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An Integrated, Virtual Design and
Construction and Lean (IVL)
Method for Coordination of MEP

By

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An Integrated Virtual Design and Construction and Lean (IVL) Method for coordination of MEP Systems

Chapter from PhD Thesis by Atul R. Khanzode

Claimed Contribution:

The objective of this paper is to describe the contribution to knowledge and practice in terms of an Integrated, Virtual Design and Construction (VDC) and Lean (hereafter referred to as IVL) method for the coordination of Mechanical, Plumbing and Electrical (MEP) Systems in the Architecture/Engineering and Construction (AEC) industry. MEP Systems on many of the complex construction projects account for 40-60% of the project value. But the method to coordinate MEP systems is still very ad hoc and organizing project teams to coordinate MEP systems remains one of the most challenging, time consuming and poorly understood aspects of many building projects today. The lack of a consistent, well grounded and repeatable method for MEP coordination results in wasted effort of project team members, lack of metrics to track progress of coordination, suboptimal results due to conflicts in the field and inconsistent performance from one project to another. The IVL method for MEP coordination addresses these challenges and provides a repeatable method that project teams can adopt to produce consistent results for MEP coordination. The method describes:

1. How to create the goals and objectives for the coordination of MEP systems
2. How to organize the team to coordinate MEP systems
3. What metrics to use to track progress during the coordination of MEP systems
4. What technical logistics need to be setup to manage MEP Coordination
5. How to create a schedule for the coordination of MEP systems
6. How to operate, manage against the objectives and doing managerial interventions to track against metrics

The IVL method for MEP coordination is based on case study research of four distinct cases where the author observed MEP coordination. The practical significance of this research is that project teams in AEC industry can organize MEP coordination in a much more consistent manner than before and this research also highlights the aspects of coordination processes in general that are important in AEC industry.

Introduction:

Mechanical, Plumbing, Electrical and Fire Protection (MEP/FP) systems on modern day high tech projects account for about 40 to 60% of the total project cost. The complexity of these systems has increased over the years. At the same time the cost of materials has increased and the availability of skilled labor to install these systems is steadily declining. Owners are demanding projects to be delivered quicker and at lesser cost. Project teams are constantly seeking newer and better methods to address these challenges. One of the biggest areas of improvement is the design and coordination of MEP/FP systems. On many construction projects the coordination is still done using 2D drawings and light tables in what is called as a Sequential Composite Overlay Process (SCOP) (Korman, Fischer and Tatum, 2003). This method of coordination has proven to be inadequate and has led to many conflicts between systems, lack of confidence amongst subcontractors to pre-fabricate, rework in the field and an overall lack of productivity installing these systems in the field. Recently Project teams are exploring the use of Virtual Design and Construction (VDC) (Fischer and Kunz, 2004) tools like 3D-4D and collaborative project delivery approaches like Lean construction (Ballard and Howell, 1997) to reduce the inherent waste in this process and bring a greater efficiency and productivity to the projects. On one of the case study projects which implemented VDC to manage the coordination of MEP/FP systems in Northern California and the results indicate that there are tremendous benefits to applying VDC to coordinate the MEP/FP systems. On this project using the VDC tools for the coordination of the MEP/FP the project team has realized the following benefits (Khazode, Reed and Fischer, 2007):

- virtually zero field conflicts between various systems
- less than 0.2% rework
- productivity improvement of more than 30% for the mechanical contractor
- less than 2 hours per month spent on field coordination issues by the Superintendent for the General Contractor
- Only two field issues related Request for Information
- Zero change orders related to field conflict issues

This suggests that project teams and owners gain to benefit significantly by applying VDC tools (specifically 3D and 4D CAD) and Lean methods to manage the MEP / FP coordination process. In my observation of the four case studies it was clear that even though project teams had the opportunity to use VDC tools and Lean processes for coordination, there was not a single, consistent way to perform and organize MEP coordination. I summarize the observations from the case study in the following section.

Case Study Summary:

In order to understand the impact of the use of Lean Construction Methods and VDC tools for MEP coordination I studied four projects that used a combination of VDC and Lean methods to perform MEP coordination. The case studies are described in more detail in the Case Study chapter of the Thesis. The findings from the Case studies are summarized in this section. The 4 cases I reviewed are as follows:

Case Study	VDC used for MEP Coordination	Lean Methods used for MEP Coordination
Camino Medical Office Building	Yes	Yes
Autodesk 1 Market Project	Yes	No
Stanford Medical Center	No	Yes
PAMF MOB	No	No

Table 1: Table shows the Four Case Study projects and the use of VDC and Lean Methods for the coordination of MEP systems on the four case study projects. Study is result of analysis of each of the possible uses of VDC and Lean and forms a complete multi-factorial prospective study of MEP coordination.

The reason I chose the four cases as described above is because between the four cases and the varied use of VDC methods and Lean Construction for MEP coordination forms a multi-factorial prospective case study pertaining to the domain of my research which is MEP coordination. To be consistent I also chose case studies that belong to the same domain i.e. office building construction. Three of the cases are for healthcare medical office building and one case is for a slightly complex office and customer gallery space.

There are multiple aspects of MEP Coordination that one can study. One of the goals of MEP coordination is to be able to produce an efficient MEP system that can be installed in the most efficient manner, i.e. the best outcome of the MEP coordination is to be able to have the most efficient building process. Efficient building process can be described by the outcomes from the process of manufacturing and installing MEP systems. The measure of how efficient the process is can be obtained by observing:

1. Amount of hours spent by each trade installing the systems and comparing this to the estimated hours
2. The field conflicts between the various systems that had to be resolved.
3. The amount of prefabrication enabled by the process
4. The actual prefabrication by each trade contractor
5. The productivity of crew installing the systems
6. The amount of time teams spent on rework to fix problems in the system
7. The number of unnecessary or avoidable change orders

The metrics that are traditionally tracked by most General Contractors and MEP subcontractors to track the efficiency of the building process are as follows:

- Schedule Compliance: This metric compares the estimated schedule to actual schedule completion
- Change Orders: This is a measure of how efficiently coordination was done, the less the change orders the better was the outcome of MEP coordination

- RFI or Requests for Information during construction phase: RFIs are used to clarify un-resolved issues. The lesser the number of RFIs during construction the better the outcome of MEP coordination
- Rework during construction: Lesser the rework during construction better the coordination is
- Field Conflicts during installation: The lesser the field conflicts the better it is since this means coordination has resolved all the conflicts
- More Prefabrication: More prefabrication leads to systems being built offsite in a controlled factory environment and requires less skilled craft people on site so a coordination which enables more prefabrication is better.
- Hours spent by Superintendents in the Field to resolve conflicts between trade contractors: The lesser the number of hours a superintendent has to spend in the field to resolve installation conflicts between trade subcontractors the better the outcome of MEP coordination is.

In the four case study projects I documented the how the project teams performed the MEP coordination process and managed it. This included the controllable factors that teams used to perform MEP coordination. I also studied the way the project teams tracked performance during MEP coordination and the outcomes on the project as a result of what was coordinated. The outcomes were traditional quantitative metrics such as change orders and Requests for Information but also qualitative metrics such as the amount of time superintendents and foremen spent on site to resolve field conflicts. I also interviewed multiple team members that directly worked on these projects. The results of my observations are described in detail in the section below.

Impact of the use of VDC and Lean Methods on Prefabrication of MEP Systems

Based on the interviews of the jobsite teams on the four case study project I identified the gross % of prefabrication on each of the Case study project for the Mechanical, Electrical and Plumbing Systems. The % of Prefabrication is mapped against the use of VDC and Lean methods for the 4 case study projects in Figure 1.

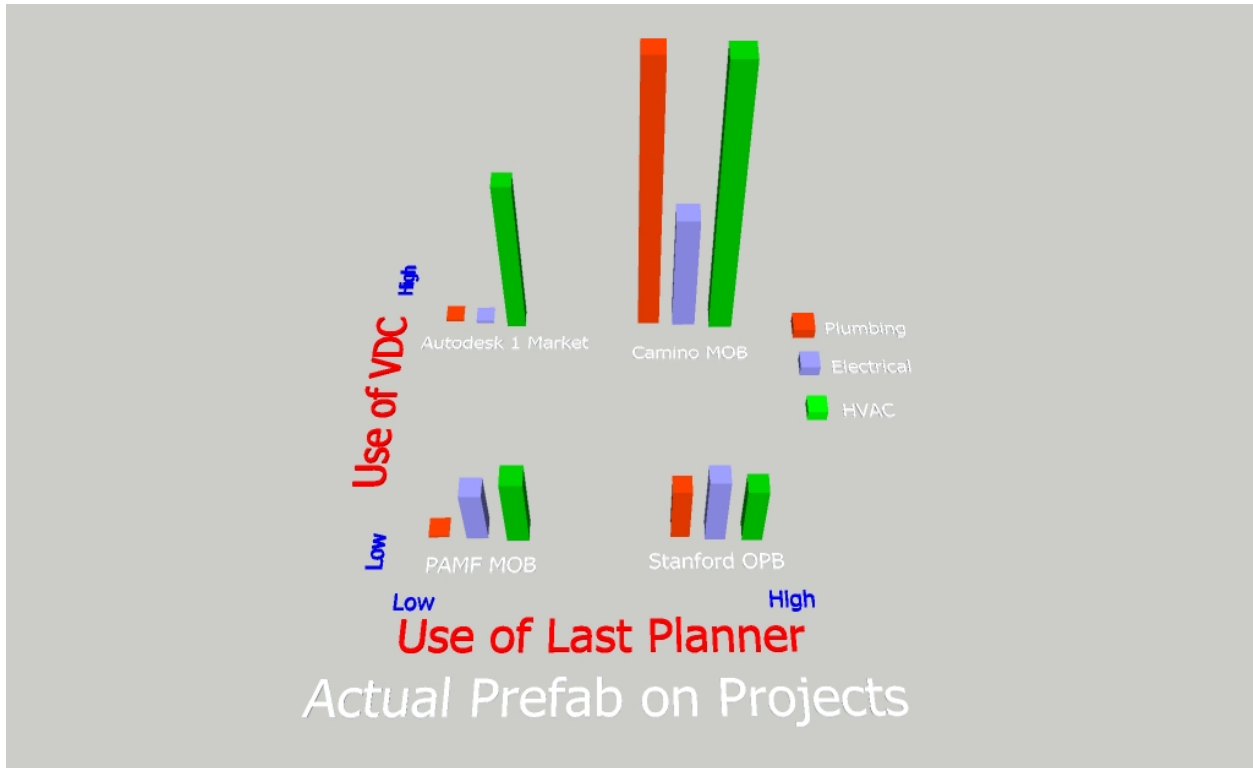


Figure 1: Picture shows the Actual % of Prefabrication (for Mechanical, Electrical and Plumbing) on 4 case study projects. The data suggests that when VDC methods are used for coordination the % of Actual prefabrication is higher for Mechanical systems. The data also seems to indicate the greater the use of VDC and Lean methods greater the % of Actual Prefabrication for MEP systems.

