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The Scope and Role of Information Technology in Construction

By

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THE SCOPE AND ROLE OF INFORMATION TECHNOLOGY IN CONSTRUCTION

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1. CURRENTLY PREVALENT SCOPE AND ROLE OF IT

To set the stage for the points in this paper we first summarize current use of information technology (IT) in construction. The last twenty years have seen dramatic improvements in and widespread use of IT to describe and document the work of the many disciplines involved in construction projects. Today, practically all project information is entered into software tools or generated by computer programs and is represented in the many different formats used by the many disciplines involved in a project. The software tools tend to be general purpose tools like spreadsheet and text processing software or specialized, discipline-specific tools like mechanical CAD programs or cost estimating software. As shown in Figure 1, the formats commonly used to represent information in construction include text documents, 2D and 3D drawings, schedules in bar chart and other formats, various diagrams and charts, tables, etc. For most decisions about a project, engineers from different disciplines like those shown in the picture of a typical project meeting (Figure 1) (a designer, project manager, cost estimator, scheduler, and MEP (mechanical, electrical, and piping) coordinator) need to share their information with others on the project team. The purpose of the meeting shown in Figure 1 was to coordinate the detailed design and construction methods, cost, and schedule for an office building. In this meeting, each engineer formed an image of the current status of the project and visions of future situations in his head based on his own interpretations of the documents from the other engineers. These interpretations formed the basis for discussions and decisions about the most appropriate design of the facility and its parts, when, how, and by whom it should be built, how long the whole project or a part of the project should take, how much things will cost, etc. In this way, a large portion of the planning and coordination on the project occurred primarily in the engineers' heads and was not supported by IT. In our experience, this use of IT is typical on projects. Because decisions are mostly based on personal and human interpretations of information generated by many engineers from many disciplines the decision process and resulting actions and results are not consistent and repeatable from meeting to meeting and project to project. As a result it is difficult to predict the outcome of the current design and construction process, and IT contributes little to predict the outcome of projects more reliably.

Since most of these discussions and decisions require the input of engineers from several disciplines, it is, of course of paramount importance that the information in the documents of the various specialists is based on the same information and that it is coordinated and communicated effectively. Coordinating and integrating information across disciplines and throughout several project phases has become increasingly difficult and costly as the amount of electronic information each discipline generates has increased.

Fig. 1: On every project, several specialists from different disciplines come together to plan the project and move it forward. Each specialist documents his or her work using different IT systems and formats to represent the information they need for their work.

At the Center for Integrated Facility Engineering at Stanford University, we have been working on methods and approaches to integrate project information and leverage information across disciplines and phases to create efficient work processes and enable better project decisions since 1988. There are certainly improvements necessary and possible in the software tools and underlying methods used by the individual disciplines today. However, in our opinion, the major opportunity for improving the design and construction of facilities lies at the interfaces between disciplines. Hence the remainder of this paper focuses on the role and scope of IT in support of multidisciplinary planning and coordination of construction projects. Finding a way to participate in such an integrated project design and construction process will be a key challenge and opportunity for individuals and firms in the foreseeable future.

2. EXAMPLES OF MULTI-DISCIPLINARY DESIGN AND COORDINATION

To illustrate the issues outlined above and to set up the role and scope of IT in construction we will consider two examples of multi-disciplinary design and coordination from recent projects.

(1) Renovation of a large office building
A large public owner recently needed to plan the renovation of one of its largest office buildings. Several functional units of the owner (e.g., real estate, operations, human resources, project management, facility management) as well as an external design team consisting of several consultants (e.g., architect, various engineers, construction manager) considered several options for this renovation. In one approach, all the tenants in the building moved out temporarily while the building was going to be renovated. This approach gave the design team maximum flexibility and opportunity to redesign the layout, structural and mechanical systems, etc. of the building and organize its construction. In another approach, only half the tenants moved out in the first phase to make room for the renovation of half the building. After the completion of the renovation of the first half the tenants in the second half would move into the new part to make room for the renovation of the second phase, which, upon completion, would then be occupied by the tenants who had moved out originally. This approach provided significant savings in the cost of leasing temporary facilities and minimized the impact of the renovation and move on some building occupants. However, it required the careful coordination of the spaces and various building systems into two self-contained parts and the careful planning and coordination of the renovation work with the remaining tenants.

(2) Large retail development
On a retail development that suffered a two-month delay due to unforeseen site conditions, the develop of the project asked the general contractor (GC) to develop a recovery schedule so that the project could still finish

at the originally scheduled time. Together with its subcontractors the GC considered various acceleration options and analyzed their resource and other organizational needs along with their schedule and cost impact. Together with the developer and some of the subcontractors the GC also evaluated several options to redesign parts of the project to enable partial opening or faster construction.

(3) Opportunity for IT support illustrated in the examples
These examples illustrate that many situations and decisions in construction require the involvement of several parties and tradeoff between scope, schedule, and organizational issues under consideration of cost, safety and other criteria. In the case of these projects the involved parties considered many of the tradeoffs in their heads, using some computer-generated descriptions of some of the aspects of an option, such as 2D and 3D drawings, cost estimates, schedules, or 4D models. However, virtually all decisions were made without formal predictions for the expected performance of a particular option with respect to decision criteria and business objectives.

These brief examples also highlight the challenges every company faces with respect to its physical capital assets. To provide the physical infrastructure for its own business, every company needs to:

- *Understand* the performance of physical assets and related organizations and processes in light of business objectives, over time.
- *Predict* engineering and business behaviors
- *Evaluate* predicted behaviors with respect to clearly articulated business objectives
- *Manage* the construction projects and the business to maximize measurable business objectives, e.g.,
    - Safety
    - Schedule
    - Cost
    - Delivered Scope
    - Sustainability

We suggest, therefore, that the principal role and scope of IT in construction should be the support of predictions of the anticipated performance of the design of a project's scope, schedule, and organization with respect to the business objectives of the projects' main stakeholders.

3. VISION FOR THE ROLE AND SCOPE OF IT IN CONSTRUCTION

This section provides an overview of the future role and scope of IT in construction and introduces integrated POP (product, organization, process) modeling in support of the challenges noted above and defines virtual design and construction (VDC) as a design method for more effective leverage of IT in support of integrated POP design (Figure 2). The following sections review the state-of-the-art in VDC and outline a few important research issues.

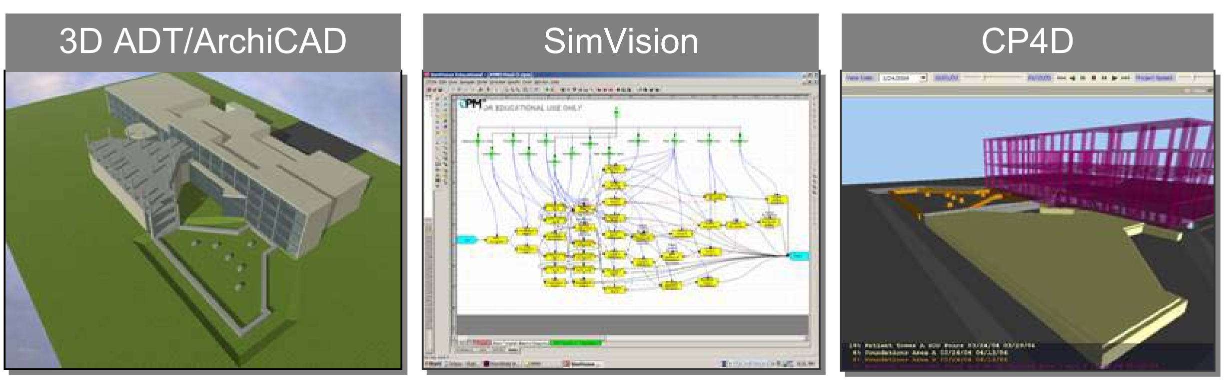


Fig. 2: Product, Organization, Process model using several commercial software tools.

