BENEFITS AND LESSONS LEARNED OF IMPLEMENTING BUILDING VIRTUAL DESIGN AND CONSTRUCTION (VDC) TECHNOLOGIES FOR COORDINATION OF MECHANICAL, ELECTRICAL, AND PLUMBING (MEP) SYSTEMS ON A LARGE HEALTHCARE PROJECT

SUBMITTED: September 2007
REVISED: March 2008
PUBLISHED: June 2008
EDITORS: T. Olofsson, G. Lee & C. Eastman

Atul Khanzode, Graduate Research Assistant and Business Analyst
Dept. of Civil and Environmental Engineering, Stanford University and DPR Construction,Inc.
email: atulk@stanford.edu or atulk@dprinc.com

Dr. Martin Fischer, Professor of Civil and Environment Engineering, Director CIFE,
Stanford University
email: fischer@stanford.edu

Dean Reed, Lean Construction Coordinator,
DPR Construction, Inc.
email: deanr@dprinc.com

SUMMARY*: Coordination of Mechanical, Electrical and Plumbing (MEP) systems is a huge challenge for many technical projects such as Healthcare projects, Bio-tech projects and projects in the area of Advanced Technology. The use of Building Information Modeling (BIM) or Virtual Design and Construction (VDC) tools and processes promises to address the challenges of the MEP coordination process. This case study presents the use of BIM / VDC tools and processes for the coordination of MEP systems on a $96.9M healthcare project in Northern California, USA. discuss the challenges project team members faced in implementing the BIM / VDC tools and processes for MEP coordination, the specific quantitative and qualitative benefits from the use of BIM / VDC tools and processes that each project team member recognized and the lessons that the project team learned by implementing BIM / VDC tools and processes for the coordination of MEP systems. Some of the challenges we discuss include the creation and organization of the MEP coordination process using BIM / VDC tools, creation of the guidelines for the most efficient use of BIM / VDC tools for the process of conflict identification and resolution between the MEP subcontractors, and aligning the contractual interests of the coordination team to meet the overall project schedule. Some of the benefits that the project team achieved by using the BIM / VDC tools and processes for the coordination of the MEP systems include labor savings ranging from 20 to 30 % for all the MEP subcontractors, 100% pre-fabrication for the plumbing contractor, only one recorded injury throughout the installation of MEP systems over a 250,000 square feet project area, less than 0.2% rework for the whole project for the mechanical subcontractor, zero conflicts in the field installation of the systems and only a handful of requests for information for the coordination of the MEP systems between contractors and the designers, and 6 months' savings on the schedule and about $9M savings in cost for the overall project. The lessons the team learned include the level and type of details team members need to include to achieve benefits from the use of BIM / VDC tools for the coordination of MEP systems.*

KEYWORDS*: Building Information Modeling (BIM), Virtual Design and Construction (VDC), Mechanical, Electrical, Plumbing Systems (MEP Systems), Design Coordination, 3D CAD, 4D CAD, Prefabrication, Productivity, RFI, Change Orders, MEP Coordination*

1. INTRODUCTION

The MEP systems on technically challenging projects like those focused on the high technology, healthcare, and biotech industries, can sometimes comprise of as much as 50% of the project value. Therefore, the coordination and routing of the MEP systems on these types of projects is a major endeavor. The MEP systems need to be routed in limited space under the design, construction, and maintenance criteria established for the systems (Barton 1983, Korman and Tatum 2001). The Camino Medical Group project in Mountain View, California, is a new Medical Office Building (MOB) facility for the Camino Medical Group (CMG) that fits the bill of a technically challenging project. The negotiated contract for this project is about $96.9M. The construction for this fast track project started in January 2005 and completed in early April 2007, and the facility is now open for business. The project scope includes a 250,000 square foot, three-level MOB and a two-level 1,400 space parking garage. The MOB includes patient exam rooms, doctor's offices, surgery and radiology rooms, public spaces, a cafeteria, numerous conference rooms, etc. This building is designed as a steel structure with the following parameters:

- floor to underside of metal deck height is about 14 feet (4,260 mm)
- floor to ceiling height in most rooms is 9 feet (2,740 mm) or 9.5 feet (2,900 mm)

This means that all the complex MEP systems supporting the facility need to be incorporated within the 4.5 (1,370 mm) to 5 feet (1,520 mm) of interstitial space on all floors. The Camino MOB project team adopted Virtual Design and Construction (VDC) technologies (specifically 3D/4D modeling tools) for the coordination of the MEP systems on this project. This paper illustrates the challenges the team addressed and the specific benefits that the team accomplished using VDC tools for the MEP coordination process.

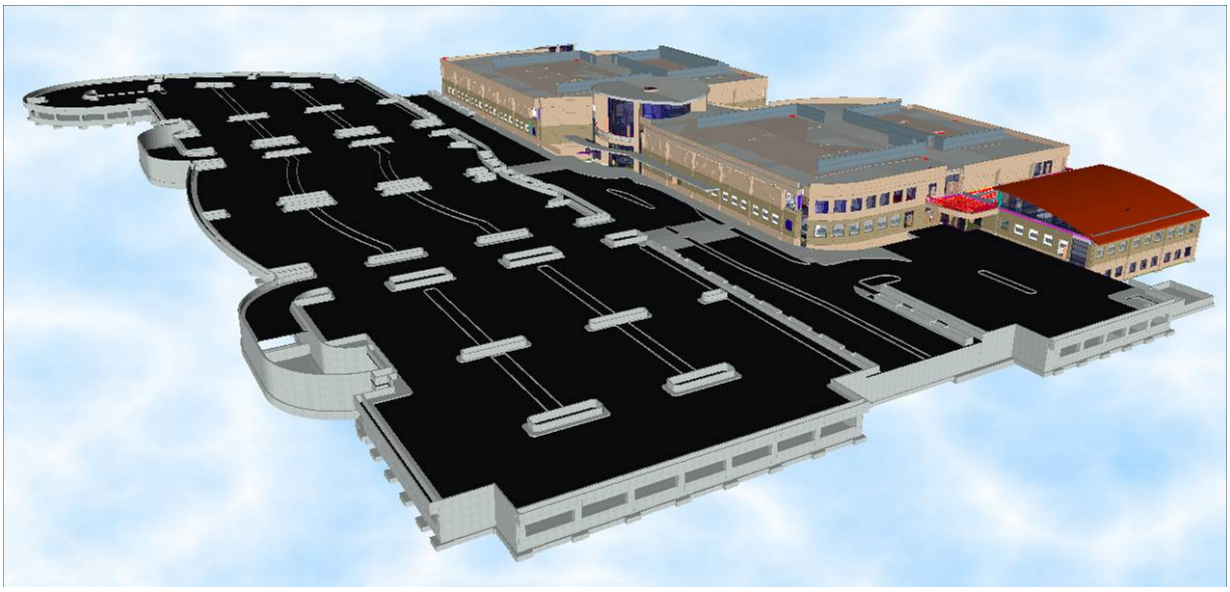


FIG. 1: 3D rendering of the three-level MOB for the Camino Medical Group Project in Mountain View, California. Image courtesy DPR Construction, Inc., CA, USA.

2. BACKGROUND

In order to document the impact of BIM / VDC tools and processes on the coordination of MEP systems it is important to understand the previous research in the broad field of BIM / VDC tools and the specific area of MEP coordination.

Although the term Building Information Model (BIM) was coined a long time ago and Virtual Design and Construction (VDC) has been used in the recent past it is fair to say that both these terms have come to indicate the use of parametric CAD models for analysis of various design, and construction problems. Some of the BIM / VDC tools such as 3D / 4D CAD have been used in practice quite a bit and there has been a lot of research on benefits of using 3D/4D tools in commercial construction. These studies include the feasibility of 4D for commercial construction (Koo et al 2000, detailed case studies that assess the benefits and limitations of these tools and their impact on project performance (Haymaker et al. 2001, Staub-French et al. 2001, Kam et al., 2003). Other studies include the critique of the functionality of 3D and 4D technologies to meet the needs of industry (Songer et al. 1998, Heesom et al. 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). Research efforts have also focused on use of 3D / 4D for specific trades such as concrete (Olofsson et al. 2004) and precast concrete (Eastman et al. 2002). 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).