Use of VDC seems to create more opportunities for Prefabrication. Looking deeper into the project case studies and through Interview of Project Superintendents and Foremen on the case study projects it was also evident that the Actual Prefabrication also depends upon other factors such as jobsite logistics issues such as access.

Number and Timing of Requests for Information on Case Study projects:

I also reviewed what the actual number of RFIs related to conflicts or potential conflicts between the various MEP systems were on the case study projects and also when were these RFIs generated and answered during the project. This data is summarized in Figure 2.

Number and Timing of RFI related to Conflicts on 4 Projects









Projects	Amount	VDC Used	Lean Used	Design Coordination to Shop Drawing Phase	Construction Phase
Autodesk 1 Market	25KSF \$12M			15 RFIs documented and incorporated in Virtual Model	0 RFIs
PAMF MOB	75KSF \$30M			RFIs not identified	22 RFIs
Stanford OPB	200KSF \$70M			RFIs not identified	30 RFIs
Camino MOB	250KSF \$97M			No formal RFI process. Coordination in BIG ROOM. Questions incorporated in model	2 RFIs

Figure 2: Picture shows the number and timing of Request for Information (RFIs) on 4 case study projects. The data suggests that the use of VDC early in the Design allows teams to identify more conflict related issues versus when VDC is not used for the MEP coordination process. The data also shows that conflict related RFIs are not completely resolved when VDC is not used.

The data suggests that the use of VDC early in the Design allows teams to identify more conflict related issues versus when VDC is not used for the MEP coordination process. The data also shows that conflict related RFIs are not completely resolved when VDC is not used.

Conflicts between MEP systems in the Field:

Figure 3 shows the actual conflicts that the project teams encountered during the installation of MEP systems. These conflicts were related to the fact that the systems occupied same physical space and were not related to the installation method. This means that the systems were not adequately coordinated to resolve the geometric clashes during the coordination of MEP systems.

The data suggests that when VDC is used for MEP coordination teams are able to resolve conflict related issues but when VDC is not used the number of actual conflicts between systems goes up. The data also suggests that impact of Lean methods without VDC is marginal in resolving conflicts between MEP systems.

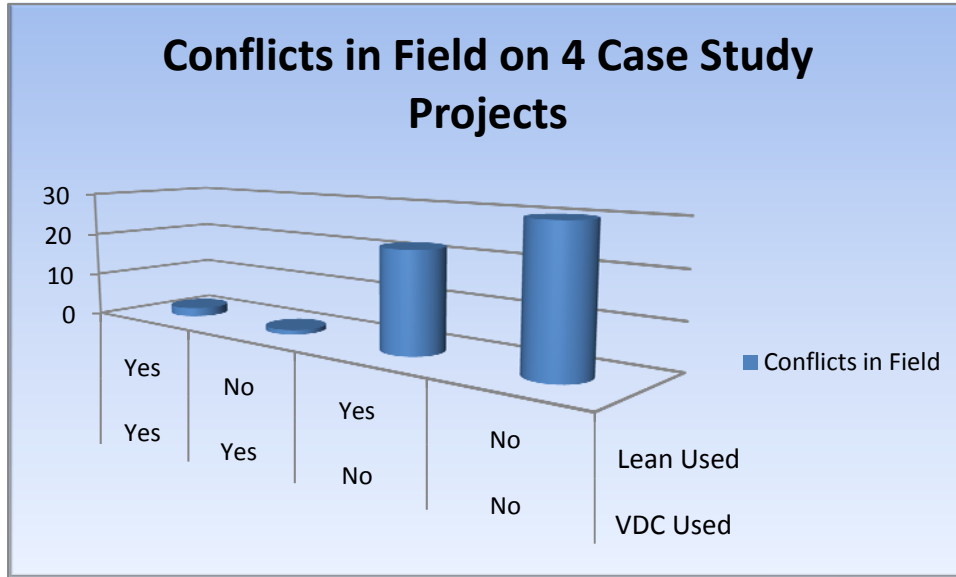


Figure 3: Picture shows the number of Field conflicts between the various Mechanical, Plumbing and Electrical (MEP) systems for 4 case study projects that used a combination of VDC and Lean methods during the MEP coordination process. The data suggests that the use of VDC results in the least field conflicts between MEP systems.

Rework during the MEP Installation process:

Figure 4 shows the % of rework during the installation of MEP systems on the 4 case study projects. The data suggests that when VDC is used for MEP coordination there is less rework during the installation of MEP systems compared to when VDC is not used. The data also suggests that use of Lean methods can reduce rework but the non use of VDC is much more significant in terms of amount of rework.

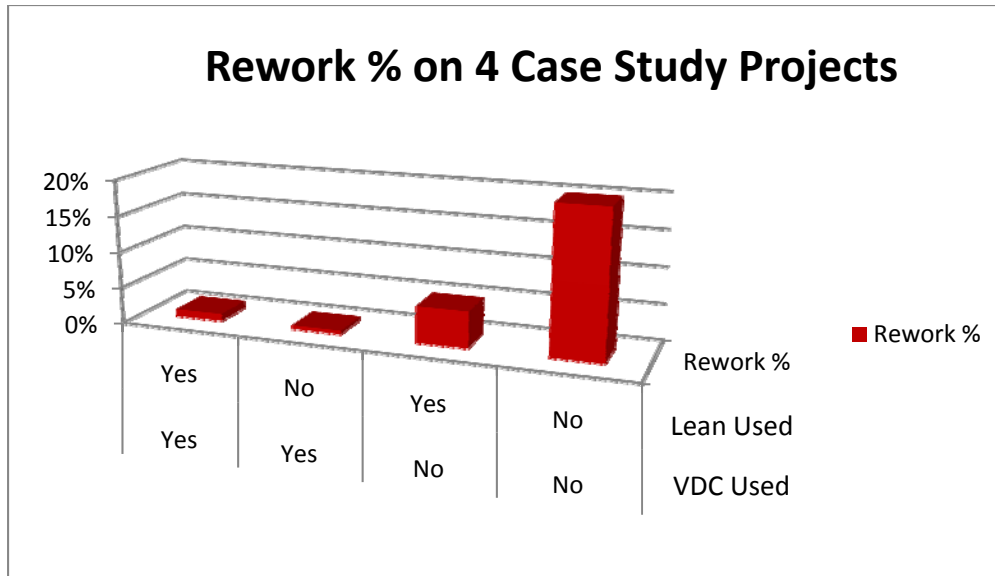


Figure 4: Picture shows the Percentage of Rework that had to be done for MEP systems on 4 case study projects that used a combination of VDC and Lean methods during the MEP coordination process. The evidence suggests that the use of VDC results in the least rework also shows that using Lean techniques alone teams can reduce rework but not completely eliminate rework.

Time spent (in minutes per day) by Superintendents in the Field Resolving conflicts between MEP Systems:

Figure 5 shows the time that the Superintendents spent (in minutes per day) in the field resolving conflict related issues between trade subcontractors during the MEP installation process. The data suggests that when VDC methods are used Superintendents spend less time in the field dealing with conflict related issues compared to when VDC is not used.

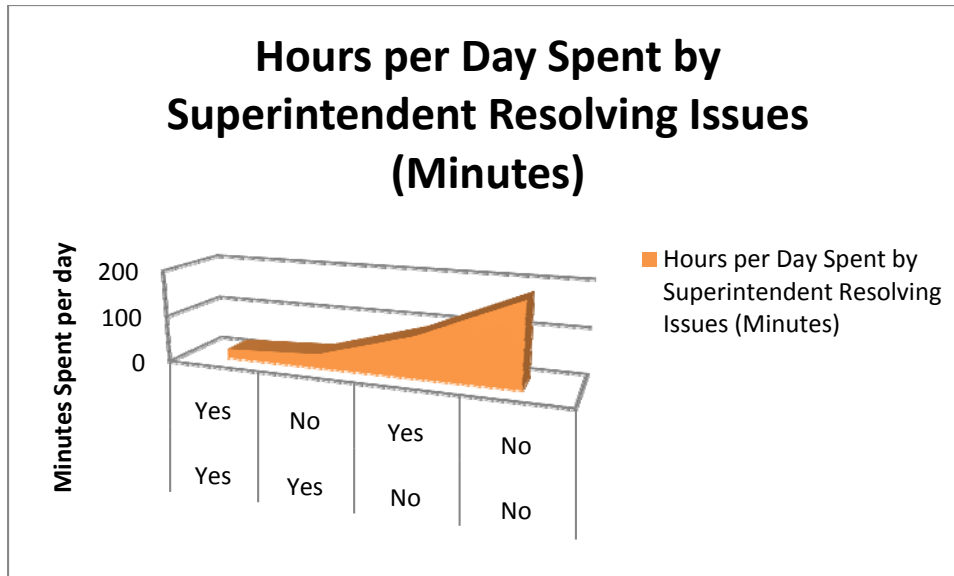


Figure 5: Picture shows the amount of time (in minutes) spent by the General Superintendent for the General Contractor in the field playing referee and resolving conflicts between the MEP trades on 4 case study projects that used a combination of VDC and Lean methods during the MEP coordination process. The evidence suggests that the use of VDC results in the least amount of time resolving issues between trades in the field and also suggests that the use of Lean techniques can result in better time spent in the field although the impact of VDC seems more pronounced.

