Industrial Case Study of Electronic Design, Cost and Schedule Integration

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ABSTRACT

Even though most documents are generated electronically, today's project management processes are still characterized by a largely manual exchange of information based on paper documents. Project teams could benefit from software technology that has been developed to integrate design, cost, and schedule information. Some of these benefits include the automatic generation of quantity take-offs directly from design drawings, improved visualization of construction schedules, improved coordination of construction disciplines, and improved communication between design and construction. This technology has existed for some time and research has shown that it is technically feasible. However, we are not aware of a project team that has accomplished design, cost and schedule integration in a collaborative environment on an actual construction project. The Sequus Pharmaceuticals Pilot Plant is a project where a project team has implemented design, cost, and schedule integration and it forms the basis of our case study. On this bio-tech facility, a design-build team consisting of a design firm, a General Contractor, and three subcontractors has jointly developed a common 3D model from the very start of the project to link with cost estimating and scheduling software. The electronic integration of design and cost information was accomplished through the CAD-estimate link developed by Ketiv and Timberline. Design and schedule integration (4D, 3D + time) was accomplished through Jacobus Technology's Schedule Simulator. This case has provided us the opportunity to investigate the status of commercial design, cost and schedule integration software and to understand the resource requirements necessary to accomplish these tasks on an actual project. This study suggests that owners, designers and builders of facilities will need to develop new skills and implement organizational changes to take advantage of the benefits offered by this technology and to stay competitive in this changing market. Specifically, general contractors will need to learn how to manipulate 3D CAD models, work more closely with the designers in design development, and provide input on how to model designs in 3D so that the CAD models are more usable by constructors. 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. Designers will need to focus more on the overall design and coordination of design tasks and less on detailed design. Finally, owners will need to bring a project team together early in the project to capitalize on the benefits of this technology.

INTRODUCTION

Current estimating and planning processes are limited by the lack of integration between electronic design and construction information. A significant part of the estimating process involves the calculation of quantities, which is currently performed manually by scaling off two-dimensional paper drawings. But why do estimators perform this task manually when this information already exists and is available in the electronic design drawings? Additionally, construction schedules are created to show the sequence for how construction operations are to proceed. Yet how can construction schedules convey this message when commonly used scheduling tools don't represent design information and the associated spatial requirements explicitly? Integration of design, cost and schedule information is necessary to improve the estimating and planning processes and to reduce the inefficiencies that result from the current fragmentation between design and construction information.

New software technologies have been developed that will help project teams to integrate design, cost and schedule information. Such integration will allow construction professionals to automate quantity takeoffs, thus shortening estimating time and eliminating the duplication of effort that exists in current estimating practices. Integrating design and schedule information (4D CAD, 3D plus time) allows project teams to visualize the construction process and virtually build a proposed facility on the computer screen [Cleveland 1989, Collier and Fischer 1996, Williams 1996]. This 4D animation helps a project team to evaluate the constructability of a proposed construction sequence prior to construction, communicate the intent of the construction schedule, and coordinate sub-trades. The software described has existed for some time. Several firms are using parts of this software internally, and many people have speculated about its benefit to project teams [Nevins *et al* 1991, Teicholz and Fischer 1994, Wickard *et al* 1989]. We are not aware of a project where multiple firms have collaborated using an integrated suite of project management software. We have used such software for design and construction planning for the Pilot Plant for Sequus Pharmaceuticals, located in Menlo Park, California.

At the start of this project, a project team was created with the explicit goal of using existing software to perform design, cost and schedule integration throughout all phases of project development. The project team consisted of the following companies: the design firm Flad & Associates, the General Contractor Hathaway/Dinwiddie Construction Group (Hathaway), the plumbing subcontractor Rountree Plumbing, the HVAC subcontractor Paragon Mechanical, and the electrical subcontractor Rosendin Electric. This project team jointly developed a common 3D model from the very start of the project to link with cost estimating and scheduling software. The integration of design and cost information was accomplished through the CAD-estimate link developed by Ketiv and Timberline. Design and schedule integration (4D, 3D + time) was accomplished through Jacobus Technology's Schedule Simulator.

In this paper, we describe the efforts of the project team to perform design, cost and schedule integration on the Sequus Pharmaceuticals Pilot Plant. 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 will start by describing the current methods engineers and construction professionals use to generate estimates and schedule sequences illustrating the inefficiencies that are created by the lack of integration between design and construction information.

CURRENT PRACTICES

Creating and Using Estimates

Currently, there is a tremendous amount of effort required to transfer and interpret design information. Designers generate hundreds of pages of design drawings and several books of specifications for the contractors to analyze, estimate and schedule. However, the current method of transferring information requires general contractors and subcontractors to calculate quantities manually. Information that designers put into the drawings cannot be reused directly because the information transmitted from designers to estimators is not in a usable, electronic form. Calculating quantities is a critical part of the estimating and planning processes, as it effects material and labor costs, and activity durations. Yet the contractors do not have electronic access to this design information, giving rise to inefficiencies in the estimating process that increase estimating time and decrease accuracy. Design-cost integration software takes advantage of existing electronic design information, and provides the opportunity for contractors to automate part of the estimating process, to validate the completeness of their estimates, and to evaluate the cost impact of different design options quickly.

Creating and Using Schedules

A major task for construction planners is to determine the sequence of construction activities so that resources are allocated appropriately and coordination of sub-trades is optimized. Current project management practice uses CPM (Critical Path Method) schedules to represent the completion of a facility design over time. CPM schedules show the dependencies between activities, but they do not provide a link between the three dimensions of space and the forth dimension of time. Yet the interdependency between this information is critical for evaluating, monitoring, and coordinating the construction process. To improve coordination, general contractors often use architectural design drawings and overlay the different sub-trades' designs to coordinate the spatial needs of each discipline. While it brings the disciplines' design perspectives together, this approach still abstracts the 3^{rd} spatial dimension and the time dimension of construction work. 4D-CAD (3D + time) is a tool that allows constructors to link design and sequencing information explicitly and to evaluate the spatial needs of each discipline over time, thus improving communication and coordination between sub-trades.