FIG. 2: MEP coordination session at the Palo Alto Medical Foundation Project in Fremont, CA, USA using the SCOP. Image courtesy DPR Construction, Inc., CA, USA.

Previous research has focused on documenting and understanding the current MEP coordination process in the US construction industry (Tatum and Korman 1999, Tatum and Korman 2000). The research describes the state of the MEP coordination process in the US construction industry and specifically focuses on how project teams coordinate MEP systems. Korman calls this process the Sequential Composite Overlay Process (SCOP). In this process, the specialty subcontractors or the engineers develop the detailed drawings for their own scope of work and overlay the drawings on a ¼” scale and then using a light table try to identify potential conflicts that might occur in the routing of the MEP systems. The conflicts are then highlighted on the transparent drawing sheets and then addressed before the fabrication and installation process. An example of this process is shown in Fig. 2 from a recent project that one of the authors was involved in.

Based on the authors’ recent experience in the US construction industry we can say that this process is still followed on a majority of projects that are delivered using a variety of project delivery approaches ranging from Design-Bid-Build to Design-Build to Design-Assist. The process leads to many challenges some of which include the following:

- Lack of ability to identify conflicts due to the 2D representation of the designs
- Delays in construction process due to conflict being identified in the field
- Lack of trust in the fabrication offsite due to the fear of system not fitting leading to a lot of on the site fabrication
- Rework to fix the conflict issues not identified during design and coordination
- Increased site supervision required to avoid conflicts between trade contractors
- Increased administrative burden of more Request for Information (RFIs) and Change Orders due to identification of conflicts in the field after budgets are approved
- “Install first” mentality amongst trade contractors so as to avoid having to move their systems in case conflicts arise leading
- Overall reduced productivity for everyone involved in the process

Some of these challenges have been substantiated by studies on MEP coordination. Prior research on impact of change orders for mechanical and electrical construction has proven that the timing and number of change orders has a significant impact on the labor productivity for mechanical and electrical contractors (Hanna et al. 1999). Another study found that a design-build contract had a significantly reduced number of unforeseen change orders compared to design-bid-build projects (Riley et al. 2005).

Past research has also focused on methods and tools that could be applied to improve the MEP coordination process. Some of this research includes the work done by Korman and Tabesh to identify the design, construction, and maintenance knowledge that is needed for the MEP coordination process, the representation of this knowledge, and a proposed computer-aided methodology that could be used to improve the MEP coordination process (Korman et al 2003, Tabesh et al. 2005). Korman proposes a computer-aided methodology includes tools such as 3D/4D models of MEP systems along with the use of automated clash detection programs that allow project teams to superimpose the models and check for conflicts in three-dimensional space to improve the MEP coordination process.

Only recently has research focused on documenting the benefits and challenges of applying 3D / 4D tools specifically to the coordination of Mechanical, Electrical, and Plumbing (MEP) systems for commercial construction projects (Staub-French et al. 2001). We have also reported in a couple of conference papers the preliminary results of the implementation of BIM / VDC for MEP coordination on large healthcare project (Khanzode et al. 2005 and Khanzode et al. 2007). We have also shared some of the preliminary issues and lessons learned in a journal paper (Staub-French S. et al. 2007) In this case study we build upon this prior research now that the project has been completed. We first discuss the specific challenges that the project team faced in implementing BIM / VDC for MEP coordination on this project, the quantitative and qualitative benefits the project team members achieved because of the use of BIM / VDC tools and processes and finally discuss the lessons that the team members learnt through this new way of doing MEP Coordination.

3. CHALLENGES OF IMPLEMENTING BIM / VDC TOOLS FOR MEP COORDINATION ON THE CAMINO MEDICAL OFFICE BUILDING (MOB)

The Camino MOB team decided early on to use the BIM / VDC tools (specifically 3D/4D and automated clash detection tools) for the MEP coordination process (Khanzode et al 2005). The project team for this project is as follows:

Project Team Member	**Role on the Project**
Sutter Health / Camino Medical Group	Owner
Hawley Peterson and Snyder Architects	Architects
DPR Construction, Inc.	General Contractor
Capital Engineering Consultants	MEP Design Engineers
Southland Industries	Mechanical Subcontractor
Cupertino Electric	Electrical Subcontractor
JW McClanahan	Plumbing Subcontractor
North Star Fire Protection	Fire Protection Subcontractor

On this project the owner, along with the architect, engineers and contractor pre-qualified the MEP subcontractors for their ability to coordinate and collaborate with the other subcontractors using 3D/4D tools. Before this project the team members had not worked previously on a project of similar size and scope and also not collectively used the BIM / VDC tools for the MEP coordination process. To begin with the project team faced a number of questions. Some of the important questions are as follows:

1. How to organize so as to best utilize the BIM / VDC tools for MEP coordination?
2. What roles should each of the project team members play in the coordination process?
3. How to address issues such as technical setup and sharing of models and drawings?
4. How should the coordination process be structured and managed?

The project team iteratively developed guidelines to help address these questions. It should be noted that these guidelines evolved and became more refined as the project team started working together and more and more questions were addressed as the team went along with the coordination process using the BIM / VDC tools. The project team also kept track of the traditional metrics on this project such as number of Request for Information related to coordination during the MEP construction phase, number of change orders due to field related conflicts, hours for rework, hours lost to injuries, estimated versus actual productivity of field crews, and amount of prefabrication. At the end of the project in a series of lessons learned meetings the team members agreed on the important aspects of the guidelines that they would follow in the future. We have captured these guidelines below in the form of best practice for doing MEP coordination using BIM / VDC tools. The guidelines include:

1. Clarifying the role of the general contractor (GC) and specialty contractors in the coordination process
2. Developing the levels of detail in the architectural, structural, and MEP models
3. Setting up the coordination process
    a. Setting up the technical logistics
    b. Kicking off the coordination process
    c. Establishing the sequence of coordination
    d. Managing handoffs between designers and detailers
    e. Working in the “Big Room”
    f. Using 3D clash detection tools to identify and resolve conflicts
    g. Managing the process using the Last Planner System
    h. The final sign-off
4. Managing the coordination of the installation process

We discuss each of the items above in more detail in the following sections.

3.1 CLARIFYING THE ROLE OF THE GC AND SPECIALTY CONTRACTORS IN THE COORDINATION PROCESS

3.1.1 Role of the General Contractor

On the Camino MOB project the general contractor (GC) enabled the BIM / VDC-supported MEP coordination process by acting as the main facilitator rather than the author of the drawings and models. The GC enabled and coordinated the hand-off of information from the architects and engineers (A/E’s) to the subcontractors as well as the modeling and coordination work itself.

The project team agreed that GC’s role in initial modeling and coordination in the BIM / VDC enabled MEP coordination process is much the same as on the project as a whole: developing a workable detailing schedule together with the A/Es and subcontractors to support the construction schedule. Once the schedule is established, the GC’s Project Engineer assigned as the MEP coordinator worked together with the detailers to achieve sign-off milestones using the Last Planner System™ (Ballard 1994) a process to manage the commitments under the Lean Project Delivery System methodology.

3.1.2 Role of the Specialty Contractors

The specialty contractors are responsible to model their portion of work using 3D tools. Using the BIM / VDC tools for MEP coordination, the HVAC contractor took the lead role in the coordination process. The HVAC equipment like VAV boxes, fire smoke dampers, duct shafts, and low and medium pressure ducts take up the most space in the above-ceiling space. It was our observation that detailers of other trades (plumbing/electrical/ fire sprinklers) would much rather like to know how the HVAC equipment, duct shafts, and main ducts are routed since that has the most impact on how they will route their utilities. The HVAC contractor should therefore model at least the main medium pressure and low pressure duct lines and shafts so that other trades can coordinate and route their utilities around these duct lines. The specialty contractors are also involved early in the process so that they can provide input into the constructability and operations issues to the design team.

