3D AND 4D MODELING FOR DESIGN AND CONSTRUCTION COORDINATION: ISSUES AND LESSONS LEARNED

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SUMMARY: *3D and 4D modeling tools have been available in the marketplace for some time. The past few years has seen a growing interest from the design and construction community to adopt these tools. As many project teams are realizing, implementing 3D and 4D modeling on an actual project is a complicated process that requires a coordinated effort. No guidelines currently exist on using these tools in a multi-disciplinary and multi-organizational environment and project teams are forced to figure this out on their own in real time as the project progresses. This paper addresses this shortcoming by providing guidelines that describe how to overcome the technical, procedural and organizational issues confronted by project teams as they undertake this new way of working. Specifically, the paper describes different approaches for assembling a project team to leverage these technologies, the modeling requirements for implementing 3D and 4D projects, the 3D and 4D modeling processes, the benefits and shortcomings of the process and technologies, the effect of these technologies on the project's outcome, and the lessons learned. This paper is intended for industry professionals interested in pursuing this type of innovative project delivery. This paper will also be of interest to researchers as it illustrates the limitations of emerging 3D and 4D technologies.*

KEYWORDS: *3D model, 4D model, computer aided design (CAD), virtual design and construction, virtual building technologies, design coordination, MEP coordination, construction scheduling.*

1. INTRODUCTION

In recent years, we have seen significant improvements in the tools available to model a construction project using 3D and 4D technologies. Current 3D modeling tools offer pre-defined objects that facilitate the development, routing, and connection of building systems in 3D, and provide conflict detection mechanisms that help to automatically identify physical interferences between components. 4D modeling tools link a project's scope in 3D with the construction schedule to graphically simulate the construction process. Many research efforts have discussed the potential of these tools to significantly improve design coordination and construction execution. However, implementing 3D and 4D modeling on an actual project in a multi-disciplinary and multi-organizational environment is a complicated process that requires a coordinated effort. There are a variety of technical, procedural, and organizational issues that must be addressed, which might explain their limited use. Moreover, there is little research that critiques these tools in the context of project teamwork on actual projects. Yet, without demonstrating their benefits and providing guidelines for implementation, it is difficult for practitioners to invest the resources necessary to adopt these technologies.

In practice, 3D and 4D technologies have been applied on a variety of construction projects. Prior research efforts have compiled detailed case studies that assess the benefits and limitations of these tools and their impact on project performance (Fischer and Haymaker 2001, Staub-French and Fisher 2001, Kam et al., 2003). Researchers have also critiqued the functionality of 3D and 4D technologies to meet the needs of industry (McKinney and Fischer 1998, Songer et al, 1998, Koo and Fischer 2000, Heesom and Mahdjuobi 2004). Some research efforts have also investigated the application of 3D and 4D modeling tools for specific purposes, such as constructability analysis (Ganah et al. 2005) and resource management (e.g., Akinci et al. 2003). Other research studies have documented the benefits and challenges of applying 3D / 4D tools specifically to the

coordination of Mechanical, Electrical, Plumbing, and Fire Protection (MEP/FP) systems on complex projects (e.g., Khanzode et al., 2005, Staub-French and Fischer 2001). Finally, researchers have also investigated techniques to enhance the interaction capabilities of 3D and 4D models using immersive technologies (Messner et al. 2006) and virtual reality (Whyte et al. 2000). These studies clearly demonstrate that 3D/4D technologies have been well established and can be applied to resolve complex design and construction challenges. Although much has been written on the application of 3D and 4D technologies, few guidelines exist that outline what is required for multi-disciplinary project teams to apply these tools in real time on actual construction projects.

This paper provides 3D and 4D modeling guidelines for industry professionals interested in pursuing this type of innovative project delivery. These guidelines generalize the authors' unique experience as model developers, integrators, and coordinators on two different building construction projects, and outline an optimized process for implementation based on their lessons learned. We discuss the technical, procedural and organizational issues confronted by project teams as they undertake this new way of working. Specifically, the paper describes different approaches for assembling a project team to leverage these technologies, the modeling requirements for implementing 3D and 4D projects, the 3D and 4D modeling processes, the benefits and shortcomings of the process and technologies, the effect of these technologies on the project's outcome, and the lessons learned. This paper is intended for industry professionals interested in implementing these technologies on actual projects. This paper will also be of interest to researchers as it illustrates the limitations of emerging 3D and 4D technologies and the challenges of using them in practice.

The projects studied demonstrate that although there is room for improvement, current 3D and 4D technologies provide significant benefits to project teams in developing coordinated and constructible designs and construction sequences. Specifically, 3D and 4D models help project teams to identify design conflicts, design errors, sequencing constraints, access issues, fabrication details, and procurement constraints that impact the efficiency of the project delivery process. We believe that the use of these tools help project teams minimize risk and attract quality team members to construction projects and will be commonplace in the coming years as the industry copes with the realities of a tight labor market. We found that these technologies had a dramatic impact on project execution, including:

- the elimination of field interferences,
- less rework,
- increased productivity,
- fewer requests for information,
- fewer change orders,
- less cost growth, and
- a decrease in time from start of construction to facility turnover.

The next sections describe the scope and organization of the projects studied, the 3D and 4D coordination processes, and the impact of 3D and 4D technologies on the project's outcome.

2. PROJECT SCOPE AND ORGANIZATION

The authors worked on two different building construction projects that implemented 3D and 4D modeling to various degrees throughout the design and construction process: (1) Camino Medical Center in Mountain View, California; and (2) Sequus Pharmacueticals Pilot Plant Facility in Menlo Park, California. The next sections describe these projects in detail, including the scope, the organization, the modeling responsibilities, and the authors' roles on the project.

2.1 The Camino Medical Group Project

The Camino Medical Group project in Mountain View California is a new Medical Office Building facility. The project scope includes a 250,000 square foot, three-storey Medical Office Building and a two-storey 1,400 space parking garage. The Medial Office Building includes patient exam rooms, doctor's offices, surgery and radiology rooms, public spaces, a cafeteria, numerous conference rooms etc. The project owner, Sutter Health, a major provider of Healthcare services in Northern California, adopted Virtual Building technologies (specifically 3D / 4D tools) for the successful delivery of this project. The negotiated contract for this project is about $100M. Construction started in January 2005 and the project was completed on April 30th, 2007.
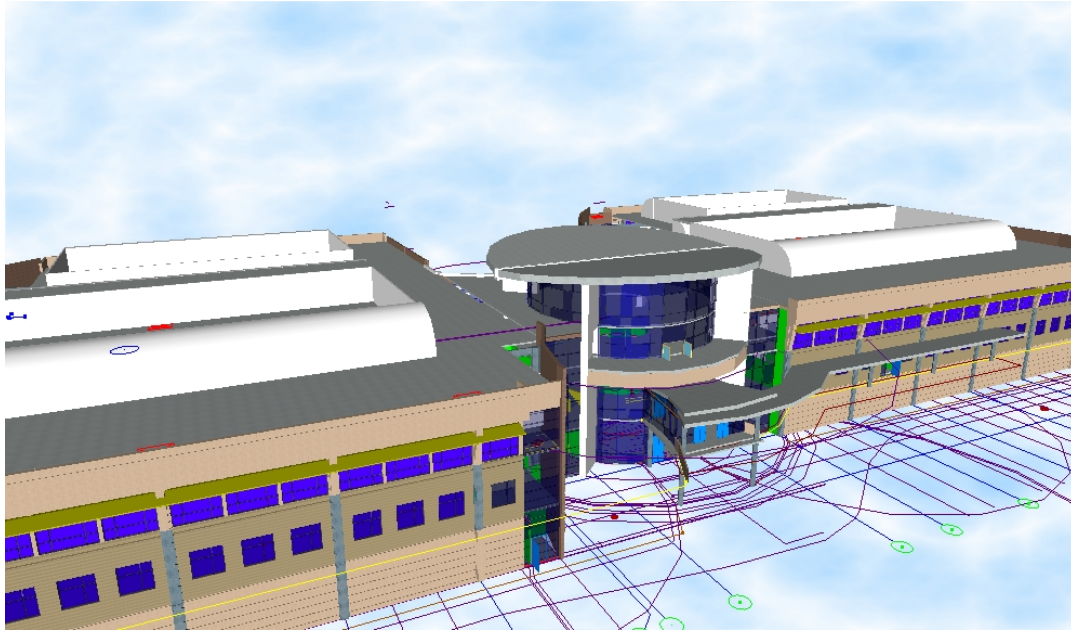
FIG. 1: 3D rendering of the three-storey medical office building for the Camino Medical Group Project in Mountain View, California.

2.1.1 Project Organization

The Architect for this project is Hawley Peterson and Snyder Architecture, the Mechanical Engineer is Capital Engineering, and the General Contractor is DPR Construction Inc. The owner, along with the Architect, Engineers and Contractor pre-qualified the MEP and FP subcontractors for their ability to work using the 3D / 4D coordination and collaboration tools. A detailed guideline was created to pre-qualify the subcontractors for their ability to collaborate using 3D / 4D tools. This guideline included the ability to produce 3D models using parametric objects, and compatibility of software products with the design review software. The MEP/FP subcontractors selected for this project include Southland Industries (HVAC), JW McClenahan Company (Plumbing), Cupertino Electric (Electrical) and North Star Fire Protection (Fire Protection).

2.1.2 Modeling Responsibilities

The Architect was responsible for providing the 3D model for the architectural and structural scope of work. The subcontractor team used these architectural and structural models to model their scope of work. The General Contractor was responsible for coordinating the MEP Design process, which included performing clash detection and resolution using the 3D models, coordinating the installation sequence for the MEP trades, and producing 4D models. The subcontractors agreed to develop their design using 3D tools under a Design-Assist method and agreed to complete coordination using 3D / 4D tools.

The MEP Design on this project is unique in the sense that it is being managed using the Lean Project delivery process. It is not the intent of this paper to explain Lean Construction. For more information, refer to the Lean Construction Institute website (www.leanconstruction.org). In essence, Lean Construction advocates early involvement of subcontractors in the design process, the elimination of negative iteration, and pulling the design from the construction sequence. On the Camino Project, the MEP subcontractors were brought on board in the Schematic Design phase. They were responsible for assisting the engineers in the Detailed Design phase and producing a fully coordinated set of 3D MEP models in the Construction Documents phase. Table 1 shows the modeling responsibilities for the Camino project and the project phase that the model was created. The starting point for the coordination process was the Architectural and Structural 3D model that was created in the Schematic Design stage. The subcontractors then took these models and developed the 3D models on their own in the Design Development stage. The objective of the program was to eliminate negative iteration and reduce the cycle time by using the 3D models created by the subcontractors to develop a fully coordinated MEP / FP model that could be used for fabrication and construction.

TABLE 1: Modeling Responsibilities for the Camino Medical Group Project.