Inferences from Case Studies:

What the evidence from the case studies suggests:

1. Use of VDC seems to be the key for MEP coordination process. i.e. when VDC is used the outcome of coordination is better (more prefabrication, lesser RFIs during construction, virtually no conflicts during construction, substantially less rework during construction, lesser the number of conflict related change orders and less the amount of time spent by superintendents to resolve trade conflicts during construction) but when VDC is not used the outcomes of MEP coordination process get negatively impacted (more conflicts, more rework, more and later RFIs, lesser prefabrication, more number of conflict related change orders and more time spent by superintendents resolving the issues between trades in the field during construction). Upon further studying the use of VDC on these four case study projects it was also clear than when VDC was used it was used by a cross-disciplinary team of designers, GC and subcontractors and the team identified the specific trade input during the use of VDC as one of the key benefits of using VDC for MEP coordination. This observation is critical since this substantiates the claims of other researchers in the industry who have studied the benefits of early involvement of specialty contractors on the project outcomes (Liker et.al., 1996)
2. Early involvement of subs seems to be the key in MEP coordination process. On the two case study projects when the subs were involved in the coordination process earlier (during

schematic design) the outcome of MEP coordination was better. This also confirms the benefits of early involvement by specialty trade contractors during the design process as observed by others in the industry. (Gil et. al., 2000)

3. Use of VDC can lead to more prefabrication and schedule acceleration due to parallel offsite work. Comparing the actual prefabrication that happened on the Camino MOB project as well as discussing the prefabrication that was enabled through the coordination process with the trade foremen it is clear that use of VDC is a necessary condition for more prefabrication and a way to accelerate onsite installation schedule since prefabrication activities can be undertaken at offsite facilities in parallel. The foremen also acknowledged that the decision to prefabrication also depends heavily on the jobsite logistics. For example although the team at Autodesk 1 Market felt that they could prefabricate quite a lot more the limitation of bringing the materials in to the site meant that the prefabrication was less. On the flip side when VDC was not used the foremen did not feel comfortable with getting prefabricated materials due to lack of certainty that it will fit in the field although the jobsite logistics would have allowed for more prefabrication.
4. Use of Lean seems to impact the most in terms of avoiding rework during construction process. Compared to all other outcomes of coordination rework seems to be most impacted through the use of Lean Last Planner method during coordination.
5. Use of Lean methods, more specifically the Pull Planning and Last Planner system adds more reliability to the coordination of MEP systems. The Pull planning was considered important by the project teams to align the rate at which coordination was done as well as doing coordination based on the way the construction process was structured. Specifically the work breakdown structure for coordination needs to match that of construction process for the process to be most efficient. The use of Last Planner method also added more reliability to the team commitments and when this was not done the commitment reliability was considered lower.
6. When the team members who performed coordination using VDC tools as compared to light table coordination were also the ones who were involved in construction the outcome of MEP coordination was better. This indicates that the use of VDC tools allows the team members a better simulation environment to try and test solutions and also enhances their knowledge of how the systems can be assembled in the field. This is an important point and confirms observations made by others about the notion of practice using simulation tools leads to better prototypes and better outcomes (Schrage, Michael, 2000).
7. Collocation seems to have an impact on the coordination process due to the early resolution of issues. Out of the 4 case study projects one team had a fully collocated coordination, one other team had collocated partially and two other teams had weekly work sessions for coordination. The outcome of the collocated team in terms of MEP coordination was the best. On further observation it was also clear that having the multi-disciplinary team collocate was what was

important. This highlights the importance of collocation and also confirms the observations made by others about collocated teams (Chachere et. al., 2004 and Liker et. al. 2000). A more recent observation of collocated teams and outcomes to coordinate drywall construction in the construction coordination process also points to the benefits of collocating teams in Big Rooms to resolve coordination issues (Mikati et.al. 2007).

8. Most of the team members I interviewed agreed with the outcome metrics I have described above but only a few explicitly tracked this during the coordination process. They also agreed that if one has to look at the efficiency of construction then using some of these metrics to track performance would be beneficial. Review of the four cases also showed that the tracking and understanding of these metrics was also different amongst the different project participants.
9. Team members that I interviewed who participated in the MEP coordination process also acknowledged that the MEP coordination process was different from project to project and that it varied depending on the project team, general contractor they worked with and that there was a lack of consistency between the various projects they had previously worked on and also acknowledged that they sometimes felt helpless to influence the direction either because of the role they were slotted for did not allow it or they did not consider it being part of their job but someone else's job, mostly the General Contractors job. They also acknowledged that many times the coordination process began with the sole aim of resolving the conflicts to the greatest extent possible but the projects did not have a strategic goal or specific objectives in terms of change orders, prefabrication etc. which they acknowledged were important factors that should be looked at to measure the outcome of coordination.

The *I*ntegrated, *V*irtual Design and Construction and *L*ean (*IVL*) MEP Coordination Method:

Based on the inferences above from the four cases it is clear that a consistent, repeatable and well understood method for MEP coordination that is based on tracking metrics during the coordination, involves multi-disciplinary team in coordination and uses VDC tools and Lean methods to perform coordination is required if the industry has to see a consistent outcome from the MEP coordination phase of the project.

To address the challenges found in the test cases the specific components of the IVL method are as follows:

1. Strategic goals and specific objectives for the coordination of MEP systems
2. A multi-disciplinary team to coordinate MEP systems
3. Specific performance metrics to track progress during the coordination of MEP systems and outcome metrics to measure outcomes
4. Technical Logistics to manage MEP coordination

5. Pull Schedule for the coordination of MEP systems
6. Operating and managing MEP coordination against the objectives, making adjustments and measuring outcomes and results

I propose the Integrated Virtual Design and Construction and Lean (IVL) method for coordination of MEP systems. The IVL Method is illustrated in the Figure 6.

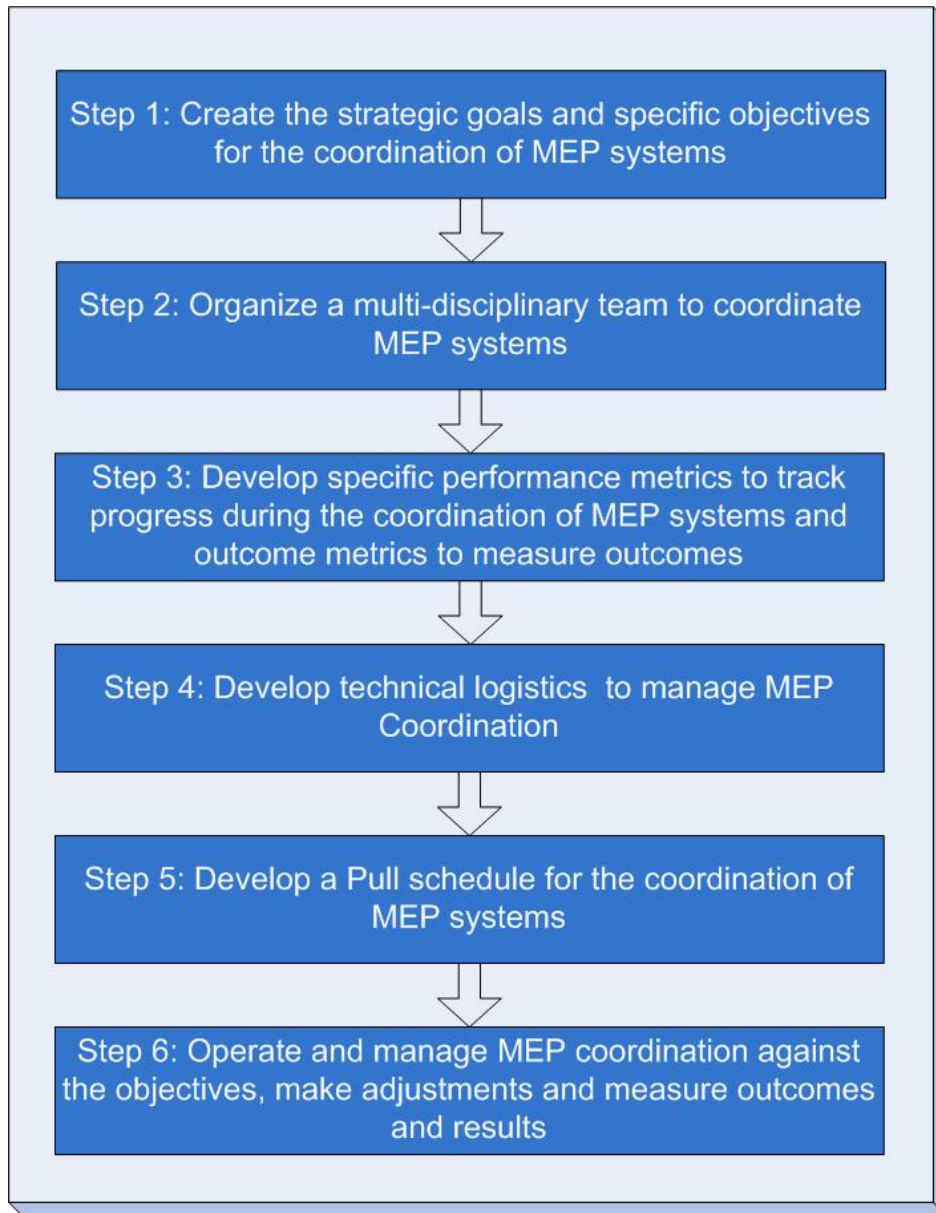


Figure 6: Figure illustrates the Step by Step Integrated Virtual Design and Construction and Lean (IVL) Method MEP Coordination Method starting in the clockwise direction in the Top right hand corner of the Mind Map. Each of the steps in described in more detail in this section.