(1) Role of IT
To support such predictions, practitioners will utilize IT to simulate, analyze, and evaluate the expected performance of the facility design, the design of the facilities delivery process (design and construction

schedule), and the design of the organization carrying out the process. These simulations, analyses, and evaluations should be based on an integrated model describing the designed facility, organization, and process. The simulation, analysis, and evaluation results should then be visualized so that the results make clear what the tradeoffs are between optimizing the facility, organization, and process design for a particular discipline vs. the overall project for the wide range of criteria typically found on construction projects. IT should also support automation of the generation of the input for simulation, analysis, and evaluation and automate the simulations, analyses, and evaluations as much as possible. Eventually, IT will support the optimization of a project's design from the perspective of multiple disciplines.

(2) Scope of IT

As illustrated in the two small case examples above, the scope of IT needs to be multi-disciplinary, i.e., IT needs to support the integration of the information and perspectives about project alternatives for many disciplines. IT also needs to cover the design of the product (facility, project scope), the project organization carrying out the design and construction, and the process (schedule) to carry out the project. We call this scope 'integrated POP design', where POP stands for product, organization, and process. As the examples illustrate many decisions involve tradeoffs between product, organization, and process design. We suggest that the design of a project is not complete until the product, the organization, and the process have been designed and the interactions between these three areas understood. The reason for making the product, organization, and process of a project in the main scope of IT is that project stakeholders can decide what to build, who should build it how, and when to build it, i.e., the product, organization, and process design are the independent variables on a project. These decisions then lead to a particular performance of the integrated POP design with respect to cost, safety, and other project criteria. These performance predictions provide the yardstick to evaluate the relative and absolute merits of a particular design. Such an integrated POP design requires the modeling of the systems and components that make up the product, the actors, teams, task assignments, and other organizational aspects, and the activities that comprise the design, construction, and operations processes. The activities provide the main glue between the product design and the organization, since each component of the product design leads to one or several activities for its design, construction, and operation, and each actor or team in the project organization is assigned to one or several tasks.

(3) Definition of Virtual Design and Construction

Today, integrated POP design is largely done in the heads of project participants. We envision that integrated POP design will be carried out increasingly with IT. Modeling, simulating, analyzing, visualizing, and evaluating the performance of the product, organization, and process with IT simulates how the real project might happen. Therefore, we define Virtual Design and Construction (VDC) as the use of such multi-disciplinary performance models of design-construction projects, including the product (i.e., facilities), organization of the design-construction-operation team, and work processes, to support explicit and public business objectives.

By building POP project models early and often before committing large money or time, VDC supports the description, explanation, evaluation, prediction, alternative formulation, negotiation, and decisions about a project's scope, organization, and schedule with virtual (computer-based) methods. The advantage of computer-based POP design is that POP design is carried out with formal (computer-interpretable) models of the product, process, and organization. This is important to make the models and corresponding predictions and decisions consistent on a project and from project to project. Such a consistent design process will make it more likely that explicit and public project objectives can be addressed in an objective way. Virtual methods are also important because they can support the rapid generation of visualizations of aspects of a POP design to support the multi-discipline, multi-view, and multi-stakeholder design process. POP models are critical to support the efficient generation of the information needed for project decisions. Visualization of is critical to communicate the discipline-specific aspects of a project's POP models to the many stakeholders effectively. In the absence of (or in addition to) formal analysis and simulation methods, visualizations can also foster better design, planning, and coordination among the project stakeholders.

In summary, VDC provides an integrating theoretical framework to predict engineering behaviors, and systematically manage projects and the business using the predictions and observed data, to achieve measurable business objectives. The theoretical basis for VDC includes:

- *Engineering modeling methods* for the product, organization, process
- *Model-based analysis methods* including, schedule, cost, 4D models, process risks, etc.
- *Visualization methods*
- *Business metrics, strategic management*
- *Economic impact* (i.e., models of the cost and value of capital investments)

We are not aware of a project that has been designed, planned, and managed with integrated product, organization, process models that relate the different levels of detail needed by the key project stakeholders across disciplines and project phases. However, aspects of POP modeling can be found on many projects. The most relevant technologies are 3D, 4D, and building information modeling and organization-process modeling and simulation. The following sections review the role and scope and application of these technologies as observed in practice today.

4. PRODUCT AND PROCESS MODELING

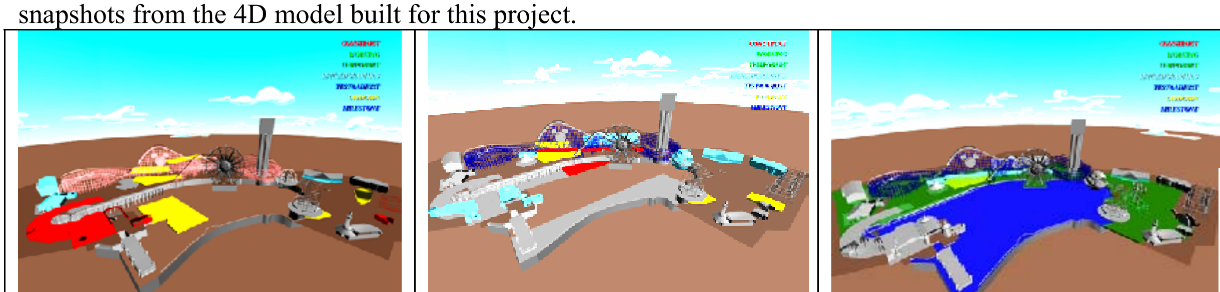
3D models are the prevalent method to represent the information that relates to the physical scope of a project. They are used increasingly on many types of projects, and their visualization and data modeling functionality and interfaces are increasing rapidly. Since 3D modeling technology is well-known, we will not elaborate it in this paper, but rather focus on 4D modeling, since 4D models integrate the spatial and temporal aspects of a project.

(1) The 4D Concept

4D Models link components in 3D CAD models with activities from the design, procurement, and construction schedules. The resulting 4D model of a project allows project stakeholders to view the planned construction of a facility over time on a computer screen and to review the planned or actual status of a project in the context of a 3D CAD model for any day, week, or month of the project.

(2) 4D Model Benefits

4D models enable a diverse team of project participants to understand and comment on the project scope and corresponding schedules in a proactive and timely manner. They enable the exploration and improvement of the project executing strategy, facilitate improvements in constructibility with corresponding gains in on-site productivity, and make possible the rapid identification and resolution of time-space conflicts. 4D CAD models have proven particularly helpful in projects that involve many stakeholders, in projects undergoing renovation during operation, and in projects with tight, urban site conditions.
For example, Walt Disney Imagineering used 4D models to plan the construction of the Paradise Pier portion of Disney's recently opened California Adventure in Anaheim, CA. Tight site conditions, a must-meet completion deadline, and many non-construction stakeholders made the project ideal for the application of 4D project management. The 4D model enabled the project team to produce a better set of specifications and design drawings for the construction of the project, resulting in fewer unplanned change orders, a smaller construction team, and a comfortable completion of the project ahead of schedule. Figure 3 shows several snapshots from the 4D model built for this project.



February 1, 2000	June 1, 2000	November 1, 2000

Fig. 3: 4D model snapshots

By improving project communications, the 4D models have reduced unplanned change orders by 40% to 90%, reduced rework, increased productivity, and improved the credibility of the schedule and the project management teams. The application of 4D modeling also demonstrated that an easy to learn and use 4D interface that allows the project team to maintain an up-to-date 4D model with little effort and that makes it possible to explore schedule alternatives easily is essential for the widespread deployment of 4D models.

(3) The Project Manager's Desktop: 4D Interface

An interactive, easy-to-learn and use, and flexible 4D modeling software was developed in collaboration between Walt Disney Imagineering Research and Development and the Center for Integrated Facility Engineering (http://cife.stanford.edu) at Stanford University. 4ure 3 shows the interface to the 4D software, which runs on the Windows platform. This interface allows the 4D modeler (typically the project scheduler) to organize, link, and view all scope and schedule information necessary for 4D modeling. The hierarchical organization of the project information makes it easy for the user to maintain the 4D model over the life of a project as more 3D and schedule detail become available. The drag and drop functionality makes it easy to link 3D model components and activities. The resulting 4D model enables everyone interested in a project to grasp and review schedules quickly.

