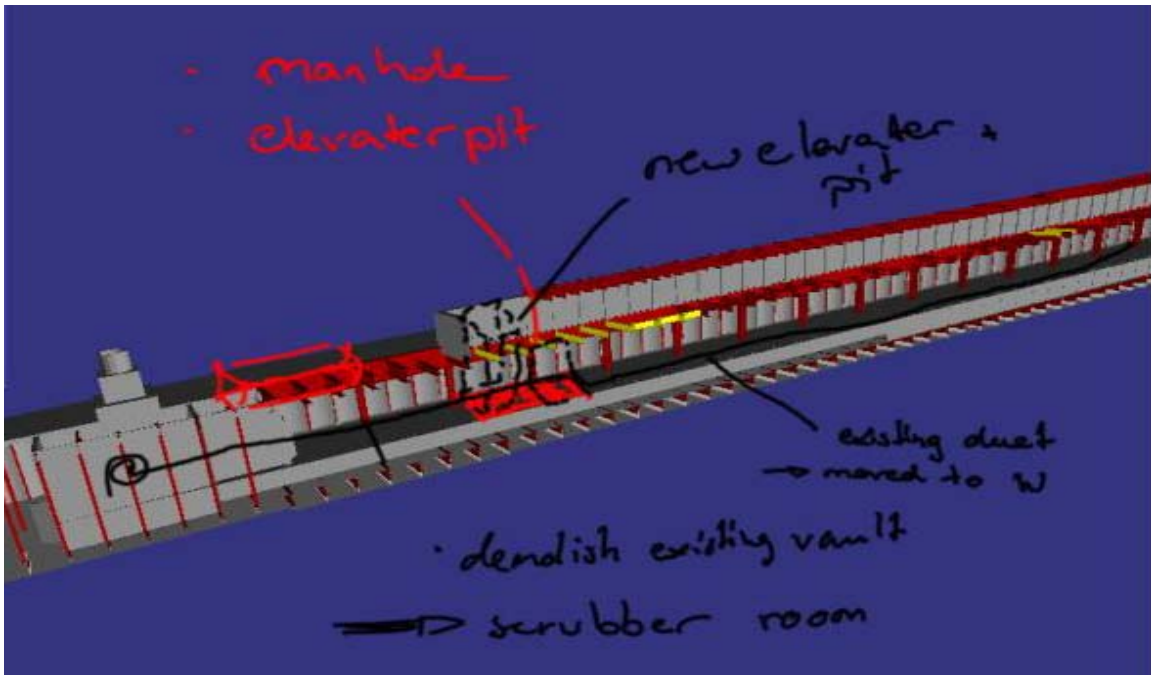
Figure 8: Marked-up 3D model reflecting the design changes of the 2/3 line

4/5 Southern Entrances

Description:	4/5 Southern Entrances
Scope of Work	• New Southbound and Northbound entrance structures • Structural modifications to existing track walls • Utility work to accommodate the new entrance structures • Removing adjacent basement vaults affected by new structure
Start of Construction	December, 04
Substantial Completion	November, 06
Application of 3D/4D Model	• Constructability review • Construction sequencing • Support of master schedule review • Support of contractor schedule review • Support of team communication • Visualization support for client and public

The design of the FSTC project incorporates the construction of new street entrances at the south end of the 4/5 line station. While most of this construction will not affect any of the train operations and passenger traffic of the subway line, it is necessary for the contractor to excavate from the street level at one of the street intersections with Broadway. Thus, the project managers have to implement a construction sequence that assures that the traffic is maintained on the affected streets during all times of construction. The CCM team used the 3D/4D model for this part of the project supporting the constructability review, construction sequencing, support of master schedule review,

support of contractor schedule review, support of team communication and visualization support for client and pubic.

Creation of the 3D Model

The 3D modelers modeled this part of the site using the first preliminary design submission. Though the design changed after the client had already awarded this bid package the CCM team did not decide to remodel the 3D model to reflect the new design.

Constructability Review

In one of the first constructability review meetings the CCM team used the 3D model to evaluate an adequate construction sequence that allows the maintenance of the required 11' lanes. For this evaluation task the 3D model was used and overlaid with a 2D drawing of the existing intersection of Cortland Street, Maiden Lane, and Broadway. In this way two different types of information were combined within one 3D model. Furthermor, the 3D/4D modeling team used the dimensioning feature of the CAD application to directly measure distances [Figure 9]. In this way the CCM team could easily determine a steel erection and concrete placement sequence that allowed the maintenance of the required traffic lanes. After the evaluation of the construction sequence the CCM team could easily define different areas of the necessary excavation.
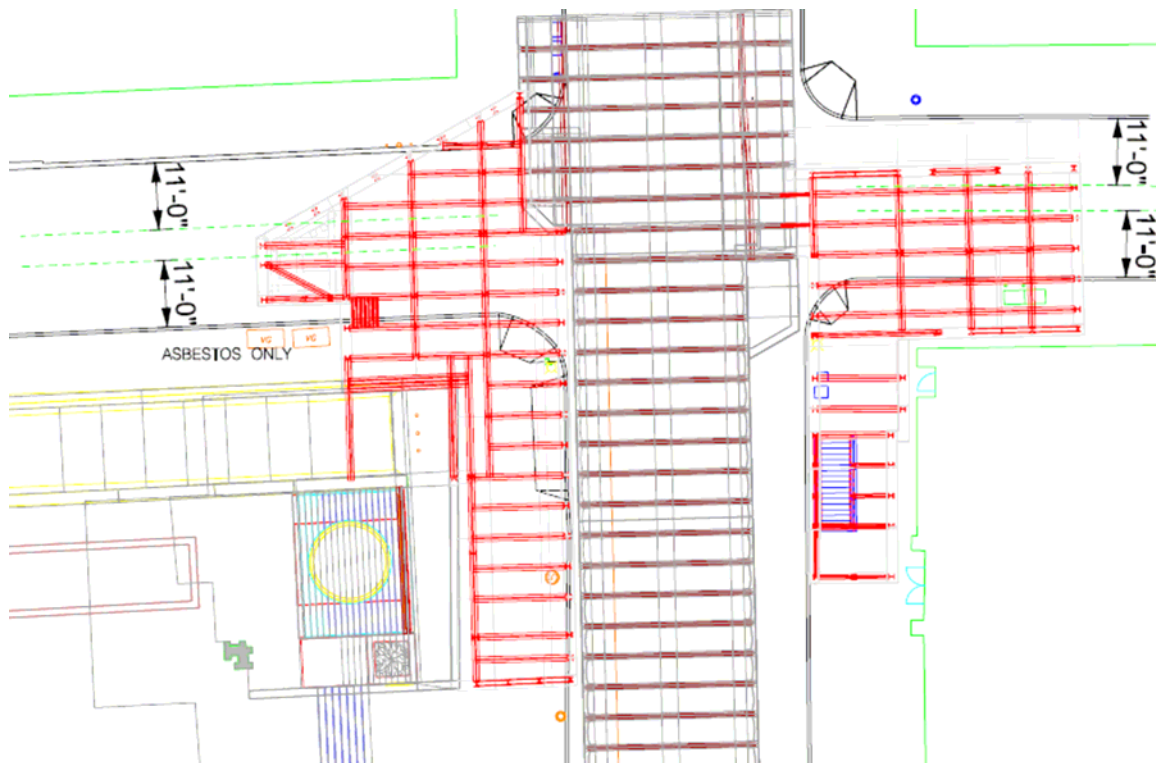
Figure 9: Top view of the overlay of 2D CAD drawings with a 3D model

Visualization support for client and public

After the CCM team established the construction sequence the team had to represent this sequence to the client. For this purpose the 3D/4D modeling team created 4 photo-

realistic renderings to support the communication of the planned sequence [Figure 10 a-d]. As an accurate 3D model of the respective portion of the site was readily available it only took the CCM team approximately eight hours to create the renderings compared to an estimated week if visualization specialists would have had to start from scratch.

Figure 10a: Rendering of construction stage 1 of the 4/5 Southern Entrance. Work-zone in N-W corner of street.

Figure 9b: Rendering of construction stage 2 of the 4/5 Southern Entrance. Work-zone in N-E corner of street.

Figure 9c: Rendering of construction stage 3 of the 4/5 Southern Entrance. Work-zone in S-E corner of street.

Figure 9d: Rendering of construction stage 4 of the 4/5 Southern Entrance. Work-zone in S-W corner of street.

Transit Center Deconstruction, Removal of Hazardous Material and Foundations

Description:	Transit Center - Deconstruction, Removal of Hazardous Material, and Foundations
Scope of work	- Hazardous Abatement of all buildings that need to be demolished - Deconstruction of the buildings - Secant pile wall installation - Foundations for the Transit Center
Start of Construction	October, 05
Substantial Completion	September, 06
Application of 3D/4D Model	- Constructability review - Construction sequencing - Support of master schedule review - Support of team communication

The centerpiece of the FSTC project features an above ground subway terminal consisting of a low-rise mixed used structure and a domed oculus structure. There are four existing buildings at the future site of this structure that the responsible contractor for this part of the project needs to demolish [Figure 11]. Furthermore, the structure of the dome and oculus has to be integrated into the adjacent Corbin Building that is a historical landmark. Challenges for this construction include a risky large scale excavation, the underpinning and preservation of the Corbin Building and the removal of the hazardous material within the buildings that are to be demolished.

Figure 11: Existing Buildings at the proposed site of the FSTC dome and oculus structure.

The CCM team used the 3D/4D model of the Transit Center deconstruction and foundation work for constructability evaluations and construction activity sequencing. Furthermore, the team used the model to support internal team communication as well as constructability review meetings with the design team.

3D Model Creation

The 4D modeling team integrated different 3D sub-models within the 3D/4D model of this part of the site. An existing 3D model created by the designer was used to represent the Corbin building. The 3D/4D modeling team modeled the other existing buildings using simplified mass-elements for each level of the buildings. Furthermore the 3D/4D modeling team modeled the secant pile foundation walls that are to serve as water retention walls for the excavation according to the preliminary design issue. To evaluate various design scenarios for the support of the water retention wall the 3D modeling team modeled a number of different support alternatives including tie-backs, walers and rakers, and a version using trusses as lateral support [Figure 15].