Step 1: Create Strategic Goals and Specific Objectives for the coordination of MEP systems.

The team needs to identify strategic objectives for the coordination process. The strategic objectives play the role of setting the overall vision for developing specific goals, objectives and metrics for the MEP coordination on the project. Strategic objectives can be as broad as no field conflicts, maximize prefabrication but can involve organization factors such as time to answer questions (latency) etc. The doers should participate in developing these strategic goals and specific objectives based on these goals.

Step 2: Organize Multi-disciplinary Team to coordinate MEP systems.

This involves organizing the team of designers, general contractor and trade subcontractors that will eventually perform coordination. The team members need to be the doers who will play a specific role in the coordination process, should be available for the duration of the project and should be involved continuously in the process from conceptual / schematic design all the way to finish of construction.

Under this step the specific roles of Owner, Designers, General Contractor and Specialty MEP Trade Subcontractors should be explicitly identified.

An example is given below:

Role of the General Contractor

The General Contractor (GC) enables the VDC process by acting as facilitator rather than author of the drawings. The GC enables and coordinates 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 GC's role in initial modeling and coordination is much the same as on the project as a whole: developing a workable pull schedule for coordination together with the design team and subcontractors to support the construction schedule. Once the schedule is established, the GC's Project Engineer assigned to MEP coordination works together with the detailers to achieve sign-off milestones using the Last Planner System™. (Ballard, 1994)

Role of the Specialty Contractors

The specialty contractors are responsible to model their portion of work using VDC tools. Typically the HVAC Contractor takes a lead role in the coordination process. The HVAC Contractor models 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 or Design-Build or Integrated Project Delivery contracting methods. In these 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.

Step 3: Develop specific performance metrics to track progress during the coordination of MEP systems and outcome metrics to measure outcomes

Based on the observation from the 4 case studies and the inference from case studies the following metrics should be tracked by the teams to manage the performance of MEP coordination.

Metric	How Frequently	Who Tracks the metric	Players Collaborating on Metric
Planned Percent Complete	Weekly	General Contractor	Owner, Designers, Subs
Pull Schedule Milestone Compliance	At planned Pull schedule milestone date - Review weekly	General Contractor	Owner, Designers, Subs
Clashes Identified to Resolved Ratio	Weekly	General Contractor	Owners, Designers, Subs
Signoff date for coordination area	At the planned coordination signoff date - Review Weekly	General Contractor	Designers, Subs
% Prefab Enabled	After Signoff of each area	GC / MEP Subs	Subs, GC
Team participation	Weekly	All Team members	Owners, Designers, Subs / GC
Latency	Daily	All Team members (Informal)	Designers, Subs, GC
Cost / Production Estimate at beginning and end of coordination	At end of signoff for an area	All Team members	

Table 2: Table shows the Performance Metrics for VDC Lean Method for MEP coordination.

These metrics should be:

1. Explicit and Transparent to the whole team and should be posted prominently where everyone can see them being tracked on the project
2. Used to make changes in the behavior of team members. For example if team participation is low then the metric should be used to improve this.

In addition to the Performance metrics the following metrics should be tracked to measure the outcome of coordination process.

Metric	How Frequently	Who Tracks the Metric	Players Collaborating on Metric
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% Actual Prefab	Weekly	MEP Trade Foremen	GC / Subs
Productivity compared to Estimate	Monthly	MEP Trade PM's and GC	GC / Subs
Actual RFIs related to field issues	Weekly	General Contractor	GC / Subs / Desginers
Change orders related to field issues	Weekly	General Contractor	GC / Subs
Hours spent in field to resolve issues	Daily	General Contractor	GC / Subs Foremen
Planned versus Actual Deliveries	Daily	General Contractor, MEP Trade Foremen	GC / Subs
Planned Percent complete	Weekly	General Contractor	Subs / Designers / Owners
Milestones met	Weekly	General Contractor	All

Table 3: Table shows the Outcome Metrics that Project Teams should track under the VDC Lean MEP Coordination Method.

Step 4: Develop Technical Logistics to manage MEP Coordination.

Technical Logistics can be broken down into two things:

1. Modeling applications that support the goals for coordination and work with the fabrication process for the specific trade contractors
2. Technical Infrastructure necessary to create the same version of reality in terms of architectural, structural, mechanical, electrical, plumbing and fire protection models.

The issue of Technical Logistics should be answered before any coordination begins. The issues team members should specifically address should be:

1. Resolving Interoperability between software applications to be used by various team members during coordination
2. Developing criteria for details to be included in the model to support identified Prefabrication objectives.
3. Agreeing on the specific process mechanisms to merge the models and create a combined MEP model
4. Agreeing on the collaboration system and process for model collaboration

The outcome teams should thrive for is that the various team members should:

- See the same version of model reality
- Models should enable fabrication and also the approval of permit documents

An example of Technical Logistics is provided below:

The coordination of MEP / FP systems using VDC tools requires that project teams plan to create 3D models for:

- Architectural elements like interior walls, ceilings
- Structural elements like the main structural framing, slabs and foundations
- Mechanical systems like duct work etc.
- Plumbing systems like the gravity lines, 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 or other depending on the project

A summary of the various models involved in the MEP coordination process is described below followed by a table that documents what benefits are possible for the corresponding level of details in a particular model.

Architectural Model

Architectural model forms the basis of design and is used by the team members as a reference point for their own systems. Ideally the architect should design in 3D, rather than modeling 2D design drawings in 3D. If the 3D model is created from the 2D design documents, it is critical that it be kept up to date, i.e., that it reflect changes in design.

Wall thickness and height, hard ceilings and soffits, and suspended acoustical ceilings, casework with correct fixture locations must be accurately modeled because these are necessary for effective coordination of MEP/FP systems. On the Camino Medical Office Building (MOB) project the architect modeled the external wall panels, internal walls, doors, and the parking garage in 3D (figure 8). Modeling these systems in 3D is a must as it allows the other team members to accurately locate their own systems. For example the interior wall and ceiling model allows the HVAC subcontractor to locate the diffusers in the rooms and allows the electrical contractor to locate fixtures in the room accurately.

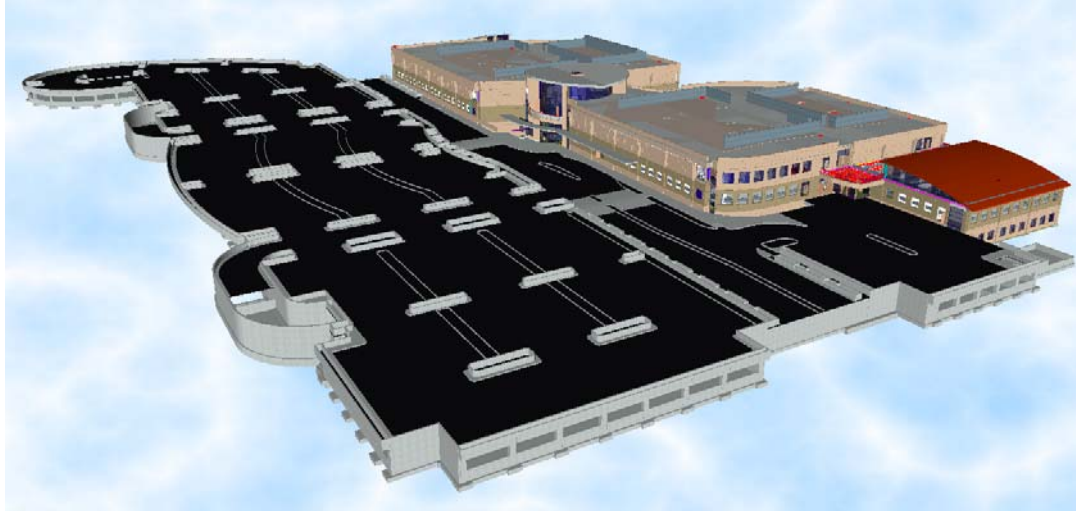


Figure 8: Figure shows an isometric view of the Camino Medical Office Building (MOB) project. The snapshot shows a three story MOB and a two story parking structure. This 3D formed the basis of the MEP / FP coordination for the Camino MOB project.

Structural Model

An accurate 3D model of the foundation system and vertical and horizontal structural steel framing is also a must for the MEP / FP contractors. If it is a steel framed building the model should also include some of the connections like gusset plates and brace frame connections. The structural model should also include the miscellaneous metal supports and connection points to external building elements like GFRG panels. All these details play a very crucial role in the modeling of MEP / FP systems. For example the underground plumbing lines and electrical conduits are located in reference to the foundations; the seismic bracing for the ductwork and other systems is located in reference to the structural elements like slabs and steel beam and columns. Figure 9 shows a structural steel and foundation model of the Camino MOB that was created by the structural designer for the project.

As with the architectural 3D model, the structural model must accurately reflect design changes at all times because detailing of the MEP / FP systems will be done in reference to the structural steel framing.