Company	Role	Modeling Scope	3D Software	Phase Model Created/Coordinated
Hawley Peterson and Snyder	Architect	Architectural Modeling in 3D	Autodesk Architectural Desktop (ADT)	Schematic Design
KPFF Engineers	Structural Engineers	Structural Steel, Concrete Foundation, and Shear Walls in 3D	ADT, ETABS	Schematic Design
Capital Engineering	Mechanical Engineers	Mechanical Systems in 2D	AutoCAD	Schematic Design
The Engineering Enterprise	Electrical Engineers	Electrical Systems in 2D	AutoCAD	Schematic Design
DPR Construction, Inc.	General Contractor	Overall Coordination of MEP in 3D	NavisWorks, ADT	Design Development
Southland Industries	Mechanical Subcontractor	Ductwork and Piping in 3D	3D Pipe Designer, CADDuct, NavisWorks	Design Development and Construction Documents
Cupertino Electric	Electrical Subcontractor	Conduit and Cable Trays in 3D	3D Pipe Designer, NavisWorks	Design Development and Construction Documents
JW McClanahan Company	Plumbing Subcontractor	Plumbing System in 3D	3D Pipe Designer, NavisWorks	Design Development and Construction Documents
North Star Fire Protection	Fire Protection Subcontractor	Fire Protection System in 3D	FireACAD	Design Development and Construction Documents

2.1.3 Author's Role on the Project

One of the authors, Atul Khanzode, was intimately involved in the MEP coordination process on the Camino project while working for DPR Construction. The author was a key member of the project team and participated part time during the MEP coordination process from April of 2005 to December 2005. The author also wrote a lessons learned report for the team that included the use of 3D tools for MEP coordination and the use of the Lean Project Delivery System on the project (Khanzode et al. 2005). The author's role is summarized below (specific details are provided in subsequent sections):

- Helping the team define and setup the technical logistics on the project. The technical logistics involved defining how the servers would be setup to share the models, the file naming conventions for the model files, and how the model files would be integrated in 3D in Navisworks.
- Determining the phase schedule for coordination. This involved working with the MEP subcontractors and the architect and engineering (A/E) team to determine an overall schedule for the MEP coordination work.
- Determining the handoffs between designers and the subcontractors detailing team. This involved establishing the specific design scope that would be handed off to the subcontractors' detailers from the A/E team.
- Integrating the 3D models created by the subcontractors detailing team. This involved gathering all the model files from the subcontractor's detailers and then merging these files with the architectural and structural models.
- Identifying physical conflicts between models using NavisWorks Clash Detective program. This involved defining the batches for clash detection and selecting the appropriate systems. For example, clashes between HVAC ductwork and steel were determined by defining a batch in NavisWorks and selecting HVAC models to clash against the structural steel model. This was completed for all possible dual combinations of systems on the project.
- Publishing reports that identified the specific clashes and documented the action items for each clash that needed to be resolved. These reports were distributed to the project team to communicate the changes needed in each discipline's 3D models to resolve the issues identified.
- Tracking the commitments from subcontractors towards completion of the outstanding issues. This

involved using the weekly work planning process where commitments were sought from the subcontractors and tracked for resolution.

- Creating 4D models based on the weekly work plans created by the subcontractors. This process is described in detail in section four of this paper.
- Participating in the coordination process to determine the installation sequence for the MEP work. This process is also described in detail in the context of 4D modeling for the MEP installation work.

2.2 The Sequus Project

The project's scope was to construct a pilot plant facility within an existing warehouse for Sequus Pharmaceuticals, a bio-tech company located in Menlo Park, California. The facility contains 20,000 square feet of available space, with 3,440 square feet of office space, 3,100 square feet of manufacturing space, 2,900 square feet of process development space, and 4,800 square feet of future expansion space. The MEP systems were designed such that the majority of the work was placed on an equipment platform. The platform was necessary because the existing structure was not capable of supporting the increased loads from the MEP systems and related equipment. Construction started in May 1998 and substantial completion was completed as scheduled on February 1, 1999. The negotiated contract price was approximately $6M. Fig. 2 shows the integrated 3D model.
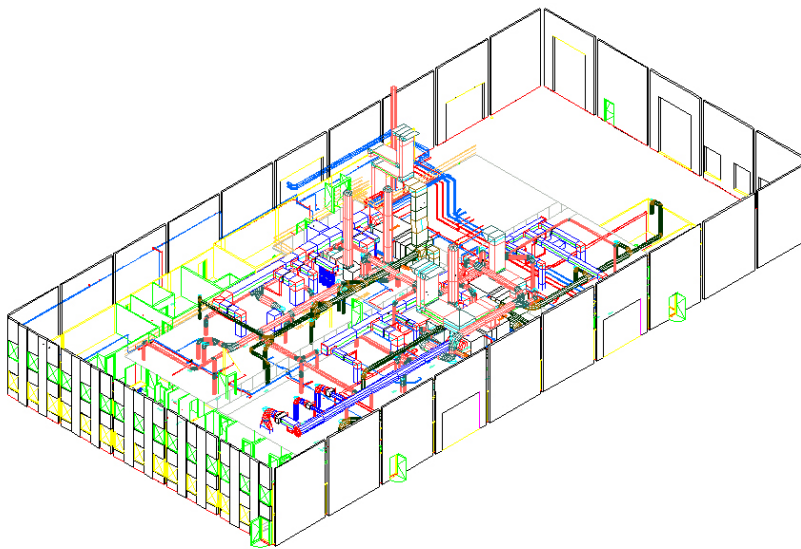

FIG. 2: Integrated 3D Model of the Sequus Pharmaceuticals Pilot Plant in Menlo Park, California.

2.2.1 Project Organization

The Sequus project was unique in that the general contractor assembled the design-build team prior to design and construction. The project team consisted of the following companies: the design firm Flad & Associates, the General Contractor Hathaway Dinwiddie Construction Company (HDCC), the engineering firm Affiliated Engineers Incorporated, the piping subcontractor Rountree Plumbing & Heating (RPH), the HVAC subcontractor Paragon Mechanical (PM), and the electrical subcontractor Rosendin Electric Incorporated (REI). The general contractor selected each member of the design-build team based on their experience using 3D CAD technology on past construction projects and previous experience working with each other. Each team member made a commitment to model their respective scope of work in 3D CAD using a design-build approach.

2.2.2 Modeling Responsibilities

In general, the design firm was responsible for managing the design process and creating the 3D model of the architectural scope of work. The general contractor was responsible for orchestrating and managing the distribution of electronic design information, design coordination, and managing the construction process. The engineering firm was responsible for providing the basis of design and schematic drawings for the mechanical, electrical, and piping work. The MEP subcontractors were responsible for the detailed design and 3D modeling

of their scope of work.

Table 2 summarizes the modeling responsibilities for the various project participants. The unique aspect of the assignment of modeling responsibilities on this project is that the designs are created by the participants who are responsible for installation and can leverage the designs throughout construction. The engineers created the Basis of Design and the schematic drawings but the subcontractors did all the 3D modeling for the MEP systems. This collaborative design approach enabled each company to get feedback quickly on their designs. Participants were able to communicate directly with the other team members to explain their design intent. Each team member had an incentive to provide the 3D models and this feedback because they could leverage their own 3D models and the designs created by others to support their project management functions throughout the design and construction processes.

TABLE 2: Modeling Responsibilities for the Sequus Project.

Company	Role	Modeling Responsibility	3D Software	Phase Model Created /Coordinated
Flad and Associates	Architect	Architectural Modeling in 3D	Archt by Autodsys	Schematic Design
Affiliated Engineers Incorporated	Mechanical, Electrical, and Process Engineers	Basis of Design and Schematic Drawings for the MEP Systems	N/A	Schematic Design
Hathaway Dinwiddie Construction Co.	General Contractor	Overall Coordination of MEP Design	AutoCAD	Design Development
Rountree Plumbing & Heating	Plumbing Subcontractor	Mechanical and Process Piping in 3D, 3D MEP Coordination	Multi-pipe by UHP Process Piping	Design Development and Construction Documents
Paragon Mechanical	Mechanical Subcontractor	Ductwork and Mechanical Equipment in 3D	Autodesk Building Systems	Design Development and Construction Documents
Rosendin Electric	Electrical Subcontractor	Conduit, Cable Trays, and Lighting in 3D	AutoCAD	Design Development and Construction Documents

2.2.3 Author's Role on the Project

The first author worked full time for Hathaway Dinwiddie Construction Company during design and construction of the Sequus Project. A significant part of her responsibilities focused on supporting the 3D design coordination process, enabling the use of the 3D models for different construction management purposes, and developing and managing the 4D model. Specifically, she supported the project team with the following activities:

- Worked with project team members to develop design guidelines to aid the electronic 3D design coordination process. These guidelines will be discussed in detail in the next section.
- Supported the electronic 3D design coordination process. This included integrating the 3D models for design coordination meetings, working with the different 3D models to facilitate design coordination, and maintaining a digital archive.
- Documented the results of the 3D design coordination meetings. This involved documenting the conflicts and solutions during the design coordination meetings. In some cases, it also involved the preparation of a summary report of the meeting discussion for distribution to other members of the team.
- Developed custom 2D and 3D models to support the General Contractor's other project management functions. For example, the author prepared dimensioned 2D drawings of the concrete pads for the Air Handler Units using the 3D mechanical model.
- Identified drawing methods and data manipulation techniques to support design-cost integration of the 3D designs. Although not discussed in this paper, we also investigated the feasibility of integrating the different 3D models with cost estimating software (Staub-French and Fischer 2001).
- Developed and maintained the master construction schedule. This included working with the project superintendent, the project manager, and the subcontractors' foremen to provide summary, detailed,

and look-ahead schedules to the various stakeholders.
- Created and maintained a 4D model to assist with coordination of day-to-day construction operations. This included working with the different subcontractors to represent each discipline's workflow and relevant activities, manipulating the different discipline-specific 3D models to facilitate the linking of 3D objects and activities, and updating the schedule and 4D model as the design and construction strategy changed and evolved. This will be discussed in detail in section 4.

3. 3D DESIGN COORDINATION

In a complex building project, building system coordination is a critical and challenging task. It involves the detailed layout and configuration of the various building systems such that it complies with design, construction, and operations criteria (Barton 1983, Tatum and Korman 2000). Specialty contractors are typically responsible for the coordination of MEP systems, including responsibility for checking clearances and identifying routes, fabrication details, and installation locations (Tatum and Korman 2000).

3.1   Current 2D Design Coordination Process

The design coordination process typically begins when the design and preliminary routing of the building systems are complete. The specialty contractors encounter common constraints that determine the system routing: the building structure, corridors, shear walls, fire walls, major equipment locations, and architectural requirements, such as ceiling type and interstitial space (Korman and Tatum 2001). Consequently, each specialty contractor routes their system to their advantage as they consider these constraints, which is reflected in the preliminary drawings. This includes minimizing the length of branches and number of fittings, choosing prime locations for major components, routing close to support points, and designing for most efficient installation by their own trade (Korman and Tatum 2001). The level of detail in the preliminary drawings often varies by trade. Typically, the HVAC and piping systems are sized at this stage whereas the electrical and fire protection are not. Consequently, some of the building systems are drawn to scale while others are drawn simply as lines with references to component sizes.
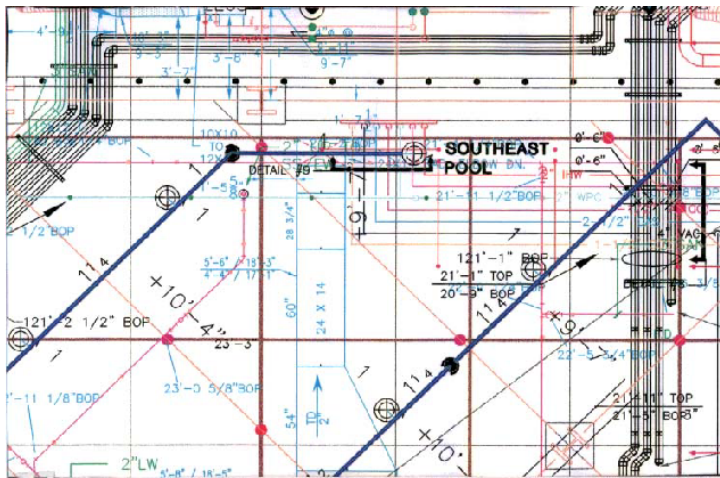

FIG. 3: Typical view of MEP systems coordinated in a 2D paper-based process.