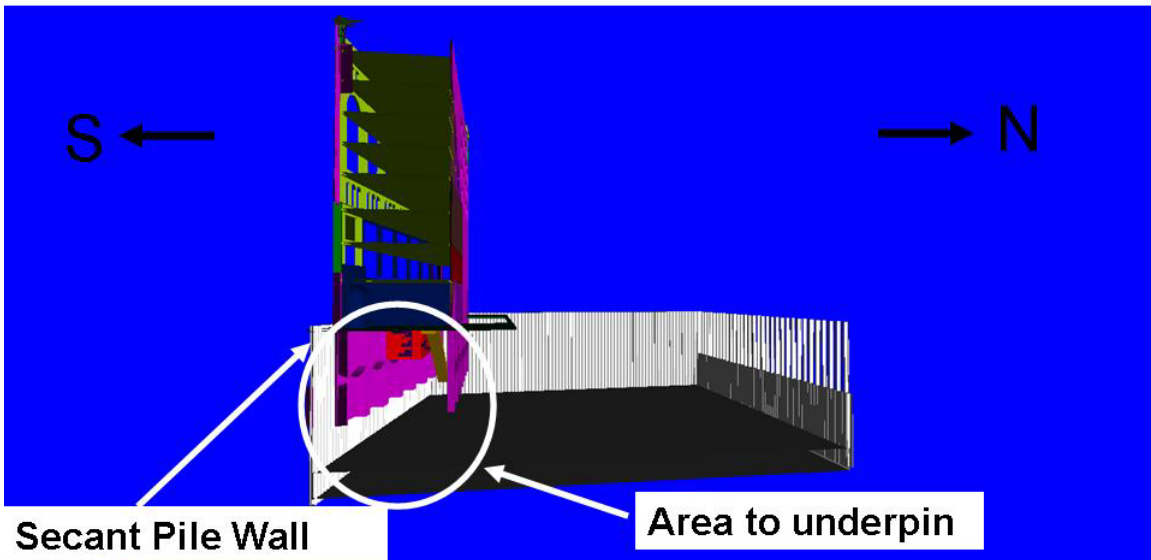

Figure 12: Secant pile wall only on south side – Underpinning of Corbin building and excavation activities are coupled
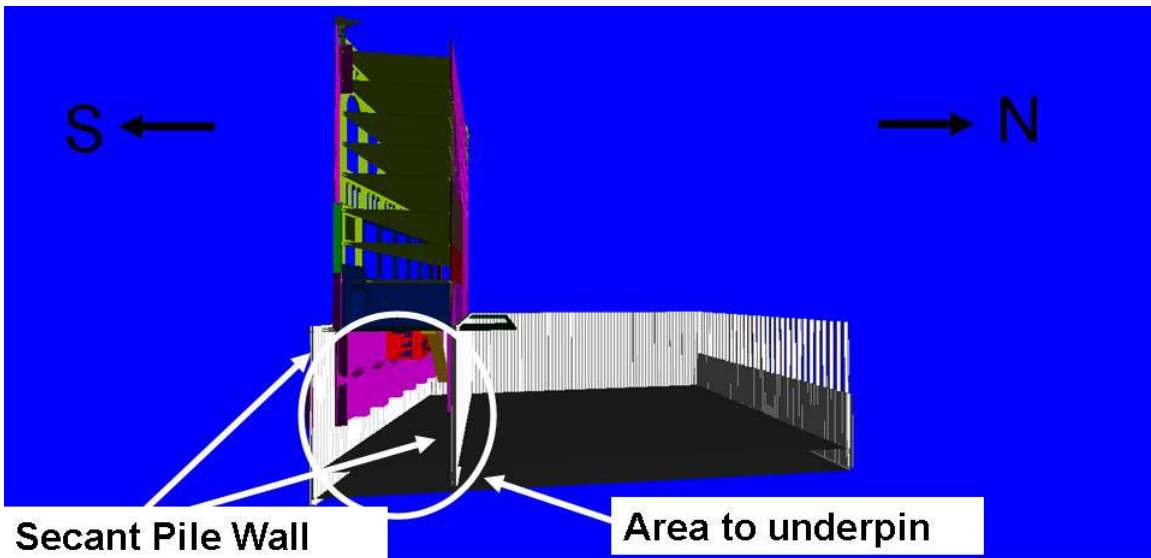

Figure 13: Secant pile wall on north side – Underpinning of Corbin building and excavation activities are decoupled
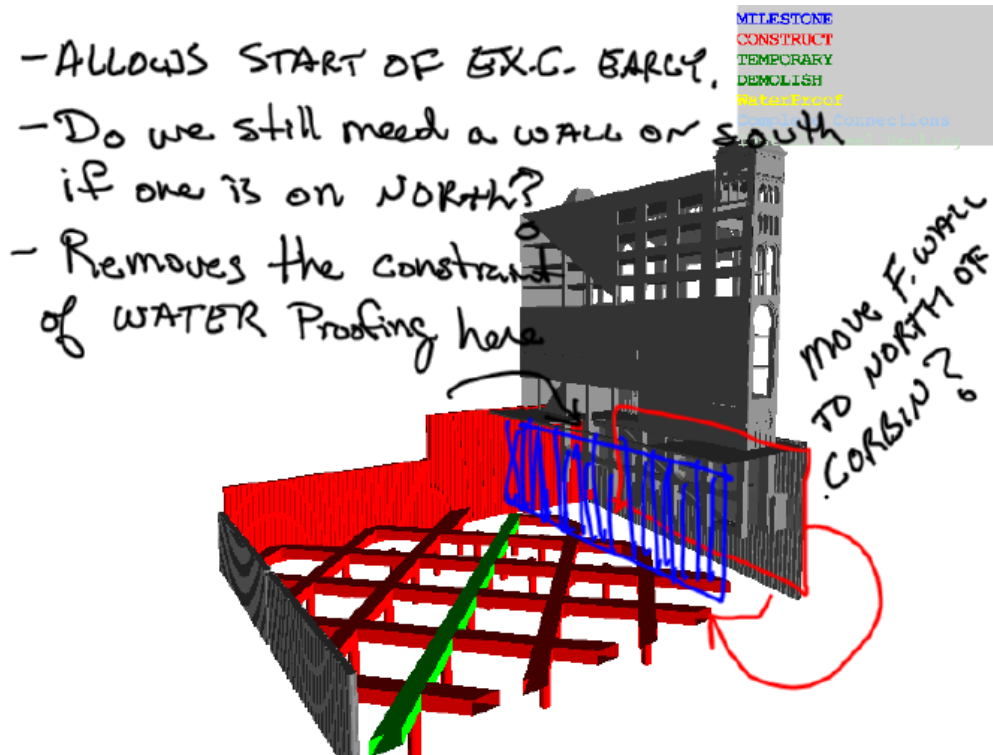
Figure 14: Marked up 3D/4D snapshot created during the constructability discussion of the secant pile wall issue

Constructability Review and Team Communication Support

To support the discussion of constructability issues with the design team, the CCM team used the model in a constructability review meeting. During the meeting the CCM team communicated an issue with the placement of the water retention wall to the design team. To maintain structural stability of the Corbin building, the design team plans to underpin the building before the construction of the Transit Center. Furthermore, the designer initially planned to build the water retention wall on the south side of the Corbin building. Thus, there would have been no physical separation of the underpinning underneath the Corbin building and the main excavation area. Therefore, the underpinning operation and the risky excavation operation would be closely coupled [Figure 12]. Using the 3D/4D model the design team could more easily understand this issue. It was decided in only one meeting to change the design and move the secant pile wall to the north of the Corbin building [Figure 13]. Thus, the excavation and underpinning operations would be decoupled and therefore the schedule constraints on the critical path could be relaxed. The CCM team electronically marked up the 3D/4D model while explaining this issue to the design team [Figure 14]. Furthermore the various support alternatives of the water retention wall and their constructability were discussed using the model [Figure 15]. Altogether the CCM team created nine marked-up screen shots during this meeting that were included in the meeting minutes.
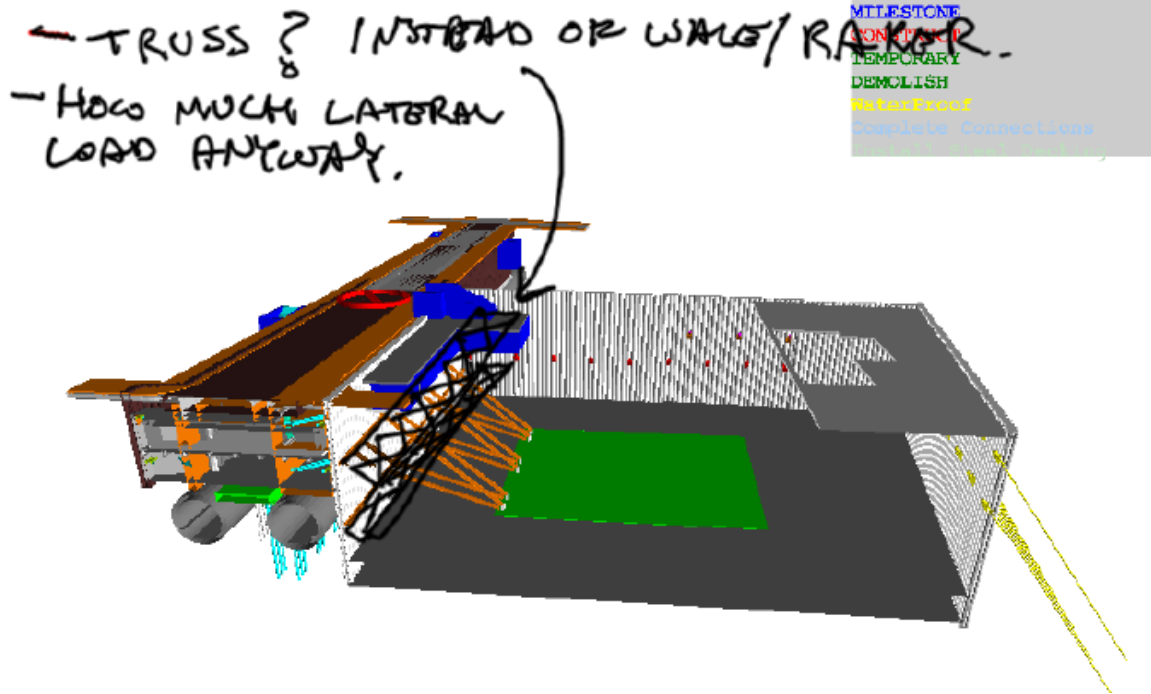
Figure 15: Marked up 3D/4D model showing various design alternatives for the retention wall support

Construction Sequencing and Master Schedule Review

To evaluate the relocation sequence for the existing tenants and the deconstruction sequence the 3D/4D modeling team linked the 3D model to the demolition schedule. This model simulated the deconstruction sequence and project managers could easily visualize and understand the inter-relations between the relocation of the tenant activities, the removal of hazardous material activities and the deconstruction activities. Using the 3D/4D model, the CCM team was better able to review the deconstruction sequence of the schedule. The project engineers found a couple of inconsistencies such as conflicts with the relocation of tenants and the demolition activities in the master schedule. Once recognized, the scheduling team could adjust these inconsistencies easily [Figure 16].
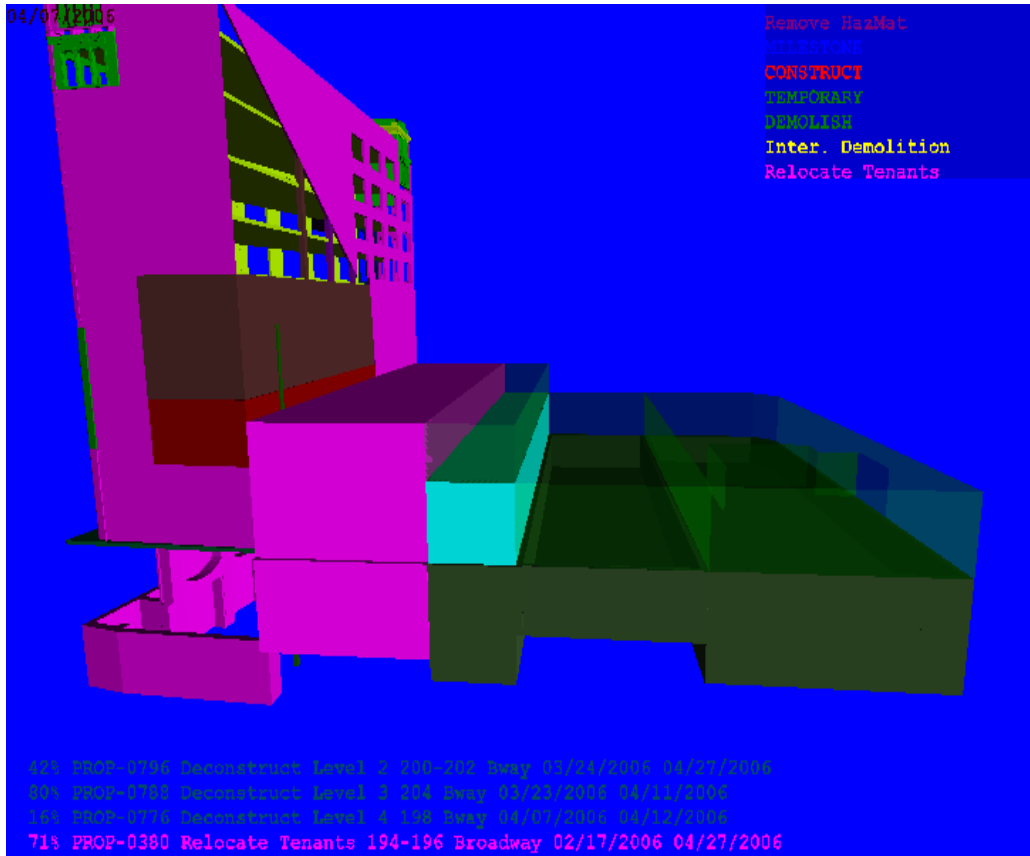
Figure 16: Snapshot of the deconstruction model visualizing hazardous material removal, internal demolition, tenant relocation and deconstruction of the existing buildings.

