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By

Sheryl Staub, Martin Fischer, and Melody Spradlin

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If you would like to contact the authors please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University,
Terman Engineering Center
Mail Code: 4020
Stanford, CA 94305-4020

Industrial Case Study of Electronic Design, Cost and Schedule Integration

Sheryl Staub[1], Martin Fischer[2] and Melody Spradlin[3]

[1]Project Engineer, Hathaway/Dinwiddie Construction Company
Santa Clara, CA 95054-2419, USA
Graduate Research Assistant, Dept. of Civil & Env. Eng.,
Stanford University, Stanford, CA 94305-4020, USA

[2] Assistant Professor, Dept. of Civil & Env. Eng.,
Stanford University, Stanford, CA 94305-4020, USA

[3]Project Manager, Hathaway/Dinwiddie Construction Company
Santa Clara, CA 95054-2419, USA

ABSTRACT

Construction professionals face increasing pressure to shorten the project delivery process. To meet these demands, contractors are compressing construction schedules by scheduling more activities concurrently. Consequently, contractors now have less time to execute their project management functions and they have increased demands for coordination as more activities are executed in parallel. Unfortunately, the tools used by construction professionals to manage and coordinate the construction process are still characterized by a paper-based exchange of information that results in inefficiencies and manual duplication of work. If construction professionals could use the electronic design information and integrate that information electronically with their project management software tools, many of these inefficiencies would be eliminated. Such integration would transform the way projects are estimated, planned, managed, and maintained throughout the project delivery process. Our vision is to use 3D CAD models that mirror the actual project, not only for design but also for project management functions. This paper shows the benefits that were realized by successfully integrating electronic design, cost, and schedule information on a construction project for Sequus Pharmaceuticals. The benefits include the automatic generation of quantity take-offs directly from design drawings, improved visualization of construction schedules, improved coordination of construction disciplines, and enhanced communication between design and construction. This case illustrates the status of commercial design, cost, and schedule integration software and highlights the resource requirements necessary to accomplish these tasks on a design and construction project. It also suggests that owners, designers, and builders of facilities will need to develop new skills and implement organizational changes to take advantage of these benefits. Specifically, owners will need to bring a project team together early in the project. Designers will need to focus more on the overall design and coordination of design tasks and less on detailed design. General contractors will need to learn how to manipulate 3D CAD models, work more closely with the designers during design development, and provide input on how to model designs in 3D so that the CAD models are more usable by constructors. Finally, subcontractors will also need to learn design software, as they will be performing more detailed design, working more closely with the architects and engineers through the design process, and addressing coordination issues early in design development.

INTRODUCTION

Current estimating and planning processes lack integration between electronic design and construction information. Construction estimators spend a significant amount of time interpreting design drawings, manually calculating quantities, and entering them into project estimates. This inefficient process is repeated as the design changes throughout the life of the project. Why do estimators perform this task manually when the information already exists and is available in the CAD drawings? Moreover, based on the same design and quantity takeoff information, construction schedules are created to show the sequence of construction operations and to coordinate the trades to optimize productivity and avoid spatial conflicts. However, today's construction schedules do not represent design information and the associated spatial requirements explicitly even though this information was used to create the schedules in the first place. Electronic integration of design, cost and schedule information reduces these inefficiencies, improves the estimating and planning processes, and increases the information content in the resulting CAD models, estimates, and construction schedules.

Commercially available software technologies can help project teams to integrate design, cost and schedule information. Such integration will allow construction professionals to calculate material quantities from design drawings automatically, to visualize the four-dimensional nature of the construction process, to improve the communication and coordination between sub-trades, and to enhance the communication between design and construction professionals. Although this software has existed for some time, the Pilot Plant for Sequus Pharmaceuticals located in Menlo Park, California is, to our knowledge, the first project where multiple firms have collaborated using an integrated suite of design and project management software.

In this paper, we describe the efforts of the project team to perform electronic design, cost and schedule integration on the Sequus Pharmaceuticals Pilot Plant from conceptual design to construction planning. Specifically, we will discuss the following:

- the software used and how it functions,
- the steps required to integrate electronic design, cost and schedule information,
- the benefits and shortcomings of the software,
- the changing roles of each discipline.

We first describe the Sequus Project and the software used to accomplish design, cost and schedule integration.

THE SEQUUS PROJECT

Sequus Pharmaceuticals is a pharmaceutical company located in Menlo Park, California. In 1997, management started exploring options to expand the company and build a Pilot Plant on a site in Menlo Park. The Pilot Plant was to be constructed in an existing unoccupied warehouse adjacent to their office building. 20,000 square feet are available, with 3,440 square feet of office space, 3,100 square feet of manufacturing space, 2,900 square feet of process development space, and 4,800 square feet of future expansion space. Figure 1 shows the 2D view of the 3D architectural model developed by Flad & Associates.