Some contracting methods that allow for early involvement of specialty contractors include the Design-Assist and Design-Build contracting methods. In both methods the specialty contractors are brought in early (somewhere between the conceptual and schematic design phases). In the Design-Build method the specialty contractor is also the engineer of record for the MEP systems while in the Design-Assist method this responsibility may rest with an independent or third party engineering and design firm. The Camino MOB project used the Design-Assist contracting method. This method worked well for the coordination process for the project.

3.2 Levels of detail in the architectural, structural and MEP models

One of the questions that most teams have when starting the 3D modeling effort is: “What to model in 3D?” This question should be answered by the whole team involved in the 3D coordination effort. The goals set out by the team for the coordination effort will play a big role in determining what to model. On most projects MEP/FP coordination can be divided into two distinct coordination efforts:

- Coordination of underground utilities like plumbing and electrical
- Above-ceiling coordination of all the MEP/FP utilities

If the team decides to do both underground and above-ceiling coordination using 3D tools then elements like foundations and framing are required for the coordination effort.

Another important question is: “What level of detail should be included in the models?” There is clearly a tradeoff between the level of detail in the models and the uses they can provide to the coordination effort. For example, including casework details in the architectural model is necessary for determining the exact locations of the plumbing rough-ins in the walls but is not needed for coordination and conflict detection with other systems like HVAC. The project team should collectively decide the level of detail question.

We identified that for the coordination of MEP systems using BIM / VDC tools requires that project teams plan to create 3D models for:

- Architectural elements like interior walls, ceiling
- Structural elements like the main structural framing, slabs, and foundations
- Mechanical systems like duct work, etc.
- Plumbing systems like the gravity lines and hot and cold water piping
- Electrical systems like the major conduits and cable trays
- Fire protection systems with the mains and branches
- Other specialty systems like medical gases depending on the project

3.3 THE COORDINATION PROCESS

3.3.1 Getting the Technical Logistics Right

Technical Logistics plays an important part in the coordination process. It is likely that many 3D models will be used on the project, and each subcontractor will create their models. Team members should agree to some basic rules at the outset of the project so that the sharing of electronic 3D models is efficient and benefits the whole team. The project team should address the following issues:

- 3D models are accompanied by standard word documents describing revisions therein
- 3D models are posted to a project website, ftp site, or a document collaboration site determined by the team which includes the GC, subs, owner, and A/E team
- The collaboration site provides secure and remote access to all the model files
- A clear file path structure is set up on the server to organize the model files and other relevant documents
- Everyone works from and posts to the same server
- The server is backed up every night
- Borders and title blocks are not transmitted with the drawings

- The insertion point for all drawings is based on the 0,0,0 insertion point established in the architectural drawings
- Anything not intended to be seen in the 3D model is erased prior to file transfer

On the Camino MOB project the project team members used the following software applications:

- Autodesk Architectural Desktop
- ETABS Structural Analysis
- Autodesk Revit Structure
- QucikPen 3D Pipe Designer
- CAD Duct
- Fab Pro Mechanical Detailing
- SprinkCAD Sprinkler Modeling
- Navisworks JetStream for Coordination and Clash Detection

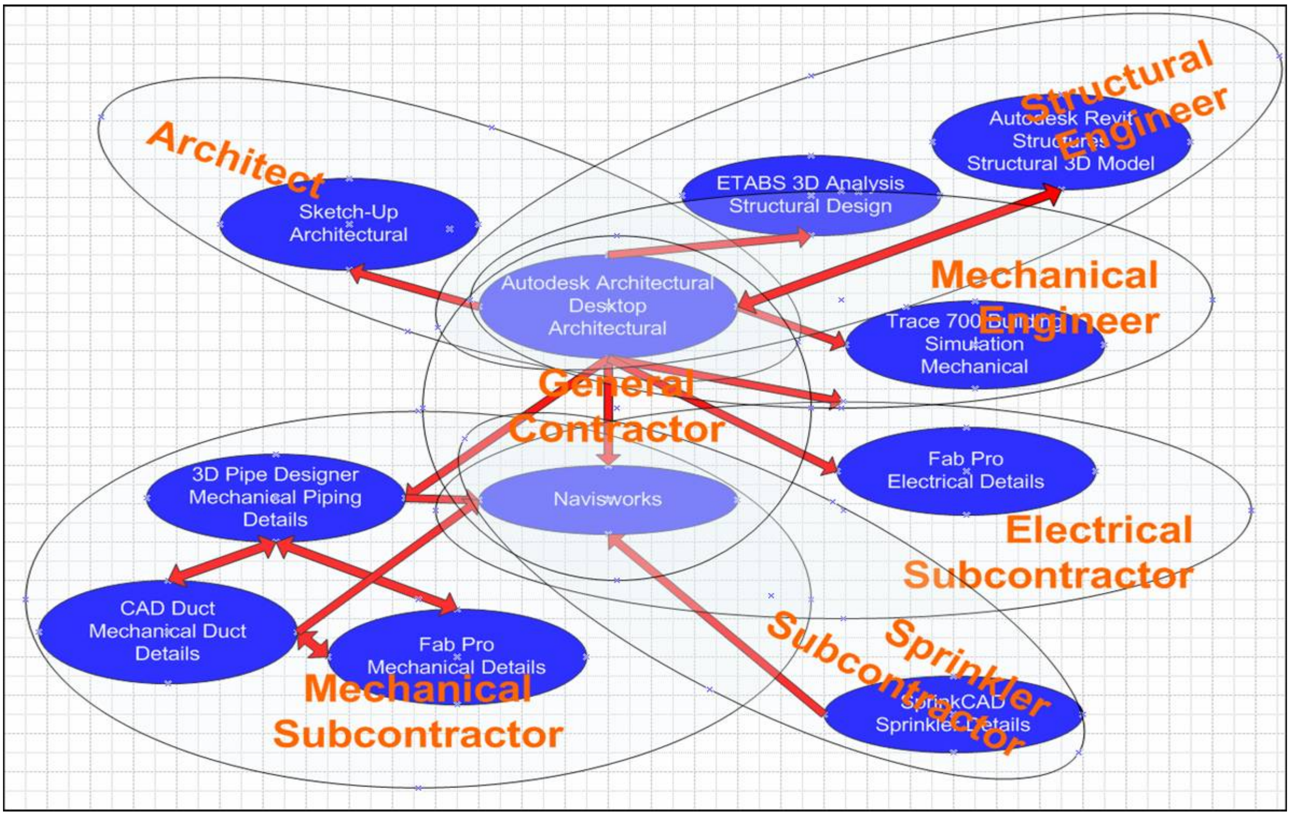


FIG. 3: Figure shows the various software systems used by the team members on Camino MOB. Navisworks JetStream was used for bringing all the models together and perform clash detection.

Navisworks JetStream was used for the Clash detection purpose on Camino MOB. The models that the subcontractors and design team members created using the systems indicated in Fig. 3 were brought in to NavisWorks JetStream by the GC and clashes were identified using the Clash Detective function within NavisWorks JetStream. The process was repeated till all major clashes were resolved. As most of the authoring tools used by project team members were developed on top of the Autodesk platform (DWG compatible) the team also identified further guidelines shown in Appendix I.