Underpinning of 4/5 and R/W Stations

Description:	Underpinning of 4/5 and R/W Stations
Scope of Work	• Construction of the new concourse structure beneath the existing 4/5 line • Construction of the new concourse structure beneath the existing R/W line
Start of Construction	June, 05
Substantial Completion	August, 05
Application of 3D/4D Model	• Constructability review • Construction sequencing • Linked to master schedule • Support of team communication

To construct a passageway between the 4/5 subway line and the R/W subway line the designer plans to connect the two lines with a new concourse. As subway riders have to reach both the northbound as well as the southbound tracks of the two lines from the underpass it is necessary to build this concourse crossing underneath the two existing subway tracks [Figure 17]. To support the existing tracks during the underpass construction, the designer developed an underpinning design using various pile supports driven from the street, as well as from the existing subway platform and the subway tracks. The main challenges during the piling sequence are to maintain the subway traffic

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on the two lines, to interfere with the existing passenger flow as little as possible and to maintain the traffic on the streets above.
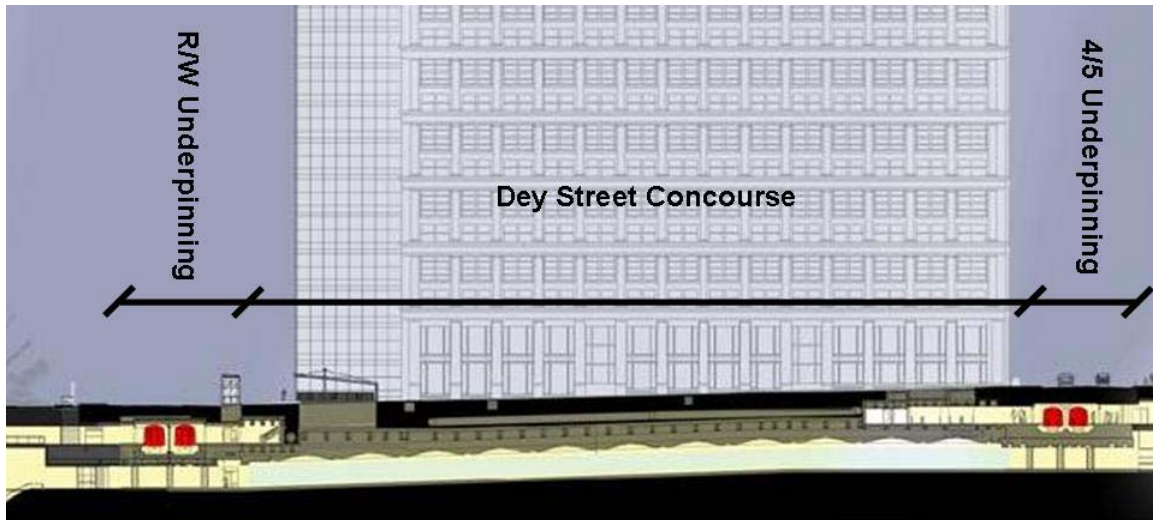
Figure 17: Section of the planned Dey Street Concourse

The project managers of the CCM team used the 3D/4D model to communicate the design to the scheduling team, to evaluate the construction sequencing of the underpinning sequence and to communicate the design to the other members of the project team.

Creating the Model

The 3D modelers created the 3D model of the underpinning piles using the second preliminary engineering submission of the design team. The 3D modelers modeled the existing subway lines using the same design submission.

Support of Team Communication

At the start of the evaluation of the piling sequences the CCM team communicated the constraints of the piling sequence to its schedulers using the model [Figure 18]. The schedulers could easily understand which of the
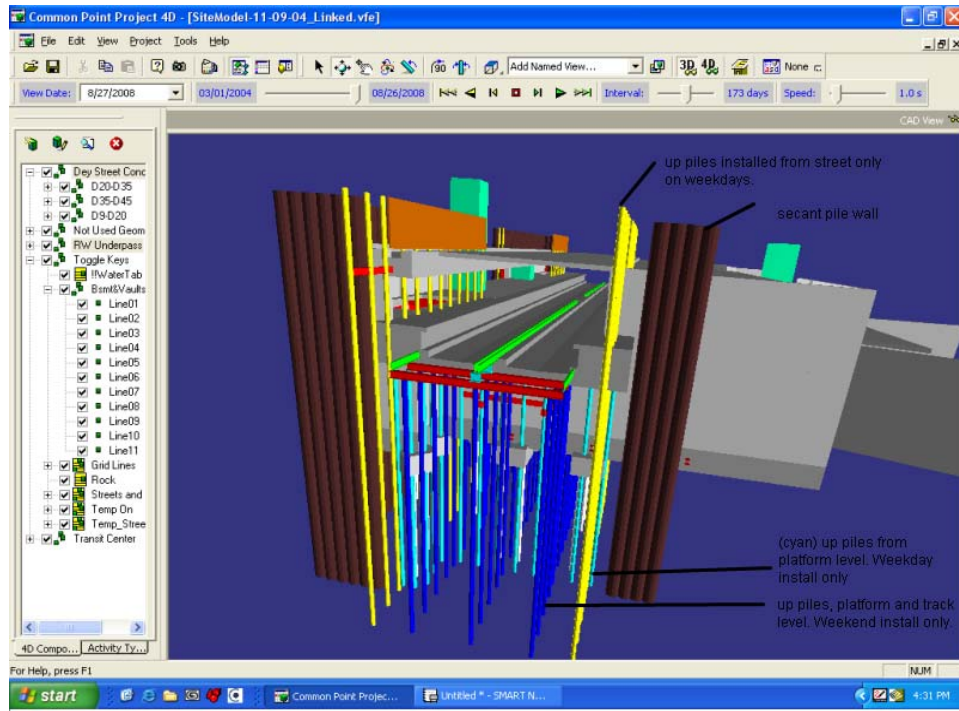
Figure 18: Communicating the construction constraints of the underpinning using a 3D model

piles would have to be driven from street level, which from the station platform and which from
the existing subway track. Furthermore, the model assisted the CCM team in explaining the integration of the support structure for the existing tracks with the underpinning piles [Figure 19].
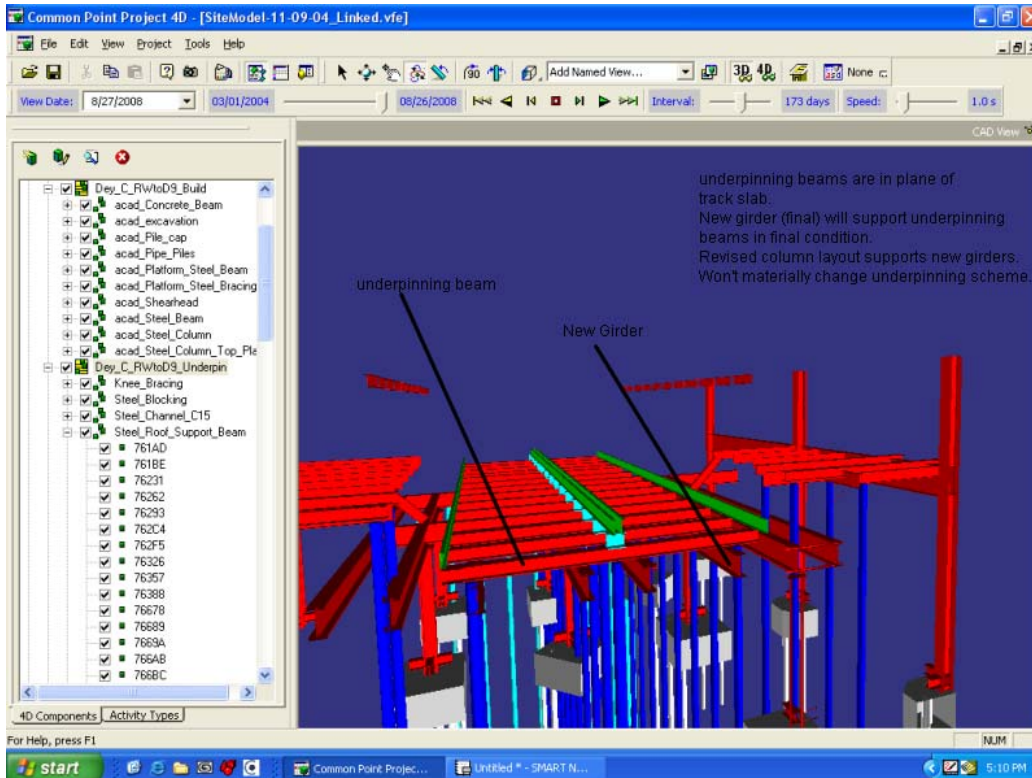
Figure 19: Communicating the design of the support of the existing lines

Construction Sequencing and Support of Master Schedule Review

After the schedulers understood the constraints of the underpinning operations, they evaluated the proposed construction sequence and integrated this sequence into the prescribed GO schedule for the two subway lines. The 3D/4D modeling team then linked the schedule to the 3D model of the underpinning piles. This process was rather cumbersome as each construction activity only included the construction of three of the numerous piles. However, the CCM team was able to use the created 4D model as reference to determine which of the underpinning activities corresponded to which piles. In this way the 3D/4D model is replacing the paper-based marked up drawings that the scheduling team created [Figure 20].

Figure 20 - Marked up 2D drawing of the scheduled piling sequence

Dey Street Concourse Structural Box

Description:	Dey Street Concourse Structural Box
Scope of Work	• Construct new concourse structure beneath Dey Street • Deconstruction of 189 Broadway • Construction of a new 5 storey Dey Street entrance superstructure at 189 Broadway
Start of Construction	June, 05
Substantial Completion	August, 07
Application of 3D/4D Model:	• Understanding complex design • Constructability review • Construction sequencing • Support of master schedule review • Support of team communication • Visualization support for client and public

The large scale excavation work and the necessary heavy structural work are the main challenges while constructing the structural box linking the 4/5 line with the R/W line underneath Dey Street.

The CCM team expects a couple of challenges during the construction of the structural box for the Dey Street concourse. For example, the responsible contractor needs to maintain the traffic on Dey Street during the cut-and-cover operation. Another concern of the construction will be to affect the adjacent abutters as little as possible during construction. Furthermore, the contractor needs to extensively plan the rerouting of the existing utilities under the street. One of the main sequencing problems will be the integration of the excavation work into the underpinning sequence. According to the packaging plan the contractor of the Dey Street Structural Box will only be responsible for the structural part, while another contractor will be responsible for the finishes. Thus, the structural contractor needs to hand over completed parts of the structure to the contractor responsible for the finishes to support a fast track construction of the concourse. Therefore, the CCM team plans to determine contractual milestones for the required hand-over dates of the structure with the respective contractors.

The CCM team used the 3D/4D model of the Dey Street Structural Box to understand the complex design with respect to the tight site conditions. Furthermore, the project team supported the constructability review taking into account the maintenance of the road traffic, the concerns of the abutters and the tight site conditions. The team then applied the 4D model for evaluating the construction sequencing with respect to the road closure and abutter interference. Additionally, the CCM team's engineers supported the integration of the various construction sequence evaluations within the schedule considering the GO sequence for the underpinning of the lines and the handover milestones between contractors with the 3D/4D model. In addition, the 3D modeling team created a couple of photo-realistic renderings for the planned construction sequences that were used to present the construction sequence to adjacent businesses and abutters.

Creating the 3D Model

The 3D modelers modeled the 3D model of the concourse according to the second preliminary design submission. The design team revised the design of the underpass by reducing the width of the structure during the value engineering process. The 4D modeling team, however, decided not to remodel the 3D model. The team made this decision as the main drivers for the constructability of the structural box are its height and the distance of its roof to the street and not its width.

Understanding Complex Design and Support of Team Communication

Early in the evaluation work the CCM team used the 3D model in a team meeting to understand the complex design. The team could understand a couple of important facts by navigating through the model. The project managers discovered several design details in the 3D models they had missed after reviewing the 2D drawings. The project managers, for example, had not been aware of a couple of pile foundations at the north side of the structural box.

Initially, the CCM team had planned to maintain the vehicular traffic of Dey Street by using a temporary road deck. However, after reviewing the 3D model the team realized that at the intersection of the structural box with the existing 4/5 line there is only about a 4' difference between the top of the Dey Street roof structure and the top of the street [Figure 22]. Thus, the responsible contractor would not be able to put a temporary road deck in place at this part of the site to maintain road traffic without interfering with the proposed roof structure. The CCM team pointed this out to the design team as it is also important to thoroughly evaluate and design the rerouting of the existing utilities through this shallow area and account for it within the design.