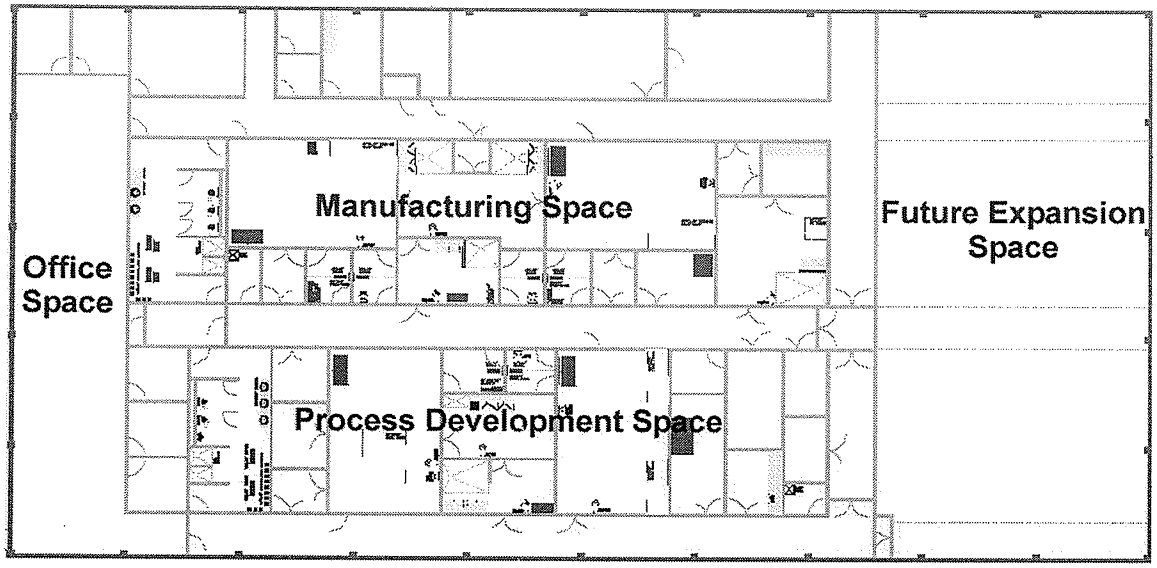

Figure 1: Architectural Layout of Sequus Project

THE DESIGN-BUILD TEAM

The general contractor assembled a design-build team based on each company's experience with using 3D CAD technology on past construction projects and the companies' experience in working with each other. The project team consisted of the following companies: the design firm Flad & Associates, the General Contractor Hathaway/Dinwiddie Construction Company (Hathaway), the plumbing subcontractor Rountree Plumbing, the HVAC subcontractor Paragon Mechanical, and the electrical subcontractor Rosendin Electric. A common goal for each member of the project team was to explore the use of existing software to integrate CAD technology with cost and scheduling software. Figure 2 shows the software used for design, cost, and schedule integration. The CAD-estimate link developed by Ketiv and Timberline supports design-cost integration. Jacobus Technology's Schedule Simulator provides design and schedule integration (4D, 3D + time). Figure 2 illustrates how the 3D CAD model in AutoCAD served as the core model for the estimating and planning software and facilitated the electronic integration of design and construction information. This figure also shows how all members of the project team were able to use the software tools with which they were familiar, tools that could leverage the 3D design information for their work. For example, the piping subcontractor used the electronic 3D model in Multi-Pipe for fabrication.