3.3.2 Kicking Off the Coordination Process – The First Steps

The first step in the coordination process is the kick-off meeting that involves all the team members (architect, engineer, GC, and subs). The items to discuss in this first meeting include the following:

- Get the technical logistics right

- Perform the initial space allocation of the above-ceiling space which involves identifying the zones that each of the trade contractors is going to occupy (Fig. 3)
- Determine the breakup of floor plans so that they can be coordinated in smaller batches

3.3.3 Sequence of Coordination

In our experience the MEP/FP coordination process using 3D/4D tools is most efficient if it follows the sequence below:

- Start with the 3D structural and architectural model
- Add miscellaneous steel details to the model
- Perform preliminary space allocation (as indicated in the previous section)
- Identify hard constraints (locations of access panels, lights, etc.)
- Draw the main medium pressure ducts from the shaft out
- Draw the main graded plumbing lines and vents
- Draw the sprinkler mains and branches
- Draw the cold and hot water mains and branches
- Draw the lighting fixtures and plumbing fixtures
- Route the smaller ducts and flex ducts around the utilities drawn before
- Route the smaller cold and hot water piping, flex ducts, etc. last

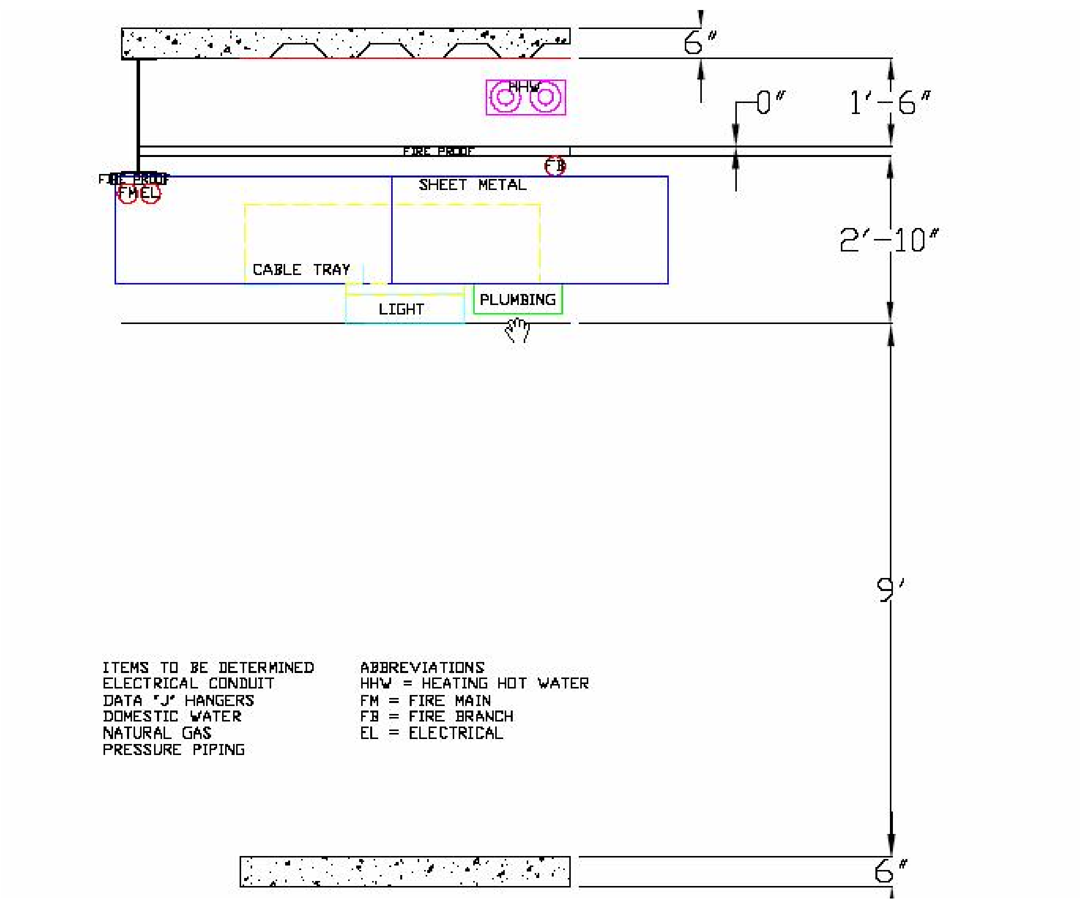


FIG. 4: Screenshot of the initial space allocation of the above-space utilities for the MEP systems. This space allocation allows subcontractors to identify the general location of their systems as a starting point for their work. Image courtesy DPR Construction, Inc., CA, USA.

3.3.4 Managing the Handoffs between the Designers and Subcontractor's Detailers

In the US construction industry, the traditional building process involves a host of specialty firms focused on specialized, small portions of work. This is true for both the design and the construction phases of the project. During the design phase architects work with a host of design consultants like structural engineers, acoustical consultants, and mechanical engineers, etc. to complete the design of the facilities. During the construction process the general contractor typically coordinates the work of many specialty subcontractors. There is no single master builder. In this environment managing the hand-off of information from designers (who are typically the engineers of record) to the subcontractors' detailers becomes extremely important. In a fast track project where design and construction overlaps managing the handoffs between designers and subcontractors is doubly important.

The project team should collaboratively determine how the design will be broken down into small enough batch sizes that allow detailers to coordinate and complete an area so that fabrication can begin. This is an iterative process between the design and construction teams. For example the Camino MOB project developed a process chart and document (shown in Fig. 5 and Fig. 6) to determine the handoff between the design and the construction teams.

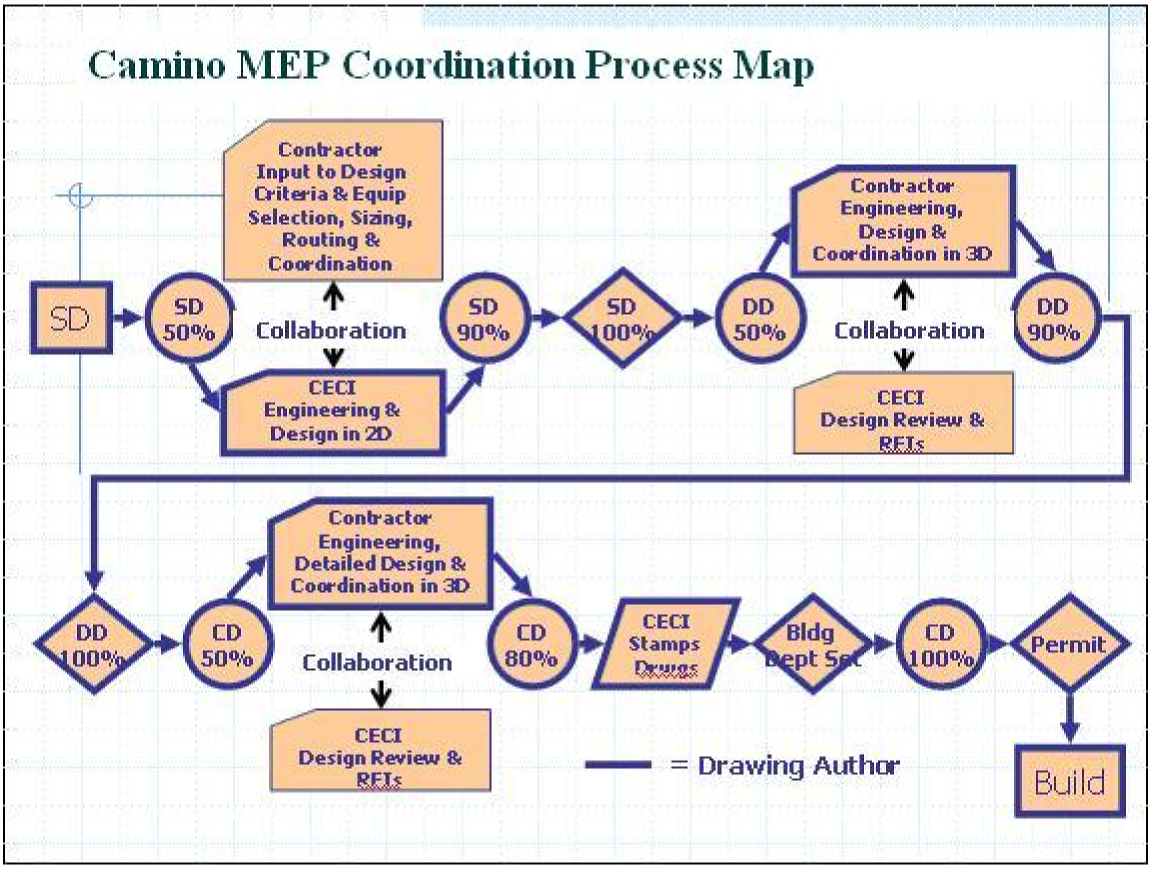
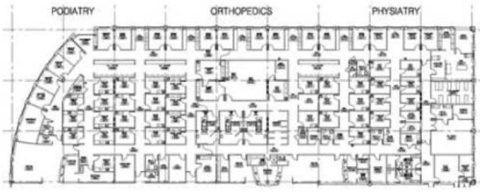


FIG. 5: The handoff process that was developed collaboratively by the Camino MOB design and construction teams. It indicates that the design and detailing teams will collaboratively work together at the beginning of the schematic design stage (50% SD), and the detailing team for the subcontractors will start creating the 3D models at the detailed design stage and complete the modeling effort with a fully coordinated design in 3D at the end of the construction documents phase. Image courtesy DPR Construction, Inc., CA, USA.

