CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Industrial Case Study of Electronic Design, Cost, & Schedule Integration

By

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SUMMARY

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1. Abstract:

This report describes the efforts of a project team to leverage 3D models for design coordination and constructability analysis, cost estimating, and construction planning to maintain integrated scope-cost-time models during design and construction of a Pilot Plant for Sequus Pharmaceuticals. We describe the benefits and shortcomings of the software, the corresponding research issues, and the resource requirements necessary to integrate this information. We also describe the project team's evaluation of this integrated approach, its affect on the project's outcome, and its affect on the roles and responsibilities of each discipline within the project team.

This experience on the Sequus project shows that early and simultaneous involvement of project teams including designers, general contractors, and subcontractors in the design and construction of a capital facility coupled with the use of shared 3D models allows project teams to deliver a superior facility in less time, at lower cost, and with less hassle. Although we have created a long functionality wish-list as part of this report, this case shows that commercial tools that can electronically integrate design, cost, and schedule information provide many benefits to project teams throughout the design and construction process.

2. Subject:

- *What is the report about in laymen's terms?* This report investigates the capabilities of existing software tools to integrate design, cost, and schedule information. We describe the benefits and shortcomings of the software, the resource requirements necessary to integrate this information, and how the use of these tools affected the Sequus Project's outcome.

• *What are the key ideas or concepts investigated?* Development and analysis of integrated scope-cost-time models and their affect on project performance.

• *What is the essential message?* Although the software tools discussed in this report could be improved, electronically integrating design, cost, and schedule information allows project teams to deliver a superior facility in less time, at lower cost, and with less hassle.

3. Objectives/Benefits:

• *Why did CIFE fund this research?* This research was not funded by CIFE.

• *What benefits does the research have to CIFE members?* This report shows the effort and time required to electronically integrate design, cost, and schedule information using off-the-shelf software tools. It also describes the benefits and limitations of the software tools and how the application of these tools affected project performance during design and construction of Sequus Pharmaceuticals.

• *What is the motivation for pursuing the research*? To accelerate the adoption of electronically integrated scope-cost-time models by investigating the resource requirements necessary to accomplish these tasks on an actual project. Additionally, to identify the benefits of this technology and document how their use affected project performance. Finally, to identify necessary research to address the limitations identified in this report.

• *What did the research attempt to prove/disprove or explore?* We explore the use of integrated scope-cost-time models and prove their usefulness to project teams and their benefit to project performance.

4. Methodology:

• *How was the research conducted?* One graduate research assistance worked closely with a project team during design and construction of the Sequus Pharmaceuticals Pilot Plant. The research assistant electronically integrated the design, cost, and schedule information from the Sequus Project and documented the benefits and limitations of the tools, the resource requirements necessary to accomplish these tasks, and the affect of these tools on project performance.

• *Did the investigation involve case studies, computer models, or some other method?* The investigation involved the generation of integrated scope-cost-time models using off-the-shelf software tools.

5. Results:

• *What are the major findings of the investigation?*

Evaluation of integrated software tools: Commercial tools that can electronically integrate design, cost, and schedule information provide many benefits to project teams throughout the design and construction process. Specifically, they enable the early detection of design conflicts, shorten estimating time and improve estimating reliability, improve the communication of schedule intent.

Impact on project performance:
This reports shows that early and simultaneous involvement of project teams including designers, general contractors, and subcontractors in the design and construction of a capital facility coupled with the use of shared 3D models allows project teams to deliver a superior facility in less time, at lower cost, and with less hassle.
Future improvements and necessary research:
Future improvements include facilitating design coordination through view generation, developing a methodology to relate design and cost information at different levels of detail, and developing tools to identify the cost impacts of schedule changes.

- *What outputs were generated (software, other reports, video, other)*

Cost estimate generated electronically from 3D CAD models, 4D model of Sequus Pharmaceuticals' Equipment Platform, this report, and the presentations shown in Appendix A.

6. Research Status:

- *What is the status of the research?* Completed.
- *What is the logical next step?* Conduct further research that addresses the limitations identified in this report.
- *Are the results ready to be applied or do they need further development?* Both.
- *What additional efforts are required before this research could be applied?*

Many of the ideas discussed in this report could be applied now but further improvements are needed to enable the sharing of design, cost, and schedule information across disparate software systems.

Acknowledgements

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- Chris Sorauf, Michael Albright, and John May from Rosendin Electric,
- Jim Brady and Dave Fazekas from Paragon Mechanical, and

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- John Hlady with Ketiv Technologies - ArchT:
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  http://www.timberline.com

Abstract

A key concern for project teams is making sure the project's scope, cost, and time are in sync throughout the project life-cycle. Systems integrating this information are emerging and have the potential to assist project teams in creating and maintaining integrated scope-cost-time models. Yet, few project teams are adopting such integration software tools and as a result, are not able to leverage the electronic design and construction information that is created today. But why do project teams continue to use these tools and integrate this information manually if substantial benefits can be gained by integrating this information electronically? This report helps to answer this question by investigating the capabilities of emerging software tools to leverage 3D models throughout design and construction and assist project teams when creating and maintaining integrated scope-cost-time models.

