CIFE

Challenges and Benefits
of 4D Modeling
on the Walt Disney Concert Hall Project

By

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SUMMARY
CIFE WORKING PAPER #064

1. Abstract:

The goal was to test the applicability and usefulness of 4D modeling and of the 4D prototype software developed between CIFE and Walt Disney Imagineering on a complex project like the Walt Disney Concert Hall project in Los Angeles. The 4D models built with the help of CIFE helped the construction team find many schedule inconsistencies, resolve access, scaffolding and hoisting issues for the exterior and interior construction in a timely manner, inform more stakeholders of the approach to construction and of the schedule, and engage subcontractors in the scheduling process.

2. Subject:

   • *What is the report about in laymen's terms?*

It describes how 4D (3D plus time or schedule) models were used on the Walt Disney Concert Hall project in Los Angeles.

   • *What are the key ideas or concepts investigated?*

4D modeling for exterior and interior work. Benefits and challenges of 4D models for projects with complex geometry.

   • *What is the essential message?*

4D models improve the communication and analysis of a proposed construction schedule dramatically.

3. Objectives/Benefits:

   • *Why did CIFE fund this research?*

4D modeling and visualization of scope and schedule information has been an important research area for several years.

   • *What benefits does the research have to CIFE members?*

It demonstrates how 4D models were useful on a complex project. It shows that the 4D prototype scales to large, complex projects. It shows pitfalls that should be avoided when embarking on 4D modeling efforts.

   • *What is the motivation for pursuing the research?*

To improve the functionality of the 4D tool. To demonstrate the need for specific 4D functionality.

   • *What did the research attempt to prove/disprove or explore?*

To what extent 4D models would be helpful for schedule and constructibility analysis and for communication of schedule and scope information.

4. Methodology:

   • *How was the research conducted?*

Onsite, real-time case studies between March and September 2000, with ongoing updates of the 4D models. Review of 4D models by construction experts from M.A. Mortenson (general contractor) and subcontractors.

       • *Did the investigation involve case studies, computer models, or some other method?*

Yes, it modeled specific parts of the project and corresponding schedule in computer-based 4D models.

5. Results:

       • *What are the major findings of the investigation?*

4D models support constructibility analyses and schedule analyses well. They are effective tools to communicate schedule and scope information.

The 4D prototype was able to model the complex geometry and schedule on PCs.

       • *What outputs were generated?*

Improvements to 4D functionality were made (e.g., a clipping plane was added). Result were disseminated in various presentations at Stanford University and elsewhere.

6. Research Status:

       • *What is the status of the research?*

Involvement with the project is ongoing and further 4D modeling efforts to help design certain systems and processes are anticipated.

       • *What is the logical next step?*

To construct more detailed 4D models for parts of the project to test the applicability of the 4D prototype for such tasks.

       • *Are the results ready to be applied or do they need further development?*

Yes, as the report shows, the results are immediately applicable on projects.

       • *What additional efforts are required before this research could be applied?*

None, other than continuous improvement of the 4D tool based on user feedback.

Challenges and Benefits of 4D Modeling on the Walt Disney Concert Hall Project

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This article describes in detail the application of 4D models for construction scheduling and constructibility analysis on the Walt Disney Concert Hall project in Los Angeles. It discusses the reasons for the use of 4D models on the project and details the technical challenges the 4D modeler had to overcome. Specific examples of the impact of the 4D model on the schedule are also shown.

The Project, Participants and Motivation for 4D Modeling

The Walt Disney Concert Hall (DCH), designed by Frank O. Gehry and Associates (FOGA), is the new 2,400 seat home of the Los Angeles Philharmonic Orchestra. Located in downtown Los Angeles, the $175,000,000 project incorporates complex architectural, structural, and acoustical requirements in a tight one-city-block site. The project is scheduled for completion in early 2003. Figure 1 shows a photo of the front entrance to the Walt Disney Concert Hall.

Figure 1: Photo of the physical model of the Disney Concert Hall

The architectural process undertaken by FOGA provides opportunities and challenges for the construction of 4D models to assist in the construction planning process. FOGA's design process yields a highly developed 3-dimensional CAD product model, which is used extensively for dimensional control and fabrication in the construction process. This product model and the process model contained in the construction schedule prepared by M.A. Mortenson Company, the general contractor (GC), with input from the many subcontractors, provide the necessary elements to begin construction of the 4D model. The GC used the 3D and 4D models as

communication tools to share project information with all project participants including architects, engineers, the general contractor, subcontractors, and the owner. John Haymaker from the 4D research team at Stanford University worked on site to help build the 4D models discussed below and to introduce the GCand key subcontractors to the 4D modeling process. He used the prototype 4D modeling software developed through the collaboration of the Research and Development group at Walt Disney Imagineering (WDI) and researchers in the 4D CAD research group at the Center for Integrated Facility Engineering (CIFE) at Stanford University.