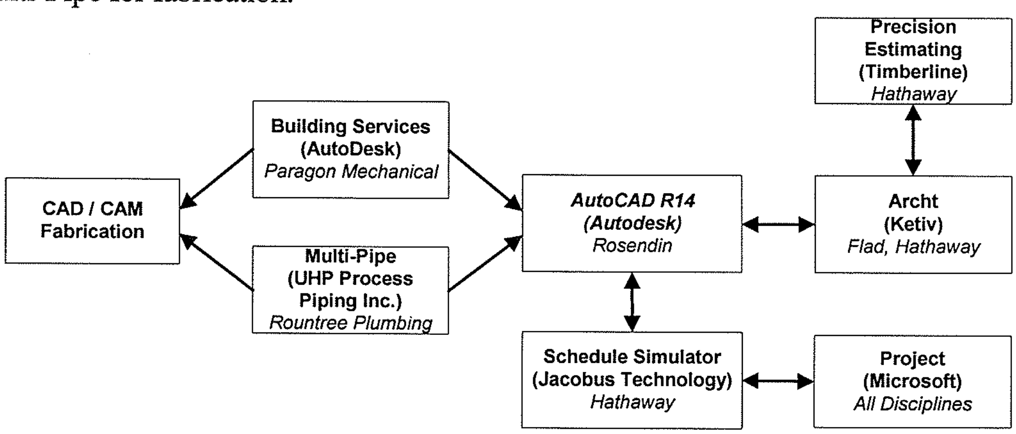

Figure 2: Software Used to Perform Design, Cost, and Schedule Integration

This was the first time each member of the project team built a 3D CAD model in a collaborative environment. This required a completely new way of transferring information among the different disciplines. Figure 3 shows how the 3D CAD model was transferred and shared between the different disciplines on the Sequus Project. The figure shows that the general contractor was the party responsible for orchestrating and managing the distribution of electronic design information.

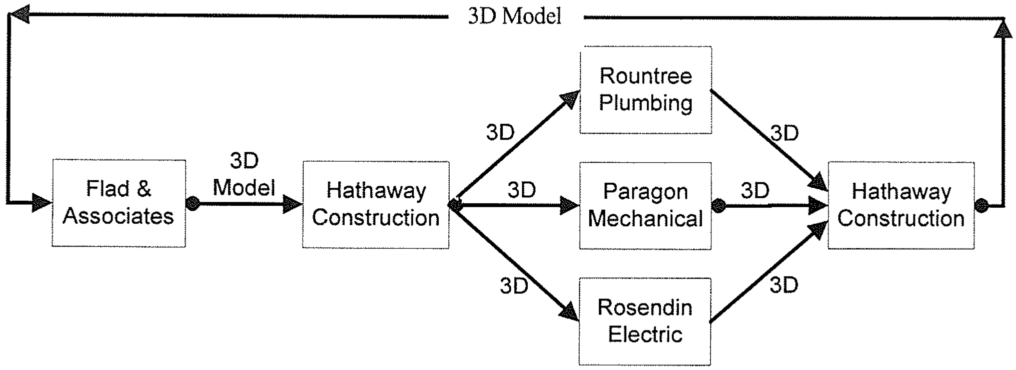

Figure 3: The Transfer of Design Information on the Sequus Project

The next section will discuss the essential steps required to perform software-based design-cost and design-schedule integration.

DESIGN-COST INTEGRATION

Overview of Steps

To perform design-cost integration, we linked estimating items and work packages from Timberline's Precision Estimating database with graphical objects created with AutoCAD R14 and Ketiv's Archt Architectural Drawing software package. Figure 4 shows an overview of these steps: work packages are attached to the objects in the CAD model, quantity takeoffs are calculated from within the CAD environment after all the work packages have been attached to CAD design elements, and estimating items are then revised if necessary. This process is repeated until the user is satisfied with the results.