Camino Medical Group – Mountain View Campus **Rev. 6/1/05**

MEP Overhead Coordination

First Floor South-East Quadrant



Schedule

A. **Information Procurement (CMG):** **Target Completion Date – 5/27/05**
B. **Design Period Duration (HPS/Design):** **7 Days / Start: 5/27 – End: 6/6**
C. **Shop Drawing Preparation (DPR/DA):** **27 Days / Start: 6/7 – End: 7/13**

Information Required / Responsible Party

1. User Acceptance of Floor Plans (CMG)	Complete 6/1
2. Radiology Overhead Equipment Weights and Attachment Layout/Dimensions (CMG/Siemens)	Due by 6/7

FIG. 6: The MEP coordination handoff document prepared by the Camino MOB design and construction team to manage the handoffs between the design and construction team. The figure shows the handoff schedule for the first floor south east quadrant. Image courtesy HPS Architects, Mountain View, CA, USA.

This handoff is a result of honest negotiation between the design and construction teams about how much information should be shared when by the A/E team with the detailing team to meet the milestones identified for coordination and fabrication for the various areas. The GC should come to these talks with a clear understanding of the critical path.

3.3.5 Working in the Big Room

Coordination of detailed design is an intensive process due to the many reciprocal dependencies between the routing of the MEP systems. It involves designers and specialty contractors. The detailing work for each trade is dependent on information from the designers and other trade contractors. For example the plumbing detailer is interested in finding out the location of waste and vent shafts from the design team and the location of the main duct runs from the mechanical subcontractor. At the same time the mechanical subcontractor is interested in finding information about the gravity lines from the plumbing subcontractor so that he can correctly locate the duct lines. The coordination effort involves a fair amount of reciprocal dependencies that need to be resolved quickly. Latency in decision making and information access can seriously impact the fast track project schedule. These challenges are addressed by co-locating the design and detailing teams (Thompson 2003), (Levitt and Kunz 2002). The goal is to create a collaborative work environment where the decision making latency can be reduced.

It is our experience that detailers must work side-by-side in one “Big Room” to model and coordinate their designs to meet the coordination schedule. Although we cannot precisely say by how much, this shortens the overall time for modeling and coordination and is more economical in the end for all concerned parties because the detailers won’t need to wait for postings to see what others are doing which greatly reduces wasted detailing efforts. Fig. 7 shows the Big Room that was set up by the Camino MOB project team. Detailers for the various specialty subcontractors sat in a single room, shared resources like servers, internet connection, printers and plotters, and coordinated the detailed design with each other and the design team in this room.

FIG. 7: The "Big Room" on the Camino MOB project with all the detailers from the specialty trades working together in a single room. Image courtesy DPR Construction, Inc., CA, USA.

3.3.6 Using 3D Clash Detection Tools to Identify and Resolve Conflicts

There are commercial tools available that allow project teams to combine 3D models from multiple CAD systems into a single model and determine if two or more systems conflict with each other. One such tool is NavisWorks JetStream which has a module called "Clash Detective" that allows teams to automatically analyze the 3D models of the different disciplines for conflicts between systems. This tool was used on the Camino MOB project.

Conflict identification and resolution is an iterative process. The models are first combined into a single model and then the clash detection program is run to identify clashes between systems. The clashes are then resolved in their native programs and the iteration is performed until all clashes are resolved (Fig. 8).

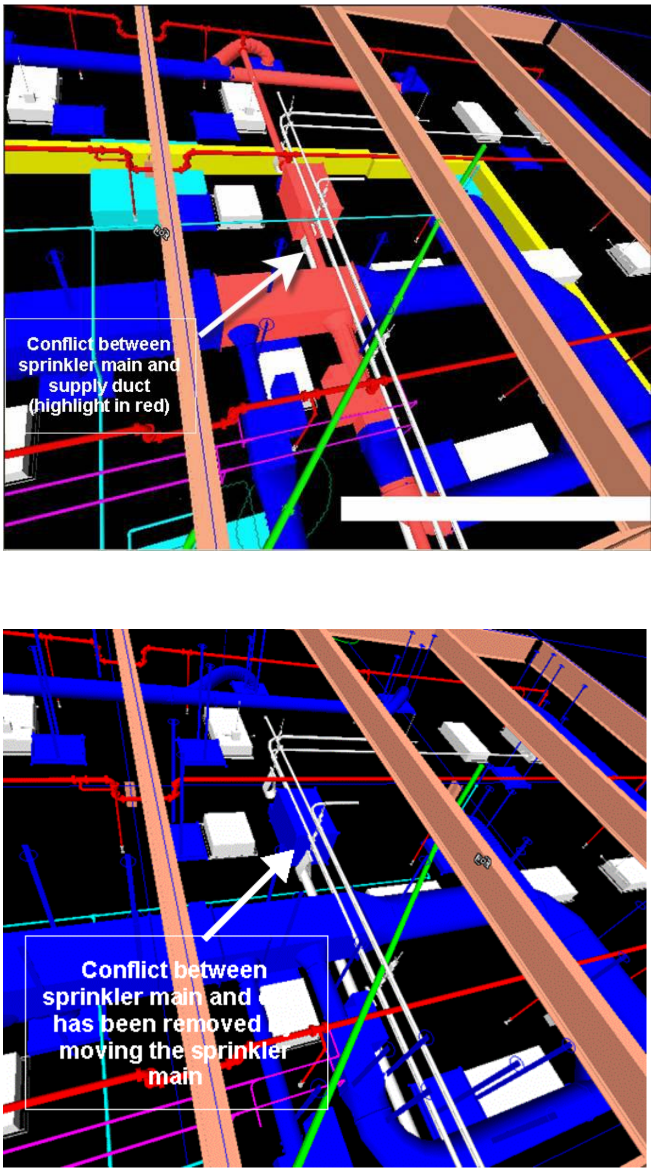


FIG. 8: The picture on the top shows a clash or conflict between a supply duct and a sprinkler main pipe, highlighted in red. The picture on the bottom shows that the clash was resolved by moving the sprinkler main to the right of the duct. These clashes were first identified by using the NavisWorks' clash detection program and resolved in a subsequent clash resolution session. Image courtesy, DPR Construction, Inc., CA, USA.

3.4 Creating the Design Coordination Schedule

The GC works with the MEP subcontractors to establish the coordination schedule. This schedule is the work plan to ensure that clash-free drawings are in the hands of installation crews in time for penetrations and hangers to be installed prior to the placement of reinforcement and concrete on the elevated decks. The coordination schedule also sets dates for a final all-hands clash detection workshop for each area in time for pre-fabrication of assemblies to meet the master construction schedule. For example, Fig. 9 shows a Microsoft Excel table that represents the coordination schedule developed on the Camino MOB project. The coordination schedule was developed with the help of designers and subcontractors. The schedule was pulled from the milestone of the MEP Insert start date (5^{th} column from the left in the spreadsheet). This means that the team worked backwards from the MEP Insert milestone date to determine the preceding activities and durations to meet this milestone date. This helped in scheduling tasks as late as possible to minimize the potential for rework as much as possible and to maximize information availability for all the team members.

