CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

# A Guide to Applying the Principles of Virtual Design & Construction (VDC) to the Lean Project Delivery Process

By

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**A Guide for applying the principles of Virtual Design and Construction (VDC) in the Lean Project Delivery Process (LPDS)**

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**Abstract**: The objective of this paper is to introduce the concepts of Virtual Design and Construction (VDC) and explain how these concepts could be applied to the Lean Project Delivery Process. The Lean Project Delivery Process has been developed by the Lean Construction Institute and is based on the principles of applying the theory of Lean Production to construction projects. VDC has been developed by CIFE, Stanford University, and is the use of multi-disciplinary performance models for the design and construction of capital facilities. This paper presents a guide to practitioners on how to use the tools and principles of Virtual Design and Construction in the Lean Project Delivery Process. A short background of both the principles of VDC and the Lean Project Delivery Process is presented. This is followed by a discussion about the benefits and challenges of applying VDC during the Lean Project Delivery process. Some of the key findings of this study include:

- VDC tools like product, process, and organization modeling tools can be applied very effectively to accomplish the objectives of the LPDS.
- Product modeling tools like 3D modeling can be effectively applied to the Project Definition, Lean Design and Lean Assembly phases of the LPDS.
- Product and process modeling tools like 4D models can be applied during the Lean Supply and Lean Assembly phases of the LPDS.

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- Product, organization and process modeling tools such as the POP method can be used to analyze the tradeoffs between product, organization and process during the Lean Design phase of the LPDS.

**Introduction**: Over the last 30 years many industries have seen dramatic productivity improvements. As some authors have discussed productivity in the construction industry over the same period has steadily declined (Teicholz, 2001).

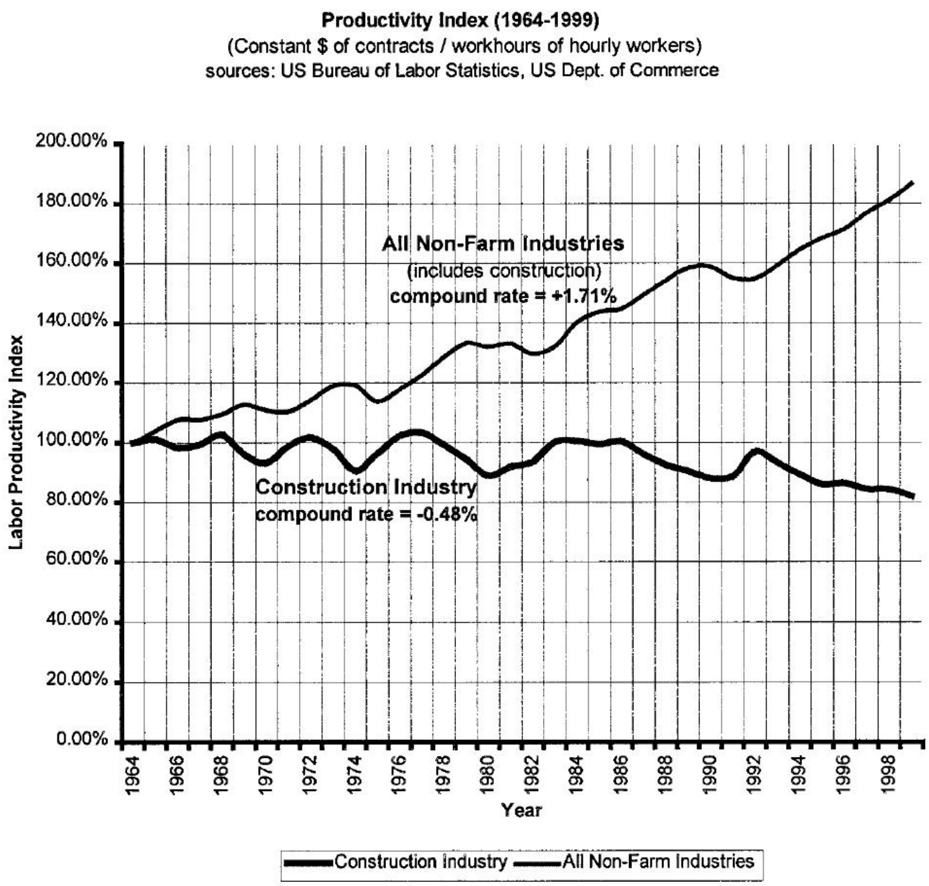


Figure 1: Productivity index for the construction industry compared with all non-farm industries. It shows the steady decline of productivity in the construction industry over a period from 1964-1998. (Reproduced from the discussion by Paul Teicholz on article "US Construction labor productivity trends 1970-1998, page 427, Journal of Construction Engineering and Management September / October 2001).

Although there has been some spirited discussion in the research community over the measures of construction productivity it is hard to ignore the fact that other industries clearly have made some rapid strides in productivity improvement compared to the construction industry in general. Some of these productivity improvements have been attributed to the use of information technology and a rethinking of the processes in other industries (Drucker, 2006). An example of this is the application of the lean manufacturing processes in the automobile industry. By some accounts the right application of Lean principles has resulted in at least 2 times improvement in productivity for some companies in the automobile sector (Womack et al, 1996)

Over this same 30 year period there have been rapid advances in the technology and tools used in the construction industry, including everything from information technology tools like computer aided drafting (CAD), web-based collaboration tools and large mechanical equipment used for excavation and hauling of large amounts of materials. The individual players in the industry (Architects, General Contractors, and Sub-contractors) have benefited from these advances in technology but, if we consider the industry as a whole, our productivity continues to decline. Some of this decline could be blamed on the inherent waste in the construction delivery process. For example, one of the recent US Government case studies has identified that the industry wastes $15.8 billion each year because of the fragmentation and lack of interoperability between tools to share information between the project participants (Gallaher et al, 2004). Not surprisingly, the major focus of a variety of research initiatives in the construction industry is on finding a more integrated approach to construction and studying processes that have helped make dramatic productivity improvements in other industries.

The research at the Center for Integrated Facility Engineering (CIFE) at Stanford University has focused on developing an integrated, model-based approach to address some of the underlying issues affecting productivity in construction. CIFE conceptualizes projects as a set of information flows that can be modeled and represented in a computer using symbolic representations of Products, Organizations and Processes. The essential premise is that these symbolic models can then be simulated to observe the interplay between the form, function and behavior of the products, organizations and processes that they represent. CIFE argues that an integrated, model-based approach that allows professionals to capture and simulate the project performance using symbolic representations of a project in the form of Product, Organization and Process models is what is needed to help bring about a change in the industry. An example of this is a product-process model or 4D visualization model, which allows a multi-disciplinary stakeholder team to quickly and rapidly visualize and analyze the different construction sequences and helps in the decision making process.

The Lean Construction Institute (LCI) has focused on applying the principles of Toyota's Lean Production system to the way construction projects are delivered. The LCI advocates a philosophy that construction projects are really production systems and can therefore be managed using lean production theory and techniques. LCI argues that to address the fundamental productivity issues in the industry a new conceptualization of construction as a production system is needed (Howell et al, 1999).

It is beyond the scope of this paper to theorize which approach is better. In fact, some large owners and general contractors are starting to explore the use of these approaches to improve the performance on their projects (Reed et al 2006), (Khanzode et al, 2005). No guidelines currently exist on how to concurrently utilize the technology tools and VDC approach during the lean project delivery process. This paper will provide initial guidelines to do so.

**Background on Virtual Design and Construction**: Virtual Design and Construction or VDC was pioneered by the research over the last two decades at CIFE, Stanford University. CIFE defines Virtual Design and

Construction (VDC) as “the use of multi-disciplinary performance models of design-construction projects, including the Product (i.e., facilities), Work Processes and Organization of the design - construction - operation team in order to support business objectives”( Fischer et al, 2004). VDC allows a practitioner to build symbolic models of the product, organization and process (P-O-P) early before a large commitment of time or money is made to a project. Thus VDC supports the description, explanation, evaluation, prediction, alternative formulation, negotiation and decisions about a project’s scope, organization and schedule with virtual methods. The objective of VDC therefore is to use these virtual models of product, organization and process to simulate the complexities of the construction project delivery, to understand the pitfalls the project teams are likely to encounter, to analyze these pitfalls and address them in a virtual world before any of the construction work ever takes place in the real world.

A variety of tools and techniques have been developed under the VDC framework including:

- Product visualization tools (3D object modeling technology such as AutoCAD ADT, Revit). The product visualization tools are used to create a common understanding amongst the project participants on how the building or the project will look like when it is completed. It can also be used to coordinate the work of various disciplines like mechanical, electrical and plumbing (Clayton et al, 2002).
- Product and process modeling and visualization tools ( 4D visualization tools such as CommonPoint Project 4D and NavisWorks Timeliner). These tools allow project teams to not only visualize the 3D model of the building but to also understand how the building will be constructed over time (Koo et al, 2000)
- Organizational and process modeling tools (such as VDT and SimVision). These tools allow a project team to simulate the organizational effort that will be needed to complete the project and

identify potential risks in project organization that might lead to eventual project delays (Christiansen,1992).

- Online collaboration tools (iRoom, Project Based Learning Lab). These tools allow collocated and geographically distributed team of project participants to collaborate using a shared model of product, organization and process. (Shreyer et al, 2002 ), (Fruchter, 1999)
- Techniques to analyze the effectiveness of multi-stakeholder meetings in order to meet the business objectives of the project and the client. (Bicharra Garcia et al, 2003)

A number of recent research studies have focused on documenting the benefits of using these tools and techniques to support the project delivery process.

These tools and techniques have been applied in a variety of projects and to accomplish the objectives including:

- Visualization of construction activities to identify time-space constraints (Haymaker et al, 2001).
- Photo-realistic representation of the built spaces for effective communication (Fischer, 2003).
- 3D modeling used for coordination of various disciplines like Mechanical, Electrical, Plumbing and Fire Protection (MEP / FP) (Staub-French et al, 2001).
- Constructability analysis of various construction methods (Akinci et al , 2002).
- Evaluation of site logistics plans (Heesom et al, 2004).
- Evaluation and analysis of various project sequences early on in the design phases of the project (Heesom et al, 2004).
- Prediction of time-space conflicts or constraints (lay down areas) during the entire project duration (Haymaker et al, 2001).
- Use of shared product models to extract quantities and reduce the time for creating estimates (Staub-French et al, 2003).

In addition to the product and process visualization tools CIFE has also developed the iRoom which provides a common framework for integration of data from commonly used engineering applications (such as Microsoft Excel, Microsoft project, Architectural Desktop etc.) and allows for rapid and iterative collaboration between a multi-stakeholder project team.