Design coordination is an iterative process that starts with the specialty contractors bringing their preliminary drawings to a coordination meeting. The drawings are typically created in 2D and printed on transparent paper at 1/4-inch scale. During the coordination meeting, each specialty contractor places their 2D drawing on a light table to compare the different building system designs. Fig. 3 shows a typical view of MEP systems being coordinated using a 2D coordination process. The specialty contractors identify conflicts and develop solutions that are red-lined on the 2D drawings. This process continues until the coordination is complete and the specialty contractors sign-off on each other's drawings to signify their acceptance.

The current 2D paper-based design coordination is time-consuming, inefficient, and often leads to sub-optimal project performance as design conflicts are encountered and have to be resolved in the field. Creating and coordinating the designs in 3D allows project teams to integrate their designs electronically in the computer and identify conflicts in all three dimensions. Moreover, sharing electronic 3D models enables the project team to

leverage the 3D design information throughout the design and construction process.

3.2   3D Design Coordination Process

Going from 2D to 3D design is a complicated process that requires a significant coordinated effort to fully leverage the benefits of 3D models. We identified the following ten steps as essential to setting up a 3D design process. These steps describe the optimal process based on the challenges we encountered:

1.   Identify the Potential Uses of the 3D Models
2.   Identify the Modeling Requirements
3.   Establish the Drawing Protocol
4.   Establish a Conflict Resolution Process
5.   Develop a Protocol for Addressing Design Questions
6.   Develop Discipline-specific 3D Models
7.   Integrate Discipline-specific 3D Models
8.   Identify Conflicts between Components/Systems
9.   Develop Solutions for the Conflicts Identified
10.   Document Conflicts and Solutions

3.2.1   Step 1: Identify the Potential Uses of the 3D Models

The project team should discuss the potential uses of the 3D models on a given project and identify the specific uses that will be implemented. For example, the 3D models could be used for thermal simulation, cost estimating, fabrication, shop drawings, user group visualization, etc. The use of the model often dictates the modeling requirements in terms of the level of detail and the modeling techniques that must be utilized. For example, if the architectural model is going to be used for thermal simulation then rooms must be explicitly modeled. If the model is going to be used for stakeholder visualization, then room details that are often important to user groups, such as light switches and electrical outlets, may also need to be modeled. If the model is going to be used for cost estimating, then the components must be modeled in a way that quantities can be extracted. If the model is to be used for creating fabrication and installation drawings then it also needs to include the correct objects that could then be pulled into a material requisition sheet and organized into a pre-fabrication work order (Fig. 4).
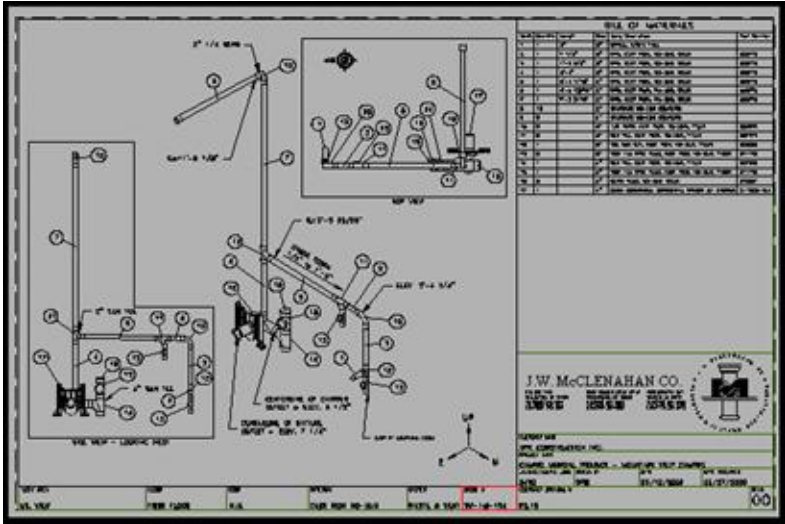

FIG. 4: Figure shows a pre-fabrication isometric drawing of a plumbing waste and vent assembly with the Bill of Materials that was generated automatically from the 3D Model on the Camino Project.

3.2.2 Step 2: Identify the Modeling Requirements

It is essential that the project team identifies who will create the 3D models, when the 3D models will be created, and how the 3D models will be created. Specifically, this step involves the following:

Identify the modeling responsibilities for the various scopes of work. This involves establishing the responsible party, and in some cases, the handoff or transition between parties. For example, on the Sequus Project the engineer was responsible for establishing the basis of design which excluded all CAD modeling, while the MEP subcontractors were responsible for creating the detailed 3D CAD models. Handoffs between parties become important if the scope of the 3D modeling efforts is shared by engineers and subcontractors. For example, on the Camino Project, the Mechanical Engineers modeled the HVAC systems to a certain point in 2D, and then the Mechanical Subcontractor detailed the scope in 3D.

Establish the scope of the 3D modeling effort and the level of detail to be modeled. To address this issue, project teams should consider the possible uses of the 3D models (step 1), as well as the cost and benefit of modeling a scope of work in 3D. For example, rebar could be modeled in 3D to facilitate procurement of these components but the benefits may not justify the expense. In contrast, the Structural Engineer on the Camino Project did not model the gusset plates in 3D, but these elements were critical for 3D coordination and should have been included.

Establish the work breakdown structure. It is important to identify how the models are going to be integrated and create a breakdown structure that is consistent and agreed upon by all parties. For example, on the Camino Project, the Medical Office Building was divided into 12 distinct quadrants, and the models were developed for each quadrant and coordinated by each quadrant.

Create a schedule that identifies key modeling activities. The schedule should specify when the models will be created, coordinated (conflicts identified), updated (conflicts resolved), and approved (ready for fabrication). Ideally, these milestones should be incorporated into the construction schedule and coordinated with related activities for installation.
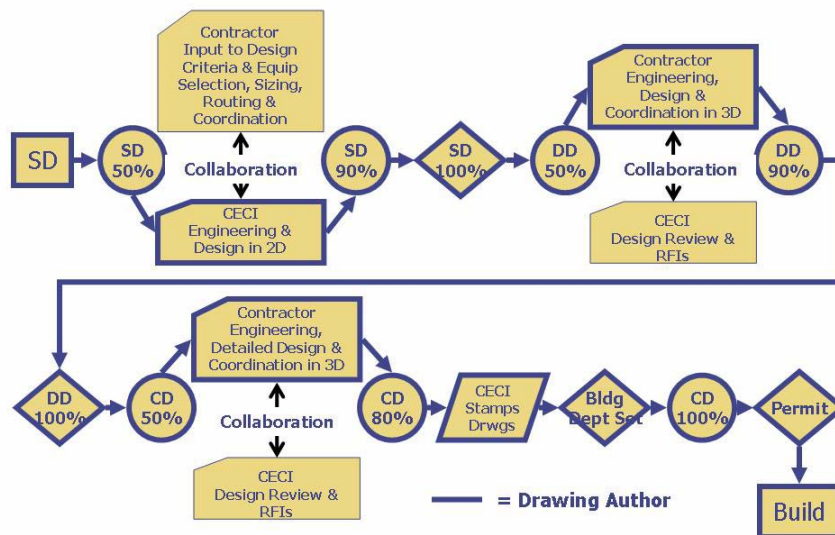

FIG. 5: Flow chart of design coordination process established on the Camino Project.

Fig. 5 shows a flow chart that illustrates the formal process established on the Camino Project for coordination and collaboration between designers, subcontractors, and the general contractor. The MEP coordination process was driven by the construction process. For example, MEP coordination was done by quadrant to meet with the schedule of installing inserts before the deck slab was poured, in a sense pulling design based on the construction sequence. Negative iteration in design was avoided by starting the modeling process early, and sharing incomplete designs early and often. The subcontractors also were encouraged to work directly with the

designers to get answers to questions quickly rather than going through the traditional RFI workflow between subcontractor – general contractor – designer and back. An online system to make and keep track of all commitments was used as a substitute for the RFI process. This system called Commitment Manager acted as a conduit between the team and supported the Design process using 3D / 4D models efficiently.

3.2.3 Step 3: Establish the Drawing Protocol

To ensure that the 3D models can be electronically integrated and coordinated, the project team should establish a protocol that specifies the drawing conventions that will be implemented by all the parties.

Project Reference Point (0,0,0): The project team must employ the same reference point so that the models integrate appropriately in all three dimensions. This is extremely important for 3D coordination otherwise the team will spend a lot of time trying to combine the models together for conflict detection purposes. For the Sequus and Camino Projects, the reference point was established by the design team, which was dictated by the architectural 3D model.

File Naming Convention: The file name should communicate the company that created the 3D model, the scope of the 3D model, and the version of the 3D model. On the Camino Project, we followed the AIA File Naming Convention but appended the initials of the subcontractor to the drawing. For example, the file name "M211A_SI.dwg" communicates the following: M = Mechanical, 2 = HVAC, 1 = 1st Floor, 1 = 1st Quadrant, A = Area, and SI = Southland Industries. However, this convention was not optimal for 3D coordination using Navisworks Clash Detective, therefore, we recommend that the company name be represented first in the file name if this software is being used.

Version Control: The version of the file can be represented in the file name by appending the file name with the date, or it can be handled separately through the use of folder names on FTP sites or collaboration sites.

Layering Convention: A layering convention should be established to facilitate 3D coordination. Any Object that requires separate coordination should be on a separate layer so that it can be viewed independently and easily turned on and off, which may include: text or annotations, structural grids, different systems (e.g., supply and return systems, junction boxes), flexible systems that can be easily routed (e.g., flex duct), and connections (e.g., sprinkler mains vs. heads).

Color Scheme: The color scheme should facilitate visual communication of the different scopes of work. Fig. 6 shows the color scheme established on the Camino Project, which shows the colors used for different systems and companies.
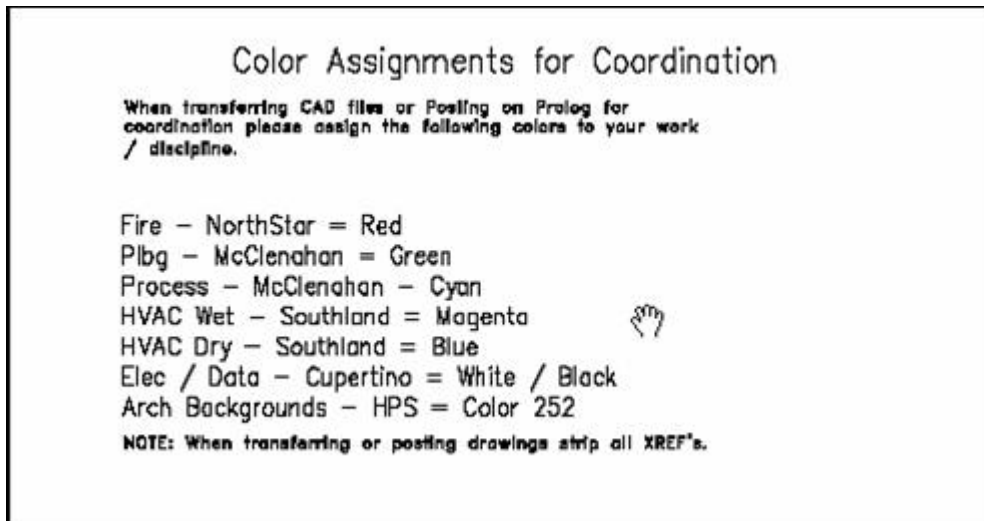

FIG. 6: Color Scheme used on the Camino Project for 3D coordination.

3.2.4 Step 4: Establish a Conflict Resolution Process

Setting up a process for identifying and resolving conflicts is extremely important to ensure that the team is

making continuous progress towards a conflict-free solution on the project. In order to do this, there needs to be a system to detect conflicts between trades, document the conflict and the responsible party, and then resolve the conflict in the same sequence.