If the design and coordination of MEP / FP systems begins before a steel fabricator is on board then the steel model from the structural designer should be used as a starting point for the modeling of MEP / FP systems. Ideally the systems should also be checked against the fabrication level structural 3D model. The General Contractor should request that the structural steel fabricator include a detailed 3D fabrication model in their price. The steel fabricator must agree to make this model available to the detailing team just as soon as it has been reviewed and approved for fabrication. This fabrication model will show all connections and be much closer to what will be installed in the field than the Structural Engineer's model. The steel fabrication model should be imported into the clash detection software that the teams are using so that clash detection can be made against it before MEP fabrication commences.

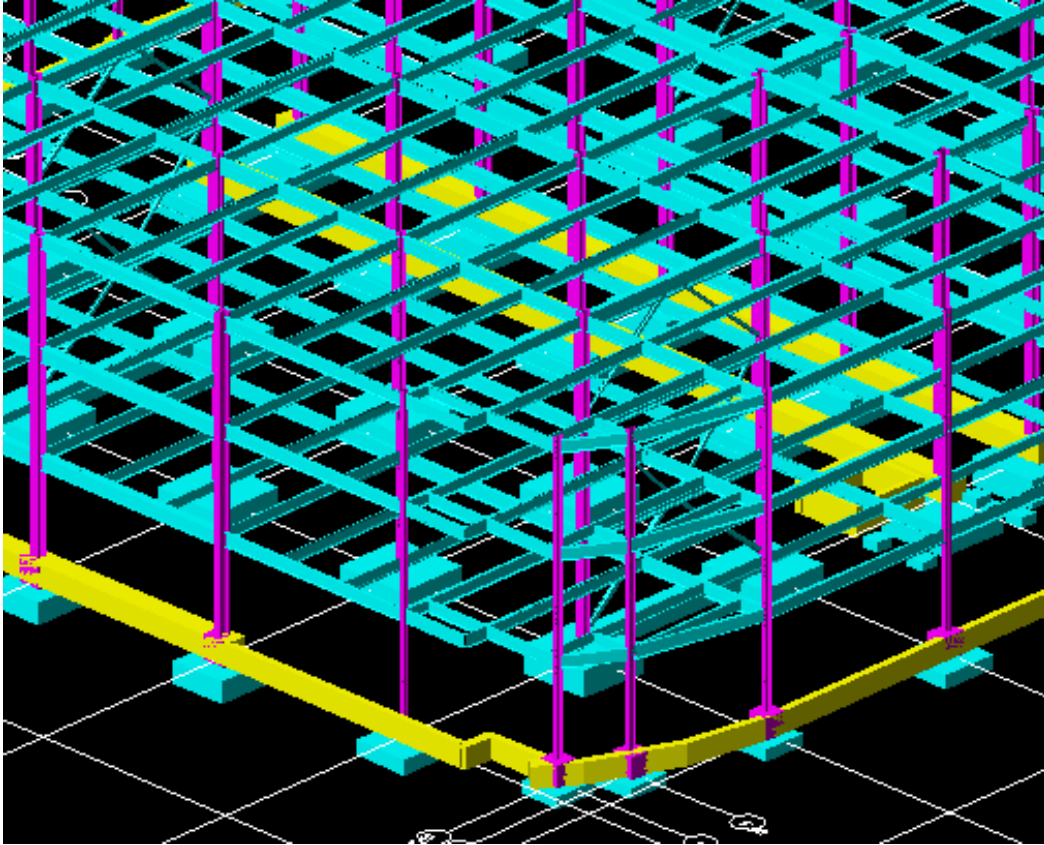


Figure9: Figure shows a screenshot of the structural 3D model for the Camino MOB. The screenshot shows the beams, columns, brace frame connections and foundation elements like grade beams & spread footings for the Camino MOB. This model formed the basis of the underground and the above ceiling MEP / FP coordination for the Camino MOB project.

Mechanical Model

One of the main goals of the mechanical contractor is to be able to use their model for the pre-fabrication of duct and piping assemblies and also use it to plan activities like installing inserts. Currently major mechanical subcontractors already have the capability to produce a 3D model of their systems but are hampered in their prefabrication efforts as they do not have the confidence that their systems will be clash free in the field because other trades only produce their designs in 2D. In a VDC enabled 3D MEP / FP coordination process all the subcontractors need to produce their designs as 3D models. This allows the mechanical contractor to have more confidence that the assemblies will fit as they have coordinated with other trades and their 3D models. The mechanical model consists of the HVAC duct, the connections between ducts, hangers and inserts, seismic supports, diffusers, VAV boxes, Fire Smoke Dampers (FSD's), shafts, duct and pipe insulation and the heating hot water piping. The duct and piping models are then used for prefabrication. The hangers, inserts and seismic support model are used to install inserts and hangers. These 3D models also allow other trades to coordinate effectively with the mechanical systems. For example figure 10 shows a snapshot from the mechanical model of the Camino

MOB project and shows the medium pressure duct, low pressure duct, the hangers and inserts and the heating hot water piping.

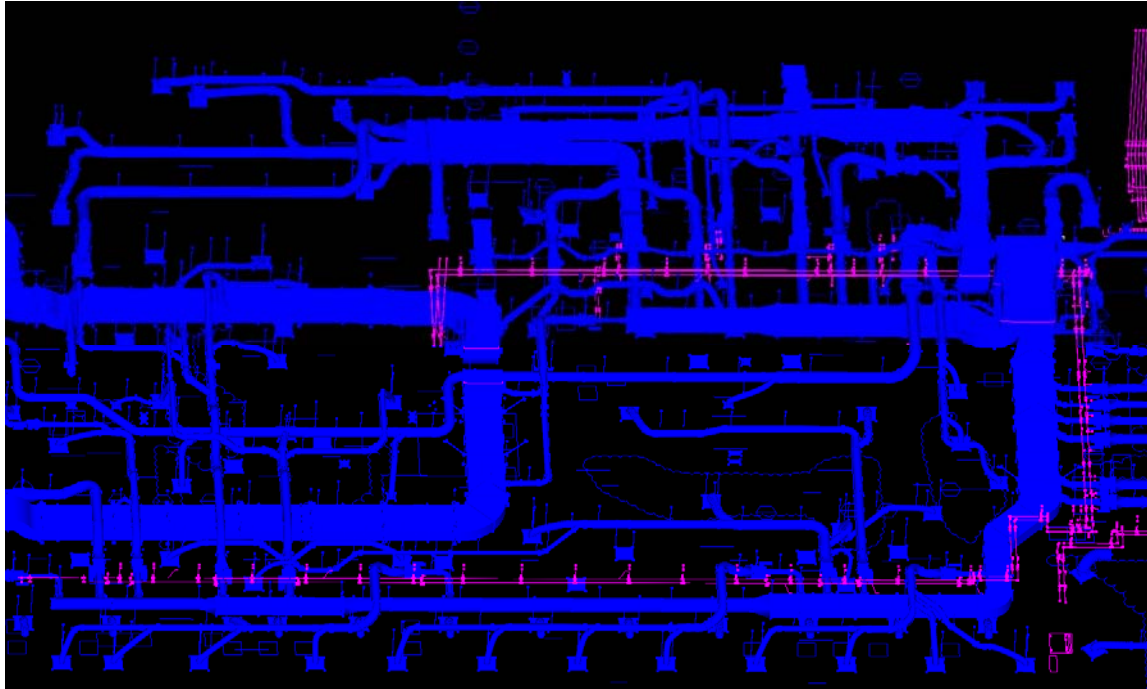


Figure 10: Figure shows a snapshot of the mechanical system (HVAC duct, VAV boxes and Heating hot water pipe) of the first floor SE quadrant of the Camino MOB project. The medium and low pressure duct (shown in blue) and the heating hot water piping (shown in purple) allows other trades to determine the location of the mechanical systems in 3D and use it to route and coordinate their systems.

Electrical Model

On most projects the electrical systems typically do not occupy a lot of above ceiling space and also have some flexibility in terms of how the routing due to the use of flexible cable and wiring. Although this can be an argument for not creating a 3D model of electrical systems it should be understood that electrical subcontractors do use rigid conduits, cable trays, junction boxes, panels etc that do need to be coordinated with other systems. To enable this the electrical contractor should model the branch and feeder conduits, all underground conduits, junction boxes, all lighting, all lighting supports for specialty lighting, all the cable trays and other supports, bundles of cables or wiring and the outlets. This allows the team to coordinate with the electrical systems and also for the electrical contractor to pre-fabricate and pre-bend most of the conduits that need to be bent and also allows them to pre-cut cables and wires to length required. It also allows them to create assemblies in the shop rather than the field. For example figure 11 shows a screenshot of the electrical systems for the Camino MOB and shows the lighting fixtures, conduits and cable trays modeled in 3D