In the next section, we will discuss the Sequus Project and the process by which information was transferred between members of the project team.

THE SEQUUS PROJECT

Sequus Pharmaceuticals is a biopharmaceutical company located in Menlo Park, California. In 1997, management started exploring options to expand the company and build a Pilot Plant on site in Menlo Park. The Pilot Plant was to be constructed in an existing unoccupied warehouse adjacent to their office building. The available space was 20,000 square feet, which was going to be broken down into office space, manufacturing space, process development space, and future expansion space. The final design has 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. The manufacturing space is made up of two compounding labs, a decontamination lab, buffer preparation with a weight room and air lock, and support areas. The process development area is made up of two process development labs, a decontamination lab, gowning areas, and support areas. Figure 1 shows the 2D view of the 3D architectural model developed by Flad & Associates.

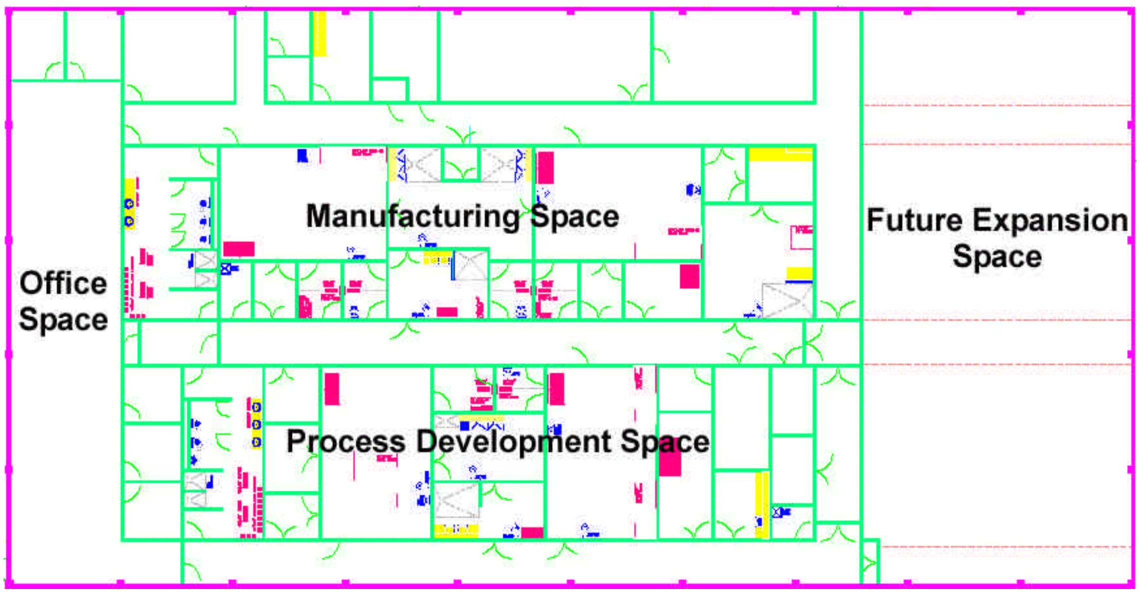

Figure 1: Architectural Layout of Sequus Project

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 team's experience in working with each other. 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 that will be utilized to perform design, cost and schedule integration.

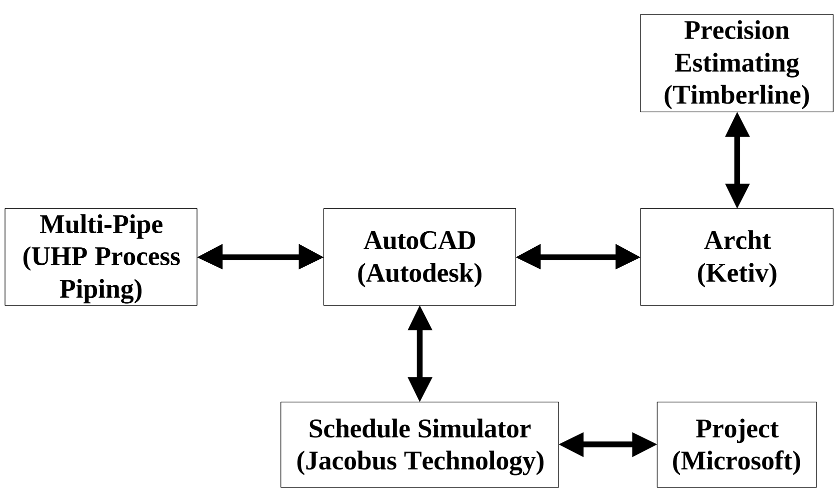

Figure 2: Software Used to Perform Design, Cost and Schedule Integration

This was the first time that each member of the project team built a 3D CAD model in a collaborative environment. As such, it required a completely new way to transfer information among the different disciplines. Figure 3 shows how the design information was transferred and shared between the different disciplines on the Sequus Project.