During the HVAC design evaluations the project team evaluated whether it is feasible to route the needed ductwork underneath the ceiling of the Dey Street structural box from the 4/5 line to the R/W line. One of the advantages of 3D models is that engineers can create and dimension arbitrary sections whenever and wherever needed. To support the design evaluation the CCM team used the 3D model to create a couple of these 2D

sections through the Dey Street structural box 3D model and measured the available space [Figure 21].
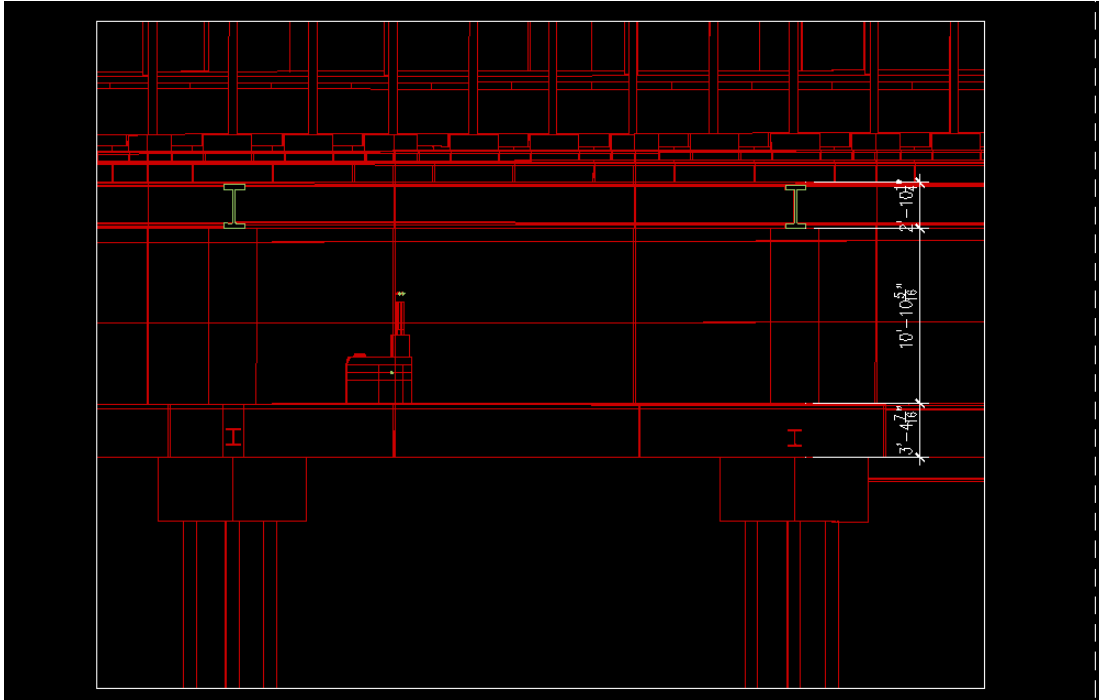
Figure 21: Example 2D Section created using the 3D model

Construction Sequencing and Visualization support for the public

Furthermore, the CCM team also used the 3D/4D model for the evaluation of the construction sequence of the piling of the water retention wall and the excavation work considering road traffic maintenance and the access to one of the main adjacent abutters, the Century 21 department store. The 3D modelers created a couple of photo realistic renderings to assist in the communication of the planned sequence to representatives of Century 21 [Figure 23, Figure 24, Figure 25, Figure 26].
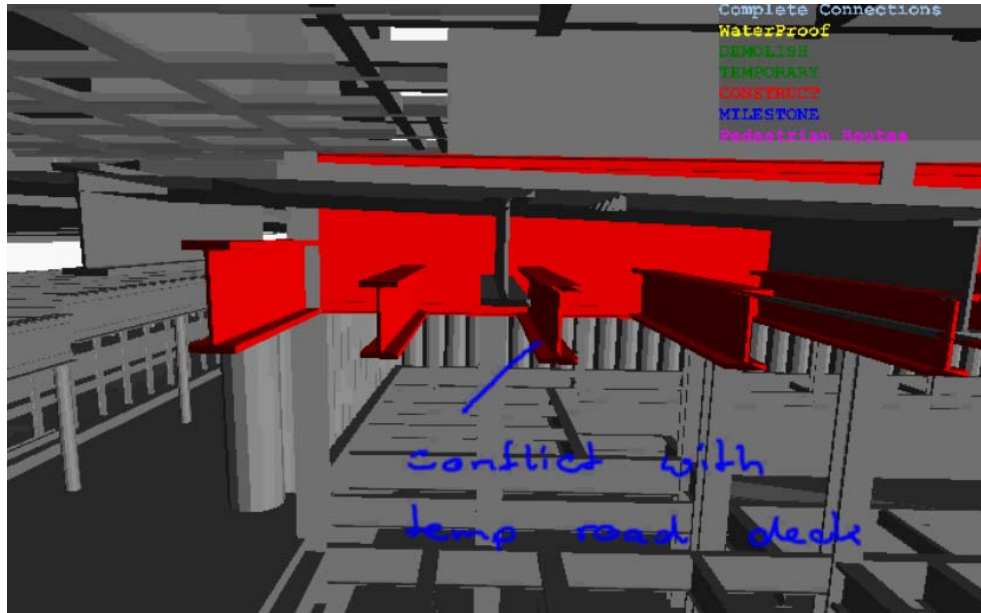
Figure 22: Design conflict with temporary road deck as possible alternative

The CCM team developed a schedule integrating the construction sequence of the structural box into the street closure sequence developed earlier and into the GO schedules of the R/W and 4/5 lines. The 4D modeling team linked this schedule with the 3D/4D model, and the scheduling sequence was controlled using the model. The 4D modelers found some minor sequencing issues and the schedule was refined accordingly.

Figure 23: Dey Street Piling Sequence Stage 1, Century 21 is not affected

Figure 24: Dey Street Piling Sequence Stage 2, Century 21 is not affected

Figure 25: Dey Street Piling Sequence Stage 3, Century 21 is not affected

Figure 26: Dey Street Piling Sequence Stage 4, in front of Century 21

AC Mezzanine

Description:	A/C Mezzanine
Scope of Work	• Rehabilitation of the A/C station to mezzanine connection to provide operational improvement
Start of Construction	January, 06
Substantial Completion	December, 07
Application of 3D/4D Model:	• Understanding Design • Construction sequencing • Support of team communication • Visualization support for client and public

As part of the overall construction the owner plans to refurbish major parts of the AC station. This work includes the replacement of the existing passenger ramps with stairs, the combination of the two existing mezzanine levels into one and the integration of the station into the new Transit Center dome and oculus facility. The main challenge for this part of the site is the sequencing of the construction work while maintaining secure access to the subway line for passengers.

The CCM team used the 3D/4D model for this part of the project to understand the complex design, for constructability evaluation, construction sequencing, scheduling and team communication. The 3D/4D model also served as a tool to communicate the schedule and construction sequencing to the client.

Creating the 3D Model

The 3D modeling team first created the 3D model of the AC West and East line station using the preliminary design submission. After the CCM team had used the 3D/4D model for early review purposes the design changed extensively due to the value engineering process. The CCM team decided to remodel the 3D model of the AC West, as the new design had changed significantly. The 3D modelers were able to manage the remodeling in approximately 30% of the time they had needed to create the original model.

Understanding Design, Construction Sequencing and Team Communication

The scheduling team then used this updated 3D model to understand the new complex design of the subway line. After understanding the design the scheduling team evaluated the constructability and the team developed the first sequencing plan. The 4D team linked this sequencing plan to the 3D model. In a subsequent review meeting, several members of the CCM team including project managers, schedulers and 4D modelers evaluated this first construction sequencing plan. The team found a couple of problems in the 3D model and the schedule. Key activities like the construction of an escalator were missing in the schedule. The 3D model still included some 3D objects that represented the old design. Furthermore, a couple of necessary temporary 3D objects such as temporary stairs were missing to adequately display the construction sequence. After this meeting the schedulers and the 3D modelers fixed these problems and the 4D modeling team included these changes in the 3D/4D model.

Visualization Support for the Client and the Public

To use the 3D/4D model for presenting the construction sequence to other engineers and non-engineers the 4D modeling team included lines and arrows into the 3D/4D model to represent available passenger routes. Furthermore, the 4D modeling team improved the overall appearance of the 3D/4D model. This enabled other engineers and non-engineers to easily understand the sequence using the model. In the end the CCM team used the 3D/4D model to present the planned construction sequence of the AC West and East line to the owner and other outside consultants of the project [Figure 27].
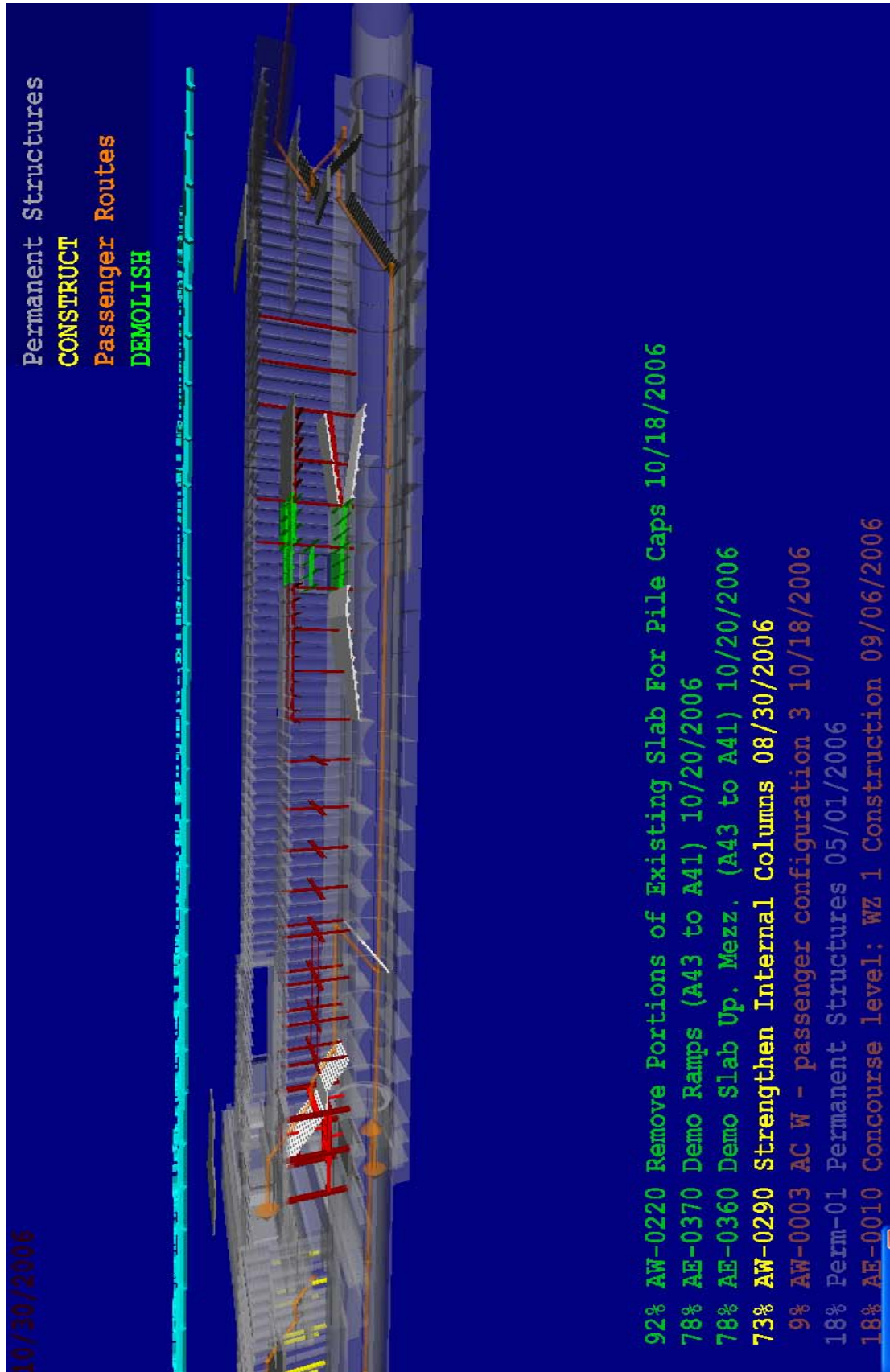
Figure 27: 3D/4D model of the AC East station with passenger routes

Applications of 3D/4D Model	Project Challenges						
	Complex Design	GO schedule	Passenger Flow	Road Traffic	Public Concerns	Tight Site Conditions	Multiple Contractors
Understanding Design	2/3 Line Dey Street AC East/West						
Constructability Review	TC Foundations AC East/West	4/5 R/W Underpinning	AC East/West	4/5 Southern Entrance Dey Street	Dey Street	TC Foundations Dey Street 4/5 R/W Underpinning	
Construction Sequencing		4/5 R/W Underpinning	4/5 R/W Underpinning AC East/West	Dey Street 4/5 R/W Underpining	Dey Street	TC Foundations 4/5 R/W Underpinning	
Support of Master Schedule Review		4/5 R/W Underpinning				TC Foundations	Dey Street General Site Overview Model
Support of Contractor Schedule Review		2/3 Line		4/5 Southern Extension			
Team Communication	TC Foundations		AC East/West	4/5 R/W Underpinning	Dey Street	TC Foundations Dey Street	TC Foundations Dey Street
Visualization support for client and pubic	AC East/West		AC East/West	4/5 Southern Entrance	Dey Street		General Site Overview Model

Table 3 – Reviewed FSTC project examples for project challenges and uses of 3D/4D model

Outlook and Summary of the main Problems Encountered

First, this section will give recommendations on how to apply the existing 3D/4D models on the FSTC project in the future. The second part will discuss the problems so far encountered for the 3D/4D modeling effort.