Identify the specific design review software that will be used during the 3D design coordination process. The software can be a CAD package (e.g., Autodesk Building Systems), or specific 3D coordination software (e.g., Navisworks Clash Detective). Although both packages facilitate the detection of physical interferences, we found that Navisworks Clash Detective was far superior in detecting some soft conflicts (e.g., interferences between physical components and clearance spaces), managing the process of detecting and resolving conflicts (e.g., conflicts can be tracked according to their status - new, active, approved, resolved, and old), and documenting the conflicts identified (e.g., conflict reports can be generated). Fig. 7 shows a snapshot of the Navisworks model for the Camino Project and the nine clash tests that were created to facilitate conflict detection between the systems.

Establish the process for sharing drawing files. We recommend that project teams use a formal collaboration website rather than an FTP site. In addition, we recommend that such a system facilitate both informal and formal information sharing. For example, the different disciplines should be able to pull the most recent model from the website when developing their 3D models, which doesn't require a formal coordination meeting.
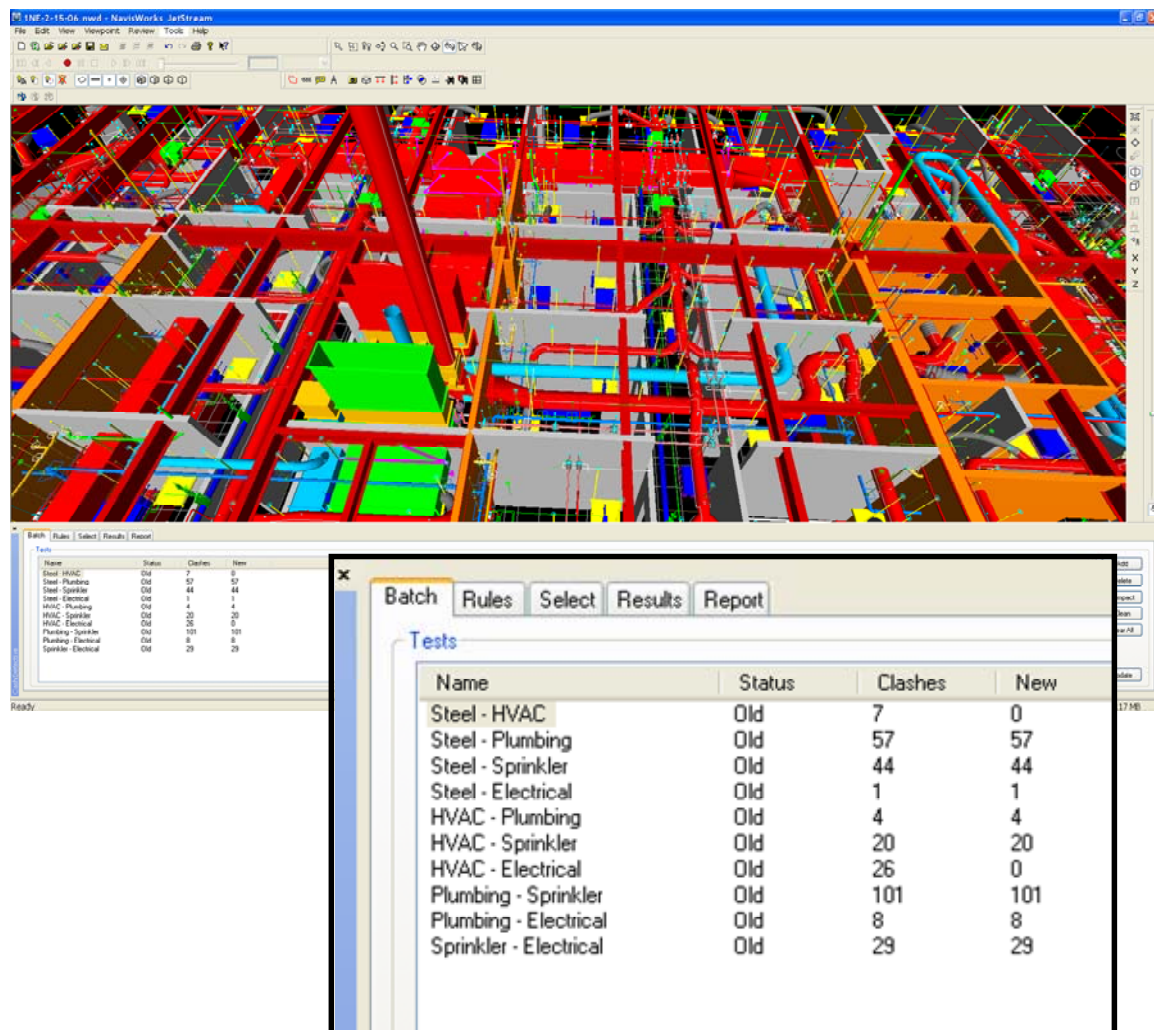

Name	Status	Clashes	New
Steel - HVAC	Old	7	0
Steel - Plumbing	Old	57	57
Steel - Sprinkler	Old	44	44
Steel - Electrical	Old	1	1
HVAC - Plumbing	Old	4	4
HVAC - Sprinkler	Old	20	20
HVAC - Electrical	Old	26	0
Plumbing - Sprinkler	Old	101	101
Plumbing - Electrical	Old	8	8
Sprinkler - Electrical	Old	29	29

FIG. 7: Screenshot from the combined MEP/FP model for one of the quadrants from the Camino project and the 9 clash tests that were created.

Establish the timing and general meeting process for coordinating the 3D models. This should include the timing of meetings, timing of 3D model uploads, organizations involved, drawings to be coordinated, objects included (e.g., no text, no flex duct, no xrefs, specific systems, etc.), and systems to be coordinated (e.g.,

structural and HVAC).

Identify a responsible party to facilitate the electronic design coordination process. The responsible party downloads and electronically integrates the 3D drawings that are scheduled to be coordinated in the meeting. This typically includes drawings for the architectural, structural, piping, ductwork, lighting, and fire protection systems. The party responsible for this activity can vary but the key issue is making sure someone is responsible. On the Camino Project this was the responsibility of the General Contractor while on the Sequus Project this responsibility was given to the Mechanical Contractor.

3.2.5 Step 5: Develop a Protocol for Addressing Design Questions

This step is necessary if the contractors are responsible for developing the 3D models. We have learned that there needs to be a very clear and unambiguous mechanism in place for subcontractors and detailers who are working on developing the models to ask questions to the design team and resolve issues quickly as they come up, particularly on fast-track projects. We realized that the normal RFI process is inadequate when using the 3D models due to the unnecessary lag time for resolving issues. On the Camino Project, we adopted a web-based system called Commitment Manager, which the team members used to ask questions of each other (Fig. 8). We also agreed that during the Design Phase, the subcontractors and detailers should be able to pose a question directly to the most appropriate member of the design team rather than route it through the General Contractor in the form of an RFI so that valuable time is saved in resolving the issue.
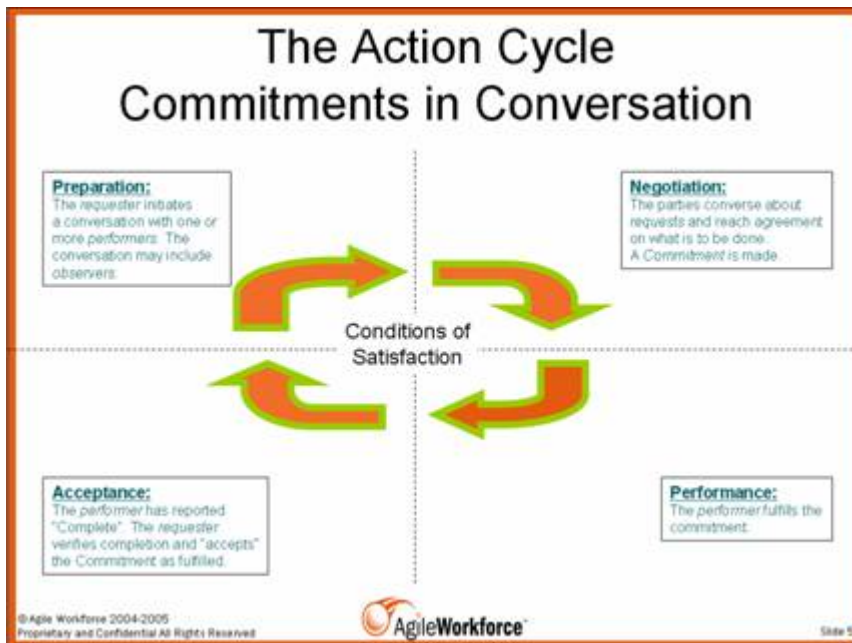

FIG. 8: Screenshot of the Commitment Manager Action Cycle being used for making requests and answering questions on the Camino Project.

3.2.6 Step 6: Develop Discipline-specific 3D Models

Each discipline creates their respective 3D model using the discipline-specific design software used in their firm. Typically, the architect creates the architectural model first and then the other members of the team use the architectural model as the background when creating their 3D designs. Then, after the first coordination meeting, all members of the team can share and use each other's 3D models as a background. In this process, designs are being optimized from a coordination and constructability perspective as they are being developed. Therefore, coordination and constructability is not simply assessed at a specific point in time during design development, it is considered throughout the design development process.

3.2.7 Step 7: Integrate Discipline-specific 3D Models

The responsible party downloads and integrates the 3D models in preparation for the coordination meeting. On the Camino project, the project team used Navisworks to coordinate the building systems in 3D. The 3D models

created using Quick Pen and CADDuct were combined into a single model in Navisworks and then the Navisworks Clash Detective module was used to define clash tests and identify clashes.

3.2.8 Step 8: Identify Conflicts between Components/Systems

A substantial amount of time in coordination meetings is spent trying to identify and resolve design conflicts. They are looking for "hard" conflicts, which are physical interferences between components, as well as "soft" conflicts, which are interferences between design components and access spaces or violations of clearances. Hard conflicts can be identified manually or automatically depending on the particular software being utilized. Fig. 9a shows a meeting between the General contractor and the Mechanical and Fire Protection contractors identifying all the conflicts between the Mechanical and Fire Protection systems for one of the quadrants of the building. Fig. 9 shows a hard conflict that was automatically identified between the Fire Sprinkler Pipe and the Supply Duct.

FIG. 9a: Formal coordination and conflict identification meeting between the General Contractor and the Mechanical and Fire Protection contractors on the Camino Project.
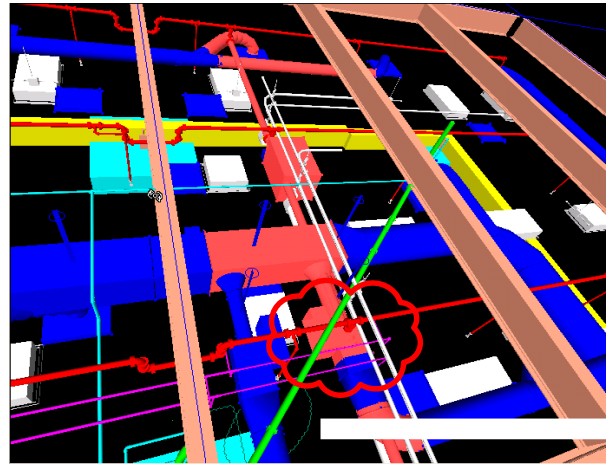
FIG. 9b: Hard conflict between the Fire Sprinkler Pipe and the Supply Duct that was automatically identified in Navisworks Clash Detective on the Camino Project.