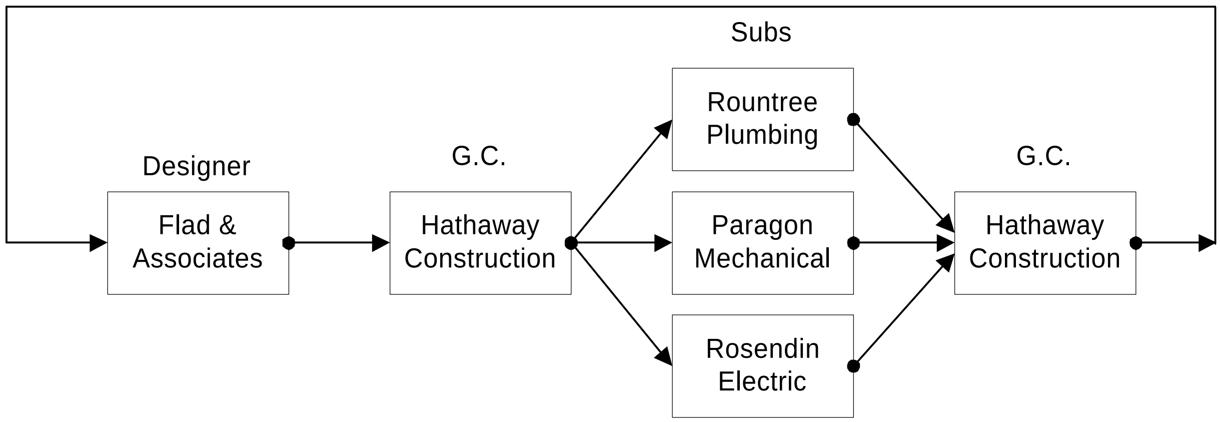

Figure 3: The Transfer of Design Information on the Sequus Project

Designing in a collaborative environment and utilizing design, cost and schedule integration software forced the project team to work together from the very start of design and to share information throughout all phases of design development. The general contractor was the party responsible for orchestrating and monitoring this process. The implications of this process will be discussed in later sections of this paper.

In the next section, we will discuss the steps required to perform software-based design-cost and design-schedule integration.

DESIGN-COST INTEGRATION

Process Description

To perform design-cost integration, we linked estimating items and work packages from Timberline's Precision Estimating database with graphical objects created using AutoCAD R13 and Ketiv's Archt Architectural Drawing software package. Figure 4 shows an overview of this process: work packages are attached to 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.

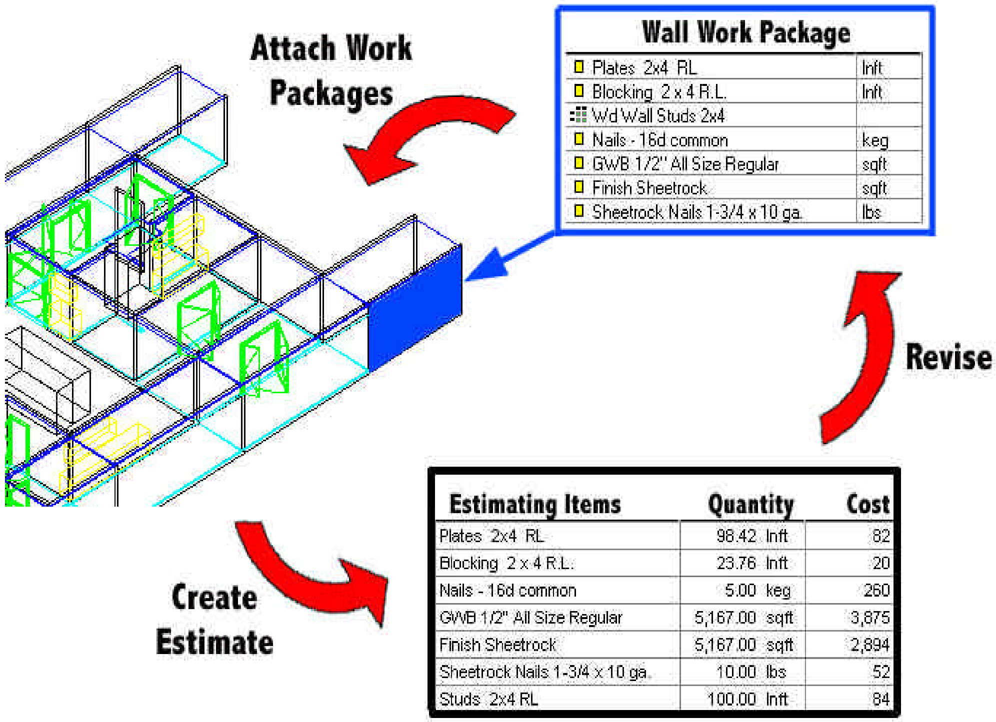

Figure 4: Overview of Design-Cost Integration

Process Details

In Precision Estimating, the user initially performs setup procedures which structure the estimating items and work packages so that they can be linked with the appropriate CAD dimension. The link is created by matching "Precision variables" with "AutoCAD 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. The table below shows the most commonly used CAD objects and the associated dimensions that can be extracted:

Table 1: Supported CAD Dimension Types

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

In addition, Ketiv objects include XDATA that can also be extracted through the Precision link, such as “Wall Height” and “Wall Length”.

Figure 5 shows the relationship between the Precision variables in the Wall Work Package and the CAD variables in the Model. The blue items under "Calculation" in the Wall Work Package are Precision variables, whereas the green items are the names of formulas that contain Precision variables. In this example, the CAD variable "Wall Length" is matched with the Precision variable "Wall Length FT".