Further Applications of the Model

One of the main challenges for which the CCM team anticipated to be able to use the 3D/4D model was the coordination of the various contractors on site. However, so far, the CCM team has only used the model for these coordination evaluation tasks on a rudimentary level. The scheduling team has created various master schedules for the various parts of the site. Local 3D/4D models for most of these schedules have been linked and used for the engineering evaluation tasks. Nevertheless, to date, the 4D modeling team has not created a 3D/4D model that may be used for evaluation of the interfaces between these contracts in detail. Only the overall project overview model has been created that offers only limited possibilities to detect conflicts between the various contracts.

The CCM team has also only minimally used the 3D/4D model to present their ideas to other engineering teams, such as the design team or the construction teams of the contractors and non-engineering stakeholders. In the first year of the work on the FSTC project the model has only been used on four different occasions in non-CCM-internal review and evaluation meetings. One of the powerful features of 3D/4D models is to support an easy understanding of sophisticated engineering and construction issues. Thus, the authors believe that the 3D/4D model should be used in more external meetings and presentations the CCM team is involved in.

In the future, a variety of issues have to be solved by the CCM team where the use of a 3D/4D model might be highly effective as well. In the opinion of the authors one of these tasks, for example, will be to use the 3D/4D model to review the contractors' schedules with respect to the constraints of road traffic, passenger flow, and public concerns. The 3D/4D model would also be useful in the construction project office once construction begins to help facilitate coordination and safety meetings.

Discussion of encountered problems

Performance and Cost Related Problems

One of the problems the CCM team encountered early on in the 3D/4D modeling effort included the finding of experienced 3D computer modelers and the ability to develop accurate budget estimates for their work. The CCM team underestimated the efforts necessary to develop engineering and construction accurate 3D models and did not adequately anticipate the number of design and value engineering changes that had to be remodeled in 3D. This section explains the factors that lead to this low budget estimate and the resulting cost overrun in detail.

At the start of the 3D/4D modeling effort it was a cumbersome process to find and educate 3D modelers so that they were able to create 3D models applicable for the 4D effort. In the beginning, the CCM team tried to work with outside design and visualization specialists. However, they often lacked the engineering knowledge to properly read the 2D drawings and create corresponding 3D models. In the end the CCM team established a 3D modeling team that utilized CAD operators. Most of these CAD operators were inexperienced in creating detailed 3D models, however they were able to properly read and interpret 2D drawings, which in this case was a more essential skill. On future projects the project team should persuade the client to task the actual design or engineering team to build the 3D models. This would provide a tighter integration of 2D and 3D CAD work in general. It would also provide a more controlled 3D modeling process so that the construction team could focus on managing and planning construction.

Furthermore, it was not possible to train the CAD operators to use parametric 3D modeling applications like Architectural Desktop, Microstation Triforma or Graphisoft's ArchiCAD in the limited time available. As Table 4 shows the 3D modelers could have been more effective by using such parametric modeling applications. The table highlights that the use of 3D Studio MAX, a design and visualization software not custom tailored for the 3D modeling of buildings, was inefficient compared to the two other 3D modeling applications. The use of Microstation, a non parameterized 3D CAD application, and Architectural Desktop (ADT), a parameterized 3D modeling application targeted for the modeling of building structures, approximately resulted in the same efficiency concerning the output of modeled 3D objects. However, modelers who used ADT were able to model a larger number of polygons per hour. This suggests that it would have been easier for 3D modelers to create more accurate and detailed models using parameterized modeling applications. Thus the CCM team could have been able to avoid the cost overrun if more resources for training or more skilled 3D modelers would have been available.

		hours	# polygons	CAD components	polygons/hour	CADComp/hour
Microstation		1,076	1,341,215	27,138	1,246	25
ADT		386	596,878	9,895	1,544	25
MAX		356	436,695	5,431	1,226	15

Table 4 - 3D Modeling output per hour and 3D modeling applications used

Another criticism of the 3D/4D modeling work was that the hours the 3D/4D modeling team has spent so far has not been in a sound relation to the overall hours that the CCM team has invested. In Table 5, the overall modeling effort for the one year duration (July 2004 – 2005) is indicated. Table 5 represents actual 3D modeling labor as well as non-modeling labor associated with coordination meetings, schedule integration and related project management activities. This table shows that 9.36% of the overall working hours the CCM team spent have been for the 3D modeling of the project. However, the authors believe that this percentage would be reduced over the duration of the project because an extensive effort was started early on in the project to quickly create the necessary 3D models. As time goes on, fewer modeling hours will need to be spent and the 3D/4D model can be applied more and more for engineering and construction evaluation tasks.

pre-november working hours CCM team			
	Non-modeling	modeling	percentage of modeling hours
Bovis	10,657		
PB	10,726	2,207	17.06%
	21,383	2,207	9.36%

Table 5 - non-modeling vs. 3D modeling hours of the CCM

The hours in Table 5 only reflect the original 3D modeling effort. It does not account for the necessary remodeling due to design changes that are common on most construction projects. On the FSTC project an intensive value engineering process took place and much of the design the 4D modeling team had incorporated in the 3D models changed. Due to the nature of this subway refurbishment project approximately 50% of the model represented existing conditions [Table 6]. Thus, the 4D modeling team estimated that only 25% of the model had or will have to be remodeled. The initial budget estimate did not account for this additional modeling effort.

Model	existing	proposed	percentage of existing structure within complete 3D model
# polygons	1366292	1596041	46.12%
# objects	25253	19458	56.48%

Table 6 - model size of existing and proposed conditions

		hours/month	Months	Total Hours
3D Model Updates Due to Design Changes				
Dey Street - New Concept		40	1.50	60
Dey Street - Final Design		20	1.00	20
Transit Center		40	1.50	60
AC West		40	1.00	40
Subtotal				180
3D Model Updates Due to Contractor Changes (Averaged over project duration)				
Revise Temporary Structural Features		4	60	240
Regroup Model Elements		4	60	240
Subtotal				480

Table 7 - Cost estimate for additional funds needed for the 4D modeling process

The low budget estimate lead to a shortage of funds after 6 months, and the client had to be asked to provide more funding to keep the 3D/4D modeling effort going. An estimate of these fund shortages for the project can be found in Table 7 that mainly takes remodeling work due to changed design into account. This table estimates that 480 or approximately 25% more hours need to be accounted for than the 2207 hours [Table 5] already spent with 3D modeling.

The authors believe that the budget problems could have been avoided by an accurate budget estimate taking 3D modeling of changed design and the inexperience of the 3D modelers into account.

Organizational Issues

In addition to the performance and cost related problems, a lot of the impeding factors of the 3D/4D modeling effort on the FSTC project were of organizational nature.

One of the main obstacles to a more widespread use of the 3D/4D models was that the 4D modeling team had only limited access to the construction schedules. If a project team plans to use 3D/4D models it is important to start linking construction sequences and schedules as early as possible to the 3D models in order to take advantage of the technology and its related investments to the full extent.

Another organizational obstacle to widespread use of the 3D model was the inability of the project managers to use the model without assistance of the 3D/4D modeling team. Whenever the project managers were able to review the 3D/4D model with the assistance of the 3D/4D modeling team, they tended to be able to improve their decision making process. However, project managers so far never used the 3D/4D model by themselves. Early on in the project the 3D/4D modeling team held a training session to enable the whole CCM team to operate the 4D modeling software. However, most of the members of the CCM team did not spend the time to learn the software and thus were not able to fully benefit from the information contained in the 3D/4D models.

One problem that was encountered early on in the project and was solved was that most of the applications of the 3D/4D model in the beginning of the 4D effort were suggested or initiated by the 3D/4D modeling team. However, it was realized that this was not the best approach as the 4D modeling team often had not enough insight into the project details and the daily work of the project managers. Once the project managers were able to get comfortable with the 3D/4D modeling process and outputs they started to request more relevant 3D/4D models to address their specific tasks.

Appendix – 3D/4D Implementation Guidelines

This appendix describes detailed guidelines for the 3D/4D process that were helpful on the FSTC project. The authors generalized the guidelines to make them independent of the FSTC project and the software applications used on the project so that the process can be implemented on other projects as well. However, the authors include examples from the FSTC project to illustrate the generalized guidelines. These examples are highlighted in grey boxes. Furthermore, the authors included recommendations that have not been used on a wide scale on the FSTC project in yellow boxes. These recommendations are not comprehensive. However, they provide additional guidelines for a 3D/4D modeling process on projects.

The guidelines are split up into three subsections. The first subsection describes steps to implement a sound process to acquire all necessary project data needed in the 3D/4D models. The second subsection then focuses on 3D modeling and 3D model organization. In the last subsection the authors describe guidelines on how to link schedules with 3D models. In the end the reader should have a good idea of how to implement a 3D/4D modeling effort on a construction project.

Data Acquisition for 4D

Data acquisition is one of the main issues when creating 3D/4D models. Project teams who plan to implement the use of 3D/4D models on their construction project need to establish effective processes and protocols to acquire all project information that will need to be represented in the 3D/4D model. To have these data readily available, contractual, technical, procedural and organizational issues should be considered early in the design phases of a project to support the start of the 3D/4D modeling process. There are two different kinds of information 4D modeling teams need to acquire, design data and schedule data. This section first focuses on the acquisition of the design data and then covers means and methods to acquire the project's schedule data.

Acquisition of Design Data

Design information is either available in the form of 2D drawings or in the form of 3D computer models. On most projects the designers submit the official design information in the form of 2D drawings and specifications. Many designers then use 3D models and renderings to enable other project stakeholders to better understand the design. In order to create a 3D model that adequately represents the anticipated design a 3D/4D modeling team needs to establish a process to acquire these available data.

2D Design Data
The most common form of design data are two dimensional drawings that designers usually submit in the form of printed hardcopies or in the form of electronic read-only PDF files. For 4D modeling teams to be able to create a three-dimensional model using

two-dimensional drawings, it is however necessary to have the original electronic CAD files available. 3D modelers can then build their 3D models directly from the underlying CAD reference files and eliminate re-inputting design data from printed versions which can introduce design and dimension errors. Using this method will ensure that the most accurate data and efficient means are used to create a corresponding 3D model. Therefore, it is necessary to establish a CAD data exchange process that enables a seamless transfer and updating of these electronic CAD data from the design team to the 4D modeling team.

Designers usually issue design drawings in various releases on dates reflecting milestones within the design schedule. Between these dates the designer will change the CAD drawings to reflect the latest developments in the design. Thus, it is generally not advisable to start the 3D modeling using these interim versions of the design. The CAD drawings have to be developed to a stable state before the designer can submit design data. Using only design data containing official drawings has the additional advantage that the submitted information of the design drawings is a contract deliverable. Nevertheless, it is important that the 3D modeling team first focuses on the 3D modeling of parts of the design that are not likely to change in subsequent design submission to avoid costly rework. To get adequate information about these design states the 3D/4D modeling team must have effective communications with the design team.