On the Sequus Project, the team focused on certain areas and building systems and identified conflicts manually. For example, in one meeting, the detailer and foreman for Rountree Plumbing met with the detailer for Paragon Mechanical to coordinate the piping and ductwork connections around the air handler units with the 3D models in the computer (Fig. 10a). Although this process enabled the team to identify most conflicts, it would have been more efficient to identify such conflicts automatically.
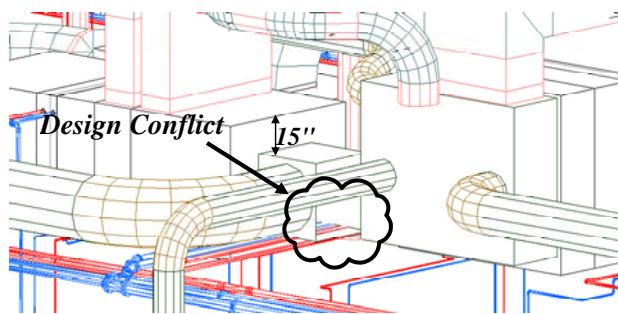

FIG. 10a: Design of connection to Air Handler Unit and conflict identified on the Sequus Project.
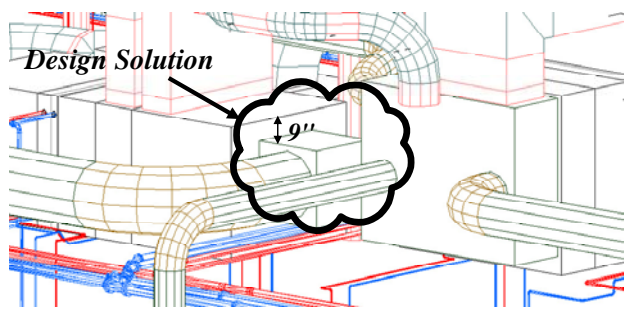
FIG. 10b: Revised conflict-free design of connection to the Air Handler Unit that was developed on the Sequus Project.

3.2.9 Step 9: Identify Solutions for the Conflicts Identified

After conflicts were identified, the team jointly develops a solution that works for all parties involved. Fig. 10b shows the solution to the design conflict at the air handler connection shown in Fig. 10a which was encountered

on the Sequus Project. This design solution called for raising the air handler connection by 6" to avoid the piping. This design solution was detected early in the design coordination process and the AHU manufacturer implemented the change at no additional cost.

3.2.10   Step 10: Document Conflicts and Solutions

It is important to document the conflicts addressed in the coordination meetings including, the design conflict (a snapshot or clash report from Navisworks), the proposed solution, the responsible party, the systems that were coordinated, the drawing files used (for version control), the meeting date, and the organizations/people involved in the coordination process. On the Camino project we used the Navisworks software to create a conflict identification and resolution report that listed a particular conflict and how it was to be resolved by the next iteration (Fig. 11). This document was used to identify and resolve the clashes. The report was generated directly out of Navisworks.

FIG. 11: Conflict identification and resolution report from the Camino Project generated directly from Navisworks Clash Detective.

3.3   Benefits

The following summarizes the key benefits of designing and coordinating building systems in 3D, and when possible, gives an example of each benefit realized on one of the projects.

- **Most design conflicts are identified prior to construction:** By modeling in 3D and electronically integrating the 3D models, design coordination and constructability analysis is performed with a more accurate representation of the building systems. On the Camino and Sequus projects, this process is further enhanced because the participants with the construction expertise that had the most to benefit from the models were actually designing and coordinating the 3D models. Moreover, many conflicts are avoided because the different disciplines are using each other's 3D models as they design.
- **Productivity is significantly improved:** Most design conflicts are identified and resolved prior to construction enabling a more efficient and productive installation process. In addition, many of the mechanical systems can be fabricated directly from the 3D model in the shop, which can lead to significant productivity gains. On the Sequus Project, the mechanical contractor used the 3D models extensively for field coordination and daily planning of construction activities, resulting in a substantial increase in field productivity. As stated by the Project Manager: "Field productivity was improved. Even on a system where we did not attempt to do any prefab, the installers were able to refer to small area isometric drawings to facilitate installation." On the Camino Project, the productivity for the mechanical subcontractor was significantly improved. They estimate approximately 25-30% improvement in productivity compared to their estimated productivity for installation of duct and piping scopes of work on traditional projects (Fig. 12).
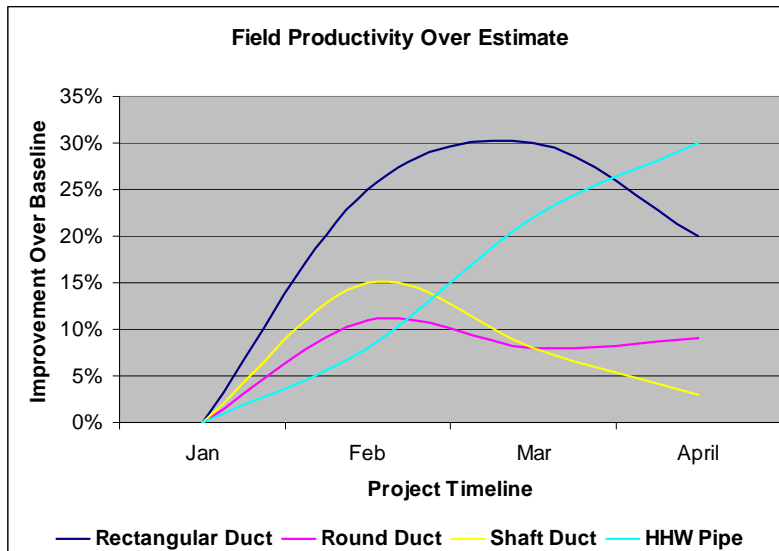
FIG. 12: Comparison of field productivity versus estimated productivity for the Camino project for installation of ductwork and heating hot water pipe (courtesy of Southland Industries, 2006).

- **Less Rework:** The MEP design coordination process eliminates most of the design conflicts prior to construction. Typically, many conflicts go undetected until they are encountered during installation, often resulting in expensive rework. On the Sequus Project, the only rework that was required occurred between trades that did not model their scope of work in 3D. In fact, the superintendent for the general contractor noted the "seamless" installation process for the 3D work. On the Camino project, after 250,000 square feet had been constructed, there was not a single field conflict during the installation of the MEP / FP work. According to the Superintendent, he has never experienced this level of accuracy of field installation before in his 35 years of experience and estimates that he is spending much less time resolving field issues compared to past projects. He estimates that on past projects he used to spend 2 to 3 hours per day dealing with these issues, and on Camino he has spent a total of 10-15 hours over an eight month period after the MEP installation began.

- **Increased opportunity for Pre-fabrication:** We believe that modeling and coordinating the MEP / FP systems in 3D provides a better opportunity to pre-fabricate materials in a shop environment. For example on the Camino Project, all of the plumbing systems (piping for water, waste and vent) were pre-fabricated. Normally the piping is cut in the field. All the low pressure duct system was also pre-fabricated. Normally only the medium pressure duct is pre-fabricated and the low pressure smaller duct runs are field assembled. On the Sequus Project, the Mechanical Contractor was able to fabricate many of the different pipe runs from the 3D models, resulting in time and cost savings and fewer errors. This was particularly useful for the extremely expensive piping that is used in Sequus' manufacturing processes. For example, stainless steel pipe can cost approximately $400/LF in cramped spaces, such as mechanical rooms, and $125/LF in open spaces, such as laboratories, according to the project manager for Rountree Plumbing. If one measurement is off in such complicated piping systems, it could cost approximately $700 to fix each mistake. In addition, the large 4" and 6" piping around the chillers was labor-intensive to install and expensive to cut. The 3D models allowed Rountree Plumbing to have the supplier fabricate the pipe in the shop at about 1/3 of the cost. The project manager for Rountree Plumbing stated that "virtually everything prefabricated from the 3D model was installed as planned."

- **Fewer Requests for Information (RFI):** There are primarily two reasons why there can be significantly fewer RFI's on 3D projects: 1) the designs are coordinated and conflicts are identified early in the construction process (as described above), and 2) the MEP subcontractors are responsible for the detailed design of their scope of work. By creating detailed 3D models in the design phase, the MEP subcontractors are able to work out how the components would fit together and how the building systems would interface. In a traditional process, these issues would often be

resolved through the RFI process. On the Sequus Project, there were 60% fewer Requests for Information (RFI) than expected for a project of this complexity. On the Camino project, out of 233 RFI's, 160 were confirming RFI's, about 10% related to the MEP / FP coordination work where the 3D models were used for coordination, and only two were related to field conflict issues..

- **Fewer Change Orders:** Rework is often a big cause for the many change orders that typically originate during construction. On both the Sequus and Camino projects, there were significantly fewer change orders than expected for such complex projects. On the Sequus Project, there was only one contractor-initiated change order for the scope of work modeled in 3D, which is remarkable for work of this complexity. On the Camino Project, there were zero change orders related to field conflicts after the construction of MEP systems for the first six quadrants.

- **Design errors can be identified prior to construction:** On the Sequus project, we identified a design error that could have potentially caused substantial rework. An AEC chiller was incorrectly designed in 3D at about 20% its actual size. When this mistake was corrected, the chiller no longer fit in the space allocated requiring the piping to be re-routed to a new location. This conflict was resolved three months before the chiller was scheduled for installation.

- **Ability to build the system with a less skilled labor force:** We believe that modeling and coordinating the MEP / FP systems in 3D provides an opportunity to create more of an IKEA type assembly rather than trying to interpret complex drawings to build a system. On the Camino Project, this has allowed the team to use a less skilled labor workforce to bolt together systems which would normally require experienced plumbers. For tight labor markets like California, less skilled labor is often required and it is imperative that tools like 3D / 4D be used to maintain the quality of installation.

- **Improved Safety Performance:** A fully coordinated model facilitates a smoother workflow by helping teams to identify their work area requirements and plan logistics resulting in a much safer jobsite. On the Camino Project, there was only one recordable injury after 178,000 person-hours.

- **Better cost control:** On the Camino Project, the MEP / FP subs have adjusted their cost downwards in finalizing their contracts due to the increased productivity that has resulted from a highly accurate bill of materials and increased pre-fabrication on the project. We believe that this has resulted in a much better cost control for the subs performing the work on the project. On the Sequus Project, cost control was a key concern for the owner. Typical cost growth on projects of this complexity range from 2% - 10%, with 2% considered extremely successful, according to the Sequus project manager. The cost growth on the Sequus Project averaged 1% for the MEP subcontractors, which was mostly due to owner initiated design changes.

3.4 Lessons Learned

On each of these projects, the project team learned many valuable lessons that were critical to the success of the integrated 3D approach that should be incorporated on future projects. These lessons learned are summarized below:

- Project teams should determine the stage in the design development process when a specific scope of work should be modeled in 3D. The sequencing and timing of the design development process needs to coincide with the design coordination process, the procurement process, and the construction process, particularly in design-build environments. On the Camino Project, we learned that the structure should be modeled in 3D before the 3D coordination for MEP trades can start, and that the HVAC duct needs to be 75% complete before the other trades can really be productive in routing their utilities as the duct is the most constraining. In addition, one other lesson learned from Camino is that for multi-storey buildings it is extremely important that the gravity system be decided very early in the project, otherwise changes to higher floors impact the design of lower floors.

- Project managers and executives committing to a team-oriented approach should carefully assemble their project staff. It is critical that each discipline's project team understands the goals of the project, the level of information sharing needed, and the level of 3D modeling required.

- Assemble teams so that the designs are created by the participants who have the construction expertise to create constructable designs, and who are responsible for installation and can leverage the designs throughout construction. A collaborative design approach also provides incentives for

team members to provide feedback on the other discipline's designs because they can leverage the designs created by others to support their project management functions. We recommend pre-qualifying all the team members for their capability to produce 3D drawings and work in 3D.