VDC also provides a method to analyze the effectiveness of meetings between a multi-stakeholder project team using the DEEPAND framework (Bicharra Garcia et al, 2003). DEEPAND stands for Description, Explanation, Evaluation, Prediction, Alternative Formulation, Negotiation and Decision making. The framework provides a way to measure the effectiveness of a meeting by classifying the discussion in a meeting as one of the seven DEEPAND activities and helps project teams move from the descriptive, explanative tasks to the more value adding evaluative and predictive tasks by using tools and techniques of VDC to share the project information in a more effective manner.

One of the areas of research in VDC is the Perspective approach (Haymaker et al, 2003). Using the Perspective approach, a multi-disciplinary team of designers, engineers and contractors can iteratively construct geometric engineering views, called Perspectives, from information in other Perspectives and control the integration of this multi-disciplinary, evolving project model as the project progresses.

One of the techniques developed at CIFE to integrate the various views generated by the multi-disciplinary design team is the Narrative approach which allows a multi-disciplinary team to formally represent the design process and the reasoning behind a design rationale (Haymaker et al, 2004).

**Background on Lean Construction and the Lean Project Delivery System**: Lean Construction (Ballard, 2000) was pioneered by the Lean Construction Institute.

Lean construction is the application of the Toyota Production System (TPS) principles to the construction project delivery process. The ultimate goal of lean construction is to eliminate waste from construction and deliver a product that a customer wants, instantly. Just like the Toyota Production System (TPS) philosophy (Liker, 2004), which is a departure from the mass production philosophy, lean construction is a departure from the traditional approach to construction project delivery. The basic idea behind the lean construction philosophy is to manage the construction project delivery as a lean production system. Although it is not the intent of this paper to describe lean production in full detail it is important to identify how lean production principles enhanced the production process in manufacturing industries that were practicing the mass production principles.

It is widely understood that the era of mass production began after Henry Ford pioneered the assembly line to produce cars for the Ford Motor company. When Henry Ford first pioneered the assembly line to build the cars he did so with an emphasis on finding the best process to transform the inputs into the production process into outputs. By building the assembly line for cars he essentially broke down the manufacturing process as a series of distinct steps, organized these steps into units on the assembly line and then organized specialized teams to manage these own units. This revolutionized the car manufacturing process. Cars started rolling off the assembly line much quicker than before.

Although it did revolutionize production, the mass production or assembly line process did result in a few unintended consequences including:

- In mass production the specialized units on the assembly line started focusing and tracking their own performance rather than the whole production process resulting in a lot of local optima which sometimes worked against optimizing the process as a whole.
- Quality problems started getting pushed off down the line as teams working on the assembly line did not feel empowered to stop the line if

they saw a quality defect for fear of being responsible for stopping the line.

- Inventories at each of the units started to increase as the emphasis on not stopping the assembly line forced teams to keep inventory on hand to continue their work when problems arose.

Toyota specifically addressed these unintended consequences of mass production when it designed the Toyota Production System (TPS). It addressed the issue of the local optima by emphasizing the need to optimize the whole system / process rather than one single unit. It also gave the workers on the assembly line an the ability to stop the production line if they detected a quality issue in order to correct quality issues when they were detected rather than at the end of the process. It also realized that keeping unused inventory at each unit is wasteful and adds to the overall production cost and reduced the level of inventory at each station to a bare minimum. Toyota also designed the process so that it could be flexible to demand from its customers. These changes are now widely regarded as some of the key elements of a new paradigm in production called lean production.

The lean construction research practitioners argue for a departure from the traditional transformation view of construction to a more holistic view which gives equal importance to the value and flow concepts along with the transformation concept. The transformation view refers to conceptualization of construction as an activity in which a set of inputs are converted to a set of outputs and the process is managed to keep this transformation within a set of constraints which typically include cost, schedule, etc. The value view refers to the concept that construction really is a process in which value is generated for the project owner. The flow view refers to the fact that construction is really a set of interdependent but distinct activities that need to flow to complete the project in time and within budget (Koskela et al, 2002).

The Lean Construction Institute has proposed a new way of delivering building projects on the basis of the principles of lean production discussed above. This new way is termed as the Lean Project Delivery System (LPDS). LPDS is envisioned as a project delivery method that conceptualizes design and construction projects as lean production systems (Ballard, 2000)

Some of the important features of LPDS are involving downstream players in the planning process, conceptualizing the project delivery as a value generating process, and creating a reliable workflow amongst the project participants. The conceptual representation of LPDS is shown in figure 2.

Figure 2 illustrates the Lean Project Delivery System:

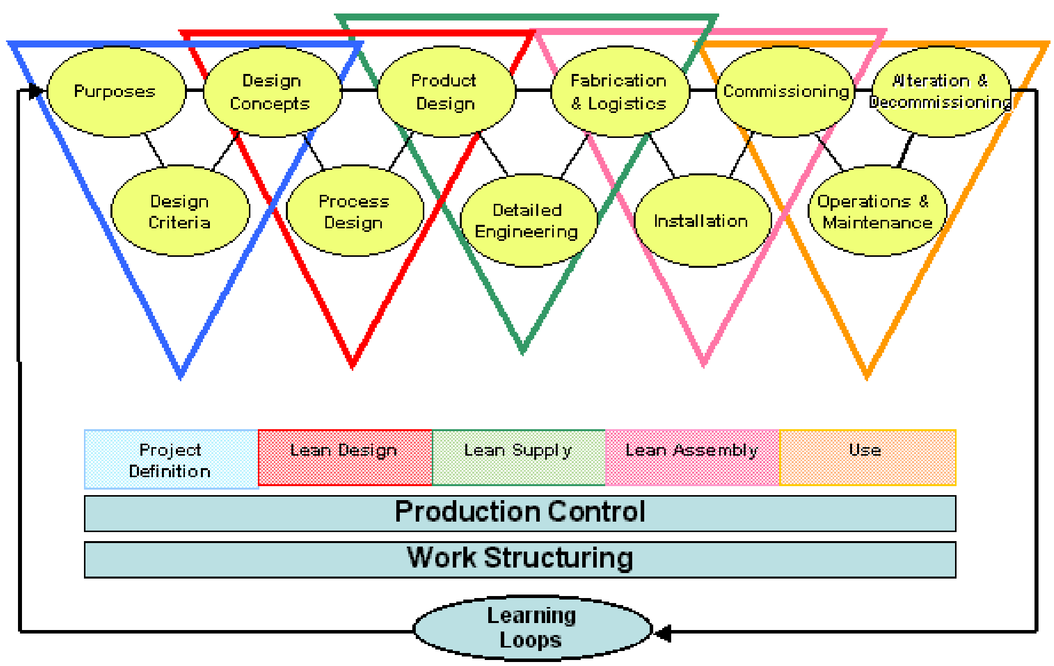


Figure 2: LPDS system (Ballard, 2000)

The LPDS model consists of five interconnecting phases that include

- Project Definition
- Lean Design

- Lean Supply
- Lean Assembly
- Use

Each of the phases contains three modules and is represented as a triad. Each triad overlaps the succeeding triad to include at least one common module. For example the Project Definition phase includes Purposes, Design criteria and Design concepts and overlaps with the Lean Design phase which includes Design concepts, Process design and Product design. In addition two modules of Production Control and Work Structuring extend throughout the lifecycle of the project.

The domain of Lean Project Delivery is defined by the intersection of projects and production systems and is therefore fully applicable to the delivery of capital projects which include the formation of a temporary production system in the form of a project team that consists of owner, architects, engineers, general contractor and sub-contractors.

**Guidelines for using principles of VDC during the LPDS:**

In this section we illustrate how the specific tools and techniques of VDC can be applied during the Lean Project Deliver process.

| LPDS Module | VDC Technique | Specific Example |
| --- | --- | --- |
| Purposes | POP Models, 3D Visualization, DEEPAND Framework | • *Better collaboration by using shared model to communicate purposes, needs and values*<br>• POP model to represent the business objectives |
| Design Criteria | POP Models, 3D | • *Explore design using 3D* |

| | | |
|---|---|---|
| | Visualization, DEEPAND Framework, Perspective approach | *blocks*<br>• Analysis of meeting effectiveness using DEEPAND<br>• Explanation of design criteria using narratives framework |
| Design Concepts | POP Models, 3D Visualization, DEEPAND Framework, Perspective approach | • *Communicate design concepts using 3D models*<br>• Analyze design meetings using DEEPAND framework<br>• Using the narratives framework to capture the design concept and process |
| Process Design | 3D Visualization, 4D product-process modeling, Organizational modeling | • *Analyze process using a shared product-process model (4D model)*<br>• *Involve downstream stakeholders (builders) early in the design process*<br>• *Using POP framework to understand impact of process change on product and organization* |
| Product Design | 3D Visualization, 4D product-process modeling | • *Involve downstream stakeholders (builders) early in the design process*<br>• *Incorporate process knowledge in the product design phase*<br>• *Using the POP framework to understand the impact of* |

| | | |
|---|---|---|
| | | *product changes on the process and organization* |
| Detailed Engineering | 3D Visualization, 4D product-process modeling | • *Involve downstream stakeholders in building detailed fabrication models* |
| Fabrication and Logistics | 3D Visualization, 4D product-process modeling | • *Fabricate using detailed 3D models* <br> • *Analyze the various logistics issues using 3D / 4D models* |
| Installation | 4D product-process modeling | • *Structure work using 4D models* <br> • *Analyze sequencing of work activities to remove constraints* |
| Commissioning | 3D Visualization | |
| Alterations and Additions | 3D Visualization, 4D product-process modeling | • Create model of a built facility to analyze constructability issues |
| Operations & Maintenance | 3D Visualization | • Use 3D as-built models to manage the facility |

Table 1: Table shows how the VDC tools and techniques can be implemented during the various stages of the LPDS.

In the following section we provide a detailed explanation of the specific examples that are presented in *italicized font* in Table 1. The examples show how each of these tools and techniques of VDC can be used on a project using the LPDS.

**Specific Examples of how VDC can be used during the LPDS:**

*Virtual Design and Construction enables Design-Assist process from the start of LPDS*:

The Lean Project Delivery Process advocates the involvement of construction professionals during the design phase of the project. A practical example of this is illustrated in Figure 3.