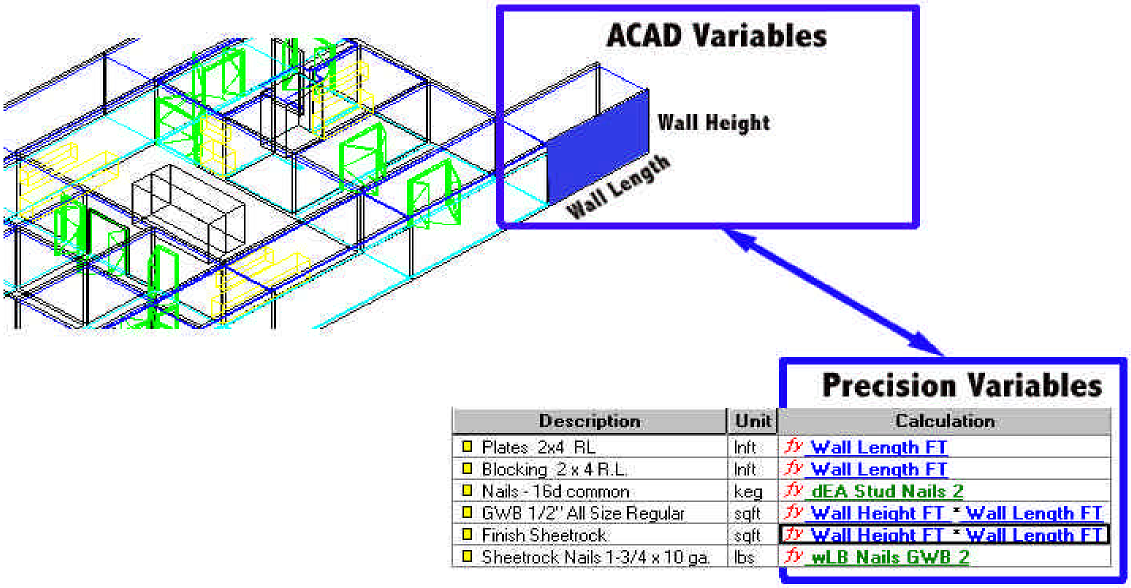

Figure 5: Relationship between Precision Variables and CAD Variables

Once the appropriate estimating items and work packages have been set-up in the Precision Estimating database, the user places essential information about estimating objects (work packages, items, and related specifications) in a text file. Ketiv's Precision Link uses this text file to build a master list of the estimating objects for use with the drawing file.

On the Sequus Project, the integration of design and cost information was complicated by the fact that the project team consisted of different companies and different sub-trades. There was no central estimating database that contained all the items necessary to create accurate and detailed cost estimates. In addition, the Precision Estimating link with Ketiv was primarily designed for 3D CAD models drawn with Ketiv. On the Sequus Project, only architectural objects were drawn with Ketiv. The three subcontractors created their 3D CAD models using Multi-pipe and AutoCAD R13. Consequently, the subcontractors had to draw using specific drawing methods that would create the desired CAD objects and the appropriate dimensions necessary for estimating purposes. Figure 6 shows specific CAD objects for each of the different subcontractor disciplines and the drawing method that was employed.

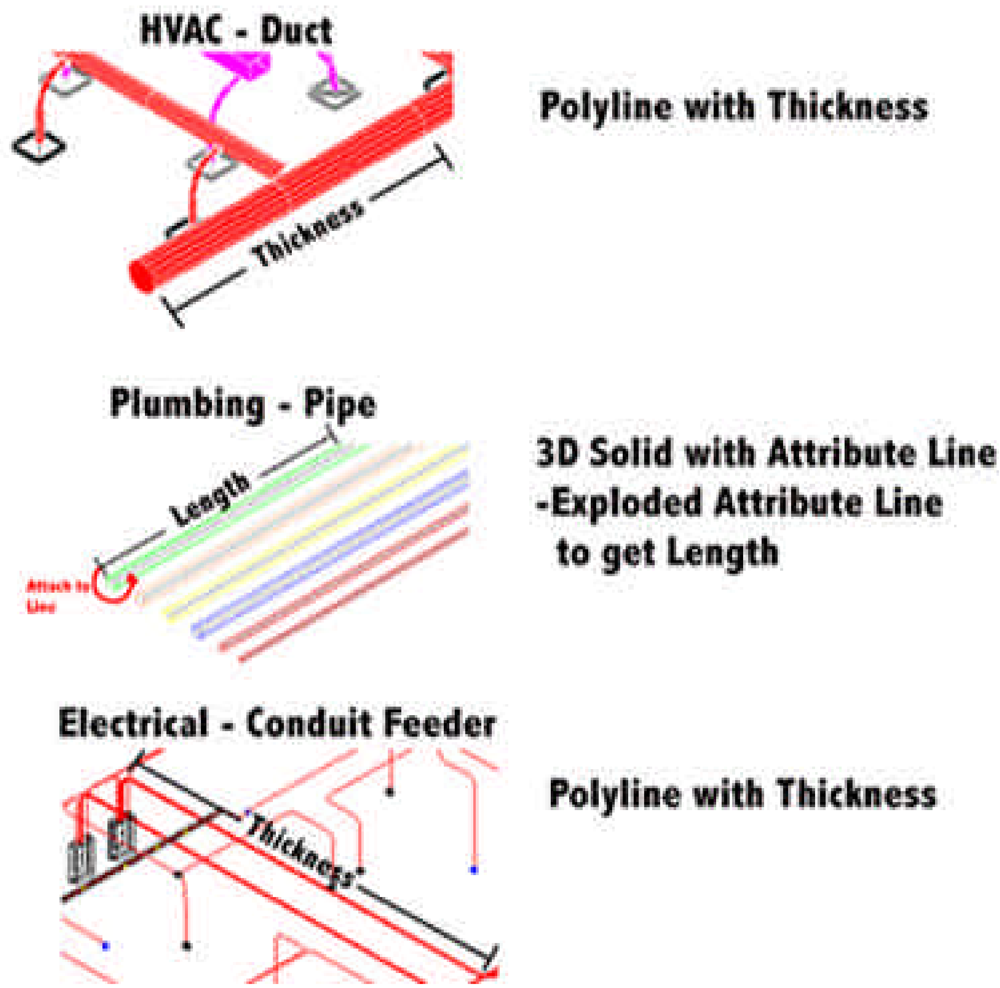

Figure 6: CAD Objects and Associated Drawing Methods

Five steps detail the effort required to perform design-cost integration on the Sequus Pharmaceuticals Pilot Plant:

1. Add items to general contractor's estimating database for all the disciplines, including crew production rates whenever possible. To capitalize on the benefits of design-cost integration, it was important to have detailed cost information for all the disciplines. The average duration to create this database was three hours for each subcontractor. The estimating item detail varied depending on the breakdown of work for each subcontractor. For example, the HVAC subcontractor often added labor, fabrication and material costs, while the general contractor added items with unit costs. A total of 314 items were added to the estimating database, with a breakdown by subcontractor as follows: HVAC – 80 items, Piping – 183 items, Electrical – 30 items, and General Contractor – 21 items.

2. Add formulas to estimating items added in step 1. This part is critical because the Precision variables identified in the formula will be linked with the CAD variables when the estimate is created. The total duration to complete this task was 12 hours.

3. Create work packages and item tables by grouping items created in step 1. The total duration to complete this task was 12 hours.
4. Attach work packages and items to each CAD Model. The Architectural Model contains 117 entities, the HVAC Model contains 185 entities, the Electrical Model contains 1,564 entities, and the Piping Model contained 3,139 entities. The amount of time necessary to attach work packages and items to each model depended completely on the complexity of the 3D CAD model. For example, the process for the general contractor only took about 2 hours total. The Piping Model, on the other hand, took about 8 hours to complete. Figure 7 shows the steps and user- interface to attach work packages or items in Ketiv.

5. Create estimates and troubleshoot. The total duration to complete this task was about 10 hours. Of the 314 estimate items created, about 75% were created such that the dimensional quantities were extracted from the 3D CAD Model, while the remaining 25% required only a count of specific objects in the CAD Model.

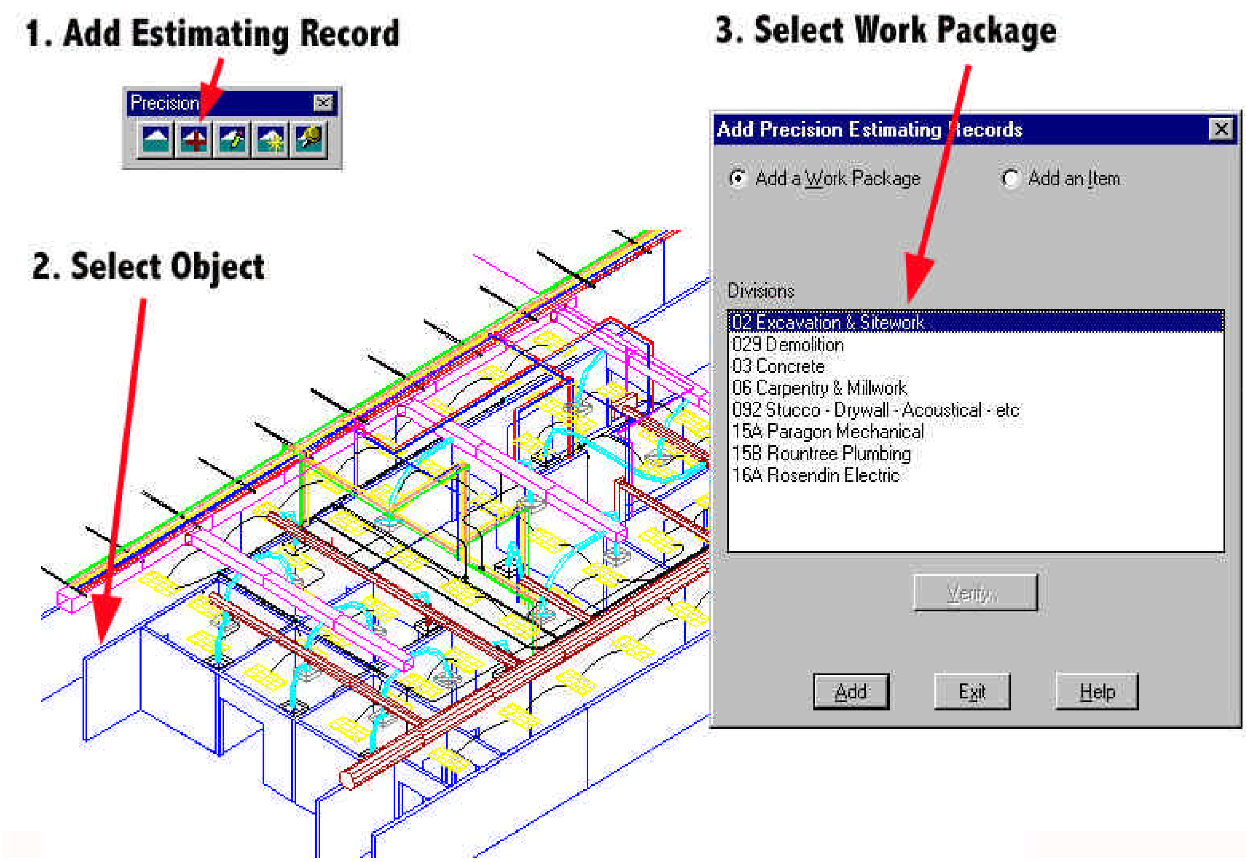

Figure 7: Steps to Add Estimating Records

Performing design-cost integration on the Sequus Project was particularly challenging because the CAD-estimate link was specifically designed for CAD objects drawn with Ketiv; 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

This case study demonstrates the many benefits that design-cost integration software will provide to each discipline. The benefits range from cost and time savings to improved flexibility in calculating the cost impact of different what-if scenarios. In addition, this case study shows the current limitations of the technology and exposes potential problems that arise when trying to implement this technology in a collaborative environment.