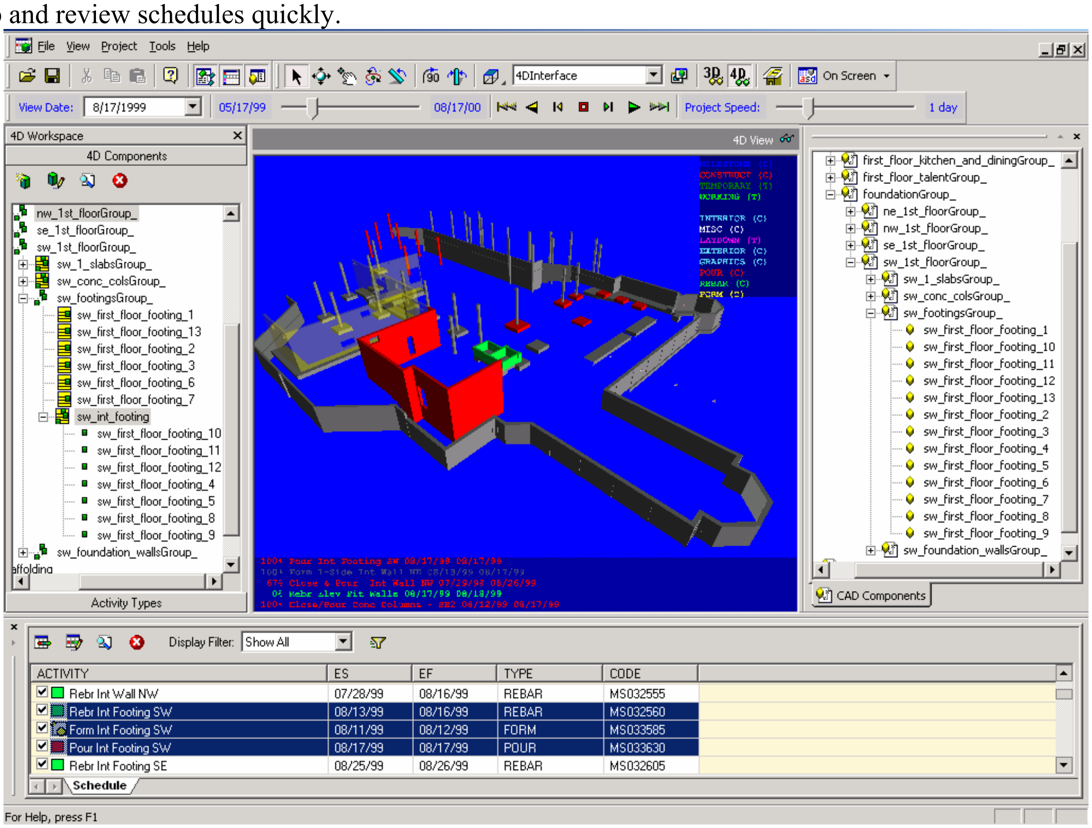


Fig. 4: 4D Model Interface, commercially available from Common Point, Inc. (http://www.commonpointinc.com).

The top part of the interface contains the time and space controls to orient and position the 3D model in the central window and to move through time in various ways (selecting a date, moving the time slider, or using the video-like controls). Users can also select the speed (intervals) for displaying the model. Here, the speed is set to 1 day, meaning that the 4D View window will show the activities that will take place on the various 3D components day by day. The CAD Components window shows the hierarchical organization of the 3D components that make up the building. This 3D model organization is imported from a Virtual Reality Markup Language (VRML) file produced by any 3D modeling software. The Schedule window shows the activities that are needed to build the project. The colored boxes next to the activity names indicate the color in which a particular type of activity will be displayed in the 4D View window. The activities and corresponding fields are imported from scheduling software like Microsoft Project or Primavera's Project Planner. The 4D Components window shows the 4D components organized hierarchically. A 4D component includes one or several CAD components (copied from the CAD components window) that is linked to one or several activities from the schedule. The 3D model can be reorganized in any way necessary for schedule visualization. For example, the 4D modeler grouped several of the footings from the CAD Components window into a 4D component called sw_int_footing (highlighted in the 4D Components window). In the Schedule window, the activities needed to build the collection of footings called sw_int_footing are highlighted (rebar, form, pour). The 4D View window shows the pouring of the concrete for these footings on Aug. 17, 1999 in red as well as other activities scheduled for that day in their respective colors.

(4) Implementation of 4D modeling
On every project, project managers, superintendents, and schedulers run mental 4D movies in their heads to think about the construction of the project. These professionals find it easy to relate to 4D models and to understand and use them. The application of 4D models has been particularly successful when focused questions about the constructibility of a design and related schedule are asked (e.g., in what sequence should the roller coaster for the Disney project be built?). Owners and contractors have been able to build 3D and 4D models that help address such questions within a few dozens of hours, which makes it economical and beneficial to support a project team's decision making with 4D models.

4D models have been built in the (early) planning phases of a project (often before the design of the facility has started or in the early phases of project design) for purposes like the following:

- 4D models for multi-year, multi-phase campus retrofit/renovation projects to sequence the individual building projects in the best possible way to support operation of the campus during the retrofit phase
- 4D models for reconstruction of facilities while they are under operation to collect the input of the affected stakeholders and synchronize construction with the operation of the facility
- 4D models for the construction phase of projects with tough temporal or spatial conditions to provide early constructibility input to the design
- 4D models for the expected (predicted) degradation of a number of buildings over their life cycle to match the needs for a level of service from a facility to the business drivers and objectives related to the facility owner's core business
- 4D models to simulate the operational procedures in industrial facilities to provide early operational input to the design

During detailed design or early construction phases, 4D models have been used in the following ways:

- 4D models to plan construction work in detail to coordinate the various subcontractors and make them more productive
- 4D models to simulate the operational procedures to refine the procedures and to keep up the operational input to design

4D models built during the start-up and operational phases have focused on issues like:

- 4D models of the operational procedures to train operators and make the start-up phase more productive
- 4D models of the life of facilities to plan future extensions, maintenance activities and budget in relation to the business needs of the facility owner

The following examples illustrate some of these uses of 3D and 4D models.

(5) Examples of 4D model application

a) Helping an owner visualize the future
DPR Construction has used 4D models to win two major expansions and one new hospital construction project. A 4D model links a project's 3D model to the schedule and generates a 3D model for any desired time interval (e.g., for each day or week of the project). A 4D model can be viewed as a continuous movie of the steps to get a project done or in snapshots at selected time intervals. 4D models allow the rapid study of different design and schedule alternatives. DPR's project managers used 4D models to demonstrate to hospital administrators that they had the best approach for maintaining 24/7 operation of critical care facilities. In all three projects DPR won, hospital administrators approved a budget line item for 4D modeling after seeing the 4D model during the proposal stage. Administrators have subsequently used their 4D models to educate physicians and staff about what would be happening during each stage of construction. DPR's 4D models subsequently maximized the construction staff's understanding of the operational needs of the hospital so that the construction approach and schedule minimized the risks to the hospital operations. On one hospital campus, the 4D model alerted the hospital to the need to change the flight plan for the medevac helicopter during steel erection (Figure 5).