The complex project and a tight site made precise coordination of construction activities a very high priority. M.A. Mortenson saw the use of 4D visualization of the construction process as a valuable tool for accomplishing four project objectives:

1. **Schedule creation**: 4D models help visualize schedule constraints and opportunities for schedule improvements through resequencing of activities or reallocation of workspace.
2. **Schedule analysis:** 4D models help analyze the schedule and visualize conflicts that are not apparent in the Gantt charts and CPM diagrams.
3. **Communication**: Many participants join the project in midstream, and it is critical to bring new participants up to speed quickly.
4. **Team building**: The GC's project superintendant, Greg Knutson, felt strongly that it was very important to construct a team atmosphere, where people solve problems together. He realized that a shared, visual model to externalize and share project issues was a valuable team building tool.

The following section details the project information that was available at the beginning of the 4D process. Subsequently we examine the process undertaken to construct the 4D models and describe the 4D models constructed for the project. We also describe some of the issues and challenges encountered in constructing the models. Finally we show how the GC used the models to accomplish the objectives.

Available Electronic Information

The interest in constructing the 4D models emerged in early 2000, as The GC mobilized to the site. At this point, the architect had already developed most of the 3D geometry, and the GC's construction schedule had about 4,000 activities. This section describes the format and level of detail of the project information at the beginning of 4D modeling process.

Available 3D geometry
The architect constructed the 3D models with CATIA. There are at least two reasons for the use of CATIA as the 3D modeling software. First, FOGA develops very complex geometry and considers the nature of the curves generated to be integral to the architectural design. CATIA uses NURBS-based curves and surfaces, which describe the curves mathematically, and therefore maintain a high level of accuracy. More traditional CAD packages for the AEC industry do not use NURBS, instead approximating the curves and therefore loosing the level of accuracy desired by FOGA. The second motivation for using CATIA is that the software handles very large, complex models. As described below, the architect modeled a great deal of the project in 3D, and the shear amount of information would overwhelm traditional AEC CAD packages.

To reduce complexity, FOGA divides the 3D model into sub-models. First, FOGA divides the project geographically into "building elements," as shown in Figure 2.
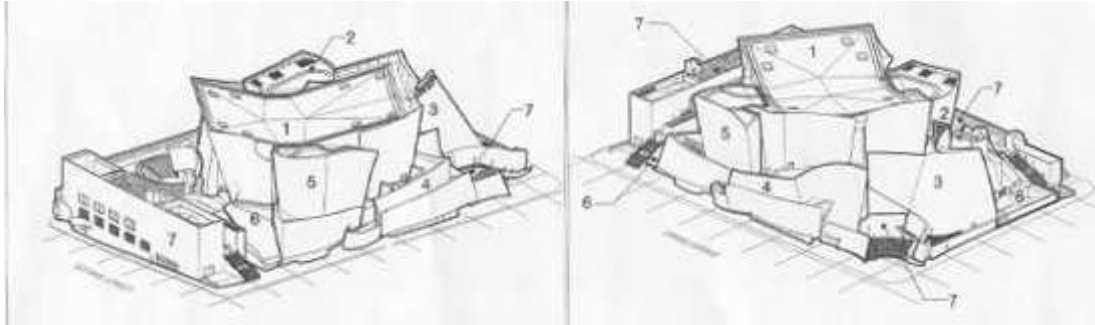
Figure 2: DCH broken down by building element.

Each building element is then further divided into models reflecting different significant building systems. Figures 3 to 7 show the different models available for building element 2. Figure 3 shows all of the building elements' surface models incorporated into one view. Figure 4 shows the surface model for element 2. The surface model contains everything that can be seen, from plaster, to glazing, to carpet, to wood panneling, etc. Figure 5 shows a pattern model. A pattern model describes any pattern in an element that is relevant for architecture or construction. Figure 5 shows the pattern of the stainless steel panels for the exterior of element 2. Figure 6 shows the concrete model, which models the structural and architectural concrete surfaces. Figure 7 shows an example of an air and water barrier model. The air and water barrier model defines the surface in space where the waterproofing systems should be placed. Figure 8 shows the structural wireframe model. This model defines a wire for each piece of steel in the building. The wire can symbolize centerline, top of steel, or bottom of steel. The steel detailer and the steel fabricator use this wire model as input and place the proper size member with each wire. The detailers detail all the connections in X-Steel or other detailing packages in 3D. The resulting detailed steel model, shown in Figure 9, is then reimported into the CATIA model.
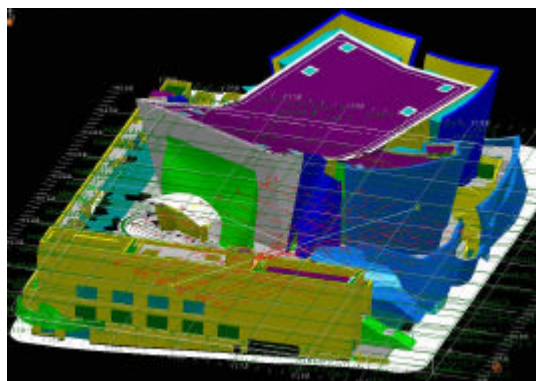