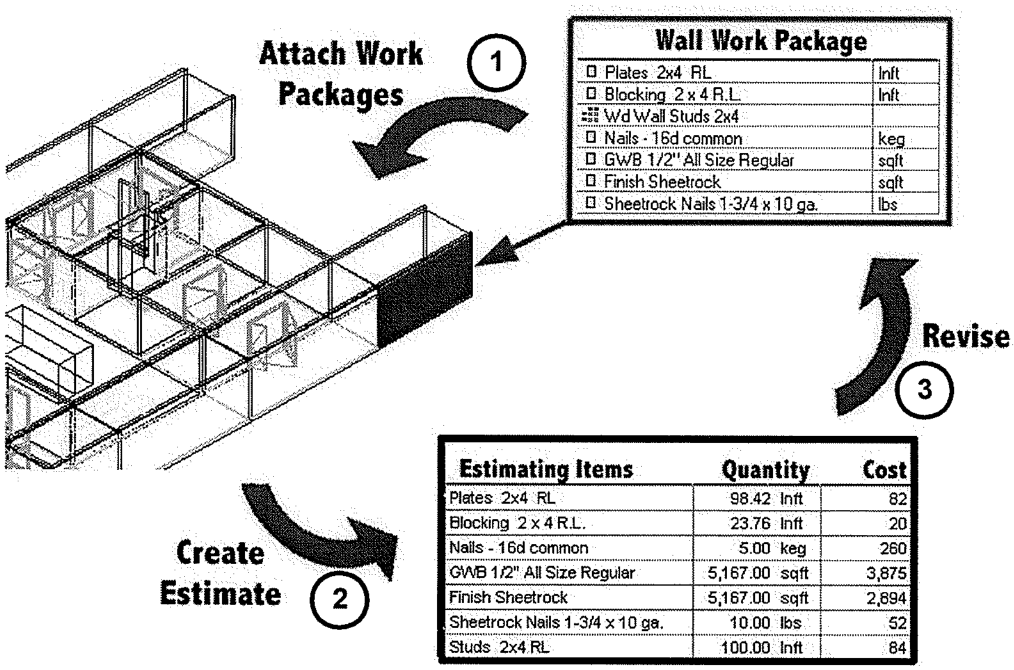

Figure 4: Overview of Design-Cost Integration

In Precision Estimating, the user initially performs setup procedures which structure the estimating items and work packages so that their variables can be linked with the appropriate CAD variables. Precision variables reside in the item or work package formula and define the unit of measure that will be used in the unit cost calculation, such as wall length or area. CAD variables are the dimensions of the graphical objects, such as length and thickness. To perform this link successfully, the user must have an understanding of the CAD model and how the graphical objects have been drawn so that the correct CAD variables are selected. Table 1 shows the most common types of CAD objects and the associated dimensions that can be extracted. Archt objects also include additional information called "XDATA" that can be extracted through the Precision link, such as "Wall Height" and "Wall Length".

Table 1: Common CAD Objects and Extractable Dimensions

CAD Object	CAD Dimension Extracted
3D Solid	Volume
Circle, or Closed Polyline	Area of object, Diameter of circle
Polyline with Thickness	Thickness
Line	Length

On the Sequus Project, the integration of design and cost information was complicated because the project team consisted of different companies. There is no central estimating database with all the items necessary to create accurate and detailed cost estimates. In addition, the Precision Estimating link with Archt was primarily designed for 3D CAD models drawn with Archt. On the Sequus Project, only architectural objects were drawn with Archt. The three subcontractors created their 3D CAD models using Multi-pipe, Building Systems, and AutoCAD R14. Consequently, the subcontractors had to draw their CAD objects with specific drawing methods to ensure that the dimensions necessary for quantity takeoff would be available. Figure 5 shows the CAD object for HVAC ducts, the dimension that was extracted, and the drawing method. Normally, HVAC ducts would be drawn using a 3D solid. However, as shown in Table 1, the only CAD dimension that can be extracted from a 3D solid is volume, which is not useful for estimating. Therefore, HVAC ducts had to be drawn as polylines with thickness to provide the desired graphical representation and CAD dimension for estimating purposes.

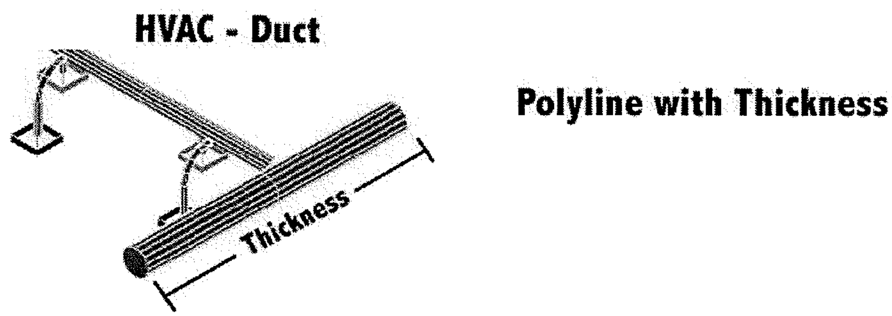

Figure 5: Example CAD Object and Associated Drawing Methods

Detailed Steps

Six steps were required to perform design-cost integration on the Sequus Pharmaceuticals Pilot Plant:

1. Add estimating items to general contractor's estimating database for all the disciplines, including crew production rates whenever possible. The average duration to create this database was three hours for each subcontractor and a total of 314 items were added to the estimating database.

2. Add formulas to estimating items added in step 1. This step is necessary whether one uses design-cost integration software of not. However, this step is particularly important when using the Archt-Precision link because the Precision variables identified in the formula will be linked with the CAD variables when the estimate is created. This step requires the estimator to interact with the CAD model so that the correct dimension is extracted for the corresponding estimating item. The total duration for this task was 6 hours.
3. Create work packages and item tables by grouping items created in step 1. This task was necessary because work package-based takeoff is usually more efficient than item-based takeoff, and the Archt-Precision link allows only one estimating record to be attached to each CAD object. The total duration for this task was 12 hours.
4. Modify CAD model, if necessary, to correspond to estimating items. For example, on the Sequus project, some walls needed to be "broken" to reflect different specifications. For example, a wall was designed as one object but needed to be broken into two objects because part of the wall was a full-height wall and part of the wall was an interior partition wall. Total duration for this task was 4 hours.
5. Attach work packages and items to each CAD model. The architectural model contained 117 entities, the HVAC model contained 185 entities, the electrical model contained 1,564 entities, and the piping model contained 3,139 entities. The total duration for this task was 12 hours. Figure 6 shows the three steps and the user interface to attach work packages or items in Archt.
6. Create estimates and troubleshoot. The total duration for this task was about 10 hours.