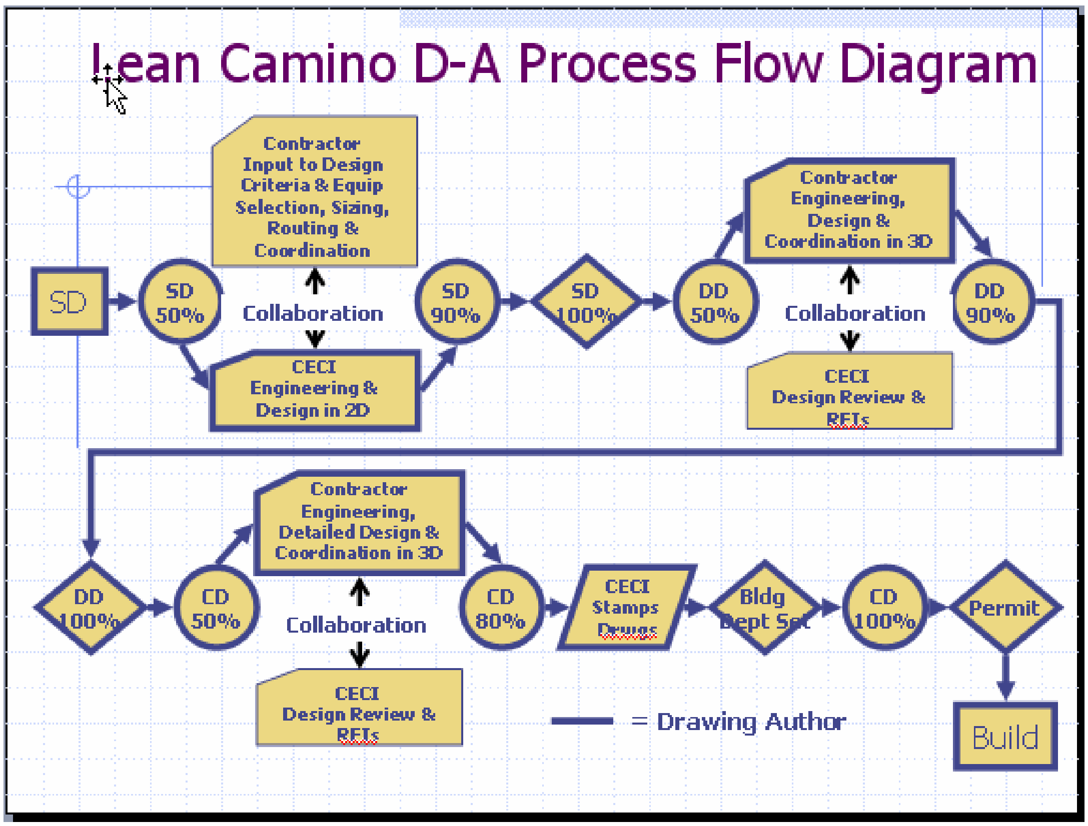


Figure 3: The Lean Design Assist process on the Camino Medical Group project, which implemented Lean and VDC principles and methods. Image courtesy DPR Construction, Inc., CA, USA.

The figure illustrates how the team on the Camino Medical Group project implemented the Design Assist process using the principles of Lean and VDC. The figure shows that Design Assist contractors for Mechanical, Electrical, Plumbing and Fire protection (MEP / FP) are involved during the Schematic Design phase to provide feedback to the Designers on the construction process and constructability issues. After the 50% DD phase the design process relies on the Design-Assist subcontractors developing coordinated 3D models that could be used during the fabrication and assembly phases of the LPDS. This demonstrates how VDC, more specifically 3D coordination tools, can be used from the early phases of the LPDS.

*Better Collaboration from Shared Vision of Needs, Values and Purposes in the Project Definition phase*:

The first phase of LPDS is Project Definition where purposes, needs and values of the users of the facility are assessed and a program is developed. By using 3D massing models early in the project definition phase the design team can communicate the look and feel of the project to the stakeholders. Use of a 3D model early in the process allows the design team to create a shared vision of the building and its functioning.


Figure 4: A 3D rendering of the interior of the lobby of the Camino Medical Group Project. The rendering was developed in the early Schematic Design phase to communicate the finishes in the lobby to the owner. Image courtesy HPS Architects, Mountain View, CA, USA.

The picture shows a 3D rendering of the lobby of the Camino Medical Group facility that was developed in the Schematic Design (SD) phase of the project. The model was used to communicate the architectural finishes to the CEO of Camino Medical Group and was extremely useful to create a shared vision of the facility for the occupants of the building. These 3D models / renderings were created using a program called Sketch-Up (Google website 2006) during the programming phase and also helped with issues such as flow of patients, proximity of services to patient rooms, layout of the nurse call station, reception areas in the building, the walk from the parking lot to the inside of the building, etc.

*Communicating construction sequence early on to all the stakeholders*:
One of the fundamental principles of LPDS is incorporating the process knowledge in the product design phase. The process knowledge in the early phases of the project includes sequencing and logistics of the project. By utilizing a product-process model or a 4D model of the project early on in the project teams can communicate the overall sequencing and logistics of the project. This allows project teams to incorporate downstream process knowledge much more effectively during the design phase of the project.

4D models can be used in communicating the construction sequence both at a macro level and a micro level. At the macro level the 4D models can be used to communicate issues like material movement and staging areas over the course of the project, access routes and disruptions due to construction on other areas surrounding the construction project. An example of how a macro 4D model of construction sequence can be used is illustrated in Figure 5.

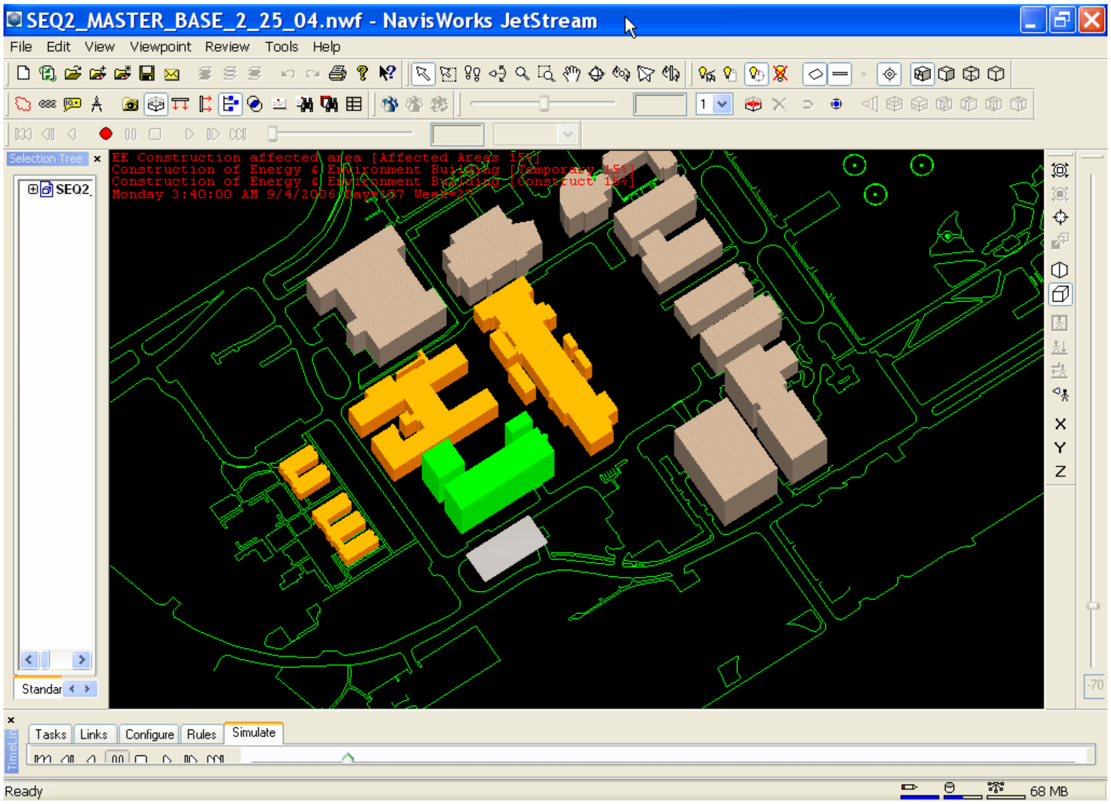


Figure 5: The figure shows a snapshot of a 4D simulation of the sequencing of the planned Science and Engineering Quad Phase 2 project on the campus of Stanford University. The picture shows an image of the construction (green) and buildings that might potentially get impacted due to construction activities (orange) according to the SEQ2 Master Plan during September 2006. This 4D model allowed the project participants to evaluate the impact of the SEQ2 sequencing on the overall campus traffic and also on the impact to classrooms in adjacent buildings that surround the construction site. Image courtesy Stanford Department of Project Management, Stanford University, Stanford, CA, USA.

On the micro level the 4D models can be utilized to demonstrate the construction sequence for a particular area or period of a project. This allows project teams to determine the lay down areas that would be available during construction, the overall sequence of their own work compared to work done by other trades, potential time space conflicts they might encounter and access points for delivery of materials into the area. See Figure 6. This figure shows the construction of mechanical, electrical and plumbing systems for one of the quadrants of the Camino MOB project for DPR Construction, Inc. The pictures show how this particular quadrant will be built and the sequence of installation of drywall, fire protection, ductwork, pressure pipes and gravity plumbing systems. This was used by the project team to determine who will occupy what area as well as to determine lay down areas and delivery of the prefabricated systems to the work areas.

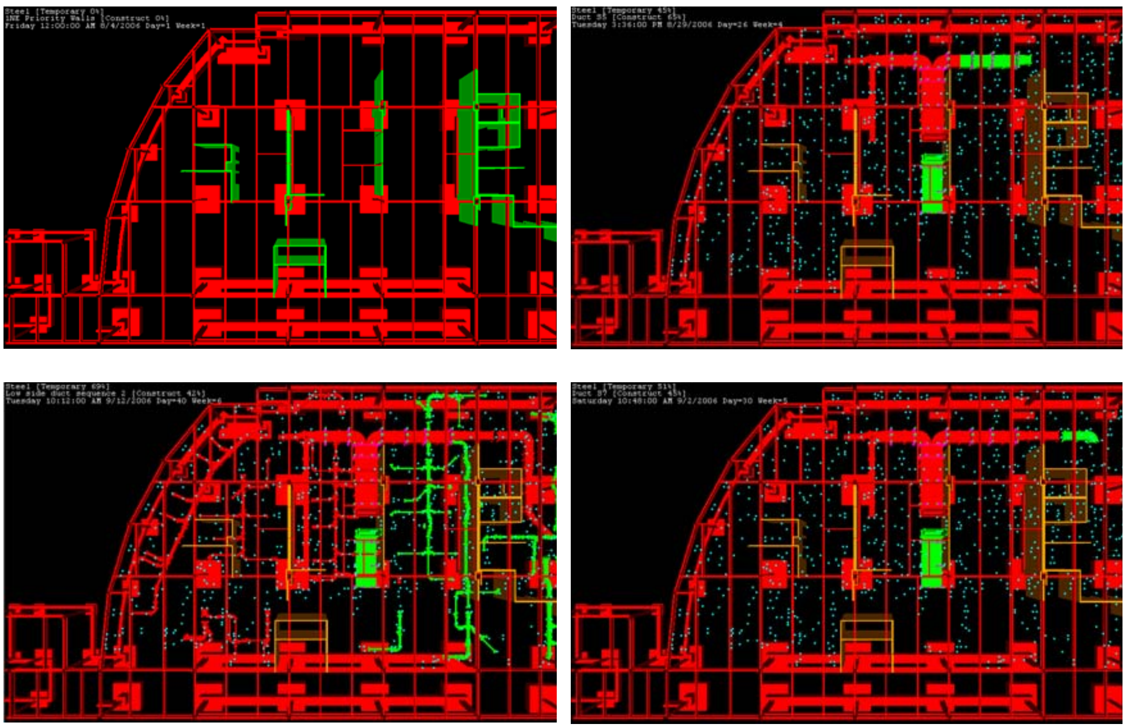

FIGURE 6: The 4D snapshots of the ductwork and wall framing for the 2nd Floor North East quadrant for the Camino Project. Clockwise from top left the figure shows the installation sequence of the wall framing and ductwork for this quadrant. Image courtesy DPR Construction, Inc., CA, USA.