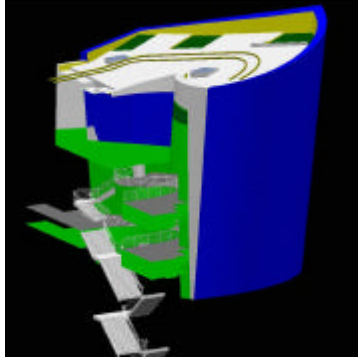*Figure 3: Surface models for all building elements.*
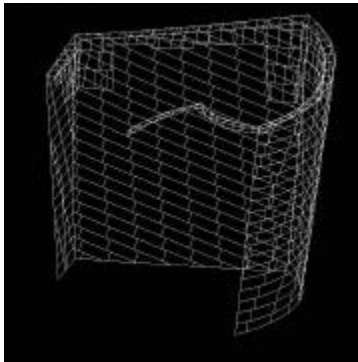
Figure 4: Element 2 surface model.

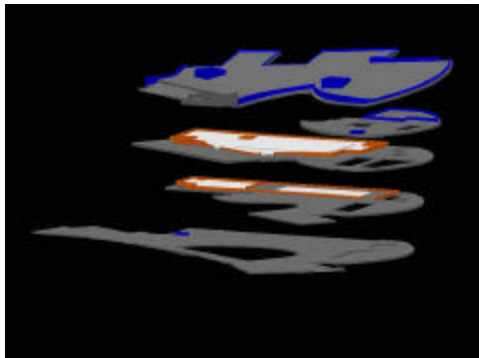*Figure 5: Element 2 pattern model.*

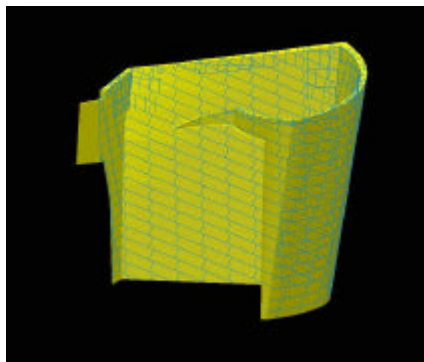*Figure 6: Surface model for element 2.*

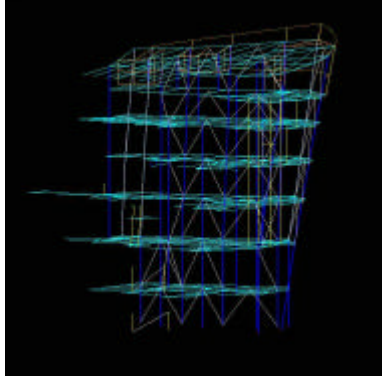*Figure 7: Air and water barrier model for element 2.*

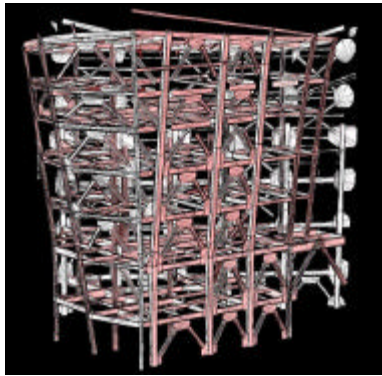*Figure 8: Element 2 steel wire frame model.*

Figure 9: Detailed steel model.

Each 3D model consists of layers reflecting different sub-systems. Table 1 shows a partial listing of the layers. These layers are helpful for 4D modeling because they isolate certain scope information in the 3D model, which facilitates the identification of the appropriate geometric elements for a particular activity. However, frequently the layering organization is different from the organization of the schedule, and the 4D modeler needs to reorganize the geometric information for the 4D model to fit the schedule organization.