Specifically, in this report, we describe the efforts of a project team to leverage 3D models for design coordination and constructability analysis, cost estimating, and construction planning to maintain integrated scope-cost-time models during design and construction of a Pilot Plant for Sequus Pharmaceuticals. We describe the benefits and shortcomings of the software, the corresponding research issues, and the resource requirements necessary to integrate this information. We also describe the project team's evaluation of this integrated approach, its affect on the project's outcome, and its affect on the roles and responsibilities of each discipline within the project team.

This experience on the Sequus project shows that early and simultaneous involvement of project teams including designers, general contractors, and subcontractors in the design and construction of a capital facility coupled with the use of shared 3D models allows project teams to deliver a superior facility in less time, at lower cost, and with less hassle. Although we have created a long functionality wish-list as part of this report, this case shows that commercial tools that can electronically integrate design, cost, and schedule information provide many benefits to project teams throughout the design and construction process. Specifically, the following benefits were realized during design and construction of the Pilot Plant Facility for Sequus Pharmaceuticals:

- shorter estimating duration,
- fewer quantity takeoff errors,
- better documentation and reproducibility of the estimating process,
- elimination of field interferences,
- improved communication of the schedule intent,
- construction completed on time and under budget,
- less rework,
- increased productivity,
- 60% fewer requests for information,
- fewer change orders,
- less than 1% cost growth, and
- decrease in time from start of construction to facility turnover.

To our knowledge, this is the first project where multiple firms have collaborated from the project's beginning using an integrated suite of design and project management software. As such, the project team learned many valuable lessons that were critical to the success of this integrated approach and that should be incorporated on future projects. These lessons learned are summarized below:

- Project teams should determine the level of detail in 3D to model each discipline's scope of work prior to design development. This is necessary because there are varying levels of detail that components can be modeled in 3D. For example, a transformer can be modeled simply as a 3-dimensional box, or it can be modeled to show all the switches, access points, indentations, etc. Moreover, some work may only require 2D modeling because there may not be any substantial benefit or because the benefits may not be worth the investment. For example, project teams would need to determine if the light switches should be modeled in 3D or 2D. To resolve this issue, project teams should consider all the possible benefits of 3D modeling, including visualization, constructability analysis, design coordination, cost estimating, and scheduling.
- Project teams should determine the stage in the design development process when a specific scope of work should be modeled in 3D. The sequencing and timing of the

design development process needs to coincide with the design coordination process, the procurement process, and the construction process, particularly in design-build environments.

- Project managers and executives committing to a team-oriented approach should carefully assemble their project staff. It is critical that each discipline's project team understands the goals of the project, the level of information sharing needed, and the level of 3D modeling required.
- Assemble teams so that the designs are created by the participants who have the construction expertise to create constructable designs, and who are responsible for installation and can leverage the designs throughout construction. A collaborative design approach also provides incentives for team members to provide feedback on the other discipline's designs because they can leverage the designs created by others to support their project management functions. Therefore, a collaborative design process allows the construction companies to reap the benefits from investments in information models.
- It is important to set up a design protocol early in the design process. This includes setting the coordinate system, file naming, layering, and file sharing standards.
- Every essential trade on the project should put their design (scope of work) into the 3D model to leverage the benefits of electronic 3D design coordination. The structural work was only partially modeled in 3D and the fire sprinkler work was not modeled at all in 3D on the Sequus Project, resulting in the only design conflict problems during construction.
- Project teams modeling in 3D require increased design and coordination time. Although this is offset by benefits in construction, it does need to be addressed in each discipline's estimate and contract.

The Sequus Project also demonstrates that owners, designers, and builders of facilities will need to develop new skills and implement organizational changes to take advantage of these benefits, as described below.

- 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.
- 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.

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Chapter 1

Report Overview

In this report, we describe the efforts of a project team to leverage 3D design information for design coordination and constructability analysis, cost estimating, and construction to maintain integrated scope-cost-time models during design and construction of the Sequus Pharmaceuticals Pilot Plant. Through this case study, we describe the capabilities of commercial software tools to maintain integrated scope-cost-time models, the resource requirements and specific tasks, and the corresponding research issues. We also describe the project team's evaluation of this integrated approach, its effect on the project's outcome, and its effect on the roles and responsibilities of each discipline within the project team. We conclude the report by describing our vision for leveraging 3D models and managing the project's scope, cost, and time throughout the project life-cycle.

1.1 Introduction

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. Thus, reliable and timely access to information is critical for construction professionals to work efficiently and to capitalize on their investments in information models. 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 when creating and maintaining design and construction information and leads to inconsistencies between the project's scope, cost, and time. If construction professionals could easily leverage the electronic design information and integrate that information electronically with their project management software tools, the project's scope, cost, and time would be in sync, and many of these inefficiencies would be eliminated.