- When setting up a 3D project, it is preferable to have one person or one company that is responsible for the electronic design coordination meetings. Ideally, the company responsible for the 3D coordination meetings will also be responsible for MEP coordination in general. On the Sequus Project, however, the mechanical contractor was responsible for electronically integrating the 3D drawings that were scheduled to be coordinated in the meeting while the General Contractor was responsible for the MEP coordination process, which led to inconsistencies in the management of this process.

- Every essential trade on the project should put their design (scope of work) into the 3D model to leverage the benefits of electronic 3D design coordination. On the Sequus Project, the structural work was only partially modeled in 3D and the fire sprinkler work was not modeled at all in 3D, resulting in the only design conflict problems during construction.

- Project teams modeling in 3D require increased design and coordination time. Although this is offset by benefits in construction, it does need to be addressed in each discipline's estimate and contract. On the Sequus Project, the mechanical trades reported a 30% increase in design time.

- It is important that all team members agree on a coordination and conflict resolution process. There needs to be a formal process in place for addressing the conflicts and issues identified in the 3D MEP coordination process. On the Camino Project, we learned that when using Navisworks Clash Detective it is best to proceed with clash detection in a sequence otherwise fixing one clash has the potential to generate other clashes. Also, it is important to keep track of who is fixing what using the Clash Report. Also, defining a process that can guarantee reduced latency to answer design questions raised by the subs during the modeling process is key to success and allows the subs to keep working on their models.

- Most of the professionals involved, from the designers and consultants to the subcontractors and trades and foremen, are used to communicating and understanding a 2D presentation of the design. To facilitate acceptance and understanding of the 3D models, project teams should provide both 2D and 3D representations when adopting this type of process.

- Issues and conflicts identified in an MEP coordination meeting need to be documented in a way that facilitates ease of use and interpretation. The 3D model alone does not provide this type of documentation. There needs to be a complementary document that provides the necessary annotations and labeling to convey the issues identified and their resolution.

4. CONSTRUCTION COORDINATION

This section describes the current practice of creating and maintaining construction schedules and contrasts it with the 4D process used on the Sequus and Camino projects. We describe the specific steps required to create 4D models, the issues that must be addressed to ensure successful implementation, and the benefits and limitations of 4D technologies.

4.1 Current Practice

A major task for construction planners is to determine the sequence of construction activities so that resources are allocated appropriately and coordination of sub-trades is optimized. Current project management practice uses CPM (Critical Path Method) schedules to represent the completion of a facility design over time. CPM schedules show the dependencies between activities, but they do not provide a link between the three dimensions of space and the fourth dimension of time. Yet the interdependency between this information is critical for planning, evaluating, monitoring, and coordinating the construction process.

Most construction managers, through years of experience, are able to visualize the construction process in their heads. Communicating that conceptualization of the construction process, however, is ineffective with traditional CPM networks and bar charts, resulting in differing perceptions about how the work will actually be installed in the field. Consequently, many problems go undetected resulting in reactive project management and sub-optimal project performance as problems get resolved during construction. To proactively manage the construction process, project teams need to be able to visualize the four dimensional nature of the construction process.

4D-CAD (3D + time) is a tool that links 3D CAD objects with construction activities and allows project teams to visualize the construction process as a computer animation. As a result, project teams are better able to evaluate the spatial needs of each discipline over time, thus improving communication and coordination between sub-trades (Koo and Fischer 2000, Haymaker and Fischer 2001).

The next sections describe how 4D models were created and used on the Sequus and Camino Projects. We describe the different tasks that are required to create a 4D model, and then describe the different techniques used on each of the projects to accomplish those tasks.

4.2   4D Construction Coordination Process

One of the goals of the coordination process on both the Sequus and the Camino projects was to limit the interaction between the subcontractors installing the different systems so rework could be avoided and productivity maximized. The 4D model was used for this purpose. We identified the following six steps as essential to developing a coordinated and detailed 4D model for construction coordination. Fig. 13 shows these steps using the Sequus project as an example. On the Sequus project, the 4D model was created by the General Contractor using Bentley's Schedule Simulator software and on the Camino project the 4D model was created using NavisWorks JetStream Timeliner software:

1.   Establish Work Breakdown and Flow
2.   Establish Installation Sequence
3.   Reorganize 3D Models
4.   Refine Schedule
5.   Link 3D Objects and Activities
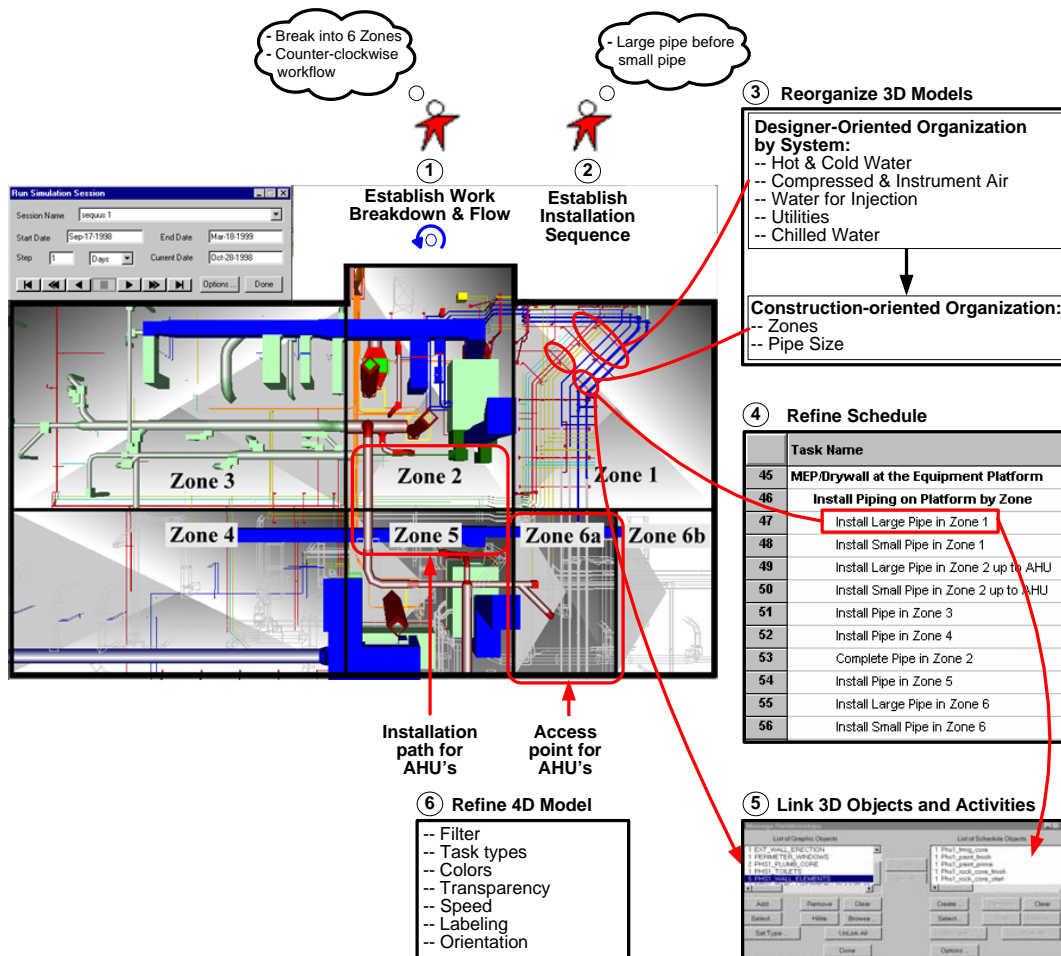6.   Refine 4D Model

FIG. 13: Primary steps required to create a 4D model using the Sequus Project as an example.

4.2.1 Step 1: Establish Work Breakdown and Flow

The first step in the creation of a 4D model is to identify how the work is broken down and how it will flow through the project for the various subcontractors. This process involves working with the subcontractors' trade foremen who are planning the work. On both projects, the GC consulted the foreman for each of the three MEP trades and the superintendent to determine what activities were necessary, how the work would be sequenced, and how work would flow through the project.

On the Sequus Project, the 4D model was used to coordinate the mechanical, electrical, and piping work with the equipment installation on the mechanical platform. It was necessary to show the access point and installation path for the AHU's (Fig. 13) as well as the areas that must remain clear. For example, the piping subcontractor would not be able to install the different pipe runs continuously as planned. Rather, he had to postpone the installation of the piping that ran between the AHU's (zones 2 and 5) because it interfered with the space required for the AHU's installation path. The GC consulted the foreman for each of the three MEP trades and the superintendent to determine the overall flow of work. Based on these conversations with the sub-trades, the area was broken down into six zones with work flowing in a counter-clockwise direction (see Fig. 13). The MEP work in part of zone 2 and all of zones 5 and 6 would have to wait until after the AHU's were installed.

On the Camino project, the overall break down of the work was developed by the Foremen for each trade and the General Superintendent. The project was divided into 4 separate quadrants and a center area for each floor (Fig. 14). The construction sequence was developed so that for each floor the South side was built first and then the north side. A phase schedule was developed to determine the flow of work and handoffs between trades for each quadrant. For each of the three floors, construction was started at the South East End and flow was determined to go from SE-SW-NE-NW and then through the center. This allowed for efficient movement for the materials as the center area was used for staging and was the main access point for all quadrants.
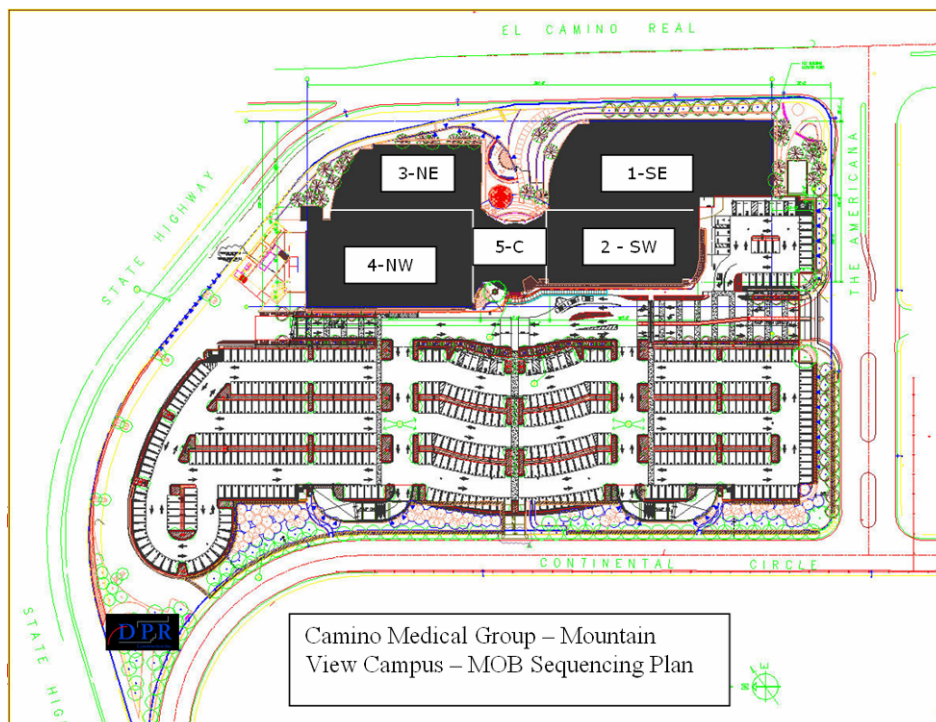

FIG.14: The sequencing plan for the Camino Project showing work proceeding clockwise from the southeast corner (1-SE) and finishing in the center (5-C).

4.2.2 Step 2: Establish Installation Sequence

After the work breakdown and flow has been established, the next step is to determine the installation sequence within each of the smaller work areas. The installation sequence is established by consulting with the different sub-trades and the project superintendent to identify the activities that need to be executed by the different disciplines and the relationships between activities and trades for each work area. On the two projects we studied, the installation sequence

was the same for each work area but that may not always be the case.