LAYER NUMBER	CATIA LAYER CONTENTS	LAYER NUMBER	CATIA LAYER CONTENTS	LAYER NUMBER
	GENERAL PROJECT DATA (1 THRU 10)		STONE (46 THRU 55)	
1	PROJECT GRID	46	VERTICAL STONE CLADDING	86
2	COLUMN GRID LINES	47	SLOPED STONE CLADDING	87
3	PROPERTY LINE	48	STONE COPING	88
4	VACATION ENVELOPE	49	STONE PAVING	89
5	PROJECT REFERENCE GEOMETRY	50	STONE BASE	90
6	PROJECT WORKPOINTS	51	DECOMPOSED GRANITE	91
7	CATIA CONSTRUCTION GEOMETRY	52	NOT USED	92
8	EXISTING CONSTRUCTION	53	NOT USED	93
		54	NOT USED	
	GLAZING ASSEMBLIES (11 THRU 25)	55	NOT USED	
11	SKYLIGHT GLAZING		ROOF ASSEMBLIES (56 THRU 65)	96
12	SLOPED GLAZING			97
13	VERTICAL GLAZING	56	ROOF MEMBRANE TYPE 1	98
14	MULLION WIREFRAME (CENTER LINE MULLION)	57	ROOF MEMBRANE TYPE 2	99
15	MULLION	58	ROOF HATCH	100
16	METAL CLOSURE TRIM	59	ROOF DRAIN	101
17	METAL CLOSURE PANELS	60	STAINLESS STEEL GUTTER	102
18	METAL GUTTER	61	EXPANSION JOINT ASSEMBLY	103
19	METAL FLASHING	62	ROOF DAVIT PEDESTAL	104
20	GLAZING ANCHOR ASSEMBLY	63	ROOF ASSEMBLY TYPE 3	105
21	GLAZING BOUNDARY	64	NOT USED	106
		65	NOT USED	107
	METAL PANEL ASSEMBLIES (26 THRU 45			108
			MISCELLANEOUS EXTERIOR ASSEMBLIES	109
26	METAL PANEL ASSEMBLY CONDITION TYPE 1			110
27	METAL PANEL ASSEMBLY CONDITION TYPE 2	66	NOT USED	
28	METAL PANEL ASSEMBLY CONDITION TYPE 3	67	METAL GRILL	
29	METAL PANEL ASSEMBLY CONDITION TYPE 4	68	METAL GRATING	
30	METAL PANEL ASSEMBLY CONDITION TYPE 5	69	BUILDING MAINTENANCE EQUIPMENT	126
31	METAL PANEL ASSEMBLY CONDITION TYPE 6	70	BUILDING MAINTENANCE TRACK	127
32	METAL PANEL ASSEMBLY AIR AND WATER BARRIER	71	STAINLESS STEEL CLAD DOOR	128

Table 1: A portion of the layer list.

Available schedule information

The GC created the construction schedule with Primavera's P3™ software. At the start of the 4D modeling process in March 2000, the schedule contained about 4,000 activities. By Fall 2000, the schedule consisted of approximately 7,200 activities. The schedule divides the 3D project geometry into chunks that are relevant to an activity. Figure 10 shows the breakdown key for the activity ID in the schedule. Activities are identified by building element, floor, area, and subarea, then by phase, system, component, and action. However, some activities do not fit easily into this breakdown. For example, steel installers like to break the steel into manageable chunks, called sequences, which are a grouping of steel that is self supporting and can be erected in a reasonable amount of time. These sequences often span more than one building element, or cover more than one floor. Even though it was useful to have one main way to organize the schedule (as shown in Figure 10), many methods for decomposing the geometry and linking a scope of work to an activity are required to suit different types of work. Figure 11 shows the project broken into levels (red) and sequences (green). The figure also shows the main potion of the Concert Hall broken into thirds (blue) as The GC organized some of the work in the main hall in this way.
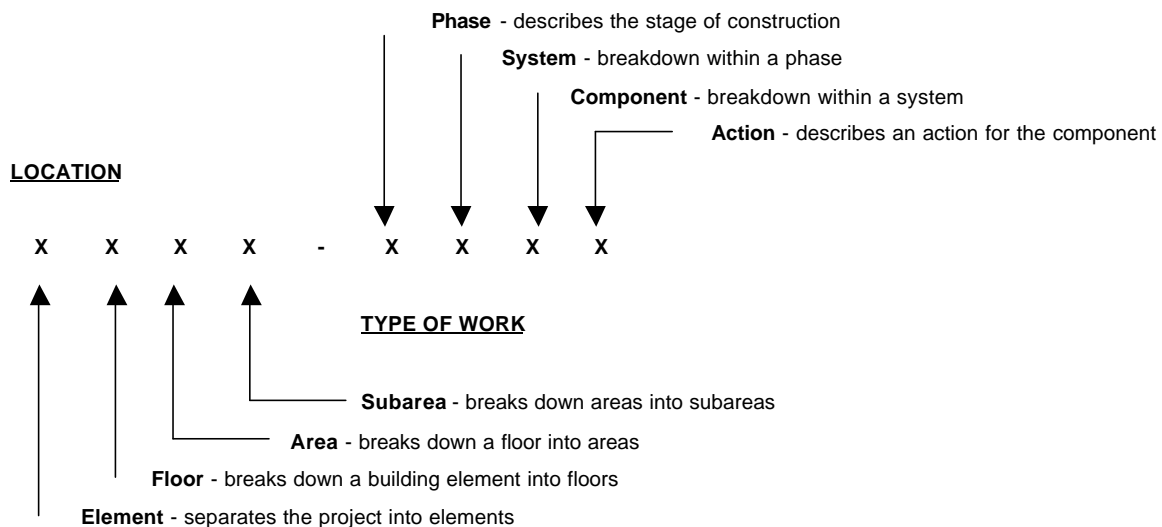

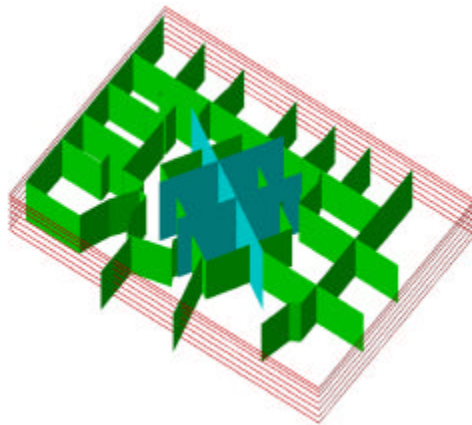*Figure 10: Activity code key for defining activities and relating them to the 3D model.*

Figure 11: Organization of 3D model into levels, sequences and thirds.