Commercially available software technologies can help project teams to leverage 3D design information to support a variety of project management functions. 3D models can be leveraged to support design coordination, visualization using 3D walk-thru's, constructability analysis, automated quantity takeoff, and 4D modeling. Although such 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. On the Sequus project, the project team, consisting of a general contractor, architect, and mechanical and electrical subcontractors, modeled their respective scopes of work in 3D CAD, coordinated their designs in 3D, and used commercial software tools to integrate the 3D CAD models with cost and scheduling software. In summary, the Sequus Project demonstrates that off-the-shelf software tools can leverage 3D design information and improve the efficiency of project managers by enabling the elimination of conflicts and improving the constructability of facility designs, automating material quantity takeoffs when generating cost estimates, and visualizing the four-dimensional nature of the construction process.

In this report, we describe the efforts of a project team to leverage 3D design information for design coordination and constructability analysis, cost estimating, and construction planning from conceptual design through construction on the Sequus Pharmaceuticals Pilot Plant. Specifically, we discuss the following:

- the software used and the steps required to coordinate the design process and electronically integrate design, cost and schedule information,
- the benefits and shortcomings of the software,
- recent and on-going research addressing the shortcomings of the software,

- the project team's evaluation of this integrated approach and the effects of this integrated approach on the project outcome, and
- the changing roles of each discipline.

In the next sections, we summarize the problems with current practice, describe our research objectives and analysis approach, and summarize the results of the case study.

1.2 Limitations of Current Practice

Design coordination and constructability analysis, cost estimating, and construction planning are critical tasks for project teams. Unfortunately, the tools used by designers and contractors do not explicitly capture the relationships between the electronic design, cost, and schedule information. Consequently, changes must be *manually* propagated to the related information to ensure the project's scope, cost, and time are in sync. On many projects, designs change often and there are thousands of relationships between cost items, schedule activities, and product model components. Therefore, it is unlikely that designers and builders will be able to manually update all the electronic links between 3D components, cost information, and schedule activities in a timely and complete manner to maintain an accurate computer model with linked scope, cost, and time information throughout a project's life cycle. Without computer support to store and use these relationships, the designers and contractors need to remember when to adjust the information if the design, construction method, planning strategies, or activity sequences change so that the cost estimate, schedule, and project scope descriptions are in balance.

Today, design coordination is performed by overlaying each specialty contractor's 2D drawing on a light table to compare the different building system designs. The specialty contractors identify conflicts and develop solutions that are red-lined on the 2D drawings. This process continues until the coordination is complete and the specialty contractors sign-off on each other’s drawings to signify their acceptance. The current design coordination process of overlaying 2D drawings on a light table is time-consuming and inefficient. Many design conflicts go undetected as 2D does not adequately represent the spatial requirements of the building components. Moreover, without an explicit link between the design components and the corresponding cost and schedule information, there is no way for project teams to quickly evaluate the impact of their design changes on the project's cost and schedule. Creating and coordinating designs in 3D and integrating design information with cost and schedule information will enable project teams to make more informed decisions about the constructability of their designs and to optimize the design configuration.

Current cost estimating processes do not leverage the electronic design information to help estimators quantify, create, and maintain cost information. The information designers put into drawings cannot be reused directly because the information transmitted from designers to estimators is not in a usable, electronic form. As a result, cost estimating remains a largely manual process - designs are interpreted manually, quantities are calculated manually[1], cost information is identified manually, and cost estimates are maintained manually - giving rise to inefficiencies in the estimating process that increase estimating time and decrease accuracy. Therefore, we advocate the use of design-cost integration software that explicitly links components in the design with cost assemblies and items in a cost database. Design-cost integration software takes advantage of existing electronic design information. It provides the opportunity for contractors to automate the quantity takeoff process, to validate the completeness of their estimates, and to evaluate the cost impact of some design alternatives quickly.

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 these dimensions is critical for evaluating, monitoring, and coordinating the construction process. As a result, current schedule representations make it difficult to visualize and communicate the schedule intent and analyze the feasibility of the proposed sequencing. 4D-CAD (3D + time) is a tool that

[1] At best, quantities are calculated with a digitizer by tracing the CAD drawings.

addresses these limitations and 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 summary, current project management practices are limited because they do not leverage the 3D design information, resulting in inefficiencies when creating and maintaining design and construction information and leading to inconsistencies between the project's scope, cost, and time. On the Sequus Project, we tested the capabilities of commercial tools to leverage 3D design information for design coordination, cost estimating, and construction planning. The Sequus Project demonstrates that off-the-shelf tools can leverage 3D design information and improve the efficiency of project managers by enabling the elimination of conflicts and improving the constructability of facility designs, automating material quantity takeoffs for cost estimates, and visualizing the four-dimensional nature of the construction process.