Benefits

- The quantities are automatically calculated and inserted into the estimate. As shown in Figure 3, after the user attaches work packages to the CAD model, quantities are automatically calculated and estimates are automatically created while in the CAD environment. This automation can eliminate most of the process of calculating quantities, which is often the most time consuming part of the estimating process. To estimate a project of this size would typically take Hathaway about 40 hours to complete. Using this automated process, the project manager at Hathaway believes estimating time could be reduced by 25%.
- What-if scenarios can be handled quickly. Users can quickly explore and compare the cost impact of different design alternatives and changes to material specifications. For example, on the Sequus Project, the project manager for the general contractor wanted to know the cost impact of a design change that widened the clean corridor. To perform this analysis, she simply had to move the wall in the CAD model, stretch the floor and the ceiling to cover the increased area, and then regenerate the estimate. In another instance, the general contractor wanted to know the cost impact of a specification change that required a different wall finish. To perform this analysis, she had to select the new estimating item, regenerate the pi.txt file and attach the new items in Ketiv. The project manager at Hathaway believes that using this automated process will reduce the time for doing what if scenarios by 50%.
- Ketiv provides electronic verification that all objects in the CAD model have been included in the estimate. On the Sequus Project, the general contractor wanted to verify that all of the CAD objects were actually covered in the estimate. For verification, she simply had to use the Ketiv option to identify “All Objects Not Having a Record”. This command highlighted all the objects in the CAD model that did not have an estimating item attached, providing a quick verification that the project manager’s estimate was complete.

Shortcomings

- The software can only extract certain types of information from the CAD model. For example, as shown in Table 1, the only dimension that can be extracted from a 3D solid is volume. This limitation forced the HVAC and electrical subcontractors to draw some objects in a specific way in order to get the appropriate dimension for the estimating item, as shown in Figure 6.
- 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 CAD dimension. For example, estimating items could be automatically selected for different pipe objects based on the pipe diameter.
- Only one work package can be attached to each object in the CAD Model. This limitation 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, a typical wall work package

might include framing, insulation, and drywall costs, but not painting. To calculate the quantities for painting automatically, the user would need to include painting in the wall work package or create a separate paint object in the CAD model.

Calculating quantities is often the most time consuming task in the estimating process. Since quantities are currently calculated manually, there is no easy way for the estimator to validate the accuracy of the quantities, confirm the completeness of the estimate, or quickly assess the cost impact of design and specification changes. The Sequus Project has demonstrated that design-cost integration software can be a valuable tool throughout the lifecycle of a project. Electronic integration of design and cost information can help project team members to evaluate the cost impact of many design and specification alternatives, to validate the completeness of their estimates, and to automatically calculate material quantities. In addition, we believe these benefits will likely increase as CAD modeling software improves, as 3D CAD modeling becomes more commonplace, and the standardization of design objects becomes more widespread.

DESIGN-SCHEDULE INTEGRATION

Process Description

To perform design-schedule integration (4D CAD, 3D + time), we linked schedule activities created using Microsoft Project with graphical objects that were created using AutoCAD and Ketiv's Archt Architectural Drawing software. Figure 8 shows an overview of this process. First, the user finalized the content of the Schedule Model and the CAD Model in their respective programs. Then, the user exported each model in a format that was compatible with Jacobus Technology's Schedule Simulator. After each model was imported into Jacobus Technology's Schedule Simulator, the user created a 4D model by linking the CAD objects with the Schedule objects.