4D Modeling Process and 4D Models

Figure 12 maps the process for constructing the 4D models from the project geometry and schedule and shows the file formats used to translate between computer programs. Rhino3D™ proved to be very useful to import the NURBS-based geometry from CATIA, add names to the geometry, break up the geometry into relevant configurations for the respective activities, and convert the geometries to VRML. Named geometrical elements allow a 4D modeler to match geometry names to activity names quickly.
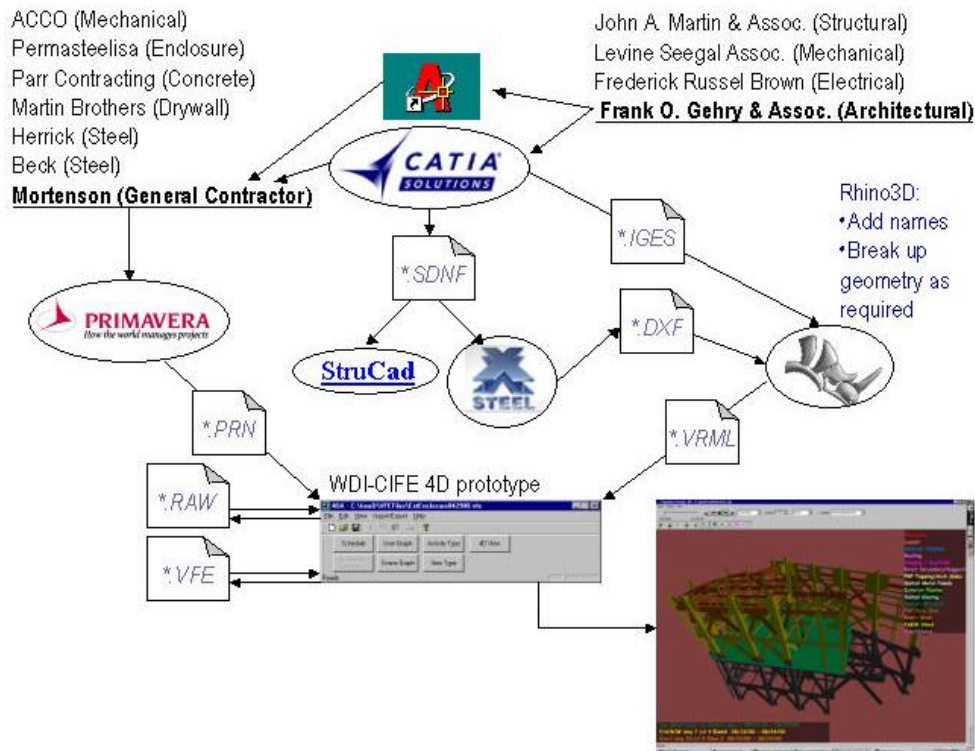

Figure 12: Process for constructing 4D models from 3D models and CPM schedules.

We built four 4D models for the project. Figures 13 to 16 show a screen shot from each of these models.

Figure 13: Steel, Concrete, and Exterior Enclosure model. This 4D model examines the overall sequencing for the major structural and enclosure activities. It shows the sequencing of steel and of structural and architectural concrete. It includes metal decking, roofing, glazing, and enclosure systems, such as metal cladding assemblies including secondary steel supports.

Statistics:
Number of 3D components: 340
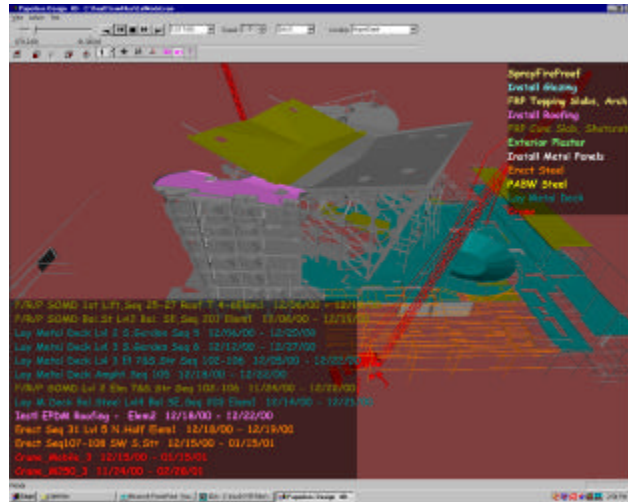Number of polygons: 515,000
Number of activities: 512

Figure 14: Element 2 model. This 4D model goes into more detail for building element 2. It includes the interior work. The model includes interior stairs, elevators, fireproofing, and finishing systems. It shows mechanical and electrical activities by highlighting the floor slabs in the area of work.