1.3 Research Objectives and Activities

The overall purpose of this research was threefold:

- ***to investigate the capabilities of commercial software tools to leverage 3D design information for design coordination and constructability analysis, cost estimating, and construction planning on an actual project,***
- ***to identify the effects of these tools and a team-oriented approach on project performance, and***
- ***to identify research needed to address the limitations of these tools and provide the necessary functionality for maintaining integrated scope-cost-time models throughout the project life-cycle.***

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 to leverage 3D design information for design coordination and constructability analysis, cost estimating, and construction planning. This technology has existed for some time and, research has shown that it is technically feasible. However, these tools are not being used by the majority of design and construction professionals. Moreover, we have not found any research that critiques these tools in the context of project teamwork. Yet, without demonstrating their benefits, it is difficult for practitioners to invest the resources necessary to capitalize on the benefits offered by these tools. Therefore, this research analyzed the capabilities of these tools so that construction professionals can make more informed decisions about adopting these tools to perform many of their project management functions.

The following describes each research objective in detail:

(1) To investigate the capabilities of commercial software tools to leverage 3D design information for design coordination and constructability analysis, cost estimating, and construction planning on an actual project.

The Sequus Project is, to our knowledge and the knowledge of the software vendors, the first project where multiple firms collaborated with an integrated suite of design and project management software. Consequently, there is little evidence available to practitioners that illustrate the effects of these tools on project performance. Therefore, this research identifies the necessary steps, the resource requirements, and the benefits and limitations of existing tools to leverage 3D design information for design coordination and constructability analysis, cost estimating, and construction planning.

(2) To identify the effects of these tools and a team-oriented approach on project performance

Today, architects and engineers create designs in 2D, transfer them to subcontractors in paper-based form. The subcontractors then coordinated them using light tables. The current process is inefficient and does not allow the construction professionals to leverage the design information throughout the construction process. In contrast, the Sequus Project team was assembled prior to design and construction, and each team member was committed to modeling their scope of work in 3D. The designs were created by the subcontractors who had construction expertise to create constructable designs, who were responsible for installation, and who could leverage the designs throughout construction. This research documents the changes in team member responsibilities and the impact of collaborative design on project performance. Specifically, we measure the effects of a team-oriented approach on project performance by observing changes in team member responsibilities, and compare the number of requests for information, change orders, rework, and productivity to other projects of this complexity that used a more traditional approach.

(3) To identify research needed to address the limitations of these tools and provide the necessary functionality for maintaining integrated scope-cost-time models throughout the project life-cycle.

Working with the Sequus project team, we investigated the capabilities of commercial tools to leverage 3D design information for design coordination and constructability analysis, cost estimating and construction planning and identified the functionality required to maintain integrated scope-cost-time models on an actual construction project. However, many research efforts addressed some of the limitations of these tools. Therefore, we identify necessary research to address the limitations of these tools and outline new functionality to create and maintain integrated scope-cost-time models throughout the project life-cycle.

In the next sections, we summarize the results of the research and provide a guide for readers to the rest of this report.

1.4 Summary of Results

The Sequus Project showed that commercial tools can leverage 3D design information for design coordination and constructability analysis, cost estimating, and scheduling. Figure 1.1 shows the commercial tools used and the information that is shared between the disparate systems. Today, off-the-shelf software tools allow project managers to perform the following tasks: (1) coordinate and analyze designs electronically in 3D, (2) link cost assemblies to design objects to automate the quantity takeoff process, (3) create schedule activities and calculate activity durations automatically, (4) link design objects with schedule activities to create 4D visualizations.