On the Camino project, the GC first determined the installation sequence for each area by each trade. The sequence of installation was determined so as to ensure that each crew can achieve maximum productivity by not having some other trade block their work. The following sequence of work was decided for each quadrant:

- Frame full height priority walls
- Install sprinkler pipe
- Install heating hot water pipe
- Install medium pressure duct
- Install low pressure duct
- Install plumbing graded lines, waste and vent
- Install cold and hot water piping
- Install electrical conduits, branch lines and cable tray

On the Sequus Project, the General Contractor consulted the foremen for the different trades to determine the general sequence of activities in each of the six zones on the equipment platform:

- Frame/drywall full height walls
- Install high rectangular and round duct
- Install risers
- Install large pipe
- Install small pipe
- Install low rectangular and round duct
- Install hard conduit

4.2.3   Step 3: Reorganize 3D Models

The third step in the process requires the reorganization of the 3D model so that the activities determined in Step 2 can easily be linked to the right 3D components in the model. This is necessary because the 3D models represent the design perspective (e.g., pipes are organized by system) and in a 4D model, we are trying to represent the construction perspective (e.g., pipes are organized by construction zone and pipe size), as shown graphically in Fig. 13. This task is typically the most time consuming part of developing a 4D model.

On the Sequus project, we used Bentley's Schedule Simulator to create the 4D model. We used the 3D models created by the architect and MEP subcontractors, and the master schedule created by the GC (step 4). Using Schedule Simulator, we found that it was easiest to map CAD layers to construction activities. Accordingly, each layer in the 3D model needed to be organized so that it corresponds to an activity in the schedule (e.g., move objects from the "Chilled Water Piping" layer to a new layer "Large Piping_Zone 1"). Consequently, we created new layers, renamed old layers, and moved CAD objects to the appropriate layer. For example, in the electrical drawing, there were two separate layers for wiring for lighting and wiring for power. For scheduling purposes, one wants to distinguish wiring by whether it is in the ceiling or in the wall. Therefore, the corresponding layers and objects had to be changed to "wall rough-in" and "ceiling rough-in". In addition, the 3D CAD models also had to be transformed to incorporate the work flow through the equipment platform. Consequently, the 3D CAD models had to be reorganized so that the scope of work related to each of the six zones was assigned to a separate layer. To illustrate the extent of changes required for this step, the HVAC design model originally contained six layers. After the model was modified to correspond to the schedule activities, there were 22 layers. This process was performed on five piping drawings for the different process piping and wet-side mechanical systems, the HVAC drawing for the ductwork and AHU's, and the structural drawing containing the concrete decking. If any one of these designs changed, this step had to be repeated.

On the Camino project, this step involved creating a grouping of objects by using functionality called "Selection Sets" in Navisworks Timeliner based on the information received from each trade foreman in step 2. Selection Sets act as groupings of 3D objects and are necessary to link multiple 3D objects to a single construction activity. Fig. 15 shows the Selection Sets (on the right) for the Mechanical work. The figure shows Duct S2 highlighted in Blue. In this example, the model is a combination of small duct pieces, but the way the duct will be installed depends on how the duct components are joined in a pre-fabricated assembly. Duct S2 is a combination of two elbow pieces and a rectangular duct and will be installed as one pre-fabricated assembly, which means there is a single activity in the schedule to represent the installation of Duct S2. The Selection Set Duct S2 combines the multiple duct objects into a single object (or object set).
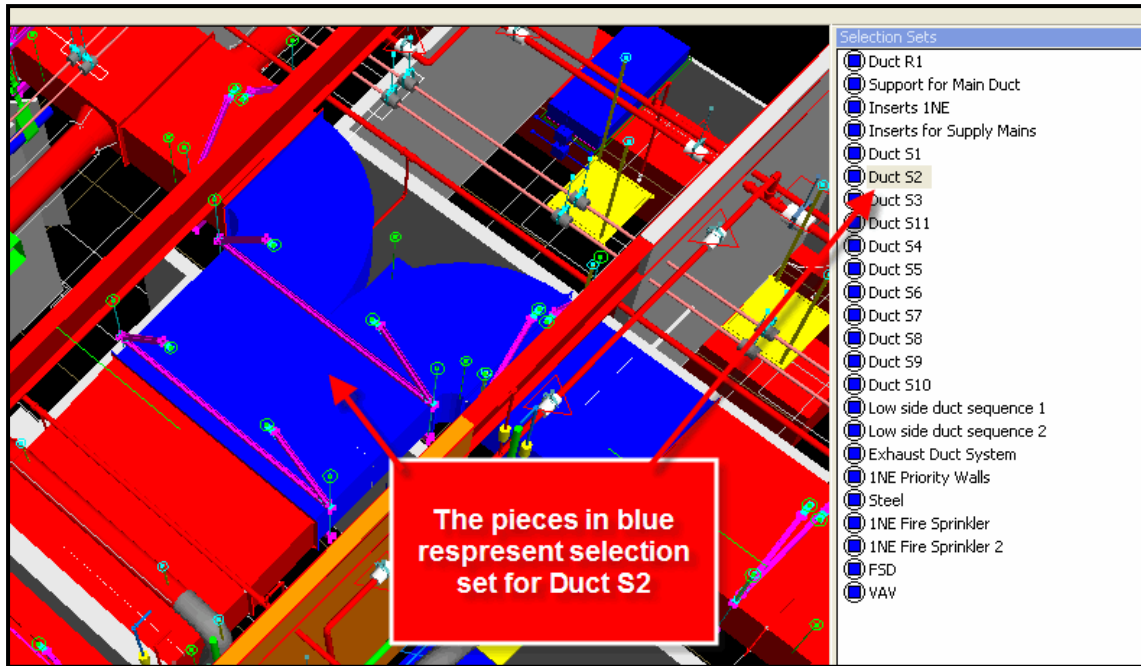
FIG. 15: Selection Sets created using Navisworks Timeliner that represent groupings of 3D objects.

4.2.4 Step 4: Refine Schedule

After the installation sequence was decided, the schedule has to be refined to represent the actual sequence of activities for each work area. To represent this more detailed sequence of activities, one can either revise the master schedule (as in the Sequus Project) or create a separate schedule for this scope (as in the Camino Project).

FIG. 16: The tasks created for each Selection Set for one of the quadrants on the Camino Project.

4.2.5 Step 5: Link 3D Objects and Activities

On the Sequus Project, the General Contractor refined the master schedule to the level of detail required to represent the day-to-day operations of the various subcontractors. This was accomplished by adding and adjusting activities to incorporate the work flow established in step 1 (e.g., activities for piping in zones 1-6) and the installation sequence established by the trades in step 2 (e.g., large pipe will go in before small pipe), as shown in Fig. 13. Consequently, the resulting schedule showed when each of the subcontractors would be working in each zone on the equipment platform. The original schedule contained ten activities for the MEP work and equipment installation on the equipment platform while the refined schedule contained approximately 55 activities for this scope of work.

On the Camino Project, the GC created a separate schedule in the 4D modeling application to represent this scope of work. This was accomplished by creating a task for each Selection Set that was created in step 3. The list of tasks is shown in Fig. 16. These tasks will then be linked to the 3D Selection Sets created in the previous step.

In this step, 3D models are imported into the 4D modeling application and 3D objects are linked with the scheduling activities. The linking process can be automated but it depends on the 4D modeling application used and the degree of coordination with the design.

To create the 4D model on the Sequus project, the team used Bentley's Schedule Simulator. This software imports CAD models and schedule models and transforms them into object-oriented models. We imported each of the CAD models as separate files so that we could easily focus on specific systems. Consequently, eight CAD files were imported into the Schedule Simulator (five process piping models, one HVAC model, one architectural model, and one structural model of the equipment platform). This allowed the project team to view any combination of the different systems in 4D. After the CAD models and schedule model were imported, we manually related the grouped CAD objects created in the third step with the appropriate schedule activity created in the fourth step. For example, one grouped CAD object was the cold water piping system in zone 1 and the corresponding activity was "Install cold water piping in zone 1."

On the Camino Project, Navisworks Timeliner was used to create the 4D model. Links were made between the Selection Sets created in step 3 and the tasks created in step 4. Navisworks provides rules that allow this linking process to be automated based on the name of items, selection sets, or layers, which was utilized on this project. All links between 3D objects and tasks were done automatically based on the name of Selection Sets and tasks, which saved considerable time.

4.2.6 Step 6: Refine 4D Model

The final step involves refining the appearance of the 4D simulation. Most 4D applications allow the user to control the appearance of the objects in the 4D simulation in terms of colors, transparency, timing, filtering, speed, labelling, orientation, etc. Typically, it is useful to create multiple simulations to show all the different perspectives (e.g., interior work and exterior work) and to communicate to different stakeholders (e.g., owners and subcontractors).

On the Sequus Project, the 4D simulation was used to facilitate communication between the general contractor and the owner and between the general contractor and the subcontractors. The 4D model of the work on the equipment platform demonstrated to the owner that the equipment could be installed as planned and wouldn't result in any rework for the MEP subcontractors. For the subcontractors, the 4D model helped identify access issues for equipment installation and identified what areas needed to remain clear to ensure that equipment could be installed as planned. Different 4D simulations were created to show these different perspectives. In terms of appearance, the 4D simulation showed work not yet started as wire-frame, work in progress was highlighted in green for non-critical and red for critical activities, and work completed was shown in the objects' original color (Fig. 13).

On the Camino Project, task types were utilized to change the appearance of the 4D simulation. The task type controls the way the linked Selection Set will be represented visually during the 4D simulation. For example, a task type 'Construction' represents something being built and is shown as green when under construction and then assumes the model color after completion. On the other hand, the task type 'Demolition' starts off with an object being highlighted as Green while the activity is under construction and then disappears after it is completed. Fig. 17 shows four snapshots of the 4D model during the simulation (clockwise from left to right): (1) the full height walls are being framed, (2) the medium pressure ductwork is under construction, and the full height walls as well as the hangers (represented by the little dots) for all the ducts are complete, (3) the low ductwork is under construction and the medium pressure ductwork is complete, (4) the low pressure duct installation is in progress and the medium pressure duct already installed.
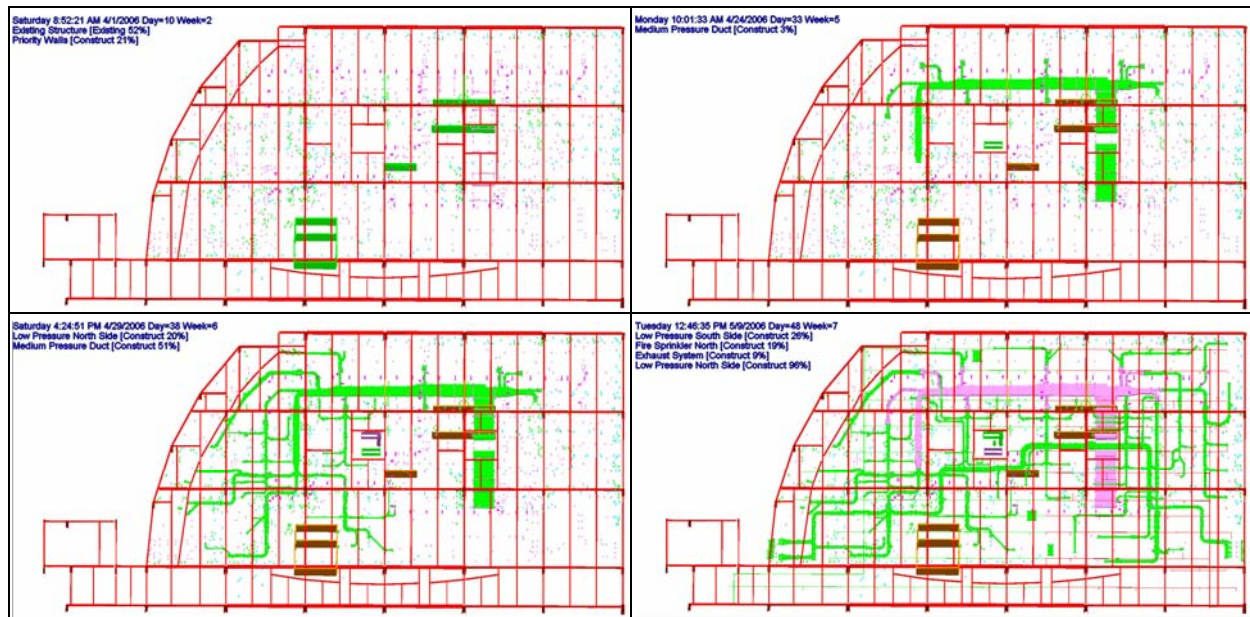
FIG. 17: 4D snapshots of the ductwork and wall framing for the 2nd Floor North East quadrant for the Camino Project. Clockwise from top left the figure shows the installation sequence of the wall framing and ductwork for this quadrant.