Statistics:
Number of 3D components: 105
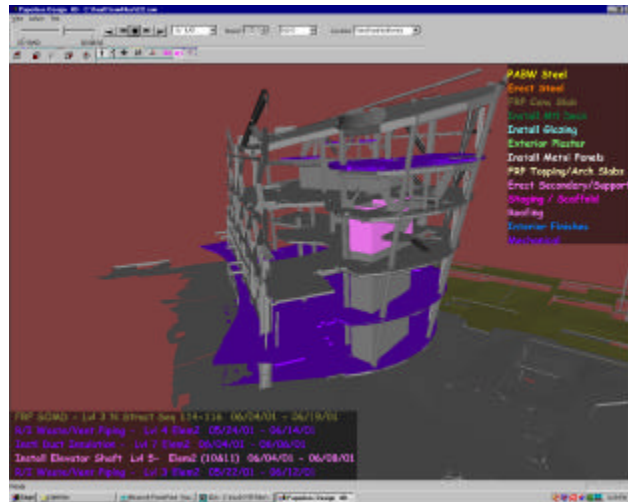Number of polygons: 85,000
Number of activities: 185

Figure 15: Interior hall model. This 4D model developed the interior of the Concert Hall, a highly congested and complex space. All of the interior activities are squarely on the critical path. The model includes all the activities affecting this space: structural steel, concrete, plaster, wood finishes, mechanical, and electrical. The model also includes scaffolding.

Statistics:
Number of 3D components: 210
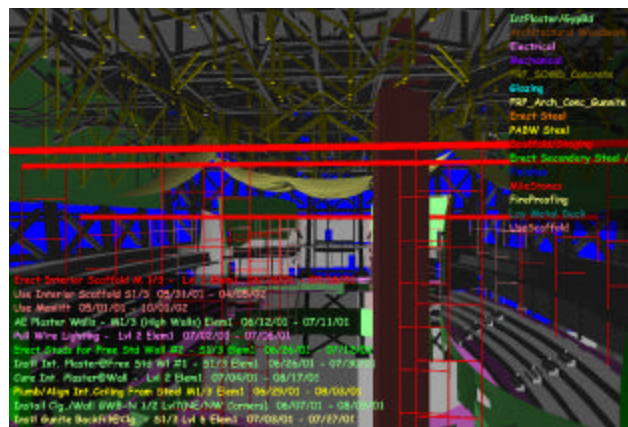Number of polygons: 325,000
Number of activities: 667

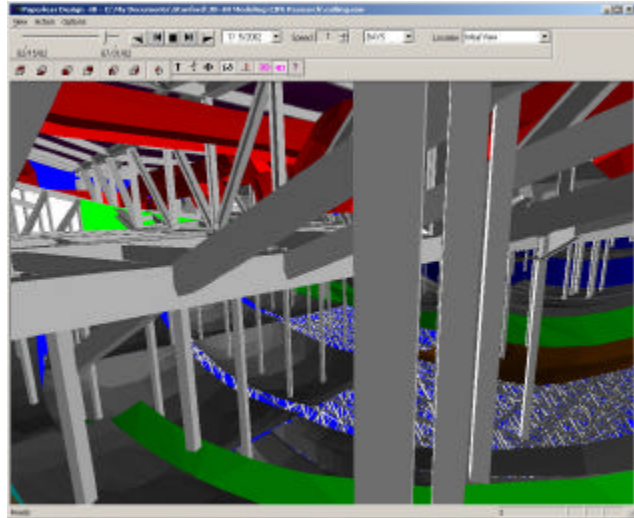*Figure 16: Detailed Hall Ceiling Model.*
In early 2001, we are constructing a fourth model to help with the detailed planning of the complex concert hall ceiling installation.

Statistics:
Number of 3D components: 180
Number of polygons: 520,000
Number of activities: to be determined

Challenges Encountered while Building the 4D Models

The construction of the models posed a number of challenges related to the geometry, the schedule, and the linking of the geometry and the schedule. In our experience, such issues are quite common during the development of 4D models, especially when the 3D models are created without knowledge of the needs for 4D modeling and construction planning. Another reason for these issues is that the construction of a 4D model requires significant project scope and schedule information. Some of this information is precisely the information that project participants want to develop or refine through the 4D modeling process, and other information is simply not yet available because of resource or other constraints. A valuable contribution of the 4D modeling process is that the process makes it very clear where complete scope and schedule information exists and where additional thinking is needed.