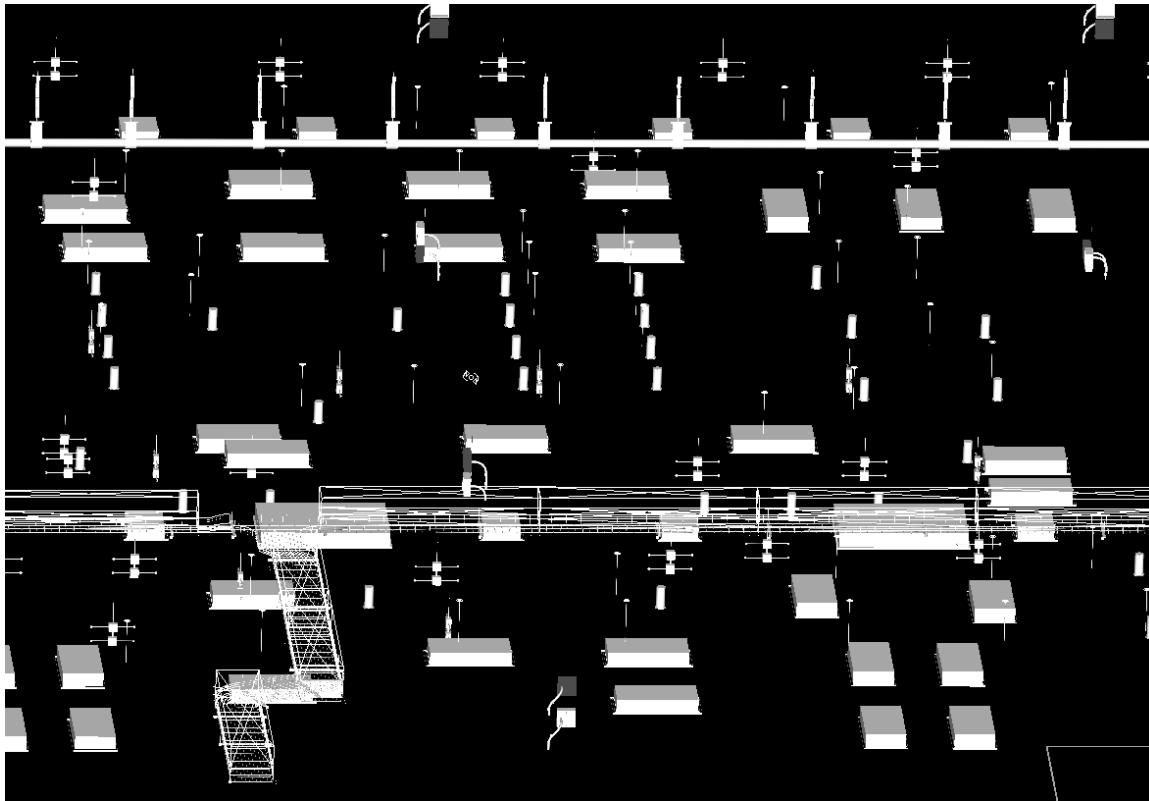


Figure 11: Figure shows a snapshot of the electrical model for the first floor SE quadrant of the Camino MOB project. The snapshot shows a 3D view of all the lighting fixtures, junction boxes, cable trays and major conduit runs for this quadrant on the Camino MOB project.

Plumbing Model

There are two major plumbing systems on most construction projects. Gravity based systems to carry the wastewater and pressure based systems to carry hot and cold water. In addition specialty systems like medical gases in hospitals are also part of the plumbing system. The challenge with the gravity systems is that the systems should satisfy the slope requirements for the wastewater to flow from one end to another. This requires the plumbing contractor to have relatively uninterrupted sloped gravity lines and is a major challenge in the coordination effort. As with the mechanical contractor, the plumbing contractor's objectives are also to pre-fabricate the plumbing assemblies and determine the location of inserts and hangers using the 3D model. What this means is plumbing systems on most major projects contractor should model all their plumbing fixtures, graded cast iron pipe lines, underground storm and sewer pipes, all major waste and vent lines, cold and hot water piping, seismic details, all boiler and other equipment and specialty piping (like medical gas piping) and specialty equipment. This allows them to pre-fabricate their materials in the shop environment. For example figure 12 shows a screenshot of the 3D model with the plumbing gravity lines, fixtures, hot and cold water pipes for the first floor SE quadrant of the Camino MOB project.

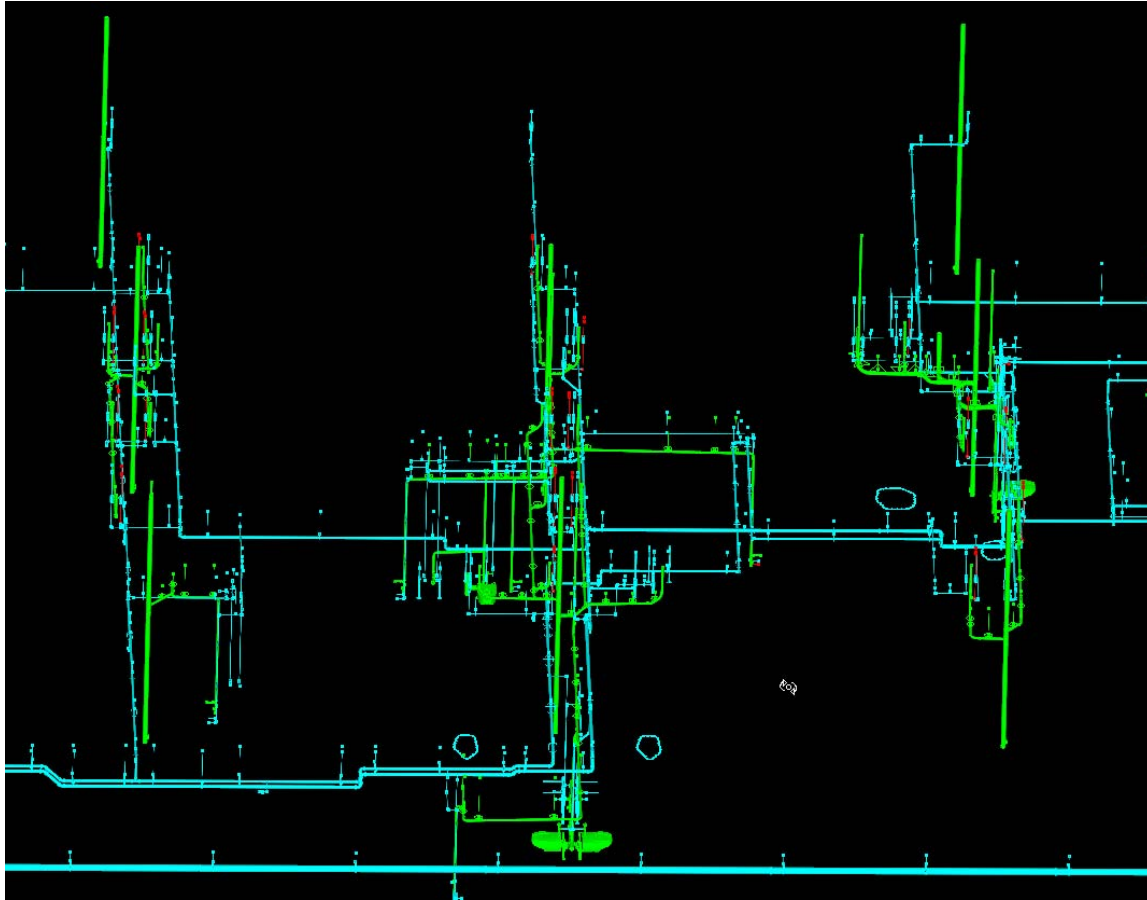


Figure 12: Figure shows a snapshot of the plumbing model of the first floor SE quadrant of the Camino MOB. The snapshot shows the waste and vents and the plumbing fixture locations (in green), the cold water supply (in blue) and hot water lines (in red).

Sprinkler Model

The fire protection contractor should model the mains and branches, the drop pipes and the exact location of drops in the ceiling. This allows them to lay out the mains and branches, prefabricate and also install inserts before the deck is poured. For example the figure 13 shows a snapshot of the 3D sprinkler model for one of the quadrants of the Camino MOB and shows the mains, branches and sprinkler drops.

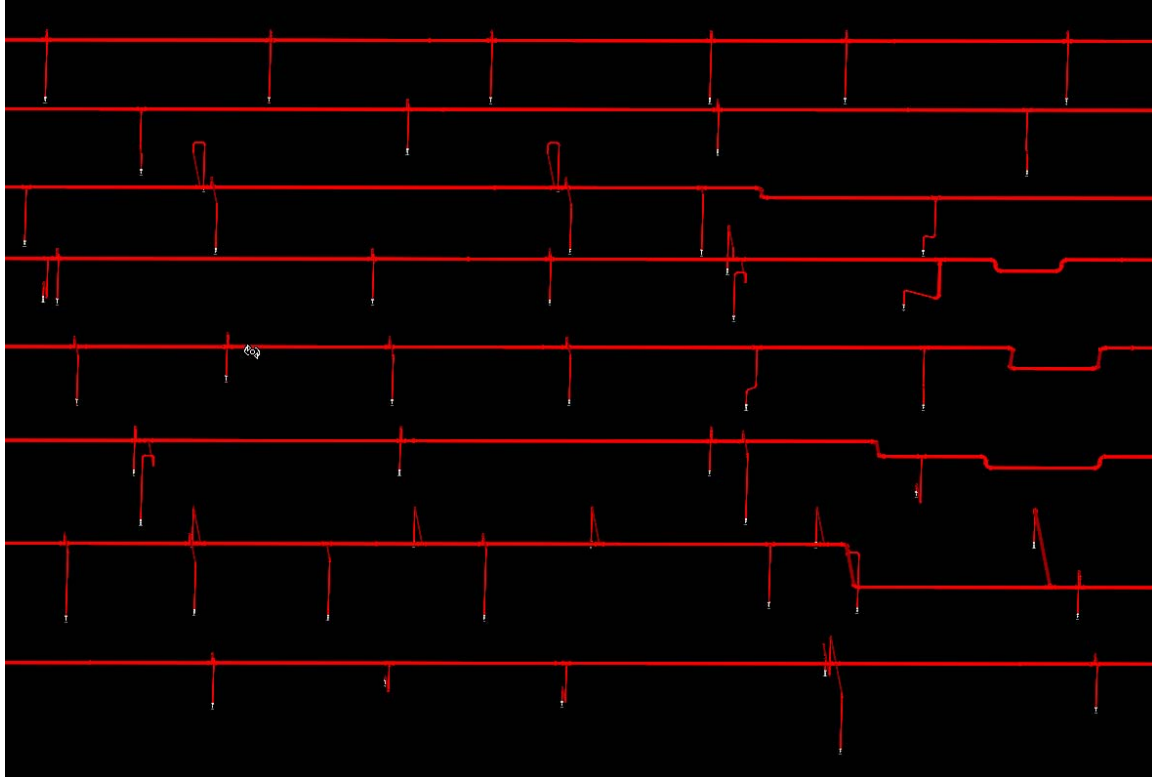


Figure 13: Figure shows a snapshot of the 3D sprinkler model of the first floor SE quadrant of the Camino MOB. The screenshot shows the mains and branches and the sprinkler drops for the first floor quadrant on the Camino MOB.