*Seeing and removing constraints in 4D:*

LPDS relies heavily on the concept of shielding the performer of any production activity from any constraints that would keep the performer from actually performing the activity. In complex facilities, especially when multiple trades are working together in a tight space constraints can very easily be identified using 3D / 4D models and removed before the work is scheduled.

The following examples illustrate how this can be done using 4D models.

On one of the projects (see figure 7) the project team used a constraints removal plan in Microsoft Project. A view of the project schedule is created by the project superintendent to identify constraints for the activities that are planned.

**Eden Medical Center**
**6th Floor Neuroscience Center**
***Constraints Analysis: 1/31 thru 3/13/05***

| ID | Task Name | Level | Area | Resp | % Comp | Start | Finish | Contr / CO's | Dsgn / Engr | Subm'l | RFI's | Safe | L | M | E | Prereq Work | Space / Access | Action |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Start: 2/7/2005 - 2/13/2005** | | | | **0%** | **Mon 2/7** | **Fri 2/18** | | | | | | | | | | | |
| 97 | Wall Close-in inspection | 6th | A | OSP | 0% | Mon 2/7 | Mon 2/7 | | | | ● | | | | | | | need elec RFI and (E) shaft plaster linen chute |
| 40 | Patch & Repair Roof | Roof | All | ALC | 0% | Mon 2/7 | Fri 2/11 | | ● | | ● | | | | | ● | | CAN and Trane need to submit calcs that support |
| 161 | Plumb rough-ins | 6th | B | JWM | 0% | Mon 2/7 | Fri 2/18 | | | | | | | | | ● | | need 5th flr above ceiling work |
| 86 | Hang & firetape drywall top-down | 6th | A | DRY | 0% | Tue 2/8 | Mon 2/14 | | | | | | | | | | | |
| 98 | Hang Drywall | 6th | A | DRY | 0% | Tue 2/8 | Wed 2/16 | | | | ● | | | | | | | RFI on (e) shaft condition at B/6 |
| 38 | Flash Curbs | Roof | All | SHT | 0% | Thu 2/10 | Fri 2/11 | | | | | | | | | ● | | install AHU curbs |
| | **Start: 2/14/2005 - 2/20/2005** | | | | **0%** | **Mon 2/14** | **Thu 3/10** | | | | | | | | | | | |
| 41 | Pick & Place New HVAC Units / Lift-off Old Equip | Roof | All | CAN | 0% | Mon 2/14 | Mon 2/14 | | | | | | | | | ● | | DPR to submit DN |
| 124 | Oh'd Rough-ins Inspection | 6th | C | OSP | 0% | Mon 2/14 | Mon 2/14 | | | | | | | | | | | |
| 154 | Overhead elec on rack | 6th | B | RTE | 0% | Mon 2/14 | Wed 3/2 | | | | | | | | | ● | | need top-out and Unistrut rack |
| 67 | 5th Floor Plumbing Complete in Area B | 5th | B | JWM | 0% | Mon 2/14 | Mon 2/14 | | | | | | | | | | ● | need asbestos abatement |
| 92 | Oh'd Rough-ins Inspection | 6th | A | OSP | 0% | Tue 2/15 | Tue 2/15 | | | | | | | | | | | |
| 130 | Wall Close-in inspection | 6th | C | OSP | 0% | Tue 2/15 | Tue 2/15 | | ● | | ● | | | | | | | need wall sconce box rating |
| 42 | Hookup Ductwork / Electrical / Plumbing to Units | Roof | All | CAN | 0% | Tue 2/15 | Tue 3/1 | | | | | | | | | | | |
| 43 | Develop & Review Commissioning Acceptance | Roof | All | CAN,EDI | 0% | Tue 2/15 | Tue 3/8 | | | | | | | | | | | |
| 131 | Hang Drywall | 6th | C | DRY | 0% | Wed 2/16 | Wed 2/23 | | ● | | | | | | | | | need IB for shower curb and pan detail at rated wall |
| 99 | Screw Inspection | 6th | A | OSP | 0% | Thu 2/17 | Thu 2/17 | | | | | | | | | ● | | |

Figure 7: Constraints removal plan spreadsheet shows the various constraints identified by the project team for activities that are planned to be done. The pre-requisite work constraint identifies if any previous work is remaining to be done for the activity. In the spreadsheet above Activity 154 Overhead Electrical Rack installation cannot be done if the pre-requisite work is not completed. Activity 67 cannot be done for space /access constraint. Image courtesy DPR Construction, Inc., CA, USA.

In this example it is hard to understand what specific activity or access issue is affecting the installation. But using 3D model can address some of these challenges.

See figure 8. In this example it is clear that to install the ductwork it is necessary that anything above it should be completed. The ductwork needs to be installed before the cable tray can be installed. This is a much better way to analyze and remove constraints for activities compare to the constraint log as project teams can visualize exactly what the constraint is.

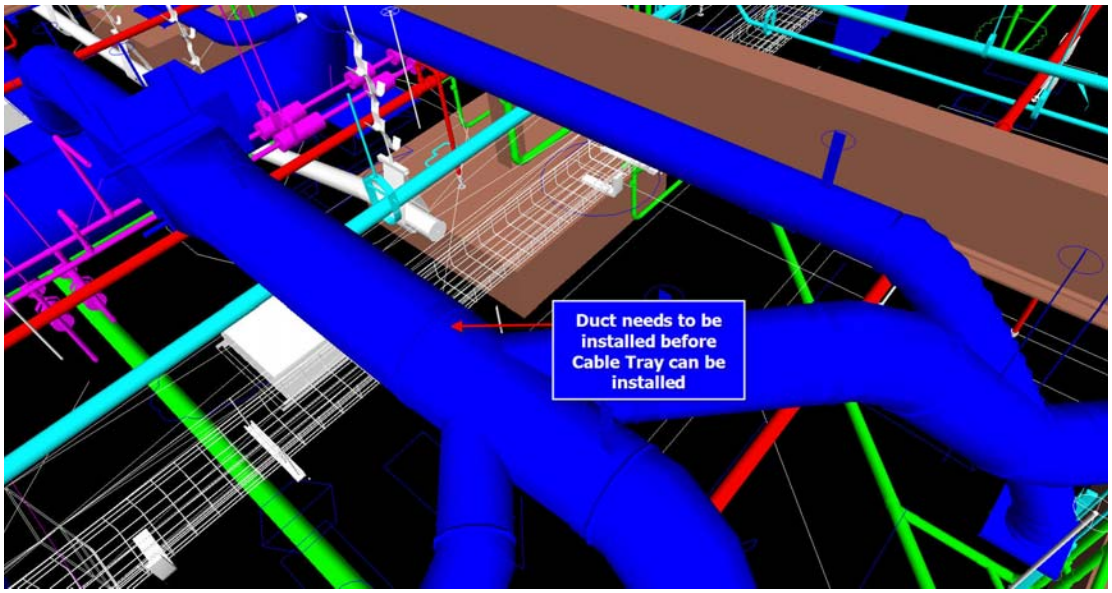


Figure 8: The constraint for installation of the overhead cable tray. The pre-requisite work of installing duct-work needs to happen before the cable tray can be installed. Image courtesy DPR Construction, Inc., CA, USA.

*Testing the work sequence in 4D before the work begins*:

LPDS tightly couples the design, supply and assembly of components on projects. This requires a deep understanding of what needs to be built on the jobsite and applying this understanding in coordinating the supply of materials and the design process. Creating and coordinating designs in 3D enables effective visualization of the product and a 4D simulation allows one to test the work sequence before the work begins. Thus 3D and 4D models can help manage the process of testing the sequence much better.

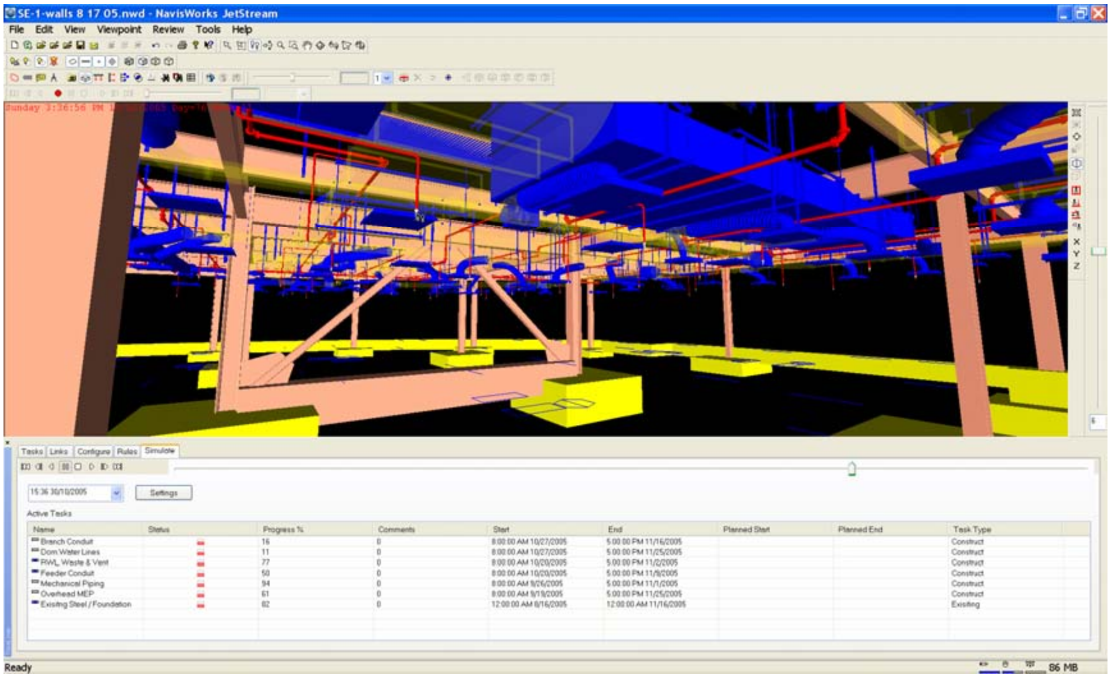


Figure 9: Screenshot of the 4D simulation of the installation of main ducts and sprinklers for the 1st quadrant of the Camino Medical Group Project in Mountain View, CA. Image courtesy DPR Construction, Inc., CA, USA.