Once the 3D/4D modeling team has established the process and protocol for obtaining the requisite design information with the design team, there also needs to be an effective means to obtain the actual digital information itself. This should be established electronically by using a FTP site or extranet. In the worst case project teams can exchange the CAD data by using CD. Regardless of the exchange method, it is important that the 3D/4D modeling team has access to the complete original CAD data set. This can be achieved by storing the CAD files on a local file or shared extranet/intranet server.

On the FSTC project the designer submitted most of their design using 2D drawings in PDF-format. After several discussions between the design team and the CCM team the designer was able to establish a process to distribute the CAD files of each of their submitted issues using CDs. During the discussions the main issue that had to be resolved was that the designer feared liability or fraud if the actual CAD data became available to anyone outside the organization and therefore hesitated to submit the CAD drawings. This problem was resolved by exchanging the files without the designer's border reference file. In this way other parties who accidentally gain access to the CAD files cannot distribute any changed files with the official border of the designer. After establishing the CAD file exchange using CDs the CCM team established a folder on a local CAD server to which the 3D/4D modeling team copied each of the design submittals.

For 3D modelers to understand the designer's CAD file structure and the naming and layer conventions, it is also advisable to get familiar with the project CAD standards. In general there is a CAD standard project manual available that the designer uses internally. This CAD standard manual should be used by the 3D modeling team for reference.

3D Design Data

In general there are three different kinds of three dimensional design models available:

- Visualization models,
- Structural analysis models and
- Architectural and Structural 3D design models.

Usually, 3D visualization models are not complete or adequate enough for the transformation into 3D models that can be used for 4D simulations of construction schedules. These visualization models are usually used to illustrate how project surfaces and visible elements will appear in reality rather than representing exactly how a project is designed. Important features like, for example, steel members that are encased within concrete and that are needed for a 3D/4D model for engineering planning processes are omitted in visualization models. Furthermore, these 3D models are often dimensionally inaccurate, and the 3D objects are not split-up or grouped according to the 3D object split convention described in these guidelines. It is not possible for 3D/4D modelers to immediately link these inadequately split 3D objects to construction schedules and even worse it is not easily possible for 3D modelers to split up these objects later on. Most of the time 3D modelers have to discard visualization models and start the 3D modeling from scratch to create adequate 3D models that can be used for 4D simulations.

On the FSTC project the design team had created several 3D visualization models representing architectural finishes and the general design intent. The CCM team anticipated that these models could be used for the creation of the engineering 3D/4D models. However, after taking a closer look the CCM team realized that most of the important structural elements were missing. Furthermore, none of the objects were split up in a way useful for a 3D/4D model as described in the 3D modeling part of these guidelines. After overlaying the 3D models with the 2D design drawings the CCM team also realized that the dimensions of these 3D models were inaccurate. Therefore, the CCM team was not able to use any of these visualization models and had to start modeling from scratch to create useful models for the 3D/4D effort.

Most of the time structural engineers use three-dimensional line models for structural and finite element analysis of steel frames. These models must be accurate in order to guarantee a structurally sound representation of the project. It is easy for 3D modelers to convert these line models into 3D models usable for 4D simuations. 3D modelers can use state-of-the-art 3D modeling applications that offer a feature to extrude 2D cross sections along lines to create 3D models. Thus, it is advantageous to obtain this type of 3D data from the structural engineers and to convert these models directly into 3D models useful for construction management.

On the FSTC project one of the main design elements is a large dome and oculus structure that comprises the roof of the Transit Center facility. The structural designer created a two-dimensional line model of the structure in the finite element analysis software ETABS. 3D modelers imported this model into Autodesk's Architectural Desktop (ADT) by using the CAD file exchange format DXF. In ADT, the 3D modelers

could then convert the structural design model into a three dimensional model representing the various cross sections of the dome and oculus structure.

The authors believe that the best design input for a 3D/4D model is a 3D model created by a parameterized building modeling application such as Architectural Desktop, Triforma or ArchiCAD. This provides a more robust and effective modeling environment. Therefore, 3D modelers will be able to create 3D models for 4D simulations more effectively. Nevertheless, it is always advisable to use the 3D modeling guidelines and conventions described later on in this report during the 3D modeling effort. This ensures the most streamlined transformation of the 3D model design data into corresponding 4D models.

Acquisition of Schedule Data

It is important for the 3D/4D modeling process to establish access for the 4D modeling team to the latest versions of the schedule. State-of-the-art scheduling software tools support this process by storing all schedule data in a central database. Read-only access to this database for the 4D team should be established. If project teams use a scheduling software that uses a file-based data storage technique it is important to store these files on a file server that is accessible by the 4D team.

On the FSTC project the 3D/4D modeling team was not able to gain direct or efficient access to the project's schedule data. As discussed in the main part of this report, schedulers did not want to grant access to any schedule data until it had first been approved by the client. This often led to confusion as, for example, 3D/4D models represented out-of-date schedules or a project manager requested 3D/4D models that could not be linked in a timely manner as the person responsible for the 4D modeling could not access the respective schedule information. The FSTC 4D modeling team believes that this lack of access to project schedules was one of the main obstacles of the 4D modeling effort.

If project schedulers plan to use file-based scheduling software it is in most cases possible to import these files into scheduling software that uses a database. It is advisable to create a second schedule database for the 4D team to simplify access. Recently, 4D modeling applications have become available commercially that link directly to these databases and can update once-established links to activities automatically. In this way the cumbersome 4D re-linking effort can be automated to a great extent if schedules are changed.

3D modeling guidelines

One of the key issues for any 4D modeling effort is the organization and the quality of the 3D models. On complex projects 4D modeling teams need to implement a standardized organization of the modeling process. This will enable multiple 3D modelers to work on one model. Furthermore, a good organization improves access to the

3D model and its information by all participants. Furthermore, not all 3D models created are suited for linking them with a construction schedule. 4D modeling teams have to consider several issues during the modeling process.

Guidelines to Handle Information Sources

As mentioned, 4D modelers can build 3D/4D models using various information sources like 2D design drawings or other 3D models that already exist. However, it is important that the whole project team is able to track the information within the 3D/4D models back to its original source. In this way the project team can make sure that it is working with models reflecting the latest design version. Thus, project teams have to implement a system that stores these original information sources.
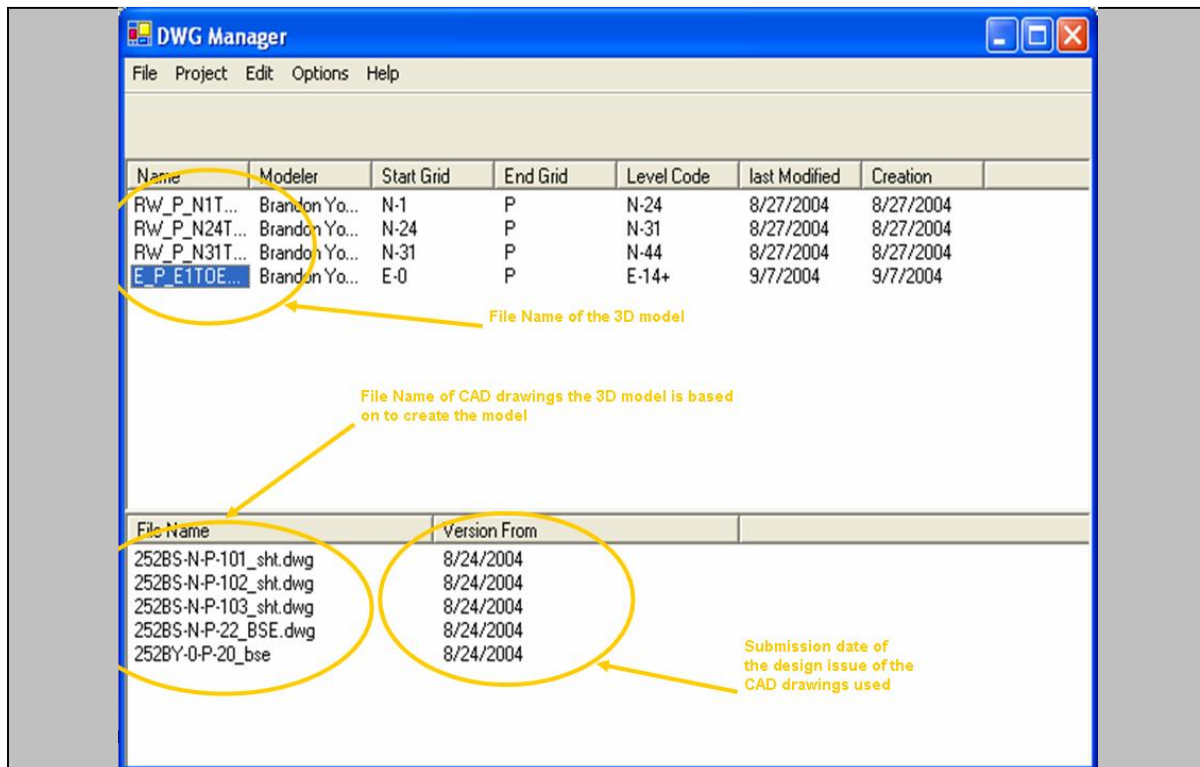
Figure 28: Graphical User Interface for the drawing reference database

On the FSTC project the modelers stored all references to the respective 2D CAD drawings they used to create 3D models with the respective submission date of the 2D design issue into a database. The 3D/4D modeling team implemented a user interface [Figure 28] that modelers used to update the database whenever they created a new 3D model or updated an old model with a recently submitted design drawing. Since this database was accessible by the entire project team, project managers could verify whether the 3D models were created based on the latest design versions by using the database and the provided graphical user interface.

The source information available to 3D modelers is often not accurate enough to create a complete 3D/4D model. 3D modelers must often use their own intuition to model apparently missing parts of the supplied design information. In this way they introduce

new information that has not been reviewed by qualified engineers. It is often better to exactly model the existing design of the source information leaving out important missing design details. In this way existing inconsistencies, for example, missing structural supports, are visible within the 3D model. Therefore, the responsible engineers for these design inconsistencies can use the 3D model to solve these problems.

If the project uses a computer supported RFI process, for example, by using software applications like Expedition, it is advisable to integrate the 3D modelers into the RFI process. This allows the 3D modeling team to request missing design information quickly. Establishing such a process also enables the project team to systematically collect the encountered problems the 3D modelers are finding in the design for resolution and later reference.

3D Model File Guidelines

One of the main problems in leveraging 3D/4D models used on large scale engineering and construction projects is that they become too large to be efficiently handled by the 3D and 4D modeling applications. In order to manage this bottleneck the overall 3D model has to be split up into a number of different 3D modeling files that can be referenced by each other.

It is important that the whole project team can easily determine what part of the overall project is included in which 3D modeling files. Thus, it is important for the 3D/4D modeling team to establish conventions on how the various 3D models are distributed and referenced among the files. 4D modeling teams need to establish a project-wide file naming convention for 3D model files. Usually a first guideline for the distribution of the overall 3D model is to create different files for the various disciplines and trades like architectural design, structural design, electrical design, etc. On the next level in the hierarchy of the 3D model distribution are local considerations of the site. 3D modelers can, for example, distribute the 3D models into files for the various existing bid packages or by using a project-wide gridline system as reference.

Another problem on large projects is that various 3D models exist that 3D modelers created with different 3D modeling applications. Fortunately state of the art 3D modeling applications often allow a mutual exchange of 3D information. However, it is important to store each of the model files in a format that all applications can import. In this way it is guaranteed that one 3D modeler using one 3D modeling application can modify the models another 3D modeler has created with a different 3D modeling application. Furthermore, the 3D modelers should export all their model files to one common file format that can be imported into the 4D modeling application with consistency and predictability.