Geometry Issues
Inconsistencies: The 3D models from the architect contained some inconsistencies. For example, an object that was on the plaster layer should have been on the gypsum board layer. Such inconsistencies create extra work during the linking of the schedule and the 3D model because the 4D modeler cannot easily identify, isolate, and show the scope of work for a particular activity in 3D.
Lack of Data: The surface model models only what is seen. In the case of a wood wainscot on a plaster wall, FOGA modeled the plaster only where the wood wainscot does not cover it. Even though there is plaster under the wood wainscot, it is not modeled. Hence, in those areas, the surface model does not provide 3D components that can be linked to activities. In addition, for some of the scope of work for steel erection the 3D models were also incomplete. The steel detailers took the wire models from the architect, and produced detailed 3D models from these wires. This process was time consuming, and at the time of 4D model construction, the detailers had detailed only some of the steel for the main concert hall box. The rest of the steel had to have a 3D representation so that it could be seen during 4D model simulation. We created an algorithm to hang a simple rectangular shape on the wires to make the important information visible without overwhelming the software or the user.
Level of Detail: Sometimes there is too little detail in the 3D model. The steel 3D model came back from the steel fabricator all on one layer. However, one might want to split primary and secondary steel into two activities, which would make it necessary to have the primary and secondary steel on two layers. In addition, FOGA modeled just the surfaces for the metal skin. A

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metal skin system requires backing support and clips, which were not modeled, but need to be installed, and should therefore be reflected in the 4D model.

Too much data: Sometimes there can be too much information, which slows down the computational processing of the 3D and 4D models. For example, the steel came back from the fabricator with all the bolts and holes modeled, but we did not need this information for the 4D models the GC wanted to create. Figures 17 to 19 show steel handled at two levels of detail for this project. The resolution of certain situations requires more detail, the resolution of others less detail.
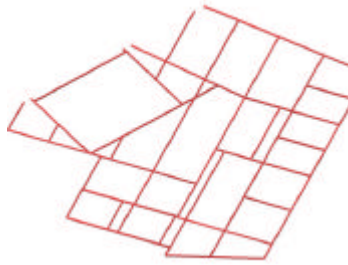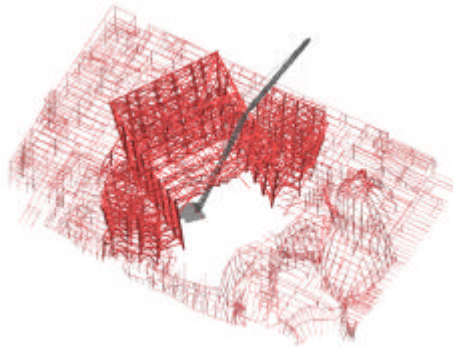
Figure 17: Simple extrusion on wire.

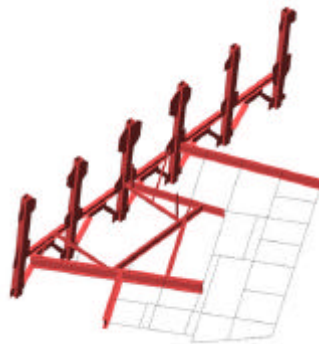*Figure 18: Mixture of two types of steel models.*

Figure 19: Steel Model from Fabricator.

Schedule Issues

Inconsistencies: Just as the geometry can be inconsistent with the design intent, the schedule can also contain inconsistencies. For example, the schedule may call for a CMU wall, whereas the

geometry models a cast in place concrete wall. The inconsistency must be resolved, which, while valuable from the project standpoint, is time consuming for the 4D modeler.

Lack of Data: Some geometry has no corresponding activity. Again, an activity may be required, but resolving this issue requires time and resources of the modeler.

Issues with Linking of 3D Model and Schedule

Inconsistencies: Often, the geometry is defined in ways that conflict with the schedule. For example, the architect defined the geometry by building elements, but the GC places concrete and steel not by element, but rather according to steel sequence. The geometry had to be broken down and recombined a great deal to get a geometrical configuration to match the schedule.

Other Data: Cranes, laydown and staging areas, scaffolding, etc. are not part of the architect's design model, but these elements play a large role on the construction site. We had to add these geometries need to the 3D model. Figure 17 shows a crane we added to the 3D model to explore the spatial relationship of the crane and its location over time with surrounding work.

Representation of activities with no geometry: Ductwork was not modeled in 3D on most of the project, but the GC was interested to know when and where ductwork was scheduled. A 4D modeler has to be sensitive as to the best way to communicate such activities, by perhaps attaching the activity to a floor slab (as we did), or ceiling framing.