Figure 9 shows an example where a 4D model was used to identify a conflict which would have happened during installation of the sprinkler pipes and the main duct on the Camino Medical Group project in Mountain View, CA. The schedule called for installation of sprinkler pipes before the duct in the above-ceiling space as it mostly occupies the higher space close to the underside of the deck. But for the area where the main supply duct runs through the mechanical shaft the sprinkler pipe was below the duct. If the original schedule would have been followed the sprinkler pipe would have been installed before the duct in this area. The 4D model enabled the crew to handle this situation. It was decided that in this area the main duct will be installed first and then the sprinkler pipe will be installed. This probably saved the HVAC subcontractor about 8 hours of work as he had clear access to the area and did not have to navigate around the sprinkler pipe which would have been installed first had the team not visualized the 4D model sequence in detail.

*Modeling concept, design and development Details*:

LPDS emphasizes the need to incorporate construction knowledge in the design process. The triads of LPDS intersect and overlap each other. For example the design concepts component overlaps the project definition and lean design phases. The lean design and lean supply phases have product design as the common component. We can use an evolving 3D model from the project definition phase to the fabrication and assembly phases of the project to enable the LPDS for a project. An example of this is shown in the 3D models with increasing levels of details that have been used in the construction of the Experience Music Project in Seattle. A massing 3D model developed at the Schematic Design stage was subsequently used in the Detailed Design, fabrication and assembly phases.

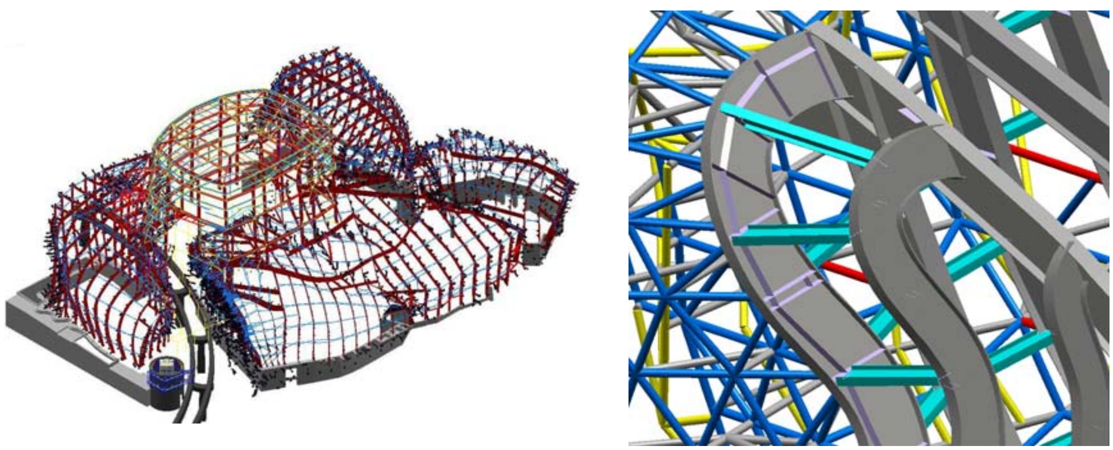

Figure 10: The conceptual 3D model of the Experience Music project in Seattle, WA, USA and a close-up of the detailed structural design that was developed using the conceptual model. Image courtesy Chris Raftery, Lease Crutcher Lewis, Seattle, WA, USA and Frank Gehry Architects, Los Angeles, CA, USA.

*Communicating Construction Sequence Early on to the Stakeholders:*

A 4D model allows a project team to communicate the sequence of construction. This can be done very early in the design process and is especially useful in planning construction in areas where the existing occupancy is high.

For example, Figure 11 shows a 3D model of a hospital expansion project in Arizona, USA. Building the model helped the contractor to better communicate the construction sequence to the project stakeholders. The 4D model was published on the hospital's website and used to communicate with the wider population about availability of parking, access pathways to hospital units etc.

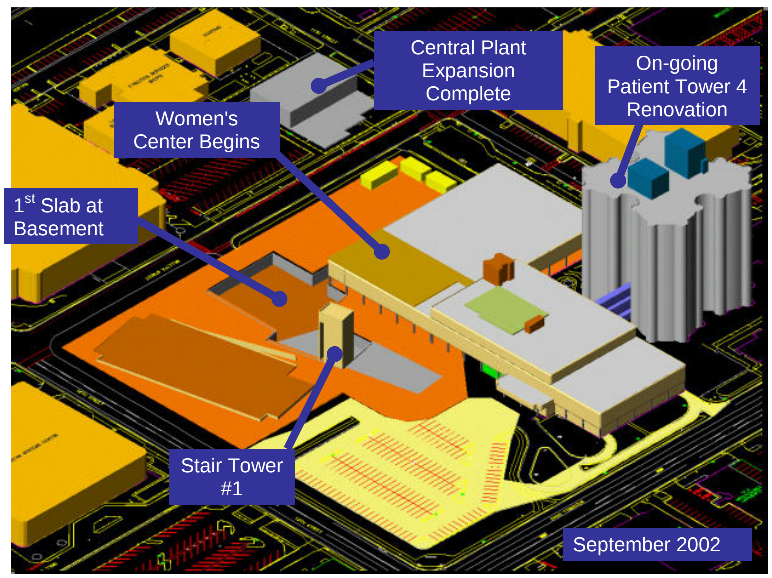


Figure 11: 3D model of site logistics and high level construction sequencing of the Banner Good Samaritan Medical Center Project in Phoenix, AZ, USA. Image courtesy DPR Construction, Inc., CA, USA.

*Seeing and planning logistics in 4D*:

Work structuring and planning early stage project logistics is an important component of the LPDS. 4D simulations allow a project team to effectively communicate the site logistics to the project stakeholders.

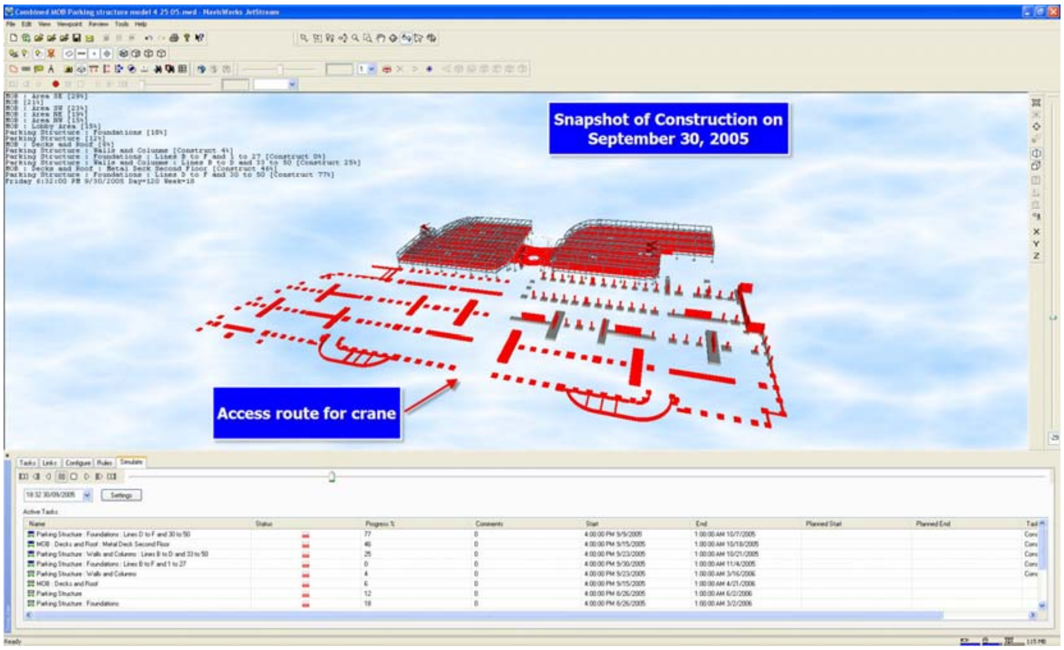


Figure 12-a: Snapshot of construction sequencing of the Camino MOB project in Mountain View, California shows the steel erection and the foundation activities on September 30, 2005. The middle section of the parking garage foundations is not constructed to allow crane access for erecting steel and GFRC panels for the MOB. Image courtesy DPR Construction, Inc., CA, USA.

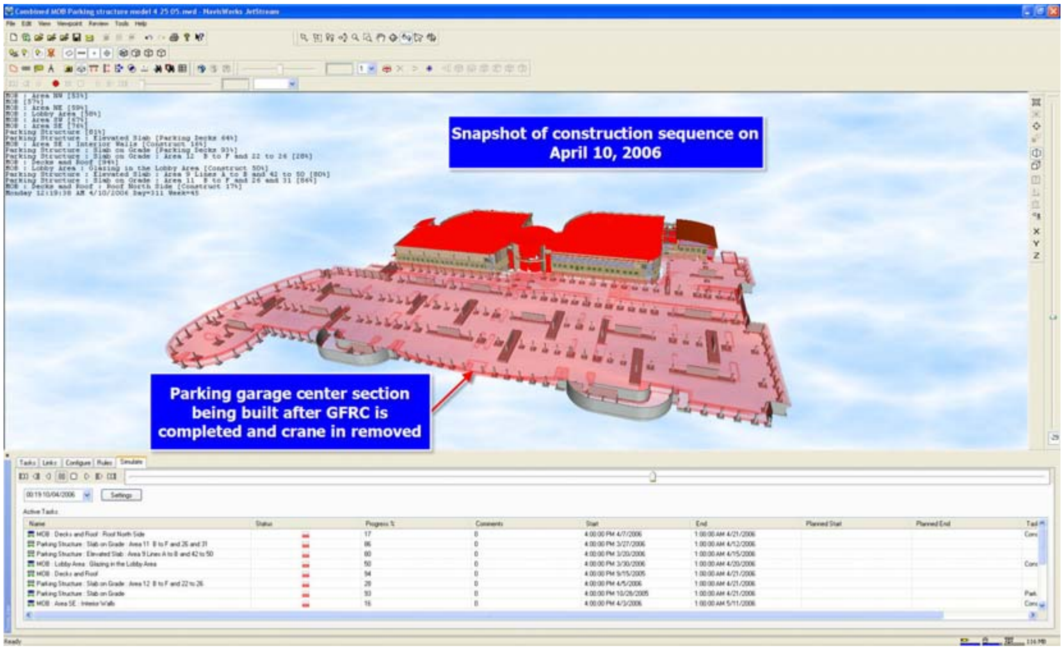


Figure 12-b: Snapshot of the 4D model of the construction of the Camino Medical Group Project in Mountain View, California showing column and shear wall construction on April 10, 2006. The center section of the garage foundations and slab on grade is constructed after the steel erection is complete, the GFRC panels for the MOB have been installed and the crane has backed out. Image courtesy DPR Construction, Inc., CA, USA.