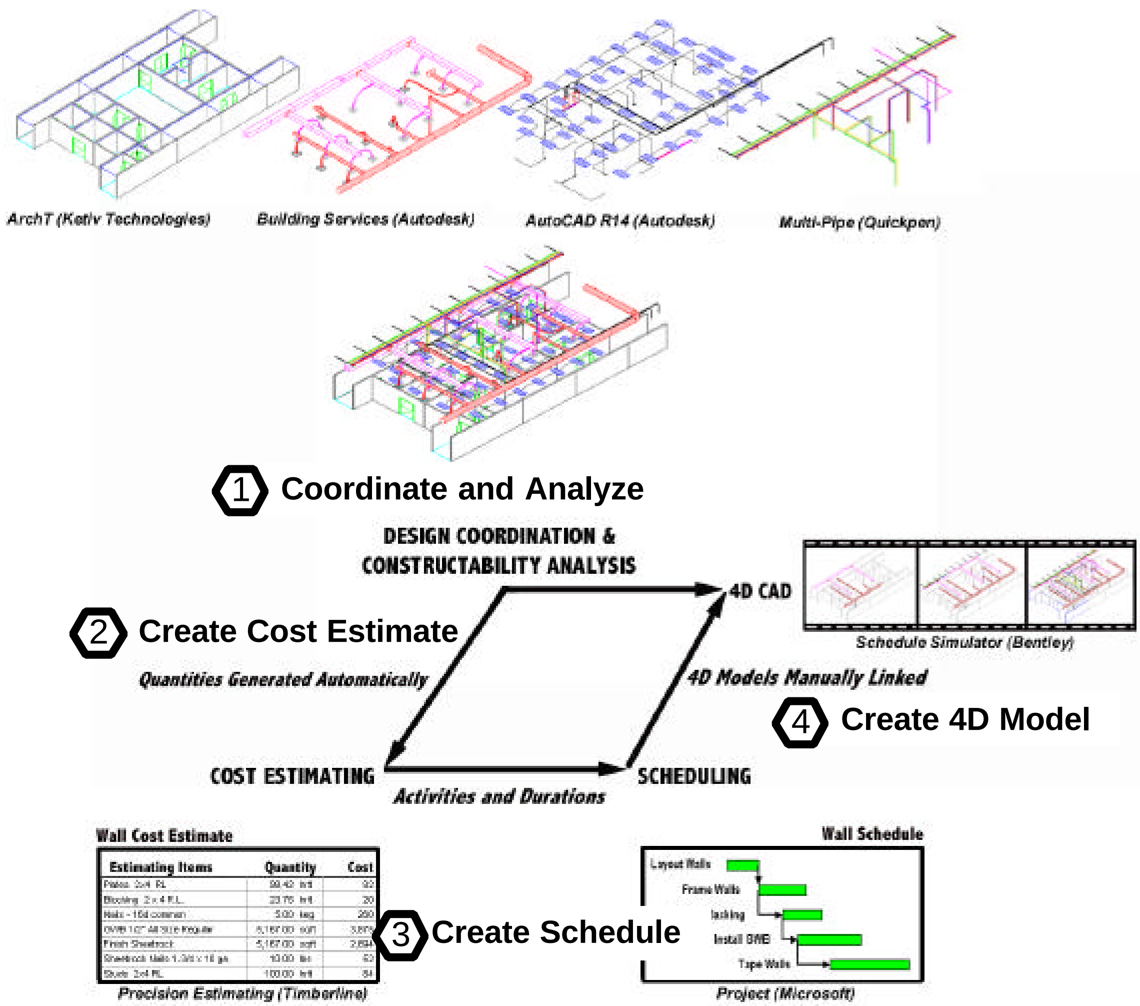


Figure 1.1: Software Tools Used to Integrate Design, Cost, and Schedule Information and Information shared between Disparate Software Applications

This experience on the Sequus project shows that early and simultaneous involvement of project teams including designers, general contractors, and subcontractors in the design and construction of a capital facility coupled with the use of shared 3D models allows project teams to deliver a superior facility in less time, at lower cost, and with less hassle. Specifically, the following benefits were realized during design and construction of the Pilot Plant Facility for Sequus Pharmaceuticals:

- shorter estimating duration,
- fewer quantity takeoff errors,
- better documentation and reproducibility of the estimating process,
- elimination of field interferences,
- improved communication of the schedule intent,
- construction completed on time and under budget,
- less rework,
- increased productivity,
- 60% fewer requests for information,
- fewer change orders,
- less than 1% cost growth, and
- decrease in time from start of construction to facility turnover.

To our knowledge, this is the first project where multiple firms have collaborated from the beginning of the design phase through construction using an integrated suite of design and project management software. As such, the project team learned many valuable lessons that were critical to the success of this integrated approach and should be incorporated on future projects. These lessons learned are summarized below:

- Project teams should determine the level of detail in 3D to model each discipline's scope of work prior to design development. This is necessary because there are varying levels of detail that components can be modeled in 3D. For example, a transformer can be modeled simply as a 3-dimensional box, or it can be modeled to show all the switches, access points, indentations, etc. Moreover, some work may only require 2D modeling because there may not be any substantial benefit or because the benefits may not be worth the investment. For example, project teams would need to determine if the light switches should be modeled in 3D or 2D. To resolve this issue, project teams should consider all the possible benefits of 3D modeling, including visualization, constructability analysis, design coordination, cost estimating, and scheduling.

- Project teams should determine the stage in the design development process when a specific scope of work should be modeled in 3D. The sequencing and timing of the design development process needs to coincide with the design coordination process, the procurement process, and the construction process, particularly in design-build environments.
- Project managers and executives committing to a team-oriented approach should carefully assemble their project staff. It is critical that each discipline's project team understands the goals of the project, the level of information sharing needed, and the level of 3D modeling required.
- Assemble teams so that the designs are created by the participants who have the construction expertise to create constructable designs, and who are responsible for installation and can leverage the designs throughout construction. A collaborative design approach also provides incentives for team members to provide feedback on the other discipline's designs because they can leverage the designs created by others to support their project management functions. Therefore, a collaborative design process allows the construction companies to reap the benefits from investments in information models.
- It is important to set up a design protocol early in the design process. This includes setting the coordinate system, file naming, layering, and file sharing standards.
- Every essential trade on the project should put their design (scope of work) into the 3D model to leverage the benefits of electronic 3D design coordination. The structural work was only partially modeled in 3D and the fire sprinkler work was not modeled at all in 3D on the Sequus Project, resulting in the only design conflict problems during construction.