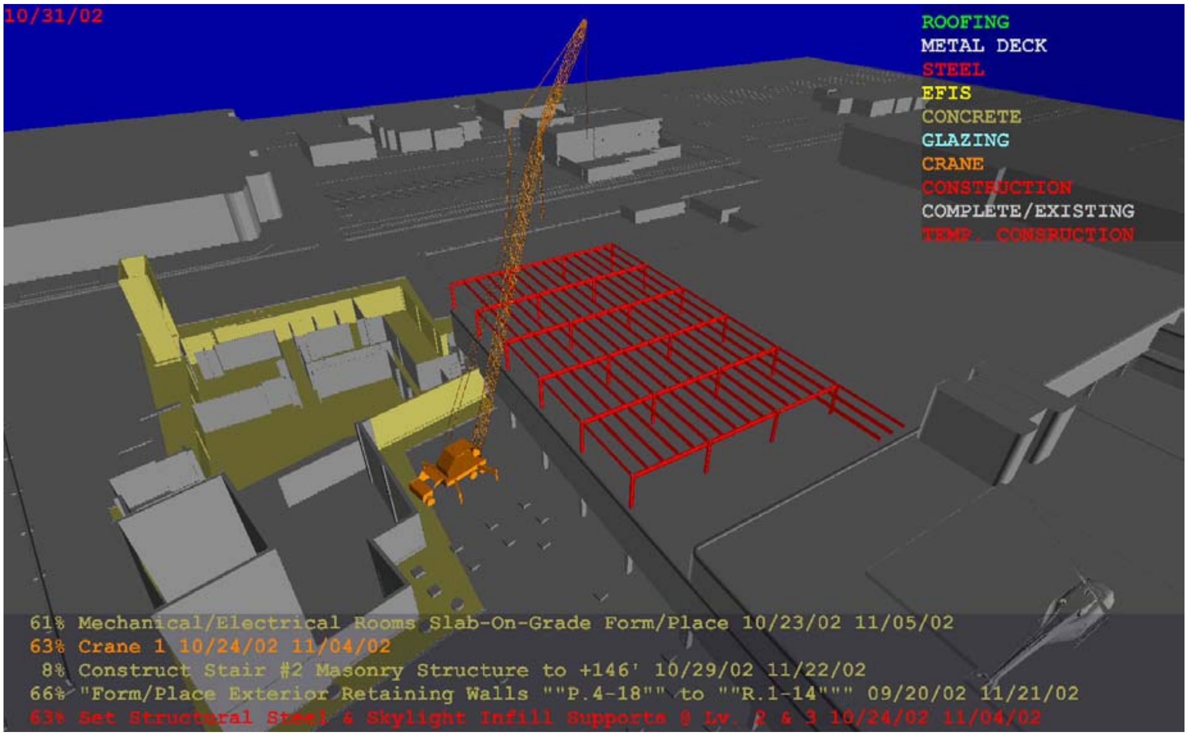


Fig. 5: Early identification of the interference between the crane needed for steel erection and the flight path for the medevac helicopter allowed the Banner Health Good Samaritan Hospital in Phoenix, AZ, to request timely approval of a modified flight path from the Federal Aviation Administration (FAA) in the U.S. (Picture courtesy of DPR Construction)

b) 3D model – cost integration

Designers and contractors are starting to take advantage of automated quantity takeoff functionality available in 3D CAD tools for cost estimating. 3D CAD tools have offered the ability to take off quantities for quite some time, and estimating tools, such as Timberline's Precision Estimating, have been able to import these quantities as part of an estimate's quantity takeoff (Figure 6). Cost data that is represented to match 3D design data will enable engineers to leverage design data for cost estimating much more rapidly than possible today. For example, Webcor Builders in San Mateo, CA, experimented with the use of 3D models for automated quantity takeoff and found that estimators could build a 3D model (with Autodesk's Revit software) and take off a project's quantities in less than half the time than they would need for the same quantity takeoff from 2D drawings (Bedrick 2003). In addition to the advantage of doing the same job faster, such a model-based quantity takeoff reduces the variability of takeoff numbers between different estimators and greatly increases the speed of re-estimating a project when the design changes.

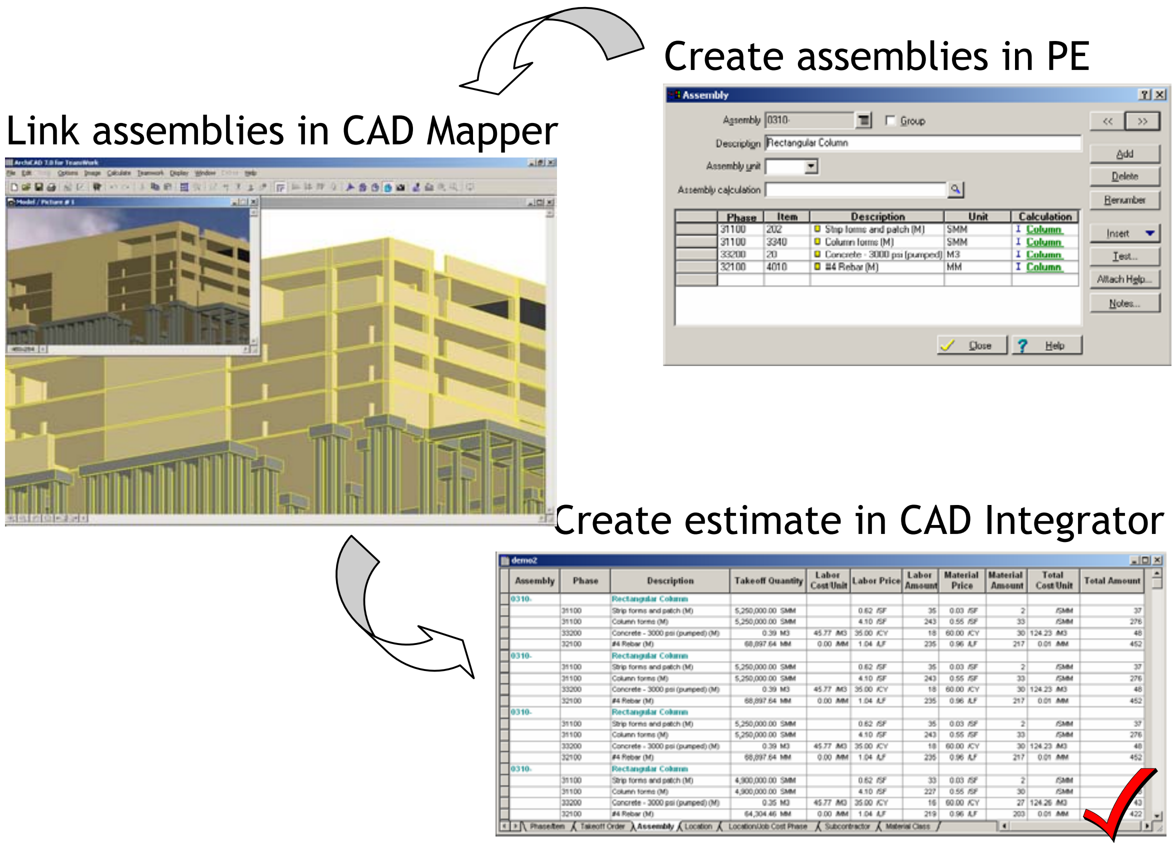


Fig. 6: Overview of 3D model – cost integration. The 3D model provides the bill of materials and quantities of a building design.

c) Concurrent detailed design for just-in-time fabrication and construction

On the Terminal 5 project at Heathrow Airport in London, the concrete contractor faces an extremely tight site that accommodates only three days worth of materials in support of construction. Hence, the typical reinforcement detailing, submittal, review, and approval cycle that lasts several weeks was not a feasible approach. The contractor needed to make sure that the detailed design could happen very quickly and was extremely well coordinated so that it could not only ensure the on-time ordering, fabrication, and delivery of the right reinforcement, but also take advantage of prefabrication opportunities as much as possible. With the support of Strategic Project Solutions, San Francisco, CA, the contractor (Laing O'Rourke, London, UK) used detailed, parametric 3D models (built with I-deas by EDS, Plano, TX) to support an integrated detailed design team. This approach was, for example, used for the design of the reinforcement for the machine launch chambers of the Heathrow Express Extension. A boring machine will connect a new cut-and-cover tunnel to the existing tunnels under the airport, beginning from the tunnel eye. The reinforcement at the tunnel eye proved exceptionally difficult to design for pre-assembly, so a cross-functional team including the structural designer and the builder was assembled to reach a solution that satisfied all stakeholders. The 3D model prototype was used for design coordination of this complicated area as well as detail drawing production and material procurement. An integrated team was created, a solution agreed to and modeled over a two week period. The team consisted of one lead engineer from the builder (Laing O'Rourke), one site foreman (Laing O'Rourke), one rebar detailer from Mott MacDonald, Dublin, Ireland (who also acted to preserve the structural integrity of the design while accommodating the principles of design for assembly), and one civil engineer from Laing O'Rourke operating the I-deas system. Over five work days the site foreman and the civil engineer built the virtual 3D prototype model in real-time on the computer (Figure 7). This 3D modeling effort was leveraged with a few one to two hour meetings with the entire team with the model being projected onto the wall for further real-time prototyping. This process reduced the number of review sessions to a minimum and ensured that the detailed design was well coordinated and maximized prefabrication opportunities and field productivity and safety. The availability of information and people were the major constraints for this process; building the model was very quick.