The sequence in Figures 12-a to 12-b show how the logistics were planned for the Camino Medical Group project in Mountain View, California, using a 4D model. The team identified that the access to tower crane to erect the steel and GFRC panels and also for the delivery of MEP / FP installation items and interior construction equipment like scissor lifts to the Medical office building (MOB) would need to be maintained when the construction of the parking structure was also going on the jobsite. If the parking structure were to be built from right to left with all the foundations constructed the access to the MOB and egress for the crane would be blocked. So it was decided to leave out two strips of foundations and shear walls in the middle of the parking structure to allow for the erection of the steel / GFRC panels using the crane and also maintain access for delivery vehicles to the center of the MOB for delivery of materials and equipment.

*Seeing hazards in 4D*:

LPDS advocates early involvement of builders in the design process. This allows the knowledge of construction methods to be used to influence the early design and address the safety concerns of the project during the design phase of the project. Using a 4D model allows the project participants to visualize potential safety issues.

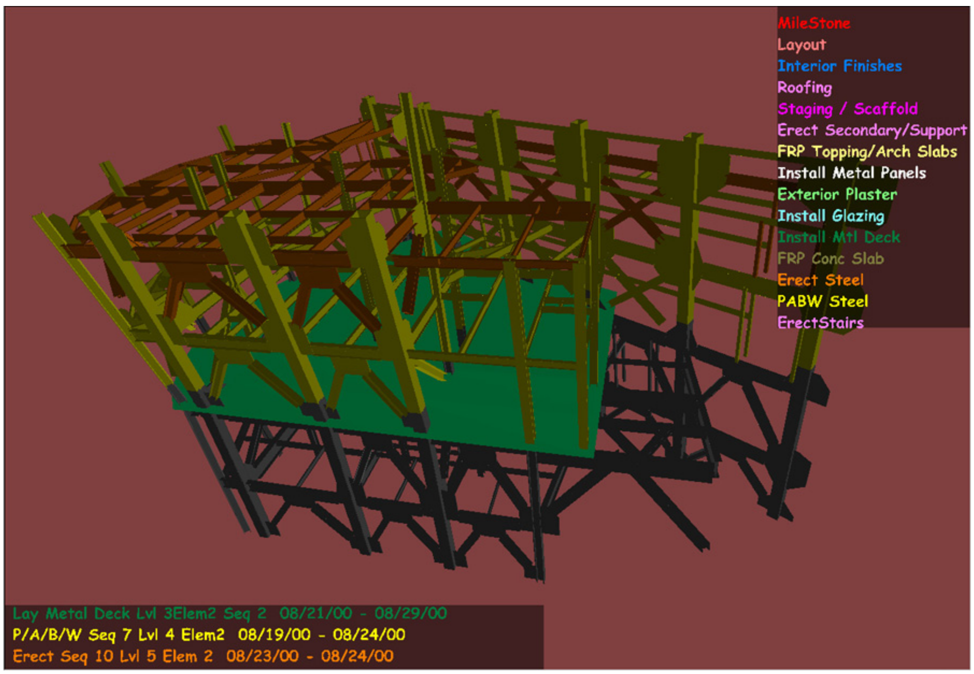


Figure 13: Screenshot of the 4D model of the deck installation sequence at the Disney Concert Hall project. It shows that the installation of the fourth floor deck is going to pose safety risks and needs to be rescheduled. Image courtesy MA Mortenson Company, Los Angeles, CA, USA.

*Making work ready by coordinating detailed 3D designs:*

LPDS focuses on shielding production activities from uncertainty by using a concept called “making work ready”. Only that work which is made ready can actually be done on the project. A detailed 3D model can help in structuring this work so that it will be free of space constraints that might impact the work from being scheduled.

The make work ready process is illustrated in Figure 14. Based on a look-ahead plan the work that should be done is identified. This work is then filtered through a 'make ready process" which identifies the constraints and releases only that work which can be done. The process of making work ready is greatly enhanced by the use of 3D / 4D models which allow a project team to visualize the work that is planned and the work that is free of any constraints and that can be done. See figure 14 and 15

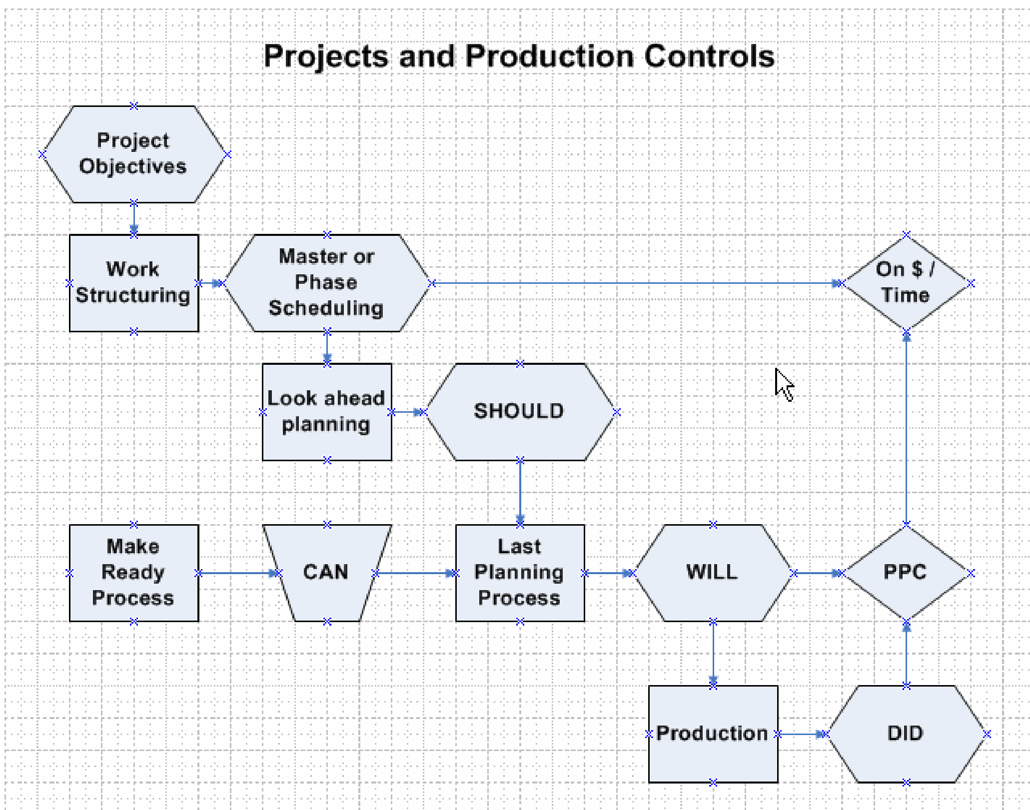

Figure 14: Outline of a make work ready planning process.

Figure 14 shows how the make ready process works. Based on the master schedule and phase schedule what SHOULD be done is identified. Make ready process is basically a filter that is applied to the activities that SHOULD be done to determine which activities CAN be done. Only those activities which SHOULD and CAN be done are then released for the actual work.

Using the 3D model illustrated in Figure 15 the project team at Camino MOB project was able to determine which activities CAN be done and used the model in many subcontractor coordination meetings to identify activities that were released for production or actual work.

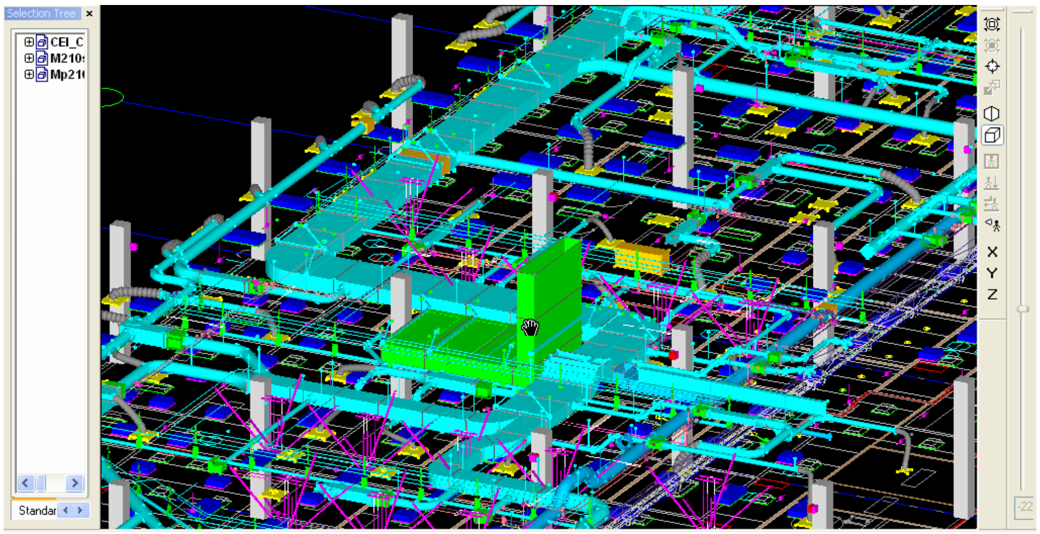


Figure 15: Snapshot of the above ceiling utilities (HVAC/ process piping, electrical conduits, electrical fixtures, etc.) for a tenant improvement project. The 3D model helped the project team identify conflicts, remove constraints and make work ready due to the ability to better visualize the work that needed to be done. Image courtesy DPR Construction, Inc., CA, USA.

*Structuring work in 4D:*

Proper sequencing of work is an important concept in LPDS. Work structuring refers to breaking the work activities into smaller chunks that can then be assigned to teams to work on. Effective work structuring allows project teams to maintain a flow of work and crews through the project, align the supply chain activities, deliver materials just in time and maintain a proper sequence of installation given the crew sizes available. Superintendents spend a lot of time in determining how to structure the day to day work on a project. On most projects this is done using the superintendents' own experience and simple tools such as a paper based weekly schedule. Using VDC tools like 4D models, project teams can determine the optimal work sequence by visualizing the various work structuring scenarios on a project. For example on the Bay Street Emeryville project the project team created a 4D model based on the schedule that the superintendent had created (see figure 16). When visualizing the work sequence for foundation activities the project team realized that a second crew could easily be mobilized to do the foundation work as the pre-requisite work of pile driving would be done and an extra crew for the foundation work was available. This allowed the project team to gain valuable time in the schedule.