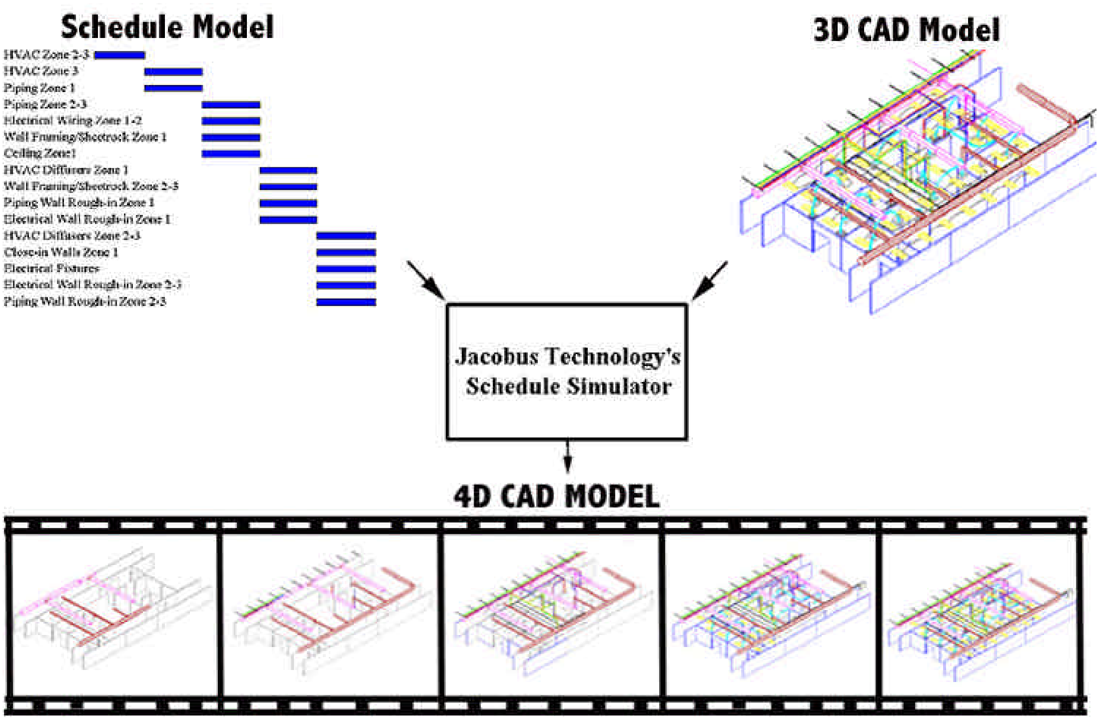

Figure 8: Overview of Design-Schedule Integration

Process Details

The user initially performs setup procedures that structure the CAD Model so that it can be automatically linked with the Schedule Model. First, the layering within the CAD Model must be structured such that it corresponds to the breakdown of work that exists in the Schedule Model. Second, the activity names within the Schedule Model should be identical to the layer names in the CAD Model to support rapid/automatic linking of schedule activities and CAD objects. After this structuring is complete, the user simply needs to execute a queue file that automatically creates the link between the Schedule Model and the CAD Model by matching the activity names with the layer names.

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

1. Obtain detailed schedules from each of the three subcontractors and general contractor.
2. Modify schedules and integrate the four different schedules into one schedule. This process involved modifying each schedule to reflect zoning, both in the activity names and precedence relationships, and to develop the sequencing between sub-trades. It also required changing all the activity names to correspond with the layer names. There are a total of 77 activities and 112 precedence relationships. The total duration to complete this task was eight hours.
3. Change CAD layer names to correspond with schedule activity names. This involves two separate processes. The first process relates to zoning. The layer name and corresponding objects had to be modified to reflect work proceeding in zones. This involved creating new layers, renaming old layers and moving objects to the appropriate layer. The second step in the process involved changing the layer and layer name for various objects. For example, in the electrical drawing, there were two separate layers for wiring for lighting and wiring for power. For scheduling purposes, one wants to distinguish wiring by whether it is in the ceiling or in the wall. Therefore, the corresponding layers and objects had to be changed to "wall rough-in" and "ceiling rough-in". The Architectural Model contained 117 entities, started out with 7 layers and ended up with 22 layers. The HVAC Model contained 185 entities, started out with 6 layers and ended up with 9 layers. The Electrical Model contained 1,564 entities, started out with 9 layers and ended up with 17 layers. The Piping Model contained 3,139 entities, started out with 9 layers and ended up with 22 layers. The total duration to complete this task was 12 hours.
4. Write queue file that creates schedule groups based on the layer names and links schedule groups to activity objects. The user has to create schedule groups to link CAD objects to activity objects when using Jacobus Technology's Schedule Simulator. The linking of activity objects with schedule groups is based on the "task_name" of the schedule object and the "name" of the schedule group.

The process of creating a 4D CAD model for the Sequus Project required the user to make several changes to each of the CAD models. This is primarily because most CAD systems do not represent the constructor's perspective. In other words, CAD designs are created without any thought about how the designed objects will go together as they are constructed. We believe that this limitation will continue to diminish as CAD systems become more object-oriented and design objects become more standardized.

EVALUATION OF DESIGN-SCHEDULE INTEGRATION SOFTWARE

This case study illustrates the many benefits and shortcomings that design-schedule integration software could provide to a design-build team. The benefits range from improved visualization of construction schedules, improved coordination of construction disciplines, and improved communication between design and construction. In addition, this case study shows the current limitations of the technology and exposes potential problems that a project team may realize while trying to implement this software in a collaborative environment.

Benefits

- The 4D model assists with coordination of subcontractor schedules. On the Sequus Project, each discipline constructed 3D CAD Models of their scope of work. Combining these 3D CAD Models with the project schedule yielded a detailed 4D model where each discipline's design and construction tasks are represented simultaneously. This 4D tool would allow all members of the team to visualize their tasks and the relationships that exist between the different sub-trades.
- The 4D model clearly communicates schedule intent. Current construction management practice uses Gantt charts or CPM plans to show the sequencing of schedule activities. These schedules abstract a complex building process to a set of horizontal lines on a page. This representation limits the user's ability to understand the schedule intent because it doesn't explicitly represent the construction in three dimensions of space, which is precisely what the user is trying to coordinate.
- The 4D model allows a project team to test and evaluate different schedule sequencing alternatives. For example, on the Sequus Project, the general contractor wanted to sequence the HVAC and piping work such that the overall project duration was minimized and space allocation was optimized. To solve this problem, the scheduler developed two different schedules that had either the HVAC work going first or the piping work going first. Based on an analysis of the corresponding 4D models, it was determined that the HVAC work should go first because the project duration was shorter and conflicts between trades were minimized.
- 4D models help the users to identify constructability issues and sequencing problems early in design development by virtually building the facility on the computer screen. For example, on the Sequus Project, the project team wanted to determine if there were going to be any scheduling conflicts between the HVAC, piping, and electrical work. The 4D visualization made it evident that the electrical work would interfere with the piping work in Zone 2. Consequently, the general contractor avoided the conflict between these construction activities by increasing the lag time between the electrical and piping work.

Shortcomings

- Designers complete their designs without any thought about how the constructors will assemble the building components. As a result, the scheduler 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 user must manipulate the CAD Model so that this semantic content resides in the layer names. However, this limitation will diminish, as CAD systems become more object-oriented.

- A schedule needs to exist before a 4D model can be built. Many team members would have like to create the schedule right in the 4D system.
- To link the CAD Model and Schedule Model requires significant understanding of how Jacobus 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. Significant efforts are pursued to make sure conflicts are avoided and crews are able to work productively. These efforts include the creation of detailed construction schedules, weekly coordination meetings, and the use of overlays of subcontractor design drawings. Although these methods can be helpful, they fail to explicitly show the physical relationships between subcontractor work and the spatial requirements of each trade as construction progresses. The use of 4D CAD on the Sequus project has demonstrated that this tool effectively represents the spatial needs of each discipline simultaneously, allows a project team to evaluate different sequencing alternatives, exposes potential constructability issues, and improves the communication and coordination between sub-trades.