Level of details in the Architectural, Structural and the MEP / FP models and potential benefits

One of the key questions when applying VDC methodologies to the 3D MEP / FP coordination process is what level of detail should be included in the model and what benefits a team can get out of it. In the following table we summarize this information:

Model	Level of Detail	Benefit in MEP Coordination Process
Architectural Model	Wall thickness and height	Required for routing main utilities, locating VAV boxes, identifying priority wall framing, wall penetrations, fire stopping
	Hard ceilings and soffits	Required for identifying HVAC diffuser locations, electrical fixture locations, routing of utilities
	Suspended acoustical ceilings	Required for identifying HVAC diffuser locations, electrical fixture locations, routing of utilities

	Casework with correct fixture locations	Useful for identifying the location of plumbing utilities rough-in in the walls
	Exterior wall / storefront	Useful for identifying the locations of rain water leaders
	Shafts, Wall chases	Required for identifying the correct locations of plumbing vents, HVAC shafts
Structural Model	Foundations, grade beams	Required for coordination of underground utilities like electrical, plumbing
	Beams and Columns	Required for coordinating above ceiling MEP / FP utilities
	Braces and gusset plates	Required for coordination the routing of MEP / FP piping
	Miscellaneous support steel like exam light supports for medical facilities or Unistrut etc.	Required for the routing of MEP / FP utilities correctly
	External wall framing connections (like connection between steel and GFRC panels)	Required to coordinate the plumbing rain water leaders
Mechanical Model	Medium pressure duct	Required for coordination and routing of other trades as well as pre-fabrication
	Low pressure duct	Required for coordination and routing of other trades as well as pre-fabrication
	Shaft locations	Required for coordination and routing of other trades and for locating smoke dampers etc.
	VAV boxes	Required for pre-fabrication purposes, coordination with HVAC heating hot water piping
	Fire Smoke Dampers	Useful for coordination, especially if walls are also provided in the model
	Flex ducts	Useful for showing how low pressure duct connects to the diffusers
	Diffuser locations	Useful for coordination of finish utilities with the other fixtures in a room (like electrical fixtures etc.)
	Hangers and seismic bracing	Required for coordination and routing of other trades and for inserting the deck correctly before installation begins

	HVAC Piping to the VAV boxes	Main lines are required for coordinating with other trades. Also required if they will be pre-fabricated. Connections to VAV boxes can be left for field routing
	Rooftop equipment	Useful for coordinating with other trades (can be drawn as a 3D block)
Electrical model	Branch and feeder conduits	Required for coordination with other trades and for pre-fabrication
	All underground conduits	Required for underground MEP / FP coordination
	Junction boxes	Required for coordination with other trades
	All lighting fixtures	Required for coordination with other trades and finish utilities like ceiling grid, sprinkler heads, HVAC diffusers, specialty lighting
	all lighting supports in case of specialty lighting	Required for routing and coordination of other trades
	all the cable trays and other supports	Required for coordination with other trades
	bundles of cables or wiring	Useful for coordination and prefabrication
	Outlets and switch locations in rooms	Useful for pre-fabrication but not required for coordination with other trades (typically can model in 2D)
	Hangers	Required for coordination with other trades and for inserting the deck.
	Equipment panels	Useful for coordination with wall framing to determine backing etc.
	Electrical rooms	Useful for coordination with wall framing and other trades
Plumbing model	Plumbing fixtures	Required for coordination with other MEP trades and casework
	Graded cast iron pipe lines	Required for coordination with other trades and for pre-fabrication
	Underground storm and sewer pipes	Required for underground utilities coordination and for pre-fabrication
	All major waste and vent lines	Required for coordination with other trades and with architectural walls , shafts and for pre-fabrication
	Cold and hot water piping	Required for coordination with other trades and for pre-fabrication
	Hangers and Seismic bracing details	Required for coordination with other trades and for inserting before installation and for pre-fabrication
	All boiler and other	Useful for coordination (can be drawn

	equipment Specialty piping (like Medical Gas piping) and specialty equipment	as a 3D block) Required for coordination with other trades and for pre-fabrication
Sprinkler model	Sprinkler mains and branches	Required for coordination with other trades and for pre-fabrication
	Sprinkler head drops	Useful for coordination with finish utilities like electrical lighting, diffusers etc
	Smaller sprinkler pipe	Required if hard pipe is used, useful if the newer type of flex pipe is used

Table 4: Levels of Details in the various models needs to be addressed as part of the Technical Logistics.

As the table above indicates there is definitely a tradeoff between the level of details in the model and the benefits it provides in the coordination process and the teams should identify what benefits they want out of the modeling and coordination process before deciding what level of details the models should include.

Other Technical Issues to address:

The other issues that the project team should address include the following:

- Drawings are accompanied by standard word document describing revisions therein
- Drawings 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 a secure and remote access to all the drawing files
- A clear file path structure is setup on the server to organize the drawing files.
- 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
- Use only standard AutoCAD fonts in model space. Do not use True type fonts or custom AutoCAD fonts.
- Insertion point for all drawings are based on the 0,0,0 insertion point established in the architectural drawings.
- 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 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
- Anything not intended to be seen in the drawing is erased prior to file transfer
- 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 the text can be turned off without turning off the graphic
- 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 in an AutoCAD environment.

Step 5: Develop a Pull Schedule for the coordination of MEP systems

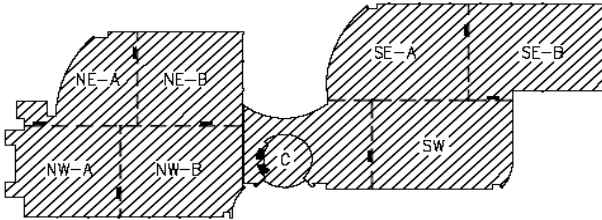
To ensure minimum waste in the process the work breakdown structure of the coordination process needs to match and follow the WBS of the construction. The sequence of coordination should match the sequence of construction or enough buffer (in terms of time) needs to be created if this is not the case. An example of the Design coordination Pull Schedule is shown below from one of the Case study projects (Camino MOB)

CAD File Naming Conventions

When naming drawings use the same name that the design team is using to name their drawing and follow it with a -XX. Replace the XX with your companies abbreviation. Use A / B to denote further break up of a quadrant for 1/4" scale drawings.

Example: M2.113A-SI

When transferring CAD files or Pasting on Prolog for coordination please break down the files by quadrant to minimize the file size. This helps when importing all the files into Navis.



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

Coordination Quadrant	A/E Drvgs 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

Figure 7: Figure shows the sequence of construction and Pull schedule milestone dates for the coordination of MEP systems for Camino MOB. The dates for coordination complete and the sequence of coordination are pulled from the construction sequence.

The pulling of coordination from construction allows the multi-disciplinary team to make adjustments on what the specific needs are for what is needed during construction and adjust accordingly as subsequent areas are coordinated.

Step 6: Operate and manage MEP coordination against the objectives, make adjustments and measure outcomes and results

This step involves the coordination using VDC methods such as clash coordination and also adjusting the process to make changes in order to accomplish the objectives of the coordination as identified in Step 1 and using metrics mentioned above.

An example of the use of VDC tools is shown below:

Using 3D Clash Detection tools to identify and resolve conflicts

There are commercial tools available that allow project teams to bring in 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 which has a Clash Detection program that allows teams to automatically analyze the models 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.

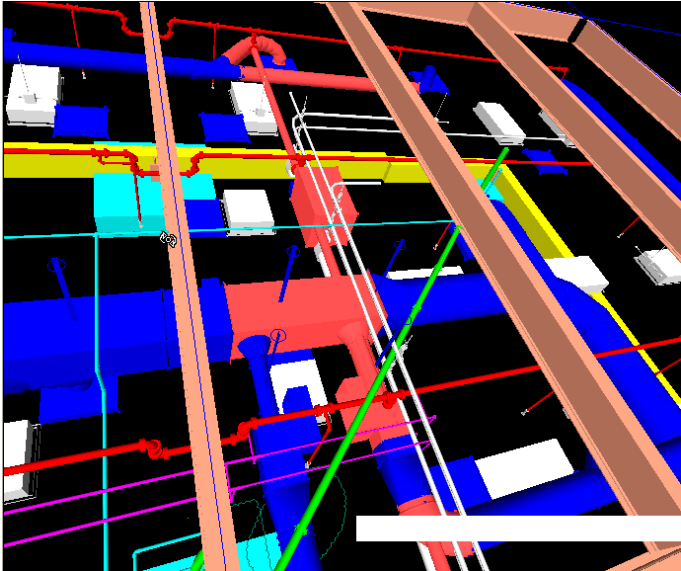


Figure 14: Clash between duct and sprinkler pipe (highlighted in red) on the Camino MOB. These clashes were identified by the Navisworks clash detection program. In a subsequent clash resolution session these clashes were resolved.