Camino Medical Center
MEP/FP DA Team MEP/FP Design Coordination Schedule

Coordination Quadrant	A/E Drwgs for Construction	Insert Navis File Posted	Insert Order	MEP Insert Start	MEP Insert Finish	Target Release for Fab Sign-off	Fab Order	Release for Fab Date	Date of DA Team Acceptance of SI Medium Pressure Duct	Date of DA Team Acceptance of JWM DW&V
1st Floor Southeast	11/22/05	10/18/05	1	10/27/2005	11/3/2005	12/7/05	1	12/6/05	12/16/05	1/2/06
1st Floor Southwest	11/22/05	11/11/05	2	11/15/2005	11/22/2005	12/21/05	2	12/21/05	12/29/05	1/12/06
2nd Floor Southeast	11/22/05	11/22/05	3	11/22/2005	12/1/2005	1/4/06	3	1/4/06	1/17/06	2/1/06
2nd Floor Southwest	11/22/05	12/7/05	4	12/9/2005	12/16/2005	1/11/06	4	1/22/06	1/31/06	2/18/06
1st Floor Northeast	11/22/05	12/28/05	7	12/30/2005	1/9/2006	1/18/06	5	2/5/06	2/14/06	3/2/06
2nd Floor Northeast	11/22/05	1/16/06	9	1/19/2006	1/26/2006	1/25/06	6	2/19/06	2/28/06	3/18/06
2nd Floor Northwest	11/22/05	1/19/06	10	1/24/2006	1/31/2006	2/1/06	7	3/5/06	3/14/06	4/2/06
3rd Floor Southeast	11/22/05	12/7/05	5	12/13/2005	12/21/2005	2/8/06	8	3/19/06	3/28/06	4/16/06
3rd Floor Southwest	11/22/05	12/14/05	6	12/19/2005	12/27/2005	2/10/06	9	4/2/06	4/11/06	4/30/06
3rd Floor Northeast	11/22/05	2/3/06	11	2/7/2006	2/15/2006	2/15/06	10	4/16/06	4/26/06	5/14/06
3rd Floor Northwest	11/22/05	2/15/06	12	2/15/2006	2/27/2006	2/17/06	11	5/2/06	5/11/06	5/30/06
1st Floor Northwest	11/22/05	1/2/06	8	1/5/2006	1/12/2006	2/23/05	12	5/16/06	5/25/05	6/13/06
1st Floor Center	11/22/05	1/11/06	13	2/24/2006	3/1/2006	12/21/05	13	6/10/06	6/19/06	7/8/06
2nd Floor Center	11/22/05	1/27/06	14	2/27/2006	3/2/2006	1/11/06	14	6/17/06	6/23/06	7/15/06
3rd Floor Center	11/22/05	2/21/06	15	2/28/2006	3/3/2006	2/17/06	15	7/1/06	6/30/06	7/29/06

FIG. 9: The pull schedule for the coordination of the MEP systems of the Camino MOB. It shows the target sign-off dates for each of the areas. The schedule was developed through a collaborative effort between the GC, the subcontractors, and the design team and was driven by the start date for MEP Inserts (5^{th} column from the left). Image courtesy, DPR Construction, Inc., CA, USA.

We now discuss the benefits that the Camino MOB project team accomplished using the VDC-based coordination process described above.

4. BENEFITS

On the Camino project, the use of 3D/4D tools for MEP/FP coordination resulted in significant quantitative and qualitative benefits for the project team members. The benefits for the owner, general contractor, architects, engineers and subcontractors are identified below.

4.1 Benefits for the owner

- The project team did not spend time on non value adding activities on the project such as dealing with Request for Information or Change Orders due to field conflicts in the MEP systems. Only 2 of 233 RFIs on the Camino MOB were related to field conflict and construction related issues, and these two RFIs were for systems that were not modeled using BIM / VDC tools, in addition 10 % RFIs were confirming only RFIs. We asked the project participants how this compares to similar projects they have worked on and found that this number is really small. Most participants put RFIs dealing with field conflicts on comparable projects somewhere in the 200-300 range. We have not yet compared this performance to similar projects but believe that this is a remarkable performance.
- There are zero change orders related to field conflicts on this project. The project is now complete and the building is operational with 100% of MEP systems installed. There has not been a single change order due to a field related conflict. We interviewed the project team to determine how much they would normally expect to spend on change orders on a project this size and the estimate was about 1% - 2% of cost of MEP systems. On this project this is a substantial savings for the owner.
- The owner has adopted and mandated the use of the BIM / VDC tools and processes for MEP coordination on all their future projects in their $6 Billion construction program. This in itself is a testimony to the success the owner perceives of using this new method for MEP coordination.

- The owner also has a fairly accurate as-built model that the facilities group is now using for facility management purpose for the new facility which is now open for almost 11 months. The facility management teams' feedback is that the information is a lot easier to find compared to traditional 2D drawings which normally get sent to the owner at the end of the project.
- The project team compared this fast track project delivery to a traditional Design-Bid-Build project delivery to compare how much savings accrued due to the use of VDC tools and a fast track project approach that hedged the effects of inflation. This study (Fig. 10) indicates a savings of $9M and 6 months to the owner due to the use of the BIM / VDC tools and a collaborative project delivery approach.

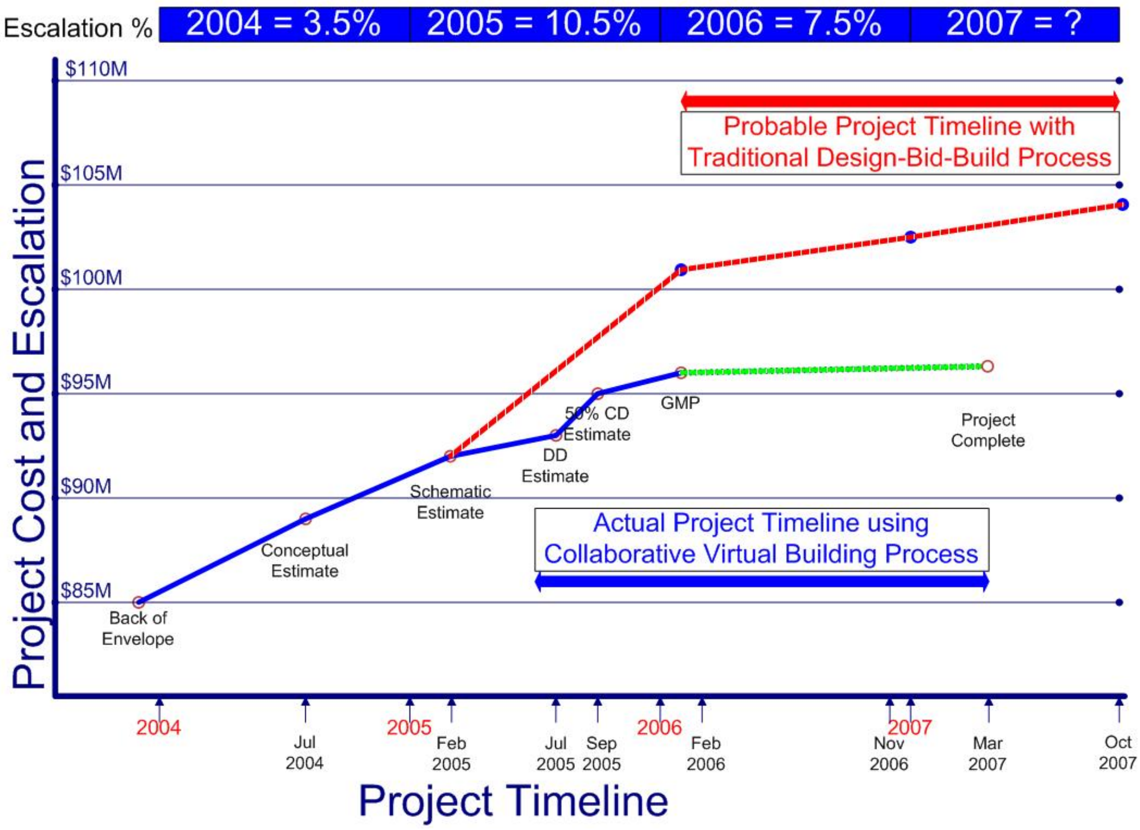


FIG. 10: Comparison of the collaborative virtual building project delivery approach adopted by the Camino MOB team using VDC tools and the traditional Design-Bid-Build method of project delivery. The graph shows that due to the use of VDC tools and a fast track approach the team was able to save $9M and 6 months as compared to the traditional process. Image courtesy DPR Construction, Inc., CA, USA.