On the FSTC project the 3D modeling team created the 3D models using three different 3D modeling applications: Bentley's Microstation V8, Autodesk's Architectural Desktop (ADT), and Descreet's 3D Studio MAX. All of these applications are able to import 3D models using the DWG format so it was decided to store a DWG model file in addition to the native file format for all model files created. As the 4D modeling application the

FSTC CCM team used Common Point's Project 4D. Project 4D imports 3D models in the VRML format, so the 3D modeling team also converted each of the model files into VRML. During the 3D modeling process the 3D modelers made sure that an actual version of their models in DWG and VRML was always saved on the 3D modeling project server. Figure 29 shows the overall conversion process used on the FSTC project.
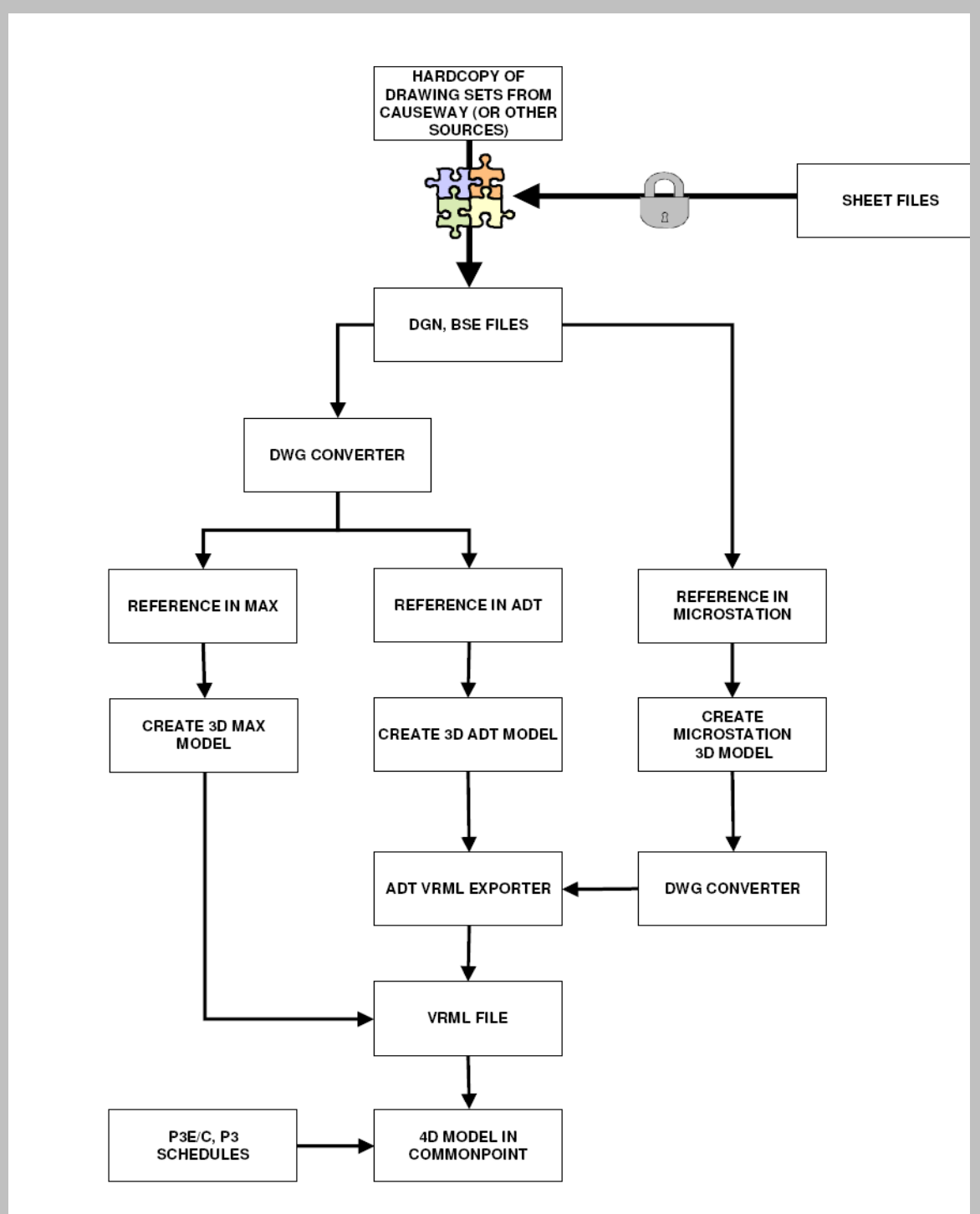

Figure 29 - 3D model conversions

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Furthermore a sophisticated naming convention was introduced using codes for subway lines, elevation levels, and gridlines. The naming convention used is shown in Figure 30. Using this naming convention the 3D and 4D modelers as well as the project managers of the CCM team could easily access the different 3D site data contained in the various modeling files.
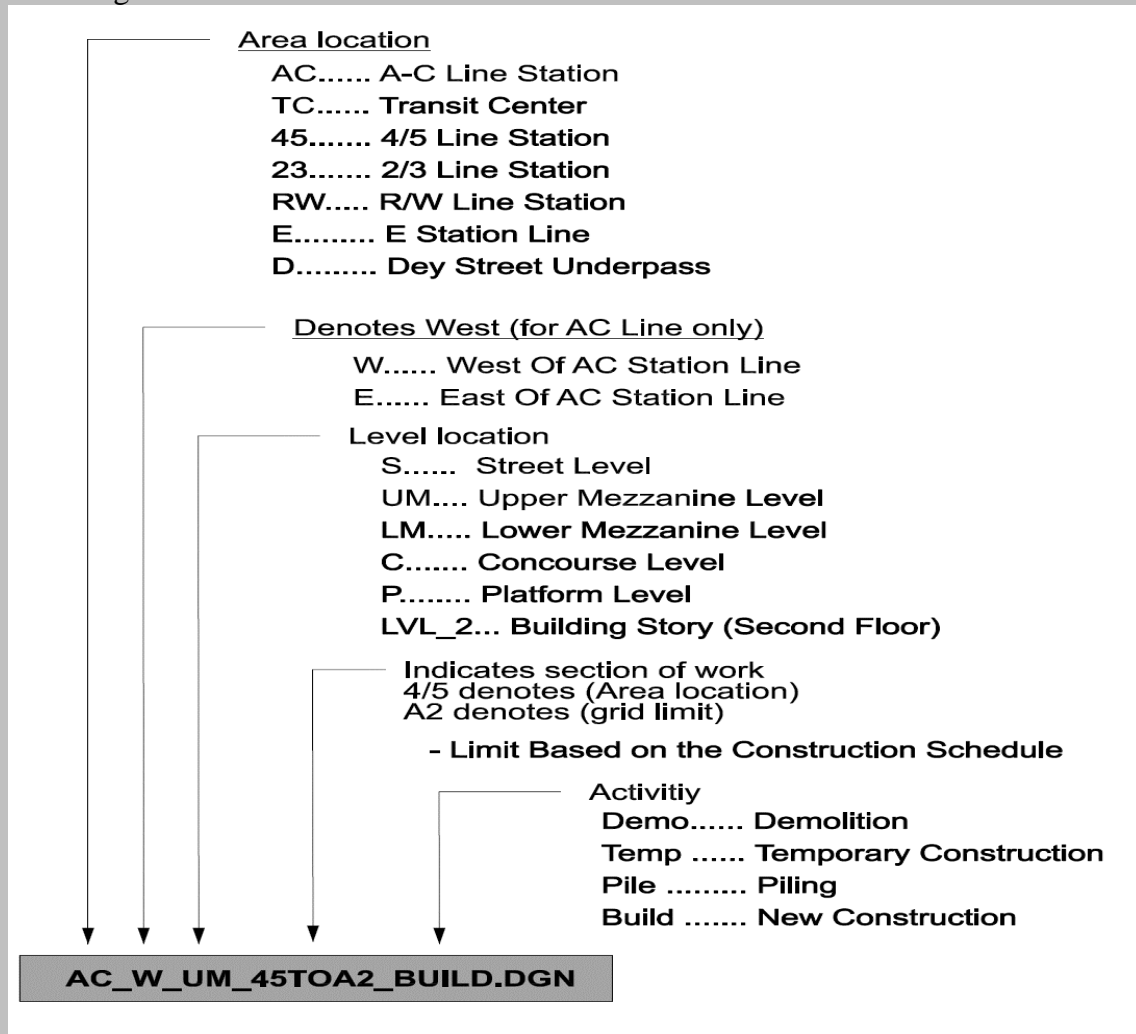

Area location
AC...... A-C Line Station
TC...... Transit Center
45....... 4/5 Line Station
23....... 2/3 Line Station
RW..... R/W Line Station
E......... E Station Line
D......... Dey Street Underpass

Denotes West (for AC Line only)
W...... West Of AC Station Line
E...... East Of AC Station Line

Level location
S...... Street Level
UM.... Upper Mezzanine Level
LM..... Lower Mezzanine Level
C....... Concourse Level
P........ Platform Level
LVL_2... Building Story (Second Floor)

Indicates section of work
4/5 denotes (Area location)
A2 denotes (grid limit)

– Limit Based on the Construction Schedule

Activitiy
Demo...... Demolition
Temp ...... Temporary Construction
Pile .... Piling
Build .... New Construction

AC_W_UM_45TOA2_BUILD.DGN

Figure 30 - File naming convention used on the FSTC project

3D Object Hierarchy Guidelines

It is important that 3D modelers model and divide 3D geometrical objects such that construction sequences and schedules can be simulated. In general the 3D modelers have to split up 3D model objects so that there is a separate 3D object for each schedule activity that is to be represented within the 4D model. As the joints between steel members are usually known early on in the design this process is straightforward for structural steel as 3D modelers can split up the steel frames at the joints. Also it is easy

for 3D modelers to split up pre-cast concrete 3D objects. For cast-in-place concrete objects this process is more cumbersome. Project managers in most cases determine the direction and size of concrete placing sequences and the corresponding schedule activities late in the project. Thus, it is usually too late to integrate this detailed information into the 3D model easily. To study the construction sequences using 4D models the 3D/4D modeling team should use a preliminary convention for splitting up 3D objects. This split-up convention should enable 4D modelers to link various schedules to the 3D model representing a number of different concrete placement sequences. As a rule of thumb large cast-in-place concrete objects can be split up at the project's gridlines. In any case 3D modelers should use already designed expansion joints to split up the 3D objects.

Furthermore, 3D modelers have to group the objects in each of the 3D model files according to various types of building components. In this way fast access to specific 3D model objects is possible. This is of extreme importance, for example, during the linking process but also during the navigation of the 3D model as engineers can select specific objects easily. The created groups should follow a naming convention using engineering terms. For example, for a structural 3D model structural member type names like "concrete column", "steel column", or "concrete beam" should be used to name the groups.

For engineering evaluations it is not necessary to have a photo-realistic rendering of the 3D model. However, to understand the material type of the 3D objects 3D modelers should use object colors representing the various materials like steel, concrete, or sheet metal. Also 3D modeling teams should use these colors uniquely within all the different model files.

The color scheme used on the Fulton Street Project is summarized in Table 8.

	Existing			Proposed		
	AutoCAD	**RGB**	**Microstation**	**AutoCAD**	**RGB**	**Microstation**
Street	250	51/51/51		250	51/51/51	250
Walkway	254	214/214/214		254	214/214/214	254
Concrete Structures	252	132/132/132		9	201/201/201	9
Steel Structures	14	153/0/0		10	255/0/0	10
Excavation		224/135/10			224/135/10	
Buildings	53	204/204/204		53	204/204/204	53
Stairs	7	0/225/225	7		201/201/201	9
Excavation		225/117/0	46		225/117/0	46

Table 8- Coloring Scheme used on the FSTC project

The use of basic colors can be a powerful tool to visualize various issues. However, it is important to provide colored models with a legend of the meaning of the colors. As it is not possible to store this legend directly in the 3D modeling files, color coding of 3D objects in the 3D model files to communicate engineering issues is not advisable and

often causes confusion. Thus, project teams should only apply the color coding in the 4D model application where the meanings of colors usually can be stored.

Guidelines for Unique Ids of 3D Objects

4D applications offer the possibility to re-link changed 3D model objects automatically. To do so the 4D applications must use the unique ID of the 3D object that is assigned in the 3D modeling application. There are two different ways how these IDs are assigned within 3D modeling applications: manually by the 3D modeler and automatically by the 3D application. If the ID has to be assigned manually the 3D modeler has to ensure that all of the IDs are unique while creating the model. While revising the model the modeler has to ensure that the IDs of objects are not changed. However, the 3D modeler has the option to delete an object that has to be remodeled and create a new object with the same unique ID as the old one.