- Project teams modeling in 3D require increased design and coordination time. Although this is offset by benefits in construction, it does need to be addressed in each discipline's estimate and contract.

The Sequus Project also demonstrates that owners, designers, and builders of facilities will need to develop new skills and implement organizational changes to take advantage of these benefits, as described below.

- 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.
- 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.

However, these benefits were not realized without compromise. While productivity was improved, design time increased; while rework was avoided, design coordination time increased; while the project team could make more informed decisions, the time it took to actually design, plan, and estimate the facility increased. Although the benefits far outweighed the costs on the Sequus Project, project teams must be aware of these tradeoffs when pursuing this integrated approach.

In summary, the Sequus Project demonstrated that commercial tools can leverage electronic 3D models for many project management functions and improve the efficiency of project managers by enabling the elimination of conflicts and improving the constructability of facility designs, automating material quantity takeoffs for cost estimates, and visualizing the four-dimensional nature of the construction process.

1.5 Reader's Guide

The following describes the remaining chapters of this report.

Chapter 2 describes the Sequus Pharmaceuticals Pilot Plant Project, the industrial organizations participating on the design-build team, and Stanford's role in the project. Chapter 2 also describes the challenges of building a pilot plant facility and the technological challenges confronted by the team as they integrated design, cost, and schedule information

Chapters 3 to 5 describe how the electronic design drawings were coordinated and leveraged for cost estimating and scheduling. Figure 1.2 graphically shows the focus of Chapters 3 to 5. Chapter 3 describes the current practice for coordinating the design process, the process used on the Sequus Project to coordinate the design process, an assessment of the benefits and shortcomings of the process, and related research. Chapter 4 describes the current cost estimating process, the process used on the Sequus Project to electronically integrate design and cost information, an assessment of the benefits and shortcomings of the tools, and related research. Chapter 5 describes the current practice for creating schedules, the process and tools used on the Sequus Project to electronically integrate design and schedule information (4D modeling), an assessment of the benefits and shortcomings of current 4D tools, and related research.

Chapter 6 describes the project team's evaluation of this integrated approach and the effects of this integrated approach on the project outcome.

Chapter 7 describes the process changes and organization impacts on each discipline.

Chapter 8 discusses our conclusions, vision of future software functionality, and remaining research issues.