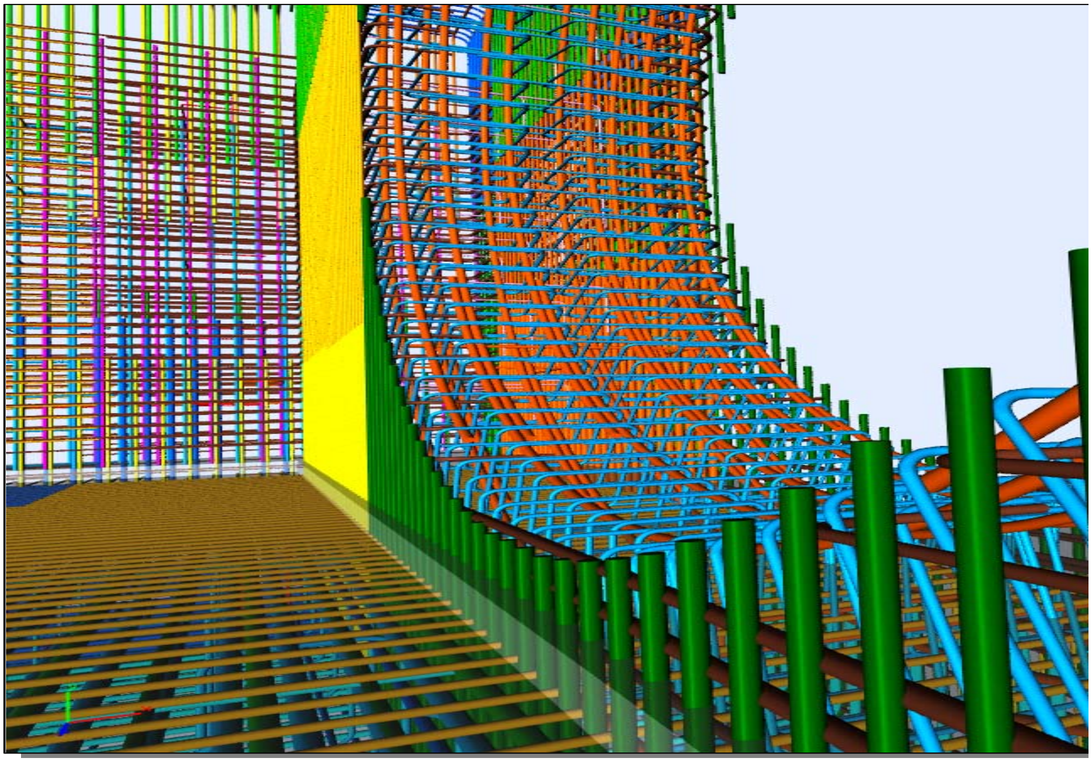


Fig. 7: Detailed, integrated reinforcement steel design with 3D models. (Picture courtesy of Strategic Project Solutions).

d) Construction coordination

For the construction phase, general contractors are using 4D models to coordinate the workflow of their subcontractors and site logistics over time, and to validate early on that their thinking of the project's overall sequencing is correct. M.A. Mortenson, for example, used 4D models for the construction of the Walt Disney Concert Hall to improve its construction schedule and to communicate the scope and schedule of the project to subcontractors and other stakeholders to solicit their input in a timely manner. The project's general superintendent, Greg Knutson, estimated that for every hour he spent working on the schedule he needed about six hours to communicate the schedule. The 4D models allowed him to reduce that time while increasing the amount of subcontractor feedback and buy-in. Mortenson built most of the 4D models before construction and updated the models monthly throughout the first year of construction. Prior to construction the 4D models were used live during subcontractor coordination meetings to review the sequence of work and related logistics and improve the constructibility of the schedule in collaboration between the general contractor and the subcontractors. During construction, the 4D models were used to preview the scope of work for the upcoming 90 days once a month in a subcontractor coordination meeting. By placing cranes into the 4D model, Mortenson and the subcontractors studied the placement of the cranes throughout construction to minimize crane movements and to ensure that the cranes could reach all areas of work as required by the schedule (Figure 8). Getting the crane usage right was particularly critical on this project, since crane access in many areas was limited to a relatively short period, which meant that the subcontractors had to organize the lifts they needed during those times. Because of the complexity of the project and schedule the 4D models were also very helpful in convincing various authorities that Mortenson had a good schedule on the project. This was particularly important for obtaining a permit to proceed with construction from the County. Since the County owns the parking garage on which the concert hall is constructed the County needed to approve the steel erection plan. Although Mortenson had generated a detailed plan (compiled in two binders) with step-by-step analyses of the crane needs and the structural reliability of the parking structure, the County was not clear on the phasing of the cranes. After several weeks of meetings with the County that did not yield the desired approval of the erection plan Mortenson showed the 4D model of the erection plan to the County officials. In 15 minutes the officials were able to understand more about the erection plan than they had been able to grasp in many afternoons of working through the binders.

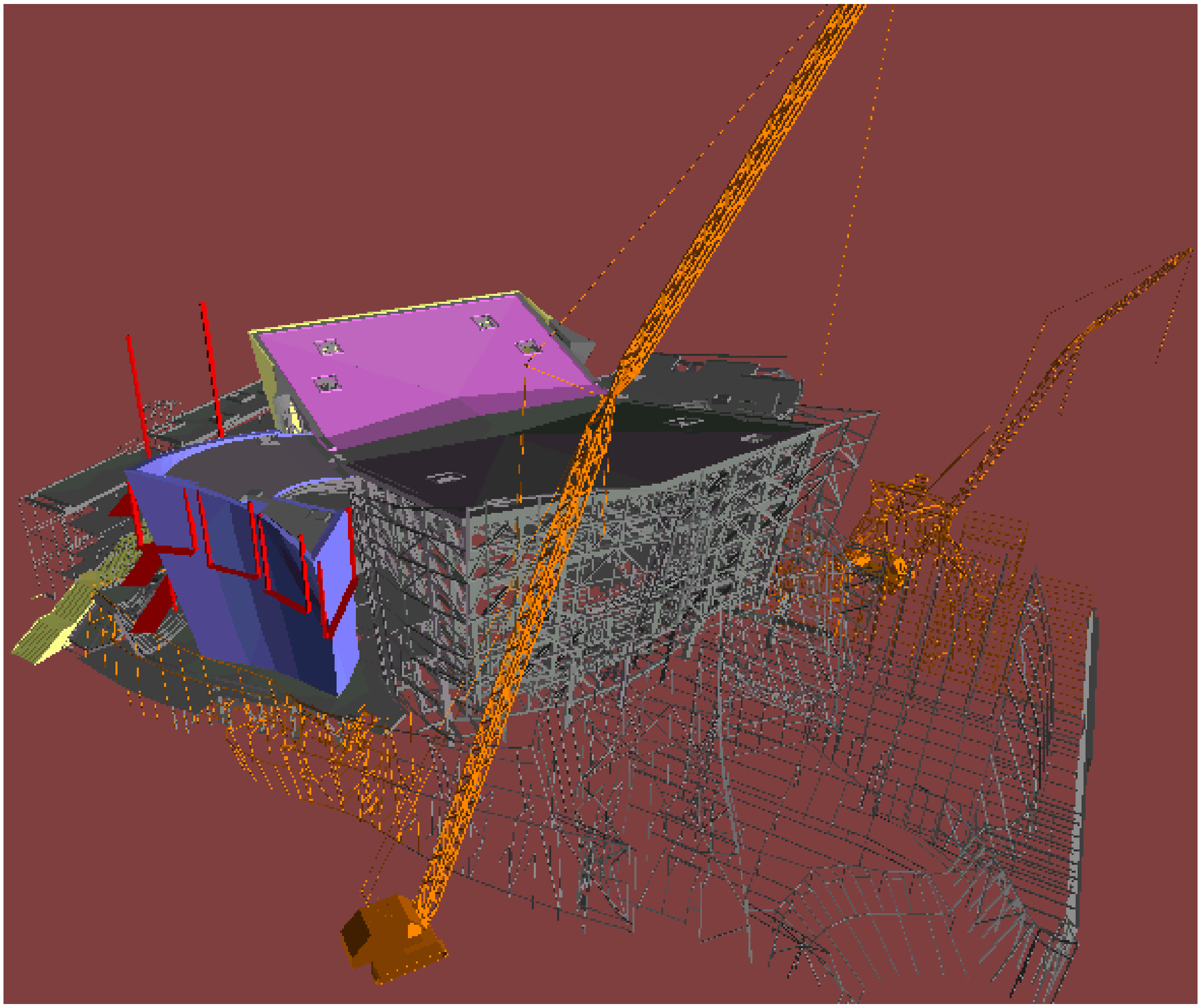


Fig. 8: Snapshot of 4D model for Walt Disney Concert Hall in Los Angeles.

e) Operations simulation and operator training

Operations simulation and operator training with a virtual model that includes a 3D CAD model (Figure 9), detailed data about each component (accessible via the graphical window or the tree structure on the left), and operating instructions and explanations (available as Word files) and linked to components in the 3D model.