ORGANIZATIONAL IMPACTS

The implementation of design, cost and schedule integration technologies are likely to change the roles of each discipline in the design and construction process. This study suggests that owners, designers and builders of facilities will need to develop new skills and implement organizational changes to take advantage of the benefits offered by this technology and to stay competitive in this changing market.

Owners

Owners could benefit from the use of design, cost and schedule integration software for the design and construction of new facilities and for retrofit work. Potential benefits include improved visualization of construction schedules and the ability to quickly assess the cost impact of different design and specification changes. These benefits will be realized if owners are able to bring a project team together early in the design process. In our experience, it is critical for the successful integration of design, cost and schedule information to have a project team assembled from the very start of the project so that team members can share design information throughout the design process. The project team needs to develop detailed 3D CAD models collaboratively. As for the actual construction, there is no single entity that has all the expertise to build a complete and accurate 3D model. This collaborative process will require extensive communication and assurances that each member is on the same page. At the end of the project, the detailed 3D CAD model can be transferred to the owner to assist in facility maintenance and operations.

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 thinks the detailed 3D CAD models could be used after construction for validation, maintenance and operation, and budgeting for future remodels or expansion.

Architects and Engineers

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. Designers also need to work closely with subcontractors who perform detailed design for their disciplines.

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 better utilize the design.

Flad also benefited from Ketiv's modeling capabilities. They were able to include specifications in the CAD objects themselves. In the traditional process, there is no link between the designed object and its specification. This linking allows the designer to better control the design process and manage design changes. In addition, Flad utilized Ketiv'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.

General Contractors

General contractors will need to change certain business practices and develop new skills to take advantage of the benefits that design, cost and schedule integration software provides. 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 a certain way and the appropriate CAD dimension is extracted for each estimating item. Finally, general contractors are likely to become the keeper of the models, 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.

The project manager for Hathaway believes that the total estimating time could be reduced by 25% by using design-cost integration and 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 using traditional methods and creating an estimate using the CAD-estimate link. The two estimates were within 5% in terms of total cost. In addition, a comparison of the two estimates showed that there was a quantity takeoff error in the estimate created using traditional methods. Furthermore, estimates created using the CAD-estimate link provide a record as to how the quantities were derived. The project manager that created the estimate using traditional methods had left the company and there were no records that showed what was included in some of the estimating items or how the quantities were derived. Therefore, Hathaway believes the benefits offered by this technology justify further commitment and plans on using this technology on future projects.

The 3D models also helped the project manager of Hathaway to better understand the design intent. In current practice, builders of facilities use 2D plans and sections to deduce the 3D design. This process often leads to misinterpretation and differing perspectives within a project team. By having all members of a project team design in 3D from the very start of the project, there is more assurance that all disciplines have a common perspective of the final product. In addition, the 3D models can be utilized to create a 4D model of the facility design. The project manager for the Sequus Project feels that 4D models will be particularly useful in coordinating construction tasks and communicating the intent of the construction schedule.

Subcontractors

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 the subcontractor's design. They are interested in being in control of the detailed design information so they can use it to automate the fabrication of components. However, we foresee that 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 and would benefit from CAD software that is specifically designed for their discipline. Some subcontractors are already benefiting from 3D CAD modeling software for fabrication as well. 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.

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 currently is no link electronic between QuickPen and Multi-Pipe.

Rountree Plumbing has much experience in 3D modeling and believes it offers substantial benefits. They have used 3D models on past projects to assist in coordination with other trades, to plan daily work activities, and for fabrication. Rountree Plumbing also believes that 4D modeling will further assist in coordination with other subcontractors and will allow them to assist general contractors in the coordination process.

Rountree Plumbing has already witnessed some changes in their roles in the project team and in the way they manage their construction tasks. They are performing more detailed design as evidenced by their experience in 3D modeling on past projects. On these projects, they received schematic designs from the Engineer and created detailed 3D CAD models independently. They have also trained some managers in CAD modeling so the field crews can use the models to plan daily work tasks and to perform fabrication.

CONCLUSIONS

Integrating design, cost, and schedule information can help a project team to improve the efficiency of the planning and estimating processes. Design-cost integration supports the automatic calculation of material quantities, thus shortening estimating time and eliminating the duplication of effort that exists in current estimating practices. In addition, it allows a project team to quickly evaluate the cost impact of different design and specification alternatives, and provides electronic validation that all the items in the CAD model have been included in the estimate. Integrating design and schedule information allows construction professionals to visualize the construction process and evaluate the constructability of a proposed construction sequence. The Sequus Project team has successfully performed design, cost and schedule integration and demonstrated the status of this software and the resource requirements necessary to accomplish these tasks on an actual project. This study shows that owners, designers and builders of facilities will need to develop new skills and implement organizational changes to take advantage of the benefits offered by this technology. Whenever possible, electronic information should be created by the party that derives the most benefits from a complete and accurate 3D model. Therefore, owners will need to bring a project team together early in the project to capitalize on the benefits of this technology. 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 to manipulate 3D CAD models, work more closely with the designers in design development, and provide input on design representation so that the designs are more usable for the constructor. Subcontractors will also need to learn design software, as they will be performing more detailed design, working more closely with the architects and engineers throughout the design process, and addressing coordination issues early in design development. In summary, 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 faster estimating time, fewer takeoff errors, better documentation and reproducibility of the estimating process, and the ability to release a construction schedule electronically with the whole project team prior to construction.

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