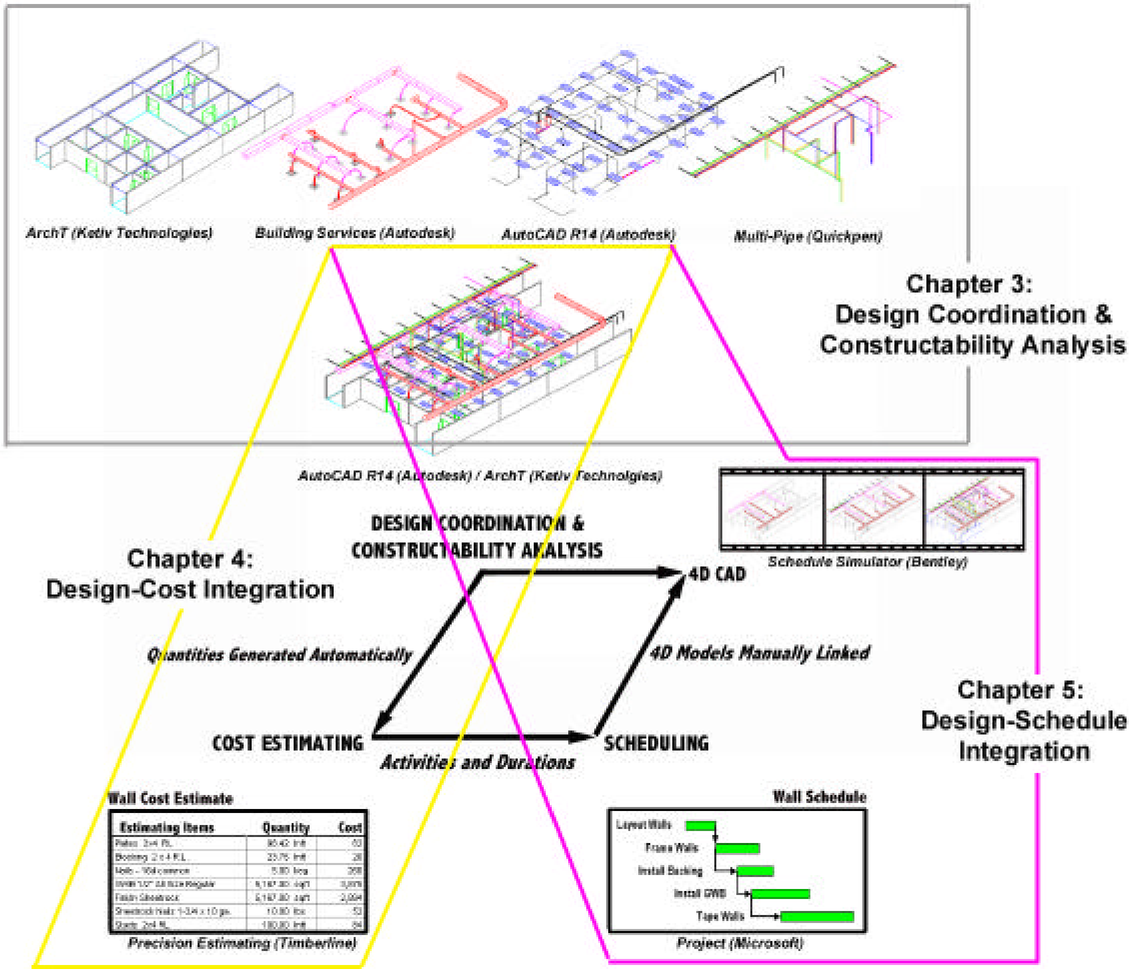


Figure 1.2: Readers Guide for Chapters 3 to 5

Chapter 2

Case Study - The Sequus Project

The Sequus Pharmaceuticals Pilot Plant facility project offered unique challenges that made it an excellent candidate for testing the capabilities of commercial tools to leverage 3D design information for project management functions. Sequus did not have a clear idea about the scope of the pilot plant facility. Modeling the facility in 3D, therefore, helped Sequus to visualize the facility design and helped the project team to communicate the design intent to Sequus. In addition, pilot plant facilities typically have complex mechanical, electrical, and piping systems. Consequently, designing and coordinating the systems electronically in 3D and coordinating the installation process in 4D helped the project team to eliminate costly rework resulting from design conflicts and identify planning solutions that enabled a more productive installation process. Finally, Sequus had an extremely limited budget. Thus, integrating design and cost information electronically helped the project team to quickly identify the cost impact of some design alternatives. Therefore, the nature of the pilot plant facility and the combination of challenges it presented made the Sequus project an excellent candidate for 3D modeling, 3D design coordination, and electronically integrating the 3D models with cost estimating and scheduling software.

The design-build team confronted many technological challenges as they leveraged the 3D design models for design coordination, cost estimating, and construction planning. The main technological challenges were centered around coordinating design information created with different discipline-specific software and performing design, cost, and schedule integration in a multi-disciplinary environment.

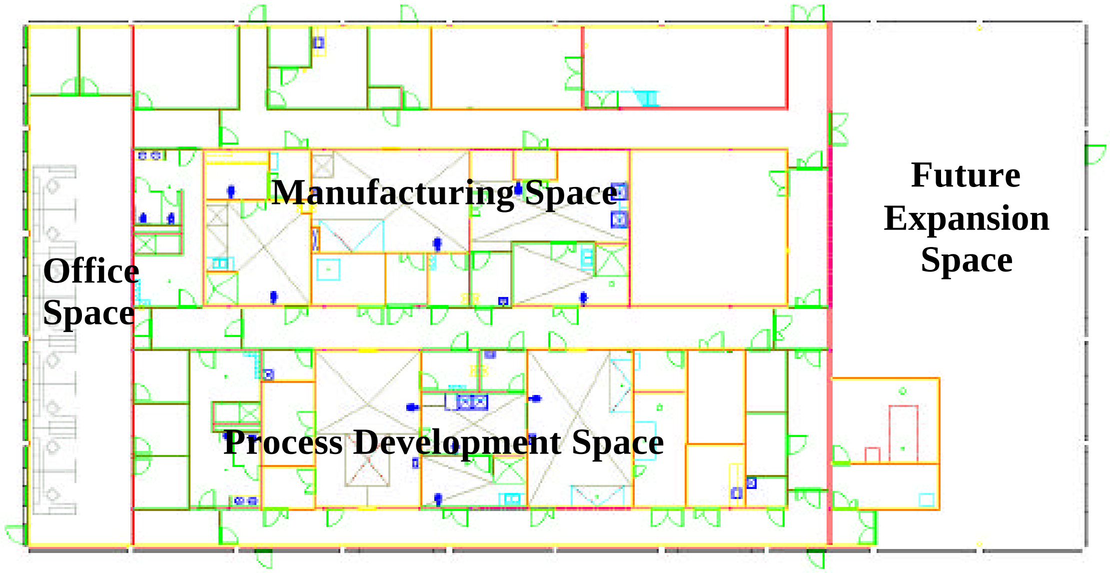


Figure 2.1: Architectural Layout of Sequus Project

This chapter describes the scope of work of the Sequus Project and introduces the members of the design-build project team. It also describe the software used by each discipline to create their respective 3D models and the software used to integrate design, cost, and schedule information. Finally, we describe how we helped the project team to successfully complete this project and how we have leveraged this case study for research.