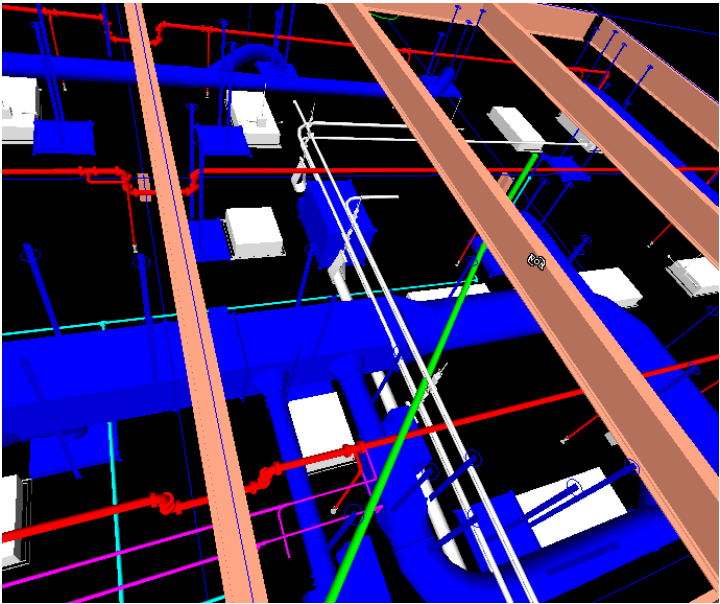


Figure15: The snapshot shows the resolution of the clash between duct and sprinkler pipe identified in the previous figure has now been resolved by moving the sprinkler pipe out of the way.

The 4D schedule should be reviewed and status of each activity should be noted in the field foremen's weekly coordination meeting.



Figure 16: Foremen meeting on the Camino MOB project to discuss the construction sequence with the aid of 2D drawings and 3D / 4D models

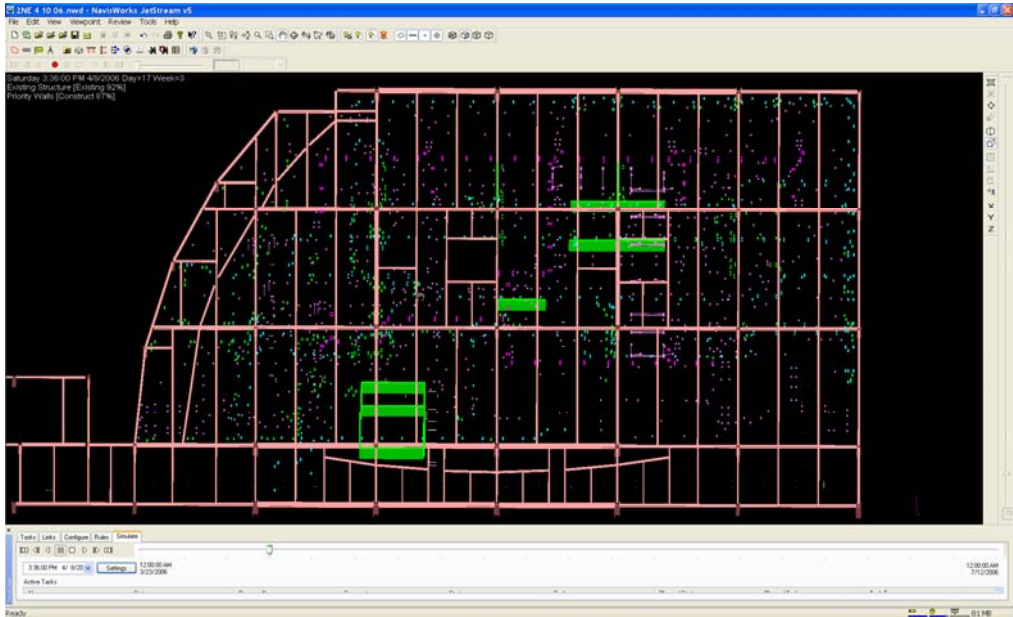


Figure 17: A snapshot of the 4D model from the Camino MOB project. The snapshot shows that the inserts (little dots in the screenshot) have been installed and construction of the full height wall framing (in green) is going on.

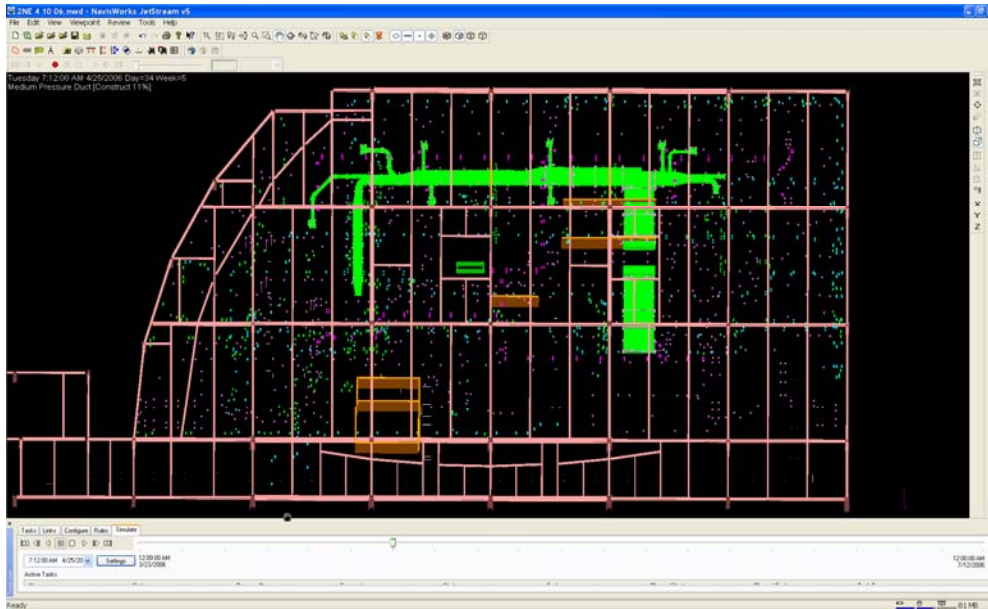


Figure 18: A snapshot of the 4D model from the Camino MOB project. The snapshot shows that the construction of the full height wall framing (in orange) is completed and the medium pressure duct (in green) is being installed.

Once the MEP systems are installed the teams can track outcome metrics identified above for the whole construction process. The outcome metrics can be similar to what has been identified in Figure 1 in terms of amount of actual prefabrication, latency, schedule compliance etc.

Validation:

An ideal method to validate that the IVL Method for MEP coordination leads to better results would be to apply different versions of the method on similar construction projects and then recording and comparing the process and outcome results. Due to the long time to conduct such a multi-project prospective study, we first validated the method by first doing an Internal Validation study and comparing the elements described in the method and how well they address issues identified in the four cases as well as parallel approaches in theories and other research that substantiate the elements of the method. This paper describes the internal validation done on the observed test cases reported in Table 1. Subsequently, we propose to do an external validation using a charrette method with a team of experts working in the industry providing feedback in a charrette workshop on this method for MEP Coordination.

Internal Validation:

The first step is to identify how the method addresses the observed problems in the four case studies. I also compared the specific elements of the method to related examples from the case studies as well as studies and research that substantiate the elements in the method although it might not have been done specifically for MEP coordination process.

The following table identified the issues or observed problems from case studies and how the various elements of the method addresses these issues as well as related theory and research that substantiates the elements of the method.

Examples of Issues from Case Study	Elements of the Method	What it does / Impact on Performance Metrics	Observations from Test Cases / Related Theory
Lack of strategic objective on projects about MEP Coordination	Multi-disciplinary team developing strategic objectives related to metrics, amount of prefabrication	Strategic Direction to the coordination process	UCSF Mission Bay example of CIFE workshop and subsequent feedback on its importance
Buy-in from everyone into common goals	Multi-disciplinary team organized in clusters that co-develops charters, metrics for the process	Buy-in to the specific metrics by everyone since they participate in it	ICE Method (Chachere, et.al, 2004)
Late involvement of trade foremen into the process leads to changes downstream	Early involvement of all stakeholders in multi-disciplinary team before coordination begins	Brings constructability knowledge upfront during coordination	Trade contractors in Design (Gil et.al, 2000)
Big batch coordination with loose tie to construction schedule leads to lack of feedback on process and needs of construction	Develop WBS and sequence of coordination schedule that matches the construction sequence	Smaller batches reduce inventory and also provide quicker feedback into the process from the needs of construction	Lean Work Structuring (Ballard, 2000) Rapid Prototyping
Technical Infrastructure does not allow teams to get on the same page	Compatible software programs and collaboration platforms that allow people to deal with the same version of reality	More time spent analyzing and deciding rather than searching for correct information	DEEPAND Framework (Christina-Garcia, Kunz et. al.), one of the 7 elements of ICE Framework from NASA (Chachere et. al, 2004)
Lack of understanding of process as well as outcome metrics and lack of buy-in in tracking these metrics	Performance metrics and outcome metrics co-created and designed to measure and adjust performance from objective of an efficient build process for MEP systems	Allows teams to make rational course correction due to tracking of metrics which are transparent and visible to everyone. Plan do Check Act	Plan Do Check Act (Deming, LCI)
Distributed teams leads to less productive coordination	Coordination in a collocated Big Room using Virtual Design and Construction Methods (3D Clash Detection, 4D	Rapid feedback, reduced latency in decision making	Integrated Concurrent Engineering (Chachere et.al, 2004) Obeya (Toyota Production System,

	sequencing)		Mikati et.al, 2007) VDC (Fischer and Kunz), MEP Coordiantion (Staub-French et.al, 2007), (Korman, et.al, 2003)
Transparency of objectives and metrics lacking	Transparency of objectives, metrics, and virtual building process	Collective understanding of where teams are, trust due to transparency	High Performance Teams (Katzenbach, 2006)

[Detailed Description of each of the method element and related research]

Conclusion:

The contribution of this research is the development of the six step VDC Lean Method for MEP Coordination. As outlined above the VDC Lean Method for Coordination allows:

1. A consistent, repeatable method that project teams can follow to perform MEP coordination.
2. Results in better outcome of MEP coordination in terms of better MEP construction process
3. Brings together the Product, Organization and Process factors that are important for coordination processes
4. Presents performance and outcome metrics that project teams can use to manage the coordination process.

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