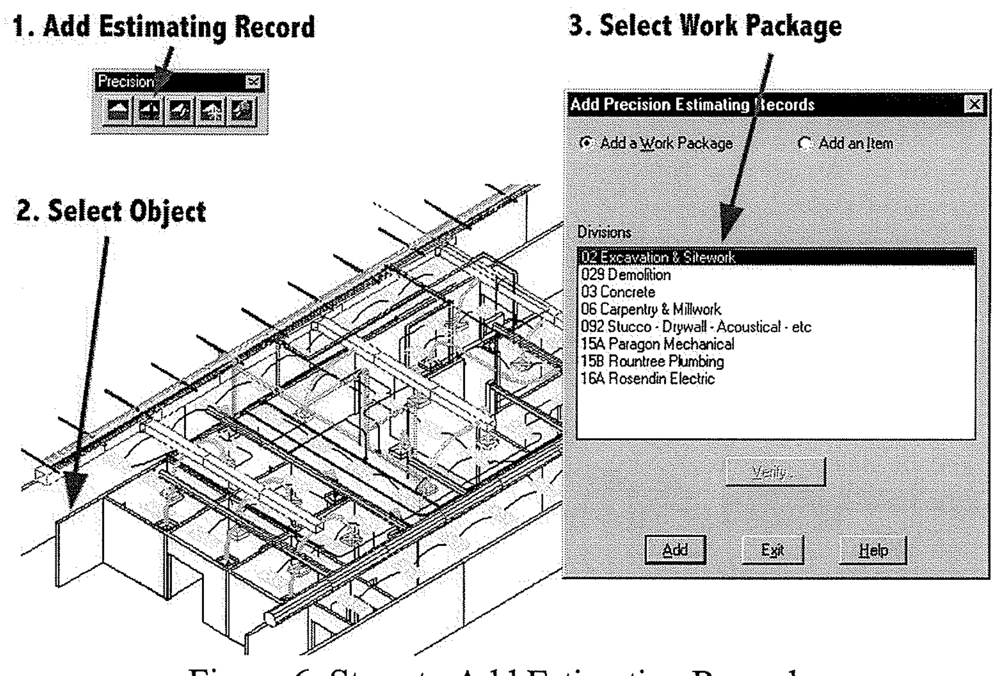

Figure 6: Steps to Add Estimating Records

Performing design-cost integration on the Sequus Project was particularly challenging because the Archt-Precision link was specifically designed for CAD objects drawn with Archt and Hathaway's Precision database had to be set up. However, as the project team applies this technology on more projects and their estimating database becomes more complete, the time it takes to perform this process will diminish and the benefits will increase accordingly.

EVALUATION OF DESIGN-COST INTEGRATION SOFTWARE

The main benefits are cost and time savings in the production of cost estimates, the generation of what-if scenarios, and the electronic documentation of estimating assumptions. Current limitations of the technology mainly relate to its use in a collaborative environment.

Benefits

- **The quantities are automatically calculated and inserted into the estimate**. Hathaway spent about 40 hours to complete the estimate on the Sequus Project (architectural features only). Hathaway reduced the estimating time by 25% by using the automated process.
- **What-if scenarios can be handled quickly**. Users can quickly compare the cost impact of different design and specification alternatives. The project manager at Hathaway estimates that the time it takes to perform what-if cost analyses could be reduced by 50%.
- **Archt provides electronic verification that all objects in the CAD model have been included in the estimate**. The user simply has to select the Archt option to identify "All Objects Not Having a Record" to verify the completeness of the estimate.
- **Archt documents the work package or item used for each CAD object**. During pre-construction, the estimator was reassigned. It was easy for the new estimator to determine where the previous estimator had left off because each CAD object contained the estimating assumptions. In addition, the estimator could query the CAD model and know exactly what CAD objects are related to a specific estimating item or work package.

Shortcomings

- The software can only extract certain types of information from the CAD model. This limitation forced the HVAC and electrical subcontractors to change their drawing process in some cases so that the appropriate dimension could be extracted.
- The user must always select the estimating item that is associated with each CAD object. Ideally, estimating items would be selected automatically based on a specific Precision variable and corresponding CAD variable. For example, the appropriate work package could be automatically selected for pipe objects based on their "pipe diameter".
- Only one work package can be attached to each object in the CAD model. This becomes an issue when a CAD object is associated with multiple estimating items that are not typically included in the same work package. For example, painting would not typically be included in a wall work package. To calculate the quantities for painting automatically, the user now needs to include painting in the wall work package or create a separate paint object in the CAD model.