2.1 Overview of 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. Figure 2.1 shows the 2D view of the 3D architectural model developed by Flad & Associates, the project's architect. The facility contains 20,000 square feet of available space, 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. The mechanical, electrical, and piping (MEP) systems were designed such that the majority of the work was placed on an equipment platform. The platform was necessary because the existing structure was not capable of supporting the increased loads from the MEP systems and related equipment. Construction started in May 1998 and substantial completion was completed as scheduled on February 1, 1999. The negotiated contract price was approximately $5,800,000.

2.2 The Design-Build Team

The Sequus project was unique in that the general contractor assembled the design-build team prior to design and construction. The project team consisted of the following companies: the design firm Flad & Associates, the General Contractor Hathaway Dinwiddie Construction Company, the engineering firm Affiliated Engineers Incorporated, the piping subcontractor Rountree Plumbing, the HVAC subcontractor Paragon Mechanical, and the electrical subcontractor Rosendin Electric. Appendix B describes each company and their project staff in more detail. The general contractor selected each member of the design-build team based on their experience using 3D CAD technology on past construction projects and previous experience working with each other. Therefore, each team member made a commitment to model their respective scope of work in 3D CAD using a design-build approach. The design firm was responsible for managing the design process and creating the 3D model of the architectural scope of work. The general contractor was responsible for orchestrating and managing the distribution of electronic design information, design coordination, and managing the construction process. The engineering firm was responsible for providing the basis of design and schematic drawings for the mechanical, electrical, and piping work. The MEP subcontractors were responsible for the detailed design and 3D modeling of their scope of work. Figure 2.2 shows the integrated 3D CAD model.

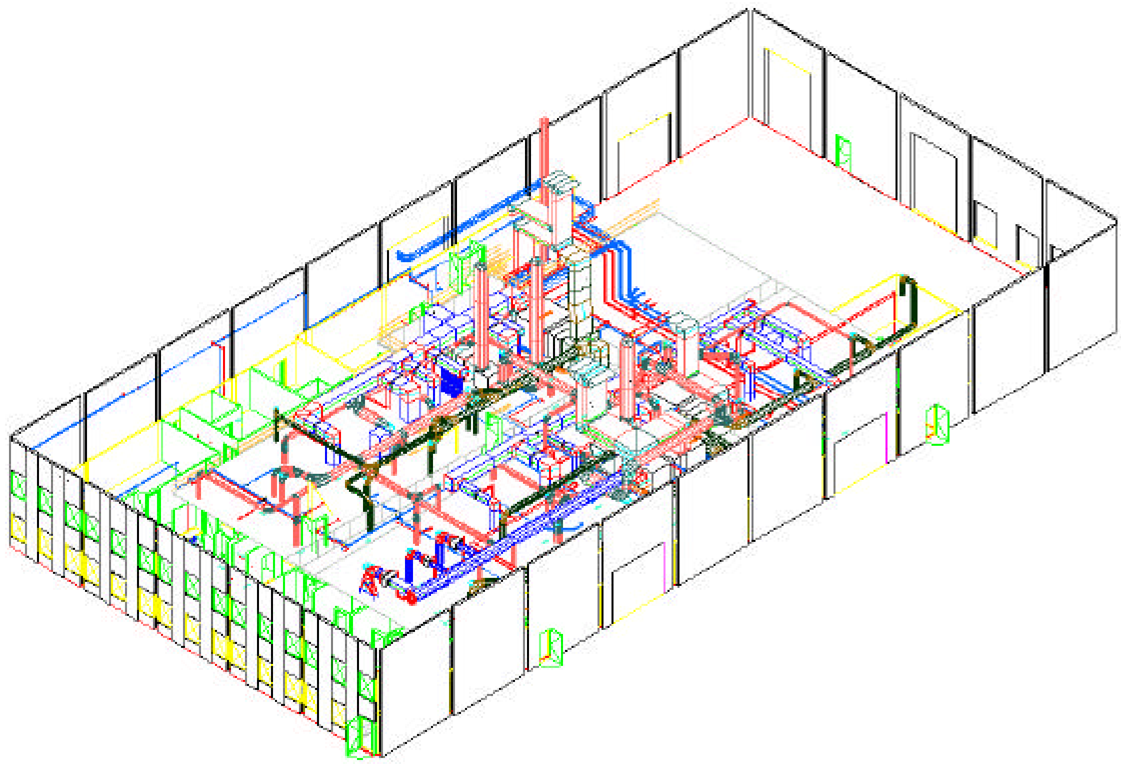


Figure 2.2: Integrated 3D Model of Sequus Project

Early and simultaneous involvement of the team members allowed the construction professionals to provide input to the design throughout the design development process and to model their scope of work in 3D. Consequently, each company was able to get feedback quickly on their designs. Participants