4.2 Benefits for the Architects / Engineers

- The Architects / Engineers spent substantially less time during the construction phase of the project doing construction administration. They did not have to deal with any RFIs related to field conflicts or deal with any change orders due to field conflict issues.

4.3 Benefits for the General Contractor

- The GC's superintendents were able to spend more time planning the job rather than reacting to field conflict issues on the project. The superintendents spent about 10-15 hours in the eight months of the project when MEP construction was going on dealing with field issues. On comparable projects they estimate that they would typically need to spend 2-3 hours each day dealing with issues related to field conflicts.

- On the Camino MOB project a total of work-hours 203,448 have been spent during MEP coordination, and there has been only one recordable injury (versus a national average of about 8 recordable injuries for these many hours). The superintendent attributes this to the improved workflow due to the use of 3D/4D models on the project which has resulted in more off site pre-fabrication, just in time material deliveries, and efficient field coordination and installation.
- The GC was able to maintain a safe and efficient site throughout the construction of MEP systems. Due to the fact that most systems were prefabricated offsite and being brought on the site in assemblies there were no setups of fabrication equipment etc on the site which meant that the site was a lot cleaner compared to other similar sized projects.

4.4 Benefits for the Specialty Contractors

- Subcontractors were more knowledgeable about the project as they have been involved sooner and are resolving issues in the design and detailing stage that would typically come up in the field. We noticed that a lot of reciprocal work that typically happens during construction has happened during design on the Camino project, resulting in more efficient construction.

• All the trades have finished their work ahead of or on schedule. The mechanical contractor estimates that their field productivity has improved between 5 to 25% (Fig. 11). This improvement is based on comparing the estimated field productivity to the actual field productivity they were able to achieve and relates to the field labor only. They attribute this increased productivity to more off-site prefabrication and more bolt-in-place assembly on site that required less labor than estimated at the beginning of the project. This project is a Guaranteed Maximum Price (GMP) project and the mechanical contractor alone is giving back about $500K over his approximately $9.4M contract due to savings on field labor.

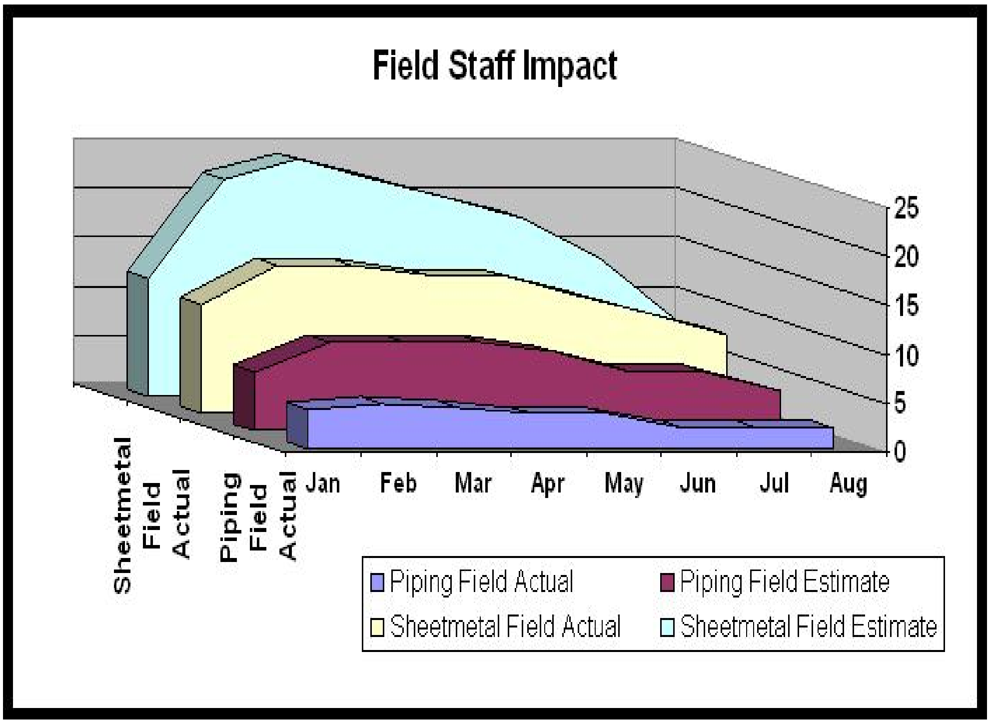


FIG. 11: Estimated versus the actual hours spent by Southland Industries, the mechanical contractor for the piping and sheet metal work at the Camino MOB. The picture shows a 5 to 25% improvement in the use of field labor. Image courtesy Southland Industries, San Jose, CA, USA.

- All the plumbing and medium and low pressure ductwork is being pre-fabricated. The subcontractors attribute this to the use of 3D models for coordination. On comparable projects none of the plumbing and at most 50% of the ducts would typically be pre-fabricated.

- The subs could use lower-skilled labor for the field work compared to other projects where higher-skilled field labor is necessary for installation as the labor force typically needs to interpret 2D drawings, etc.
- The mechanical contractor had to carry out less than 0.2% (only 40 out of 25,000 hours of field work) of rework in the field. They attribute this to the accurate and coordinated 3D models that led to accurate fabrication and installation of almost all work the first time.

5. LESSONS LEARNED

At the end of the project the General Contractor gathered the project team to do a couple sessions on lessons learned through the use of BIM / VDC for the MEP coordination process on this project. A parallel effort was also conducted by an independent researcher who used this project as an example in the BIM Handbook that was recently published by Wiley (Eastman et al. 2008). Based on these two independent efforts we can summarize the lessons learned from this project under the following sections:

- Lessons related to the Organization of Team members
- Lessons related to the use of BIM / VDC tools
- Lessons related to the level of details in the models

These lessons are summarized in more detail below:

5.1 Lessons related to the Organization of Team members

Although the majority of the subcontractors and their detailers were on site in the same “BIG ROOM” working side by side during the coordination process one of the subcontractors (Fire Protection) was not on site in the BIG ROOM with everyone else. This resulted in a lot of issues with the mechanical, plumbing and electrical systems interfering with fire protection. Eventually it was all resolved but the team agreed that it is best to have everyone working side by side in the same BIG ROOM in order for the process to work most efficiently.

At the beginning of the project the architects and designers did not anticipate that they would spend much time in the BIG ROOM with the subs when the coordination was going on but we realized that in order that the process goes smoothly they had to spend close to 2 days per week in the BIG ROOM working side by side with the detailers so that most issues could be addressed.

5.2 Lessons related to the use of BIM / VDC tools

Towards the end of the project the electrical contractor had to relocate many electrical outlets in the patient examination rooms and doctors offices. The end users requested some of these outlets to be moved after all the walls were roughed-in (meaning the flex conduit and the receptacles were installed). The flex conduit was also pre-fabricated to length and rolled up in the ceiling space to make the eventual connection to the receptacle after the wall is finished with paint etc. But due to the user requests to move the outlets to the desired locations outlets in many exam rooms needed to be moved. This also meant that the pre-fabricated flex conduit in some instances fell short in length of the new locations and had to be re-installed in the field. The team determined that the reason this happened was that we did not model the architectural finishes with furniture etc. which would have helped the doctors to identify the exact locations of outlets The agreement was that on next projects the team would create a virtual mock-up of all the rooms in the facility to address issues like this which would be easy to accomplish since the models were already being generated for coordination.

The team also encountered a few instances where systems that were modeled interfered with systems that were not modeled. An example of this is the conflict between the supports for exterior Glass fiber reinforced concrete (GFRC) panels with the rain water leaders (Fig. 12). The lessons learned is that even the miscellaneous support steel etc. should be modeled for a completely clash free installation of MEP systems.

FIG. 12: Figure shows the miscellaneous steel supports for the GFRC panels. The virtual 3D model of the supports was not created which resulted in conflicts with Rain water leaders (plumbing drains) in a couple of locations.

5.3 Lessons learned related to the level of details in the model

The architect modelled the Glass Fibre Reinforced Concrete (GFRC) wall panels in excruciating details which included the patterns of brick and the reveals etc but did not model the supports where the panels connected to the steel. For coordination of MEP systems the team needed to have the exact locations of the steel connections to the GFRC panels. This shows that the level of details should be decided with everyone's input and for the specific purpose for which the details will be used.