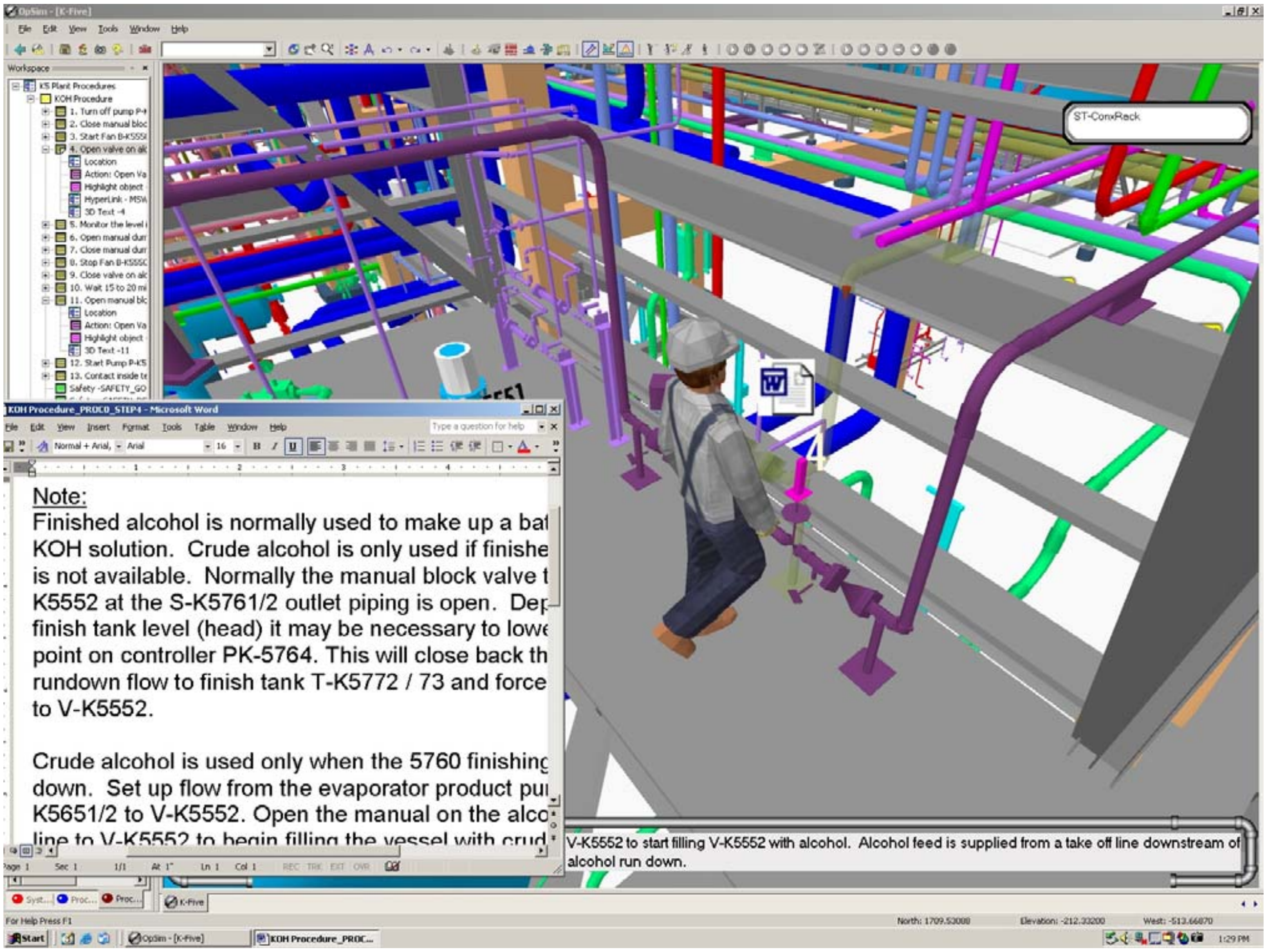


Fig. 10: Operations simulation and operator training with a virtual model leveraging the 3D model produced by the design engineers. (Snapshot of OpSim application courtesy of Common Point Technologies, Inc., San Jose, CA)

5. ORGANIZATION-PROCESS MODELING AND SIMULATION

The goal of the Virtual Design Team (VDT) project was to develop theory and tools that enable project managers to build computer models, or "virtual prototypes," of their project work processes and organizations, and then use the computer models to predict the performance of the project organization executing the given tasks. The VDT research project team had the vision that we could build theory and tools that enable project managers to design their organizations in the same way as engineers design bridges. With a theoretically founded organization and process analysis tool, a project manager could systematically diagnose schedule, cost, and quality risks associated with the planned configuration of the project. The PM could then "flight simulate" the project to explore the impact on project performance of a series of managerial interventions aimed at eliminating or mitigating these risks. After more than a decade of research and application, we, our students and collaborators have now used the VDT method on hundreds of industrial projects in many industries and in many Civil Engineering applications.

(1) Overview of Virtual Design Team application

The VDT conceptual model requires designing an input model of a project that can be simulated to produce predicted output behaviors. The input model has two main parts: the organization structure and the project work process. The organization structure consists of agents or positions in a reporting hierarchy. The project work process is the logical order of the tasks performed within that project. Both the agent and the task descriptions have a small set of attributes and relationships with each other. Agents in the hierarchy have assignments to complete one or several of the work tasks. Each task requires certain skills, and each agent may not or may in different levels have that specific skill. The VDT process model builds on the Critical

Path Method (CPM) assumption that tasks have precedence relationships. In addition, tasks may have coordination and failure dependence relationships that indicate respectively the requirements for task owners to discuss their designs and the requirement that dependent tasks must do rework if independent tasks encounter a problem. Figure 11 shows an image of a representative input model. The image is from the SimVision[1]® tool, which is the commercial version of the original VDT model.

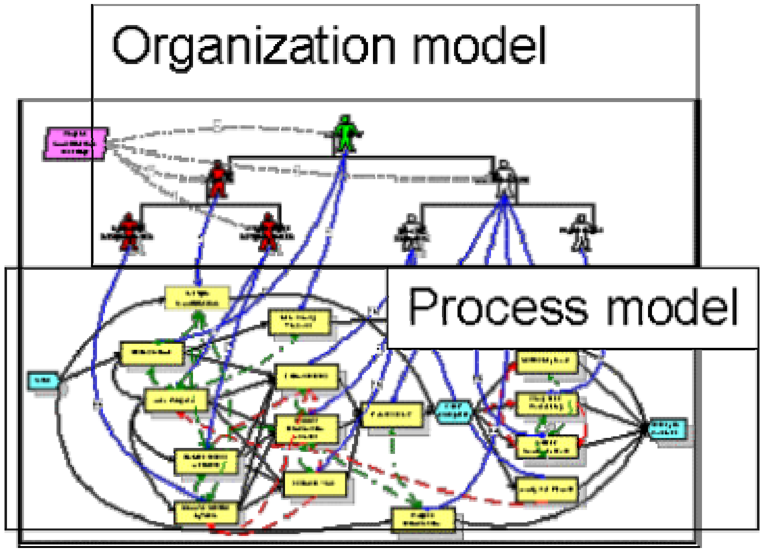


Fig. 11: VDT Input Model. This model shows the milestones (hexagons), tasks (rectangles), actors (human-like icons) and dependencies (connecting lines) for the pre-construction activities in developing a new biotech facility. Thus, the VDT model combines a traditional organization chart with a traditional project plan. In the computational VDT or SimVision model, each position and task is implemented as a computer "data structure" that has some properties and some relationships with other positions and tasks. Precedence relationships link positions to tasks (black lines). As in the Critical Path Method, precedence relationships link tasks. In addition, in the VDT method, tasks can have coordination and rework dependencies, indicated by green and red links respectively.