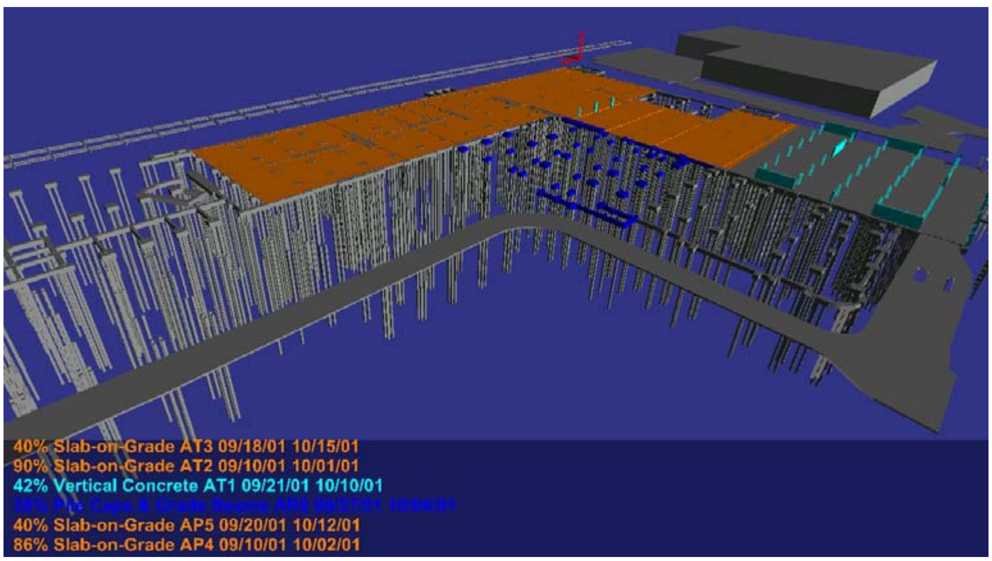


Figure 16: The work structuring on a retail development project in Emeryville, CA USA. The contractor realized that they could mobilize another crew on the concrete foundations after they saw the 4D model and realized that the pre-requisite activity of pile driving would be done they could mobilize another crew to start the foundation work sooner. Image courtesy DPR Construction, Inc., CA, USA.

*Using the POP framework to understand the impact of changes in product, process and organization on the project:*

The Product-Organization-Process framework of VDC allows project teams to identify how change in product, organization and process would impact the project as a whole. In each of the triads of the LPDS it is important to understand how changes in one component of the triad impacts changes in other components. For example in the lean design triad, which includes design concepts, product design and process design it is important to know how changing the product design would impact the process design and vice-versa. The POP framework of VDC provides a method to understand these changes on the project.

On the Camino Medical Group project the fabrication drawings for the steel had to be approved so that the steel could be fabricated and arrive in time on the site from out of state to meet the schedule. While the fabrication drawings were under review it was determined that the surgery center area for the building could benefit from having holes which can be used for routing the medical gas piping or other MEP / FP piping because of the large amount of various systems that would need to be routed in the available ceiling space. This issue presented the team with a couple of options (see figure 17):

1. To get the holes created in the beams as they were fabricated
2. To make field modifications after the beams have been erected but before the work on medical gas piping and other MEP / FP piping in the surgery center begins.

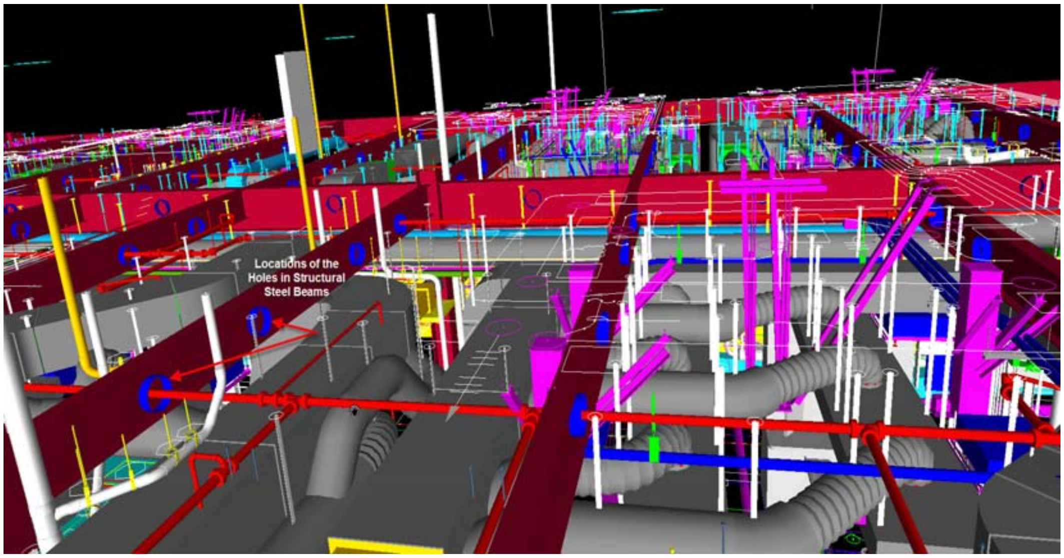


Figure 17: 3D model with the locations of holes in the beams of the surgery center. Image courtesy DPR Construction, Inc., CA, USA.

This decision making example can be illustrated using a simple P-O-P model for each stage of the decision making process during the design stages to indicate the impact of each of the stages in the decision making process on the tradeoff between the Product-Organization-Process for the project.

| | Product | Organization | Process |
|---|---|---|---|
| **Function** | Structural steel columns and beams that satisfy the requirements outlined in the drawings and specifications | Owner<br>Architect<br>Structural Engineer<br>General Contractor<br>Steel Fabricator<br><br>Need to be on the team | Finalize the Fabrication details so that the delivery schedule can be met |
| **Form** | Structural steel beams and columns per approved fabrication drawings and specifications | Owner<br>Architect<br>Structural Engineer<br>General Contractor<br>Steel Fabricator | Submittal log<br>Fabrication and delivery schedule |
| **Behavior** | Structural steel beams and columns match the approved fabrication drawings | Strutural steel fabricator under contract | Beams and columns must be delivered on time to the site to meet erection schedule |

Table 2: The P-O-P model shows the state of the Form, Function and Behavior of P-O-P for the steel fabrication example of the Camino MOB. This P-O-P model shows that the fabrication drawings need to be approved to meet the schedule requirements for steel fabrication and delivery.

| | Product | Organization | Process |
|---|---|---|---|
| **Function** | Structural steel columns and beams that satisfy the requirements outlined in the drawings and specifications | Owner<br>Architect<br>Structural Engineer<br>General Contractor<br>Steel Fabricator<br><br>Need to be on the team | Finalize the fabrication details so that the delivery schedule could be met |
| | Beams in the surgery center need to have holes for routing Med gas pipes | Mechanical Sub<br>Electrical Sub<br>Plumbing Sub<br>Fire Protection Sub<br>Miscellaneous Metal Sub<br><br>Also need to be on the team | Get the correct hole locations and modify the beams in surgery center before the installation of medical gas pipes begins |
| **Form** | Structural steel beams and columns | Owner<br>Architect<br>Structural Engineer<br>General Contractor<br>Steel Fabricator | Submittal log<br>Fabrication and delivery schedule |
| | Hole locations for the beams in the surgery center | Mechanical Sub<br>Electrical Sub<br>Plumbing Sub<br>Fire Protection Sub<br>Miscellaneous Metal Sub | Coordniation meeting for ASC |
| **Behavior** | Structural steel beams and columns to match the approved fabrication drawings | Structural steel fabricator under contract | Beams and columns must be delivered on time to the site to meet erection schedule |
| | Holes in the right places on the beams in the surgery center before the installation of medical gas pipes begins | MEP / FP subs in place so that they can provide the input on hole locations | Beams in surgery center must be have holes in the right places before installation of medical gas pipes can begin |

Table 3: The POP model of the steel fabrication example of the Camino MOB project illustrating the impact of additional functional requirement for Product (to have holes in the beams for surgery center) on the P-O-P of the project.

| | Product | Organization | Process |
|---|---|---|---|
| **Function** | Structural steel columns and beams that satisfy the requirements outlined in the drawings and specifications | Owner<br>Architect<br>Structural Engineer<br>General Contractor<br>Steel Fabricator<br><br>Need to be on the team | Finalize the fabrication details so that the delivery schedule could be met |
| | Beams in the surgery center need to have holes for routing Med gas pipes | Mechanical Sub<br>Electrical Sub<br>Plumbing Sub<br>Fire Protection Sub<br>Miscellaneous Metal Sub<br><br>Also need to be on the team | Get the correct hole locations and modify the beams in surgery center before the installation of medical gas pipes begins |
| | | | Coordinate ASC in normal sequence |
| | | | Develop plan to get holes in the beams after they are installed but before installation of piping |
| **Form** | Structural steel beams and columns | Owner<br>Architect<br>Structural Engineer<br>General Contractor<br>Steel Fabricator | Submittal log<br>Fabrication and delivery schedule |
| | Hole locations for the beams in the surgery center | Mechanical Sub<br>Electrical Sub<br>Plumbing Sub<br>Fire Protection Sub<br>Miscellaneous Metal Sub | Coordniation meeting for ASC |
| | | | Add field modification of beams to the schedule |
| **Behavior** | Structural steel beams and columns to match the approved fabrication drawings | Structural steel fabricator under contract | Beams and columns must be delivered on time to the site to meet erection schedule |
| | Holes in the right places on the beams in the surgery center before the installation of medical gas pipes begins | MEP / FP subs can be in place later but need to determine the hole locations before piping can start | Beams in surgery center must be modified in the field prior to the start of piping work |

Table 4: The POP model for the steel fabrication example on the Camino MOB project illustrating the impact of one of the options (to field modify the beams in surgery center on the P-O-P of the project.

| | Product | Organization | Process |
|---|---|---|---|
| **Function** | Structural steel columns and beams that satisfy the requirements outlined in the drawings and specifications | Owner<br>Architect<br>Structural Engineer<br>General Contractor<br>Steel Fabricator<br><br>Need to be on the team | Finalize the fabrication details so that the delivery schedule could be met |
| | Beams in the surgery center need to have holes for routing Med gas pipes | Mechanical Sub<br>Electrical Sub<br>Plumbing Sub<br>Fire Protection Sub<br>Miscellaneous Metal Sub<br><br>Also need to be on the team | Get the correct hole locations and modify the beams in surgery center before the installation of medical gas pipes begins |
| | | | Coordinate Surgery Center out of sequence prior to finalizing the fabrication drawings |
| | | | Develop plan to get hole locations determined based on coordination between MEP subs and Designers |
| **Form** | Structural steel beams and columns | Owner<br>Architect<br>Structural Engineer<br>General Contractor<br>Steel Fabricator | Submittal log<br>Fabrication and delivery schedule |
| | Hole locations for the beams in the surgery center | Mechanical Sub<br>Electrical Sub<br>Plumbing Sub<br>Fire Protection Sub<br>Miscellaneous Metal Sub | Coordniation meeting for ASC |
| | | | Modified schedule to indicate the coordination between MEP / FP subs and designers for surgery center |
| **Behavior** | Structural steel beams and columns to match the approved fabrication drawings | Structural steel fabricator under contract | Beams and columns must be delivered on time to the site to meet erection schedule |
| | Holes in the right places on the beams in the ASC Area before the piping is installed in ASC and before beams are installed | MEP / FP subs need to be on board before the fabrication drawings for steel can be finalized and work on determining the hole locations to inform the fabrication drawings for steel | Beams in surgery center need to be modified in the shop with the correct hole locations |

Table 5: The P-O-P model of the steel fabrication example of the Camino MOB project illustrating the impact of the chosen option (to modify beams in the shop) on the P-O-P of the project.