The plumbing subcontractor needed the exact location of sinks in the casework so as to draw his graded plumbing lines from these sinks. The architect did not model these locations in 3D which resulted in the plumber having to refer back to 2D and interpret the locations before grading his lines in the 3D model.

The general contractor initially did not include the scope of modeling the seismic bracing and miscellaneous steel supports in any of the subcontractors' scope of modeling. Eventually this was modelled by the mechanical contractor. This is needed for the accurate routing of pipes and ducts so as to not intersect with the seismic bracing.

6. CONCLUSION

The Camino MOB experience demonstrates the significant value that application of BIM / VDC tools and processes can bring to the complex process of MEP coordination for technically challenging projects. The paper illustrates the challenges that project teams need to address when using BIM / VDC tools for the MEP coordination process. These challenges include determining how to organize the project team and structure the coordination process to best utilize the VDC tools, how to set up the technical logistics, and how to perform the coordination in a Big Room. The Camino MOB team has been able to reap remarkable benefits by utilizing VDC tools for MEP coordination. Prior research has proposed use of computer-aided tools for the coordination process, but this is one of the first project studies that have measured the real benefits of using VDC tools for MEP coordination.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Camino MOB project team of Sutter Health, Camino Medical Group, DPR Construction, Inc., Hawley Peterson and Snyder Architects, Capitol Engineering Company, The Engineering Enterprise, Southland Industries, JW McClenahan Company, Cupertino Electric, and Northstar Fire Protection for sharing data with the authors for this case study.

8. REFERENCES

Akinci B. Tantisevi K., Ergen E. (2003) Assessment of the capabilities of a commercial 4D CAD system to visualize equipment space requirements on construction sites. Construction Research Congress, Honolulu, HI, 989-995.

Ballard G. (2000) “Lean Project Delivery System.” White Paper 8, Lean Construction Institute.

Barton P.K. (1983). Building services integration. E & FN Spon, London.

Eastman C., Sacks R., Lee, G. (2002). Strategies for realizing the benefits of 3D integrated modeling of buildings in the AEC industry. ISARC 2002. 19th International Symposium on Automation and Robotics in Construction, SP 989, (Washington DC). 2002. 9-14.

Eastman C., Teicholz P., Sacks R., Liston K. (2008). Camino Medical Group Mountain View Medical Office Building Complex in Chapter 9, BIM Case Studies – BIM Handbook – A guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, John Wiley & Sons. 2008. 358-374

Ganah A.A., Bouchlaghem N.M. Anumba C.J. (2005). VISCON: Computer visualization support for constructability. Journal of Information Technology in Construction: Special Issue: From 3D to nD Modelling, Vol 10, 69-83. [Available at www.itcon.org.]

Hanna A., Russell J., Gotzion T., Nordheim E. (1999). Impact of Change Orders on Labor Efficiency for Mechanical Construction. Journal of Construction Engineering and Management, ASCE, May/June 1999. 176-184.

Hanna A., Russell J., Nordheim E., Bruggink M. (1999). Impact of Change Orders on Labor Efficiency for Electrical Construction. Journal of Construction Engineering and Management, ASCE, July/August 1999. 224-232.

Haymaker J. Fischer M. (2001). Challenges and benefits of 4D modelling on the Walt Disney Concert Hall project, Working Paper No. 64, Center for Integrated Facilities Engineering, Stanford University, CA. [Available at www.stanford.edu/group/CIFE/Publications.]

Heesom D., Mahdjoubi L. (2004) Trends of 4D CAD applications for construction planning. Construction Management and Economics, 22(2), 171-182

Kam C., Fischer M., Hänninen R., Karjalainen A., Laitinen J. (2003). The Product Model and Fourth Dimension Project, Journal of Information Technology in Construction, Vol. 8, pp. 137-166. [Available at www.itcon.org.]

Khanzode A., Fischer M., Reed D. (2005). Case Study of The Implementation of The Lean Project Delivery System (LPDS) using Virtual Building Technologies on a Large Healthcare Project, Proceedings of IGLC-13, Sydney, Australia.153-160.

Khanzode A., Fischer M., Reed D. (2007). Challenges and benefits of implementing virtual design and construction technologies for coordination of mechanical, electrical, and plumbing systems on a large healthcare project. CIB 24th W78 Conference Maribor 2007, Bringing ITC knowledge to work, Danijel Reolj (ed.), 205-212.

Koo B., Fischer M. (2000). Feasibility Study of 4D CAD in Commercial Construction. Journal of Construction Engineering and Management, ASCE, 126(4), 251-260.

Korman T.M., Tatum C.B. (2001). Development of a knowledge-based system to improve mechanical, electrical, and plumbing coordination. Technical Report 129, CIFE, Stanford University, CA.

Korman T.M., Fischer, M., Tatum C.B. (2003). Knowledge and Reasoning for MEP Coordination, Journal of Construction Engineering and Management, Volume 129, Issue 6, 627-634.

Levitt R. Kunz J. (2002) "Design your project organizations as engineers design bridges," CIFE Working Paper 73, CIFE, Stanford University, August.

Messner, J.I., Riley, D.R., Moeck, M. (2006). Virtual Facility Prototyping for Sustainable Project Delivery.

Olofsson T., Emborg M. (2004). Feasibility study of field force automation in the Swedish construction sector. ITCon, Vol.9, 2004, 285-295.

Riley D., Diller B., Kerr D. (2005). Effect of delivery system on change order size and frequency in Mechanical construction. Journal of Construction Engineering and Management, ASCE, Vol. 131, September 2005. 953-962.

Songer A.D., Diekmann J., Al-Rasheed K. (1998). The impact of 3D visualization on construction planning, Proceedings of the International Congress on Computing in Civil Engineering, ASCE, Reston, VA.

Staub-French S., Fischer M. (2001). Industrial Case Study of Electronic Design, Cost, and Schedule Integration. Technical Report 122, CIFE, Stanford University, CA.

Staub-French S., Khanzode A. (2007). 3D and 4D modeling for design and construction coordination: issues and lessons learned. ITCon, Vol 12, 2007. 381-407.

Tabesh A. R., Staub-French, S. (2005). Case study of constructability reasoning in MEP Coordination. Proceedings of the Construction Research Congress, ASCE, San Diego, April 5-7, 2005.

Tatum C.B., Korman T.M. (2000). Coordinating building systems: process and knowledge, Journal of Architectural Engineering, 6(4), 116-121.

Tatum C.B., Korman T.M. (1999). MEP Coordination in Building and Industrial Projects, CIFE Working Paper 54, March 1999, CIFE, Stanford University, Stanford, CA.

Thompson J.D., (2003). "Organizations in Action: Social Science Bases of Administrative Theory", Transaction Publishers, republished version of the original 1967 book with preface by Mayer N. Zald and a new introduction by W. Richard Scott published by Transaction Publishers, January 2003.

Whyte J., Bouchlaghem N. Thorpe A., McCaffer R. (2000). From CAD to virtual reality: modelling approaches, data exchange and interactive 3D building design tools. Automation in Construction, Vol. 10, 43-55.

9. APPENDIX I

Guidelines for sharing the .dwg format or the Autodesk CAD file format models on the Camino MOB:

- Use only standard AutoCAD fonts in model space; do not use true type fonts or custom AutoCAD fonts
- For all AutoCAD based models each trade will use the EXTERNAL REFERENCE (Xref) command to bring any drawing needed into the "background"
- Xref's are not to be bound or inserted
- All Xref's are detached prior to transferring drawings to other trades
- Nothing is drawn in paper space
- No trades draw anything on layer zero (0) or Defpoints
- Drawings are purged (AutoCAD purge command) and audited (AutoCAD audit command) prior to file transfer to get rid of any errors or garbage in the drawing file
- Text is on different layers from the graphics so that the text can be turned off without turning off the graphics
- Any thick lines to designate wall fire ratings are on separate layers
- All layers are on and thawed
- All entities are delivered with colors, line types, and line weights set to bylayer