Given an input model for a project, the simulator invokes the VDT micro contingency theory of the way that positions do work on tasks. The simulation predicts the task and project schedule, coordination among positions and tasks, task rework, person backlog, project cost breakdown, schedule risk, quality risk and many more parameters. The schedule predicts in detail the duration of each task and whether it is on the critical path, i.e., whether the delay of that task affects the project duration as a whole. This process is called exception handling. Most importantly, the simulation explicitly predicts both the direct work to do planned tasks and "hidden" work to do coordination, rework and waiting for supervisory positions to make decisions.

The person backlog shows how much workload is in the "inbox" of each agent. The project cost breakdown shows the cost of work/rework, coordination and decision wait for each task. From these charts project managers identify the greatest risks to project performance and the tasks and positions responsible for those risks. The project manager can then intervene in the project design and change the design of the organization or the work process, with the objective to predict the impacts of those interventions. By repeatedly selecting interventions that are both feasible and valuable, the project manager and the project team can successively optimize project organization and process models. In other words, with VDT project managers can re-engineer the organization and process design by making predictions and selecting those redesign interventions that add value at an acceptable cost.

The functional quality risk chart shows the tasks at greatest risk of exception handling and failure, and thus measures the risk to project quality. The project communications risk chart measures the risk that positions will handle communications improperly and indicates the tasks with the greatest potential for being at risk. Figures 12, 13, and 14 show some of these charts.

[1] SimVision is a registered trademark of ePM.

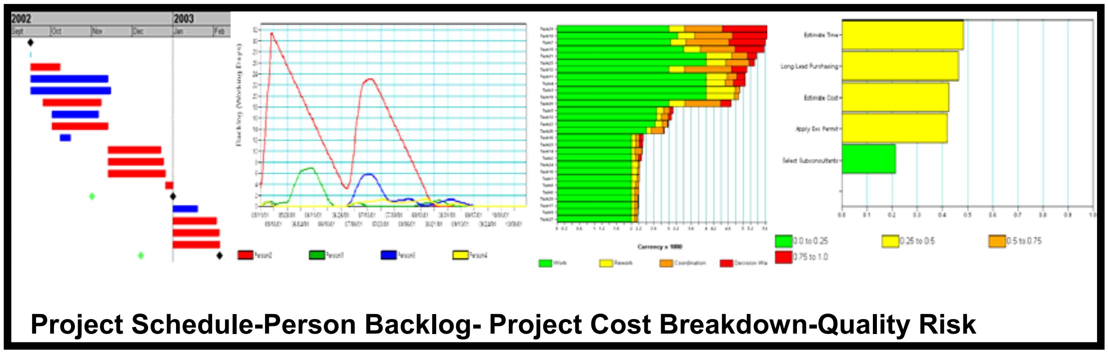


Fig. 11: VDT Outputs. VDT outputs are in the form of tables and charts. This chart shows VDT/SimVision predicted project schedule, person backlog over time, and project cost breakdown and quality risk. The project cost breakdown chart shows predicted direct work in green and predicted hidden work, i.e., coordination, rework and decision wait, in other colors.

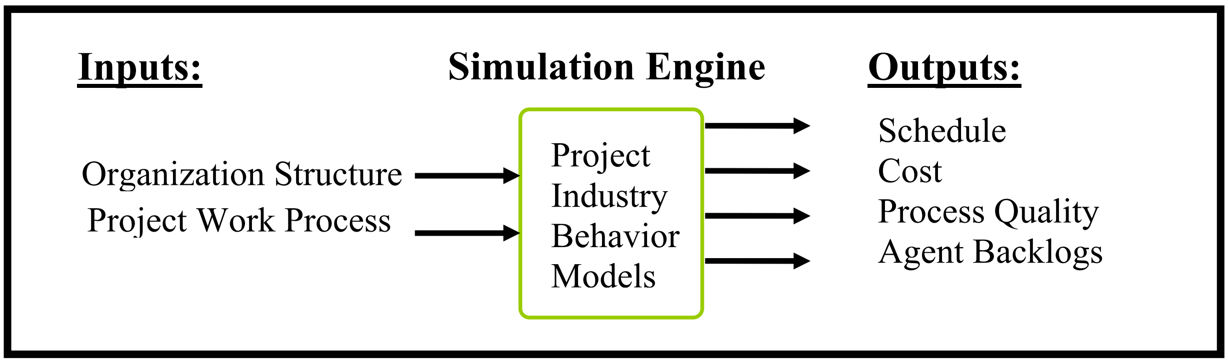


Fig.12: Overall conceptual model for VDT. Organization structure and the project work process and their relationships define the VDT input model. The simulation engine simulates positions doing tasks using the VDT micro behaviors. The simulation engine predicts the project schedule, cost, process quality, agent backlogs, etc. Based on the output we consider and then make changes to the input model and rerun the simulation, thereby optimizing the project design.

Figure 14 shows an "executive dashboard" that summarizes the duration, cost, and risk of a set of relevant cases, showing that the normal method of using the application is to develop different alternatives and quantitatively compare the performance of these different management alternatives. Figure 15 shows the prediction by the VDT simulation of the time, cost and process risk performance of a number of project design versions. The manager can see the predicted outcome of different designs and select the one that is most appropriate in the circumstance.

Legend	**Meets Goal**	**Almost meets goal**	**Unmet Goal**

Case	Sim Finish Time	Sim Cost (K$)	Risk	Comment
*Contractor increase staff	3/21/2001	244	0.515	Not feasible
All staff FT	4/16/2001	252	0.56	Very difficult for other projects
50% Design review/meetings	5/7/2001	353	0.48	Force quick owner decisions
Shorten 50% review tasks	5/21/2001	384	0.42	Encourage quick owner decisions
John Q. Full Time	6/6/2001	311	0.525	John Q. plus Gary FT
John H. Part Time	6/21/2001	324	0.545	John H. plus Gary FT
Don S. Full Time	8/5/2001	321	0.56	Don S. plus Gary FT
Gary S. Full Time	10/4/2001	335	0.485	
Split Contractor Tasks	10/19/2001	257	0.5	Add contractor resources
Gary, Amy 50%	10/22/2001	251	0.395	
Baseline	12/11/2001	350	0.515	

Fig. 13: Executive Dashboard for a project, showing a number of cases and the predicted project completion time, cost and process risk for each. Note that no case simultaneously meets the explicit duration, cost, and risk objectives of the project manager.

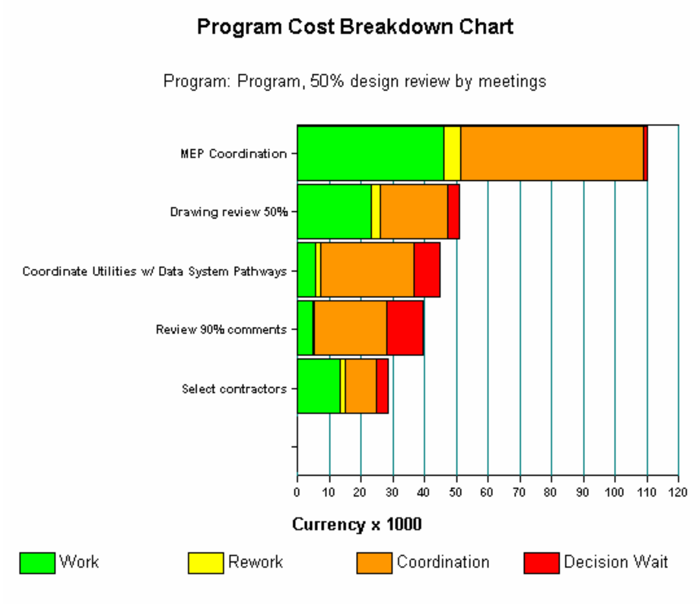


Fig. 14: Cost breakdown of tasks in a project. The VDT/SimVision simulation model quantitatively predicts the amount of direct work, rework, coordination and time spent waiting for an executive decision. The green area represents the direct work, as assumed by the Critical Path Method. The other cost segments represent the hidden work of coordination, rework, and waiting for decisions. This chart shows predictions for a project in which the volume of hidden work significantly exceeds the volume of direct work. One of the conclusions of VDT research is that hidden work represents a significant schedule risk to projects unless it is planned and managed carefully.