Uses of 4D Models

The 4D models supported M.A. Mortenson's four objectives in the following way:
1. **Schedule creation**: The GC used the 4D models to assist in planning the laydown areas for the enclosure contractor, to visualize overall project access at critical junctures in the project, to refine the interior and exterior scaffolding strategy, and to plan the installation of the complex ceiling of the main concert hall.
2. **Schedule analysis**: The GC's project management team used 4D models to discover several conflicts in the schedule which were not discovered in the CPM-based Gantt chart. Figures 20 to 22 show snapshops of the 4D models that show particular problems. Figure 20 shows a situation where a Concrete Masonry Unit (CMU) wall was scheduled too early while steel was being erected directly overhead. Because the wall that is framed by the steel leans outward the steelerection requires shoring (not modelled), which would not only interfere with the construction of the CMU wall but also cause a dangerous situation. Figure 21 shows an Air Handeller Unit (AHU) being installed too late after the steel is completely erected. There would no longer be the access necessary for the large AHU. After consulting with other project team members, The GC decided to leave some of the steel out to make it possible to slide the AHU into the structure at a later date. Figure 22 shows a conflict of scaffolding systems in the same area of the interior hall. The scaffold for the plastering of the walls will need to be removed before the ceiling scaffold can be erected. As a result of the schedule analysis through the 4D model of the interior construction The GC decided to consolidate the scaffolding contracts for the interior hall from three contracts to one contract. The 4D models supported the discovery of these (and many similar issues) during planning, well before construction started. Note, though, that because of the physical and temporal interrelationships between many scopes of work an early detection of potential problems is essential to revise the design or schedule economically. For example, even though the AHU was not scheduled to be installed for many months it was critical to identify potential AHU installation problems prior to work being released for steel fabrication to ensure that the right steel was installed (and not more).
3. **Communication**: The GC used the 4D models in training sessions with as many as 40 people, where subcontractors, owners, designers, and the GC reviewed the models and

discussed the strategy and constraints for erecting the project. Figure 23 shows a view of subcontractors in a meeting in the WDI Virtual Reality Cave.

4. **Team building**: After a 4D review session ended, it was not unusual to have people from different subcontractors remain in the room for an hour or more beyond the scheduled meeting time to discuss issues and solutions to problems or questions identified during the meeting. The GC's project superintendant mentioned that, in a tight labor market, where everyone is committed to too many projects, it is critical to get the attention and collaboration of the subcontractors focused on his project. Given the complexity of the project he wanted to make sure that the subcontractors put their creative energy into improving the construction of his project.
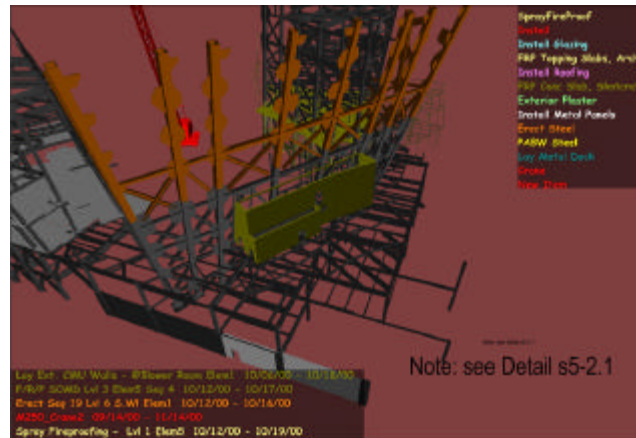

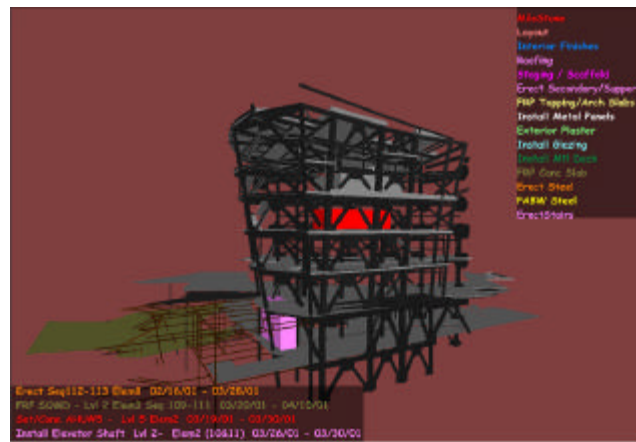*Figure 20: CMU wall (in dark green) schedulded too early.*

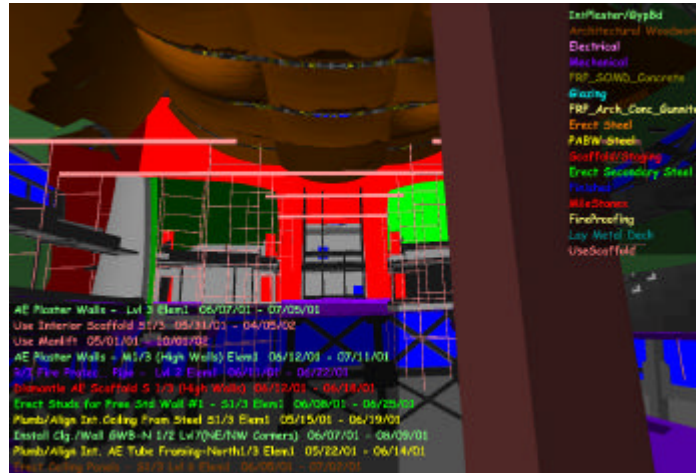*Figure 21: Air Handler Unit (shown in red) scheduled too late.*

Figure 22: Scaffolds collide.

Figure 23: Collaboration in the Virtual Reality Cave.

Acknowledgments