4.3 Benefits of 4D Modeling

The following summarizes the benefits of 4D modeling that were realized on the Sequus and Camino Projects:

- **The 4D model assists with coordination of subcontractor schedules**. A 4D model allows all members of the team to visualize their tasks and the relationships that exist between the work of the different sub-trades. On the Sequus project, the 4D model was particularly useful in coordinating the placement of equipment on the platform that was to be installed a month after the ductwork, piping, and conduit work had already started. On the Camino project, the 4D model was useful in coordinating the priority wall framing and the installation sequence of all the duct work.

- **The 4D model clearly communicates schedule intent**. 4D models provide a useful way to communicate the schedule to the different project stakeholders. On the Sequus Project, the 4D model of the equipment platform communicated the schedule intent to both the owner and the MEP subcontractors. The 4D model demonstrated to the owner that the equipment could be installed as planned and to the MEP subcontractors where and when they could work on the equipment platform. On the Camino project, the 4D model allowed the team to better understand the interdependencies between activities and their spatial relationship to laydown areas, which is hard to visualize on the CPM schedule.

- **The 4D model communicates work flow over time.** 4D models provide a superior way of communicating work flow over time compared with conventional bar-chart schedules. On the Sequus Project, the scheduling strategy was to divide the equipment platform into zones to determine the optimal installation path for the air handlers and work sequences between trades, which was communicated graphically in the 4D model. On the Camino project, the big concern was that the subcontractors would interfere with each other if the installation did not proceed in the right order, thus leading to rework and lost productivity. The 4D model helped the subs understand what the optimal sequence should be to optimize productivity for their crews. For example, the drywall and HVAC subcontractors were able to determine the specific walls that should be framed first so that the drywall crew did not have to work around the duct to install their drywall.

- **4D models help identify constructability issues and sequencing problems prior to construction.** Constructability analysis is typically performed during pre-construction by reviewing 2D drawings. However, there are many constructability issues that depend on *when* components are installed. On the Sequus project, the 4D model helped identify access issues for equipment installation and identified what areas needed to remain clear to ensure that equipment

could be installed as planned.

- **4D models show the status of construction at any time in the project.** On the Sequus Project, it was particularly useful to visualize the status of construction when coordinating equipment and material deliveries, determining the path for equipment installation, and communicating to the various parties (especially the owner) how the facility would look at different phases during construction.

4.4   Lessons Learned

The following highlights some observations and lessons learned that would be useful to consider prior to developing 4D models on future projects:

- It is important to determine the purpose of the 4D model as it dictates the level of detail required by the 3D model and the schedule. This should be considered in step 1 of the design coordination process, as mentioned previously.
- Try to set up the 3D model to facilitate 4D modeling whenever possible, particularly in terms of how objects are layered and modeled. This will help to minimize the effort required to reorganize the CAD models to represent the construction perspective (step 3).
- The shelf life of the 4D information is limited. On the Camino Project, we realized that activities for MEP installation in the 4D model are only useful if it is continuously kept up-to-date. The time during which this information is useful for the crew is when this work is in progress and most of the activities happen in one or two days. We were updating the model once a week and it was a challenge to keep up. We think that it would be necessary to keep the model up to date every day to represent the as-built condition and to represent the activities coming up during the week.
- The link between the CAD objects and the schedule activities is not intelligent so be careful if the linking is done manually. For example, we could have linked the "install piping" activity with the graphical object for the door and the system would not detect an inconsistency. It is possible to set up automated linking by giving the CAD objects the same name as the schedule activity but the spelling must be exact and this requires a coordinated effort.
- The 4D modeling system did not help the project team to automatically evaluate the feasibility of the proposed schedule or identify potential conflicts or problem areas. For example, many activities may be occurring at the same time and place resulting in congestion problems and decreased productivity, the path required to install a piece of equipment may be blocked by the execution of a concurrent activity, or the zones implemented to coordinate work flow may not adequately reflect the spatial needs of the various trades. Problems such as these must be identified manually using current 4D tools.

In summary, 4D models can help project teams to coordinate construction disciplines, to communicate construction schedules more effectively, and to assist in the identification of constructability issues early in design development. The limitations pertain to the effort required to set up the CAD and schedule models, the ability of 4D tools to deal with design and schedule changes, and the lack of automated analysis of 4D models.

5.   IMPACT OF THE 3D/4D PROCESS ON PROJECT PERFORMANCE

This section describes the overall impact of the 3D and 4D process on the performance of each project.

5.1   Camino Project

On the Camino project, the use of 3D / 4D tools for MEP/FP coordination resulted in significant benefits for the project team:

- Superintendents were able to spend more time on planning the job rather than react to field conflict issues on the project. On Camino project, the Superintendents have spent less than five hours over a three month period dealing with field issues. On comparable projects they typically estimate that they would need to spend 2-3 hours a day dealing with issues related to field conflicts.
- Subcontractors are more knowledgeable about the project as they have been involved sooner and are resolving issues in the design stage that would typically come up in the field. We think that a lot of reciprocal work that happens during construction is now happening during design on the

Camino project, resulting in more efficient planning.

- Only 2 out of 233 RFI's are related to field conflict related issues. We have not yet compared this to other similar projects but believe that by any means this is a phenomenal statistic compared to a traditional project delivery.
- There are ZERO change orders related to field conflicts after the construction of MEP for the project has been completed. This is phenomenal performance compared to similar projects in the industry.
- All the trades finished their MEP rough-in work ahead of schedule. All the MEP work is now complete and the facility is open for business. To date we have done an estimate of productivity improvements through the use of 3D/4D tools for the Mechanical work. The Mechanical trade estimates that their productivity has improved somewhere between 5% to 30% for the construction of piping and sheet metal for the project. This is represented graphically in Fig. 12.
- On the Camino project, after a total of 203,448 man-hours, there was only one recordable injury. The incident rate is 0.98 which is much better than the industry average. The superintendent attributes this to the fact that the workflow has been improved due to the use of 3D/4D models on the project.
- All of the plumbing and medium and low pressure ductwork was pre-fabricated. The subcontractors attribute this to the use of 3D models for coordination. On comparable projects, none of the plumbing and 50% of the ductwork would be the most that the subcontractors would typically pre-fabricate.
- The time spent on pre-fabrication was a lot less compared to doing the same work in the field. For example, the Mechanical Contractor spent 33% less time on fabrication by shifting it to the shop.
- Lower quality labor was utilized in the field compared to other similar projects which typically require higher quality field labor. We think this is largely due to the level of accuracy of the 3D model and because there are fewer mistakes and errors that often result from interpreting 2D drawings.

5.2   Sequus Project

On the Sequus Project, the following benefits were realized:

- Most design conflicts were identified prior to construction resulting in a more productive installation process. There was only one documented design conflict encountered in the field between the MEP subcontractors that modeled their scope of work in 3D.
- Significantly less rework than expected for a project of this complexity. The MEP design coordination process eliminated most of the design conflicts prior to construction. Typically, many conflicts go undetected until they are encountered during installation, often resulting in expensive rework. On the Sequus Project, the only rework that was required occurred between trades that did not model their scope of work in 3D.
- Substantially fewer change orders than expected for a project of this complexity. Rework is often a big cause for the many change orders that typically originate during construction. The project manager for HDCC expected change orders to range from 2-10% of total construction costs, with 2% considered an indicator of a successful project. On the Sequus Project, the percentage of total cost for the MEP work that resulted from change orders was less than 1% (i.e., less than 1% cost growth). However, none of the change orders on this project resulted from unexpected design conflicts for the MEP work.
- All MEP subcontractors reported increases in field productivity. The mechanical subcontractor in particular achieved significant productivity gains. They would dimension the 3D CAD model for the specific pipe components that would be installed for each day and print them out for the field crews. As stated by the project manager: "Field productivity was improved. Even on a system where we did not attempt to do any prefab, the installers were able to refer to small area isometric drawings to facilitate installation."
- 60% fewer Requests for Information (RFI) than expected for a project of this complexity. This is largely due to the fact that the subcontractors were responsible for the detailed design in 3D, and due to the early identification of design conflicts through 3D design coordination.
- Most piping systems were fabricated directly from the 3D model, resulting in time and cost savings and fewer errors. This was particularly useful for the extremely expensive piping that is

- used in Sequus' manufacturing processes.
- Improved communication of the schedule intent. The 4D model of the equipment platform communicated the schedule intent to the owner and the MEP subcontractors. The 4D model of the work on the equipment platform demonstrated to the owner that the equipment could be installed as planned and wouldn't result in any rework for the MEP subcontractors. The 4D model showed the MEP subcontractors where and when they could and could not work on the equipment platform.
- Construction was completed on time and under budget.

It is important to note though that these benefits were not realized without compromise. While productivity was improved, design time increased; while rework was avoided, design coordination time increased; while the project team could make more informed decisions, the time it took to actually design, plan, and estimate the facility increased. The increased efficiency of the installation process, however, made up for the increased design cost and time.

6. SUMMARY AND CONCLUSIONS

This paper provides guidelines to help project teams implement 3D and 4D modeling on building construction projects. We believe these guidelines will help project teams overcome the technical, procedural, and organizational challenges that are often a barrier to adopting these technologies. Specifically, the paper describes different approaches for assembling a project team to leverage these technologies, the modeling requirements for implementing 3D and 4D projects, the 3D and 4D modeling processes, the benefits and shortcomings of the process and technologies, the effect of these technologies on the project's outcome, and the lessons learned.

We have found that 3D and 4D modeling can have a significant impact on the execution of a project. The benefits of 3D and 4D modeling are well documented and include: increased productivity, elimination of field interferences, increased pre-fabrication, less rework, fewer requests for information, fewer change orders, less cost growth, and a decrease in time from start of construction to facility turnover. We also believe that the use of these tools will help project teams minimize risk and attract quality team members to construction projects, which will be critical in the coming years as the industry copes with the realities of a tight labor market.

To capitalize on the benefits offered by 3D and 4D technologies, owners, designers, and builders of facilities will need to develop new skills and implement organizational changes. Owners will need to bring a project team together early in the project. Designers will need to focus more on the overall design and coordination of design tasks and less on detailed design. General contractors will need to learn how to manipulate 3D CAD models, work more closely with the designers during design development, and provide input on how to model designs in 3D so that the CAD models are more usable by constructors. Subcontractors will also need to learn design software, as they will be performing more detailed design, working more closely with the architects and engineers through the design process, and addressing coordination issues early in design development.

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