The Sequus Project has demonstrated that design-cost integration software can help project team members to evaluate the cost impact of many design and specification alternatives rapidly, to validate and document the completeness and assumptions of their estimates, and to calculate material quantities automatically. These benefits will likely increase as CAD modeling software improves, as 3D CAD modeling becomes more commonplace, and standard design objects become more widespread.

DESIGN-SCHEDULE INTEGRATION

Overview of Steps

To perform design-schedule integration, we linked activities created in Microsoft Project with graphical objects created in AutoCAD, Multi-Pipe, and Ketiv's Archt (Figure 7). First, each discipline finalized the content of the Schedule model and the CAD model in their respective programs. Then, Hathaway's scheduling engineer exported each model in a format compatible with Jacobus Technology's Schedule Simulator. The scheduler then created a 4D model by linking the CAD objects with the Schedule objects.

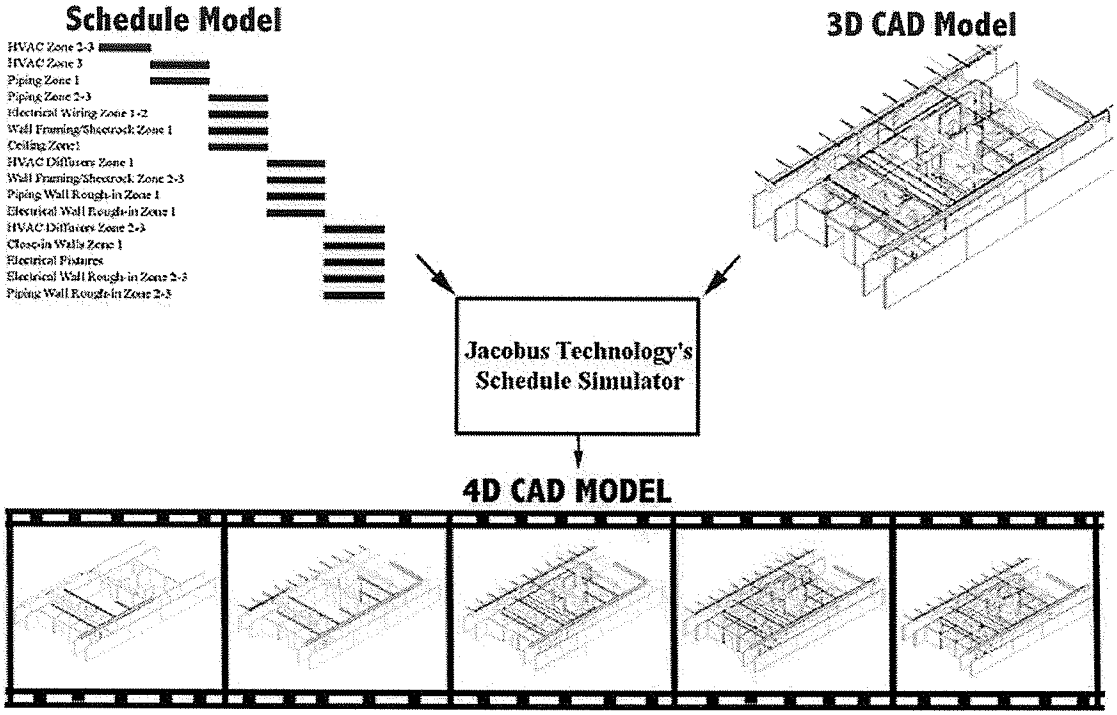

Figure 7: Overview of Design-Schedule Integration

Detailed Steps

The number of steps required to build a 4D model depends on the purpose of the model. If the planner needs a 4D model to support planning at the subcontractor level, additional detail may need to be added to both the schedule model and the CAD model. On the Sequus Project, the 4D model was going to be used to coordinate the mechanical, electrical, and piping work with the equipment installation on the mechanical platform. Consequently, the planner needed a detailed 4D model. To build a detailed 4D model, the planner first added activities to the schedule model to reflect work breakdown in zones. Next, the planner structured the CAD model such that the layering corresponded to the breakdown of work that existed in the Schedule model. Because most CAD drawings are not organized to represent the constructor's perspective, creating a 4D CAD model often requires the planner to modify the CAD models to reflect how the project will be built. Finally, to support automatic linking of schedule activities and CAD objects, the activity names within the Schedule model must be identical to the layer names in the CAD model. After this structuring is complete, the planner simply needs to execute a program that creates the link between the Schedule model and the CAD model by matching the activity names with the layer names. The planner may also choose to perform this linking manually rather than modify the activity names in the Schedule model and the layer names in the CAD model.