Nevertheless, it is usually advisable to use an automated assignment of IDs by the modeling application to ensure that the assigned IDs are unique. Using this approach the 3D modeler should not erase 3D objects unless the respective component is no longer part of the overall design. Rather it is important that the 3D modelers use the modify features of the 3D modeling software if possible. In this way the unique ID of the 3D object stays the same.

One problem the 3D/4D modeling team encountered on the FSTC project concerning the automated assignment of unique IDs by 3D modeling applications is that it is only guaranteed that the assigned IDs are unique within one file. On projects that need to use more than one 3D model file the file name needs to be incorporated in the unique IDs of the 3D objects. As the file names are unique as long as the described file naming convention is used, this again ensures that all 3D objects in all files have a unique ID assigned.

Linking schedules with 3D geometry

The two main scheduling software applications used on major construction projects are Primavera's P3 and P3 e/c. On the FSTC project both of these products were used for the scheduling process. Common Point's Project 4D was used for linking the 3D models with the schedules. P3 offers the functionality to export to PRN files in ASCII format can be imported seamlessly into Common Point. One slight problem that occurs during the PRN export is that activity descriptions from P3 can be exported to a length of only 49 characters. Furthermore, the standard option for the export is set to less than 49 characters. It is advisable to change the export settings in P3 to an export using the maximum possible length.

Importing schedules into Common Point from P3 e/c is currently more complicated. P3 e/c offers the option to export schedules into Microsoft Project's MPX format that can also be imported into Project 4D. The standard options of P3 e/c do not export the activity ID. Thus, a custom export template has to be created that exports the activity ID into the "Text 1" field of the MPX file. On import of the MPX file the 4D modeler has to adjust a couple of settings in Project 4D. First, the 4D modeler has to change the

"Activity ID" field to "Text 1". Second, the 4D modeler has to set the start and end dates that need to be used in Common Point to the "Baseline" schedule fields within the MPX file.

Another important issue to consider while importing files within MPX or PRN file format into Project 4D is to import the schedule using the right date format. Dates can be written in numerous different formats, for example, the 12th of November in US-American notation is formatted 11/12 while in a European notation it would be formatted 12/11. In order to check the date format the MPX or PRN file can be opened in a text editor where the person linking the 3D model with the schedule can find out the date format used. Then this date format has to be set into Project 4D in order to guarantee a correct schedule import.

It is advantageous that 4D modelers link 3D models with schedules in a well thought-out way so that the 4D modeler can verify the logic of the schedule and the compatibility of the geometry easily. As a first step in this the 4D modeler should decide which activities are linkable to geometry and which are not after importing the schedule. This decision is mainly based upon the type of the activity.

Basically one can link geometrical objects to four different kinds of activity types:

> Construction activities,
> Demolition activities,
> Temporary activities and
> Renovation activities.

3D geometrical objects linked to construction activities are not displayed at the start date of the schedule in the 4D application. On the start date of the activity, the respective objects are then displayed. During the duration of the activity these objects are highlighted while they are displayed with their default color upon completion. 3D geometry linked to demolition activities will be displayed only until the end date of the activity. The geometry linked to this type of activity will also be highlighted throughout the duration of the activity. Geometry linked to temporary activities is displayed and highlighted during the duration of the activity and hidden during the rest of the 4D simulation. The objects linked to renovation activities are displayed throughout the whole duration of the schedule while the 4D application highlights them during the duration of the respective schedule activity. All other types of activities, like, e.g., design milestone activities, cannot be displayed within 4D modeling applications so they can be deleted from the imported schedule immediately to maintain the model as simple as possible.

The next step in the linking process is to create 4D groups reflecting the hierarchy of the schedule or the work breakdown structure of the project if one has been established. 4D groups in 4D applications are a third hierarchy in addition to the geometry object and the schedule hierarchy. 4D groups can group several geometrical objects or other 4D groups that need to be linked to one or several activities. By using 4D groups it is possible to easily adjust the usually higher level of detail of the 3D models with the often coarser

level of detail of the schedule. After all the necessary 4D groups have been defined the 4D modeler can quickly link them to the respective schedule activities.

In a next step the person linking the 4D model has to import the required geometry for the 4D model into the 4D modeling application. This geometry has to be assigned to the respective 4D groups created. Now the logic of the schedule can be checked and controlled by running the 4D model. During the controlling of the schedule sequence it is important to verify whether inconsistencies are caused by a non-logical schedule or by an error made during the linking process.

To represent the construction sequence realistically 4D modelers need to import permanent geometry of the existing site conditions. During this task the 4D modeler has to make sure that the logic of the construction sequence is adequately represented. For example, the 4D modeler needs to import the existing supports for structural elements to avoid that 3D objects are floating unsupported in free space.

After the 3D/4D model has been linked and the logic of the schedule has been verified thoroughly it is important to define predefined views on the 4D model. The 4D modeling team can use these views to seamlessly illustrate the important sequences of the construction schedule to other participants during evaluation and review meetings.

On the FSTC project it was important to represent the existing geometry of the subway stations. With the 3D/4D model the 4D modeling team represented this existing geometry transparently [Figure 31] to allow the users of the 3D/4D model to see the construction sequences in the respective subway stations.
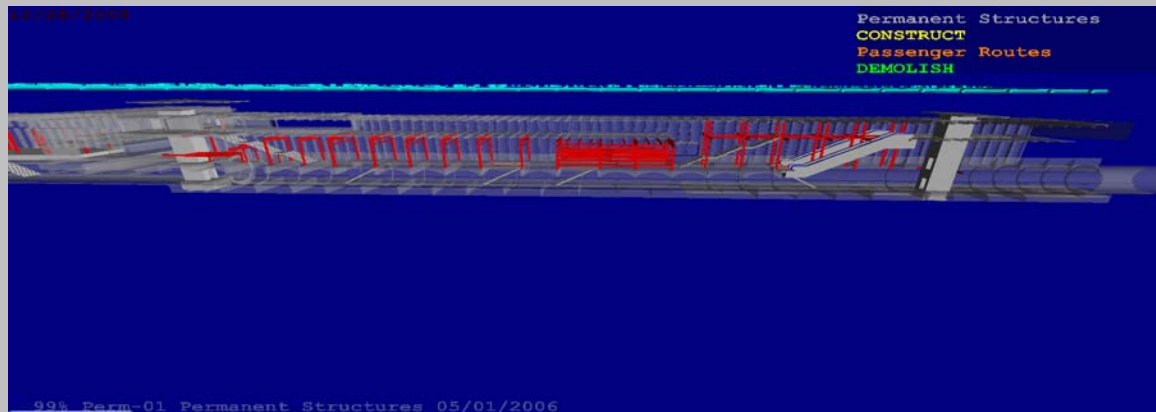

Figure 31: Using Transparency to display existing stations

4D modelers used 3D CAD objects representing construction machinery like pile-augers, cranes or excavators to represent type of work within various work zones [Figure 32]. The FSTC 3D/4D modeling team, for example, displayed the various work zones for the pile augering operations using barrier CAD objects to represent the extent of the work zone. The 4D modelers used a 3D CAD object of a pile auger to show the type of work in these work zones.
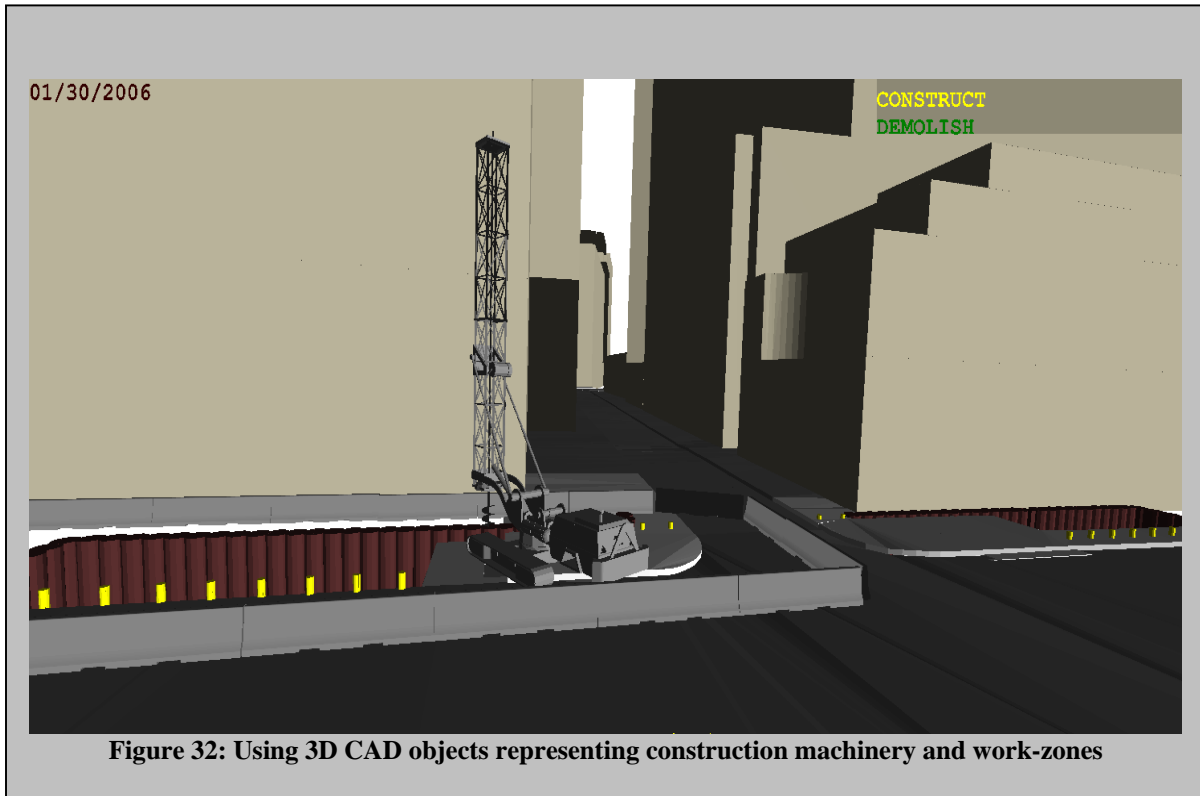
Figure 32: Using 3D CAD objects representing construction machinery and work-zones

A plan view of the project or part of the project the 3D/4D model is representing is always important. Another view that often comes in handy is a longitudinal section that displays the construction sequences from the side. A couple of cross sections can be defined to show important sequences in detail. Some 4D applications allow the definition of predefined views with an option to hide objects that hinder a straight view to the relevant parts of the site. It is highly advisable to use this feature in combination with the predefined views. In this way the 4D model team can provide even faster access to the important information needed within evaluation meetings.

In addition to the process of creating 3D/4D models in the first place it is also important that 3D modelers have a sound process in place to update the models with new geometry reflecting changed design or with new construction schedules. 4D model applications use unique geometrical object IDs and schedule activity IDs to internally store the links. Thus, in order not to loose any of the already established links, it is important that 4D modelers ensure that both object IDs of the already linked 3D geometrical objects and schedule activity IDs are consistent with the IDs assigned in previous versions of the schedules or the 3D models. After re-importing new geometry or schedules the 4D modeler should first verify whether the already established links are still consistent. Then the 4D modeler can relink the new and changed geometry and create new 4D groups in order to reflect a new level of detail within the 3D model or the schedule if necessary. In the end the 4D modeler can verify the new 4D model with respect to a logical construction sequence and temporary and spatial conflicts.

Researchers at CIFE, Stanford University, are developing a 4D database that stores the 4D links and the schedule activities separate from the geometry. One main obstacle concerning 3D/4D models currently is that state of the art 4D applications are not capable of showing 3D models beyond a size of approximately 1.5 million polygons. Thus, for large scale projects a number of various 3D/4D models have to be created that are stored in separate files. A lot of the 4D links in these models are redundant, i.e., they are used in a number of 4D models. Thus, a lot of duplicated work is necessary linking the models in the first place. Furthermore, an update of the models is cumbersome and error prone as the linked information has to be updated in various models stored in different files. Storing the 4D links separate from the geometry in a central database enables a flexible, on-demand import of the information after importing various geometry objects into the 4D model application.