The POP models presented in tables 2 through 5 show the cascading effect on the change in the product functional requirement on the organization and the process.

During the discussion of approving the fabrication drawings an additional functional requirement was identified: that of drilling holes prior to installation of MEP systems in the surgery center area and before the beams are delivered to the field. This created the immediate process change of first determining where the holes need to be and then an organizational change of getting subcontractors on board to be able to determine where the holes should be located. The process also had to be modified to locate the holes without changing the end date of the MEP system installation. The potential options the team discussed were as follows:

1. Modify the beams in the shop with the holes in the right place
2. Modify the beams in the field prior to installing the medical gas and other piping in the surgery center area.

It was decided to choose the first option to minimize cost. Therefore in this case the expected behavior constraint on the process (that of not doing any field modifications) informed the decision of modifying the beams at an additional cost in the shop. This resulted in change in the project's organizational form and function.

This example illustrates (through the P-O-P models at various stages in the process) the tradeoffs the project team faces during the design of the project. In this example the expected behavior of the process has an impact on the product and organization of the project. In this example the expected behavior plays a determining role on the course of action that the project team took to modify the product and the organization. The P-O-P framework of VDC can thus play an important role in understanding the tradeoffs that happen all the time during all the stages of the LPDS.

*Using the Narrative approach to communicate and integrate multi-disciplinary design concepts and criteria:*

Design of construction facilities is considered an evolutionary process. Design teams engage with a variety of people to create designs that meet the need of the occupants but also meet the criteria of time, budget, quality etc. Design is typically a multi-disciplinary process. The lean design phase of LPDS advocates a multi-disciplinary approach to design by considering the interplay between design concepts and product and process designs. It also emphasizes the need to involve downstream players in the upstream design process. In the iterative design process it is common to lose sight of how and why the decisions were made in the first place and what impact changes in product, process or organization would have on the values and concepts identified by the client during the concept development phase. The Narratives framework can be applied to this process in order to understand the impact of changes on the original concept.

An example of this is illustrated in the following narrative of the detailing and fabrication process at the Camino MOB. Figure 18 illustrates how the early decisions on design codified in the design criteria impact some of the downstream processes. The figure indicates how the eventual fabrication ties to the conceptual model of design and how the data is transferred between systems. Any change made in the conceptual stage in this model triggers a change in the detailed models for the systems and therefore the final fabrication level models. In this case it is easy to understand change in any step of the way can impact the eventual fabrication of structural steel on the project. The narrative also helps understand if changes down the line impact some of the values or concepts developed during the design phase of the project.

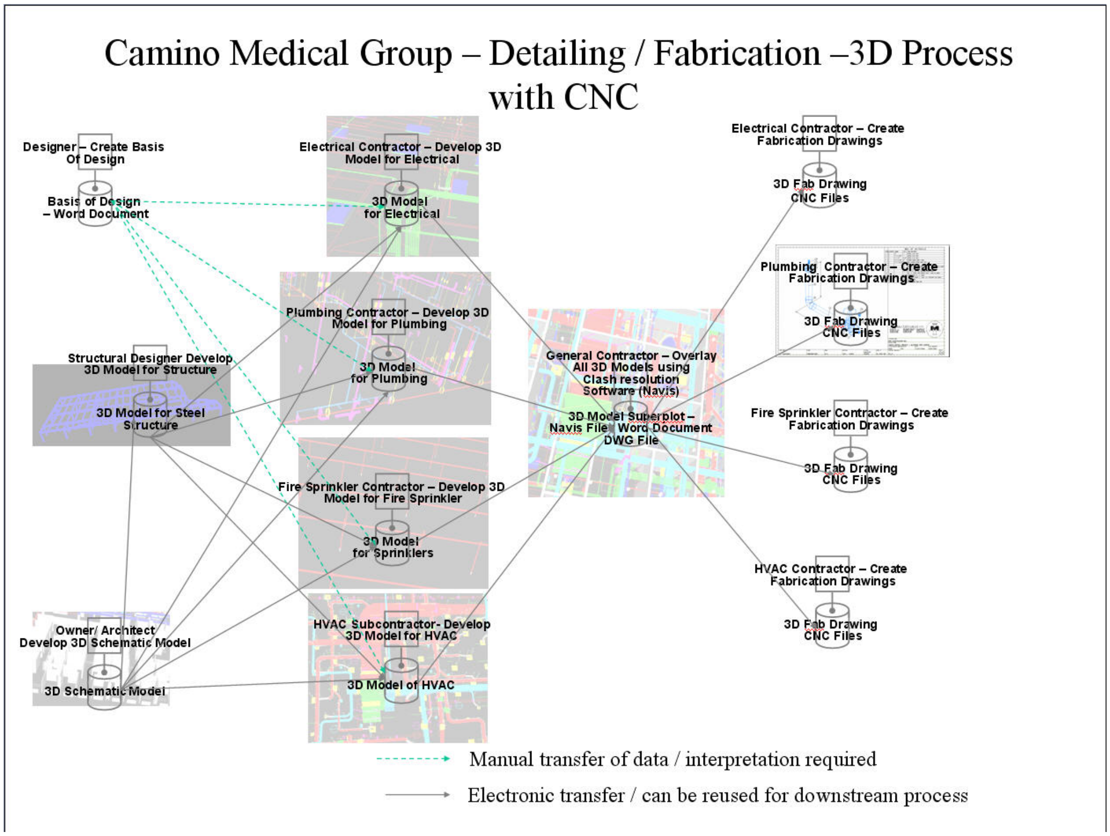


Figure 18: Narrative of the detailing / fabrication process on the Camino MOB project for DPR construction. It clearly shows how the eventual fabrication ties to the design concept / criteria that were developed in the concept formation stages of the project. Image courtesy DPR Construction, Inc., CA, USA.

**Conclusions**:

This paper illustrates how the VDC tools, technologies and methods can be used during all stages of the LPDS. The LPDS provides a framework to understand how to structure the project delivery process to accomplish the ideal of a lean production system. We have illustrated with specific examples which specific VDC tools, technologies and methods can be applied to each of the phases identified by the LPDS. Some might argue that it is not surprising that VDC enables LPDS. Our contribution in this paper is to illustrate specifically how this can be accomplished. In our opinion LPDS provides a framework for structuring the project delivery process but does not provide specific tools or methods to accomplish the objectives of a lean production system. The tools, technologies and methods of the VDC framework provide the best toolset we know to accomplish the ideals of the LPDS. The objectives of both approaches are the same: to help improve the construction delivery process. One can argue that the LPDS approach is a more process based approach while the VDC approach is based on the application of technology to simulate the process. Practitioners today are trying their best to improve the construction project delivery process and are being asked to try out these and other approaches to improve performance on their projects. We hope that this paper will act as a guideline and an inspiration to industry practitioners on how they can merge these distinct approaches in construction research to improve the construction project delivery performance. In conclusion we can say the VDC is enabler of the LPDS.

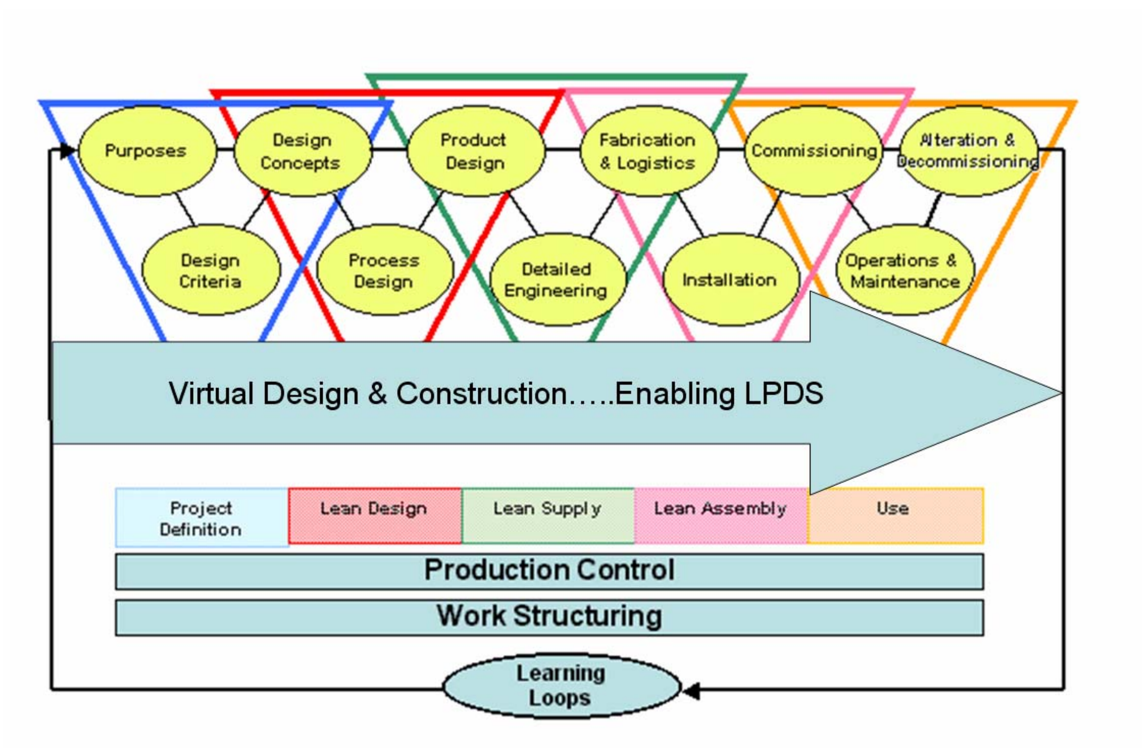


Figure 19: Figure shows the VDC is an enabler of LPDS.

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