On the Sequus Project, the following steps were required to accomplish the integration of design and schedule information:

1. Modify the general contractor's schedule to reflect detailed subcontractor sequencing and work flowing in zones. There were over 800 activities in the general contractor's schedule. The total duration for this task was eight hours.
2. Change CAD layer names to correspond with the schedule's activity names and schedule's work breakdown. This involved creating new layers, renaming old layers and moving CAD objects to the appropriate layer. For example, the HVAC design model originally contained six layers. After the model was modified to correspond to the schedule activities, there were 22 layers. The total duration for this task was 12 hours.
3. Execute a program that groups objects in the CAD model based on the layer names. These grouped objects will then be related to the corresponding schedule activities.
4. Link the grouped objects from step 3 with the schedule activities. On the Sequus Project, the linking process was performed manually. The total duration for the manual linking task was 4 hours.

The process of integrating design and schedule information on the Sequus Project was particularly complicated because most CAD models are created without any consideration for how the designed objects will go together as they are constructed. This limitation will diminish as CAD systems become more object-oriented and allow easier manipulation of CAD objects.

EVALUATION OF DESIGN-SCHEDULE INTEGRATION SOFTWARE

4D models can help project teams to coordinate construction disciplines, to communicate construction schedules more effectively, and to assist in the identification of constructability issues early in design development. The limitations pertain to the effort required to set up the CAD and schedule models and to the lack of interactivity of the 4D models.

Benefits

- **The 4D model assists with coordination of subcontractor schedules**. On the Sequus Project, each discipline's 3D CAD model was combined with the project schedule, yielding a detailed 4D model where each discipline's CAD objects and schedule activities are represented simultaneously. This 4D model allows all members of the team to visualize their tasks and the relationships that exist between the different sub-trades. The 4D model was specifically used to coordinate mechanical, electrical, and piping trades (MEP) on the equipment platform, which contained the majority of the MEP work. It was particularly useful in coordinating the placement of equipment on the platform that was to be installed months after the duct work, piping, and conduit had already started.
- **The 4D model clearly communicates schedule intent**. Current construction management practice uses Gantt charts or CPM schedules to show the sequencing of schedule activities. 4D models, on the other hand, explicitly represent the construction in three dimensions of space, which is precisely what the planner is trying to coordinate. On the Sequus project, this was particularly useful in communicating the schedule intent to the owner.
- **By virtually building the facility on the computer screen, 4D models help identify constructability issues and sequencing problems prior to construction**. On the Sequus project, the 4D model helped identify access issues for equipment installation and identified what areas needed to remain clear to ensure that equipment could be installed as planned.

Shortcomings

- When creating CAD models, designers typically do not focus on how constructors will assemble the building components. As a result, the planner needs to modify the CAD model so that the CAD objects can be related to the associated schedule objects.
- The CAD objects do not know what building component they represent. Consequently, the planner must put this semantic content into the layer names. This limitation will diminish as CAD systems become more object-oriented and CAD objects become more standardized.
- A schedule needs to exist before a 4D model can be built. Many team members would have liked to create the schedule right in the 4D system.
- To link the CAD model and Schedule model requires significant understanding of how Jacobus' Schedule Simulator creates objects and classes from the CAD and schedule models.

Avoiding spatial conflicts during construction is a key concern for all disciplines of a project team. The use of 4D models on the Sequus project has demonstrated that this tool effectively represents the spatial needs of each discipline in one model, allows a project team to evaluate different sequencing alternatives, exposes potential constructability issues, and improves the communication and coordination between sub-trades.

PROCESS CHANGES AND ORGANIZATIONAL IMPACTS

The following sections describe the benefits each discipline received on the Sequus Project by implementing this technology and discusses the organizational changes each discipline will need to make to realize these benefits on future projects.

Owners

Potential benefits include improved visualization of construction schedules and the ability to quickly assess the cost impact of different design and specification changes. The representative for Sequus Pharmaceuticals selected this project team partly because of the benefits offered by this technology. The main selling points from his perspective were the rapid response to what-if scenarios and the improved cost and time control. In addition, he felt that the detailed 3D CAD models developed would help to avoid conflicts during construction resulting in lower construction costs. Finally, he anticipates using the detailed 3D CAD models after construction for validation, maintenance, and operation, and budgeting for future remodels or expansion.

These benefits will be realized if owners are able to bring a project team together early in the design process. The project team needs to develop detailed 3D CAD models collaboratively. As for the actual construction, there is no single organization that has all the expertise to build a complete and accurate 3D model. This collaborative process will require extensive communication to assurances that each member is on the same page.