(2) Theoretical background of VDT Concepts

In Jay Galbraith's (1967, 1974) information processing view of organizations, the details of tasks are abstracted away, and work is viewed simply as a volume of information to be processed by an organization consisting of individuals or subteams with specified information processing and communication capacity. Galbraith's theory provided the kinds of qualitative predictions and recommendations listed above. VDT research operationalized and quantified Galbraith's theory at the level of individual tasks and project participants. VDT operationalizes the notion of exceptions and their resolution as packets of information passing through communication tool channels into the in-boxes of organizational participants. Actors use stochastically selection algorithms to select one of several items decide what to attend to from their in-boxes.

The information processing view of organizations, first conceived by March and Simon (1956, 1958), and introduced to managers by Jay Galbraith (1967, 1974), proposed that knowledge workers process information until they encounter "exceptions," i.e., situations in which the information required to execute a non-routine task exceeds the information available to the person performing the task. They then refer exceptions upward in the formal hierarchy to find someone who can provide the needed information to resolve the exception. In this perspective on organizations, which underlies much of organizational contingency theory (Burton and Obel, 1998), the supervisory hierarchy is the primary resource available to workers for resolving their exceptions.

Galbraith's early work focused on both the information processing limitations (the "bounded rationality") of workers and their supervisors to do work, answer questions or perform other tasks in a sequential manner, as well as the information communication limitations of earlier low bandwidth communication technologies such as memos and textual computer printouts. He asserted that bottlenecked supervisors and clogged information channels were the major limitations on the effectiveness of fast moving project teams, and proposed two kinds of generic strategies for addressing the information overload problem: reducing information processing demand, and increasing information processing capacity. Information processing demand on organizations is likely to continue to increase rather than decrease for the foreseeable future. Galbraith's second strategy proposes that organizations find ways to increase their information processing capacity. To increase organizational information processing capacity, he recommended that organizations: (1) use enhanced communication technologies (hardware and software) to augment vertical communication;

and (2) deploy matrix organizations with formalized multi-dimensional hierarchies and project-based teams to facilitate lateral communication.

Empirically and in theoretical models, exceptions that arise during project execution often result in significant amounts of additional (unplanned) communication and coordination between members of a project team. Recent VDT micro contingency theory of organization behavior, implemented as computational VDT models of organizations, assumes that project-based exception handling has largely been limited to traditional project teams where the majority of the productive project work occurs asynchronously (i.e., in a distributed, offline) mode (Jin and Levitt, 1996). VDT models have been able to predict when the emergent communication and coordination load associated with exception handling exceeds the processing capacity of affected members in significant real projects, and both prediction and empirical observation confirm that the impacts can include major schedule delays, quality issues, and cost overruns.

6. MULTI-USER MULTI-DISPLAY HUMAN-COMPUTER INTERACTION

short section about CIFE iRoom – to be added

7. BARRIERS TO EFFECTIVE USE OF VDC

In this section we would like to briefly explore some of the barriers we have observed towards effective adoption and use of VDC. It is important to be cognizant of these barriers because they often thwart implementation efforts, but they also present opportunities for companies who find a way around these barriers and for researchers to develop more integrated and automated approaches to POP design. In our experience these are some of the significant barriers today:

- Owners (CFOs) assess costs, not value of projects: We lack a formal and accepted method to determine the value of projects.
- AEC industry culture and methods minimize cost, not maximize value: Many IT systems are in place to account for costs, but very few examples exist of IT systems that address the value of projects. The same is true for university courses in construction.
- Sharp theoretical basis: Much of POP modeling and the interactions between product, organization, and process at the various levels of detail, across disciplines and project phases still needs to be formalized.
- Use that leads to improvement in the process and theory: We lack well-established metrics that would allow us to articulate the improvements VDC methods make over existing processes.
- Integrated tools: As noted the integration between the current commercial and research tools used for POP modeling is still challenging and time-consuming.

8. CONCLUSIONS

The many examples above show that many companies involved in the planning, design, construction, and operation of facilities are already leveraging their human assets and their information and information technology assets through the use of virtual building models. Companies use three different types of virtual building models (or POP – product, organization, process – models):

- *Visual 3D and 4D models:* These models help involve more stakeholders than is possible today early in a project to inject their business and engineering knowledge into the design of the facility, its schedule and organization, and they help to improve coordination in all life cycle phases. Such models can be built quite quickly today with commercially available software and can typically be funded from project budgets. They also currently offer an advantage to companies in getting work, but I don't think that this advantage will be sustainable in the long run. In the long term companies will need to figure out how to deploy such visual models effectively and efficiently across their projects.
- *Building Information Models:* These types of models support the exchange of data between software tools to speed up analysis cycle times and reduce data input and transfer errors. Their set-up, testing, and use cannot typically be financed on a project basis, but rather requires corporate funding. For example one innovative engineering company has been employing about 10% of its engineering staff in its R&D group to make their software and design methods based on product models and to learn how to use product model information other project participants produce to their benefit. When successfully

deployed, the ability to reuse project data to do more work with the same budget or the same work with far less budget should provide a competitive advantage that is more sustainable than that gained from visual models.

- *Knowledge-based models that support automation:* These models formalize and apply business and engineering knowledge to automate many of the tasks that are today repeated on a project and from project to project. These models require significant monetary and intellectual investment, but when completed they enable a company to apply and refine its knowledge base very quickly and cost-effectively. We expect that these types of models will give companies a significant competitive advantage, since they change the competitive landscape for a particular task by dramatically increasing the consistency and frequency with which a company can apply its knowledge base and by reducing the time needed to perform a task by one or two orders of magnitude.

This discussion of the role and scope of IT in construction is, of course, situated in the current industrial context with projects becoming increasingly complex technically, environmentally, socially, legally, and culturally, with increasing economic pressures on facility owners and therefore on their projects, and with shorter and shorter timelines. Putting these challenges into the POP framework:

- the high-performance *product* requirements create more interdependence between the product's subsystems
- the prevalent fast-track concurrent *process* propagates changes across subsystems in real time (this exacerbates product subsystem interdependence)
- *organizations* must process a larger number of changes, exceptions, decisions in less time

Hence an organization's capacity to process information becomes the limiting factor in determining schedule, cost and quality performance. Therefore, IT needs to support an organization's capacity to model, analyze, simulate, and predict a project's performance as outlined in this paper.

REFERENCES

John C. Kunz, Tore R. Christiansen, Geoff P. Cohen, Yan Jin, Raymond E. Levitt, "The Virtual Design Team: A Computational Simulation Model of Project Organizations," Communications of the Association for Computing Machinery, November, 1998, pp. 84-92.

Burton, Richard and Borge Obel, Strategic Organizational Diagnosis and Design, 2nd Edition, Kluwer Academic Publishers, 1998.

Galbraith, Jay and Edward Lawler, III (Contributor), Organizing for the Future: The New Logic for Managing Complex Organizations. Jossey-Bass Management Series), 1993.

Galbraith, Jay, "Organization Design: An Information Processing View," Interfaces, Vol. 4, May 1974, pp. 28-36.

Jin, Yan, and Raymond E. Levitt, "The Virtual Design Team: A Computational Model of Project Organizations," Journal of Computational and Mathematical Organization Theory 2 (3), Fall, 1996, pp. 171-195.

Levitt, R.E., G.P. Cohen, J.C. Kunz, C.I. Nass, T. Christiansen, and Y. Jin, "The 'Virtual Design Team': Simulating How Organization Structure and Information Processing Tools Affect Team Performance," in Carley, K.M. and M.J. Prietula, editors, Computational Organization Theory, Lawrence Erlbaum Associates, Publishers, Hillsdale, NJ, 1994.

March, James and Herbert Simon (with Harold Guetzkow), Organizations, Wiley, 1958.

Wegner, D.M., "Transactive Memory: A Contemporary Analysis of the Group Mind." In B. Mullen and G.R. Goethals (Eds), Theories of Group Behavior, Springer-Verlag: New York, NY, 1987, pp. 185-208.