Architects and Engineers

Flad benefited from Archt's 3D modeling capabilities. Traditionally, Flad would have created 2D plans and 2D elevations separately. There would be no link between the plans and elevations. Designing in 3D allowed Flad to create plans and elevations in one step. This link was particularly useful when the design changed, as Flad could make all modifications in one model.

Designers working in a project team performing design, cost and schedule integration will spend more time orchestrating the collaborative design process and less time performing detailed design.

They will establish the overall design process, develop the design specifications, and work collaboratively with all members of the project team. They will work closely with the general contractor in design development because the general contractor will provide input on how to build the CAD model so that the appropriate CAD dimensions can be extracted for design-cost integration and so that a 4D model can be built quickly. The project architect for Flad worked closely with Hathaway in the development of the architectural design. This collaboration allowed Hathaway to utilize the design information to perform design-cost integration. Hathaway provided input that included suggestions on how to model certain CAD objects and what objects to include in the CAD model. For example, Hathaway advised Flad to draw polylines for the ceiling and flooring so that the area could be extracted for estimating purposes. Flad would need to include this information when designing in the traditional process, but through collaboration was able to create design information that allowed the constructors to leverage its usefulness for construction.

General Contractors

Hathaway was able to reduce estimating time by 25% by using design-cost integration and believes the time to determine the cost impact of some what-if scenarios could be reduced by 50%. Hathaway compared estimating methods for the Sequus Project by creating an estimate with traditional methods and creating an estimate with the CAD-estimate link and found the estimates were comparable. The CAD-estimate link also provided electronic verification that all objects in the design had been included in the estimate. In addition, estimates created using the CAD-estimate link provided a record on how the quantities were derived. Finally, the project manager for Hathaway feels that 4D models are useful in coordinating construction tasks and communicating the intent of the construction schedule. The 4D model was particularly helpful in communicating the plan for equipment installation and coordinating the MEP trades on the equipment platform. Therefore, Hathaway believes the benefits offered by this technology justify further commitment and plans to use this technology on future projects.

General contractors will need training in CAD software so that they are able to manipulate CAD models and interpret how the CAD objects have been drawn. In addition, to perform design-cost integration, general contractors will provide input to designers so that the CAD objects are drawn in a way that supports automated quantity takeoff. Finally, general contractors are likely to become the keeper of the models during design and construction, as illustrated by Figure 3. Design information will be transferred by the designer to the general contractor and then from the general contractor to all the subcontractors. This flow of information will continue throughout the project as design changes are incorporated and propagated.

Subcontractors

Rountree Plumbing understands the benefits of linking design and cost information but believes that this process should be accomplished in-house. On the Sequus Project, we created a central estimating database that included all the disciplines' estimating items, and the General Contractor performed the integration. Ideally, Rountree would perform this integration in-house by linking their estimating software (QuickPen) with their CAD software (Multi-Pipe). Unfortunately, there is no electronic link between QuickPen and Multi-Pipe and between QuickPen and Precision Estimating. In addition, Rountree Plumbing has substantial experience in 3D modeling and has used 3D models on past projects to assist in coordination with other trades, to plan daily work activities, and for fabrication. Rountree Plumbing believes that 4D modeling will further assist in coordination with other subcontractors and will allow them to assist general contractors in the coordination process.

Subcontractors will work collaboratively with architects and engineers in the development of detailed designs for their disciplines. They will become more active in the early phases of design development as the architect and engineer develop the specifications and schematics that form the basis for their design. They are interested in being in control of the detailed design information so that they can use it to automate the fabrication of components. The subcontractors' detailed design will still require the approval of the architect and engineer through the shop drawing process. As a result, subcontractors will need to develop CAD modeling capabilities to benefit from CAD software that is specifically designed for their discipline. In addition, since subcontractors will become more active in the design process, they will also be able to assist the general contractor in the coordination of all the subcontractor trades throughout the project delivery process.

CONCLUSIONS

Construction professionals need project management software tools that facilitate integration of design and construction information. Such integration would eliminate many of the inefficiencies and redundancies that exist in today's project management processes and help project managers to meet the increasing demand of shortening the project delivery process. This study has demonstrated that electronic design, cost, and schedule integration is possible with today's off-the-shelf software products. The resulting benefits include shorter estimating time, fewer takeoff errors, better documentation and reproducibility of the estimating process, and use of the 3D model to communicate the construction schedule effectively. This study also shows that owners, designers, and builders of facilities will need to develop new skills and implement organizational changes to capitalize on the benefits offered by this technology.

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- Microsoft – Project: http://www.microsoft.com
- Timberline – Precision Estimating: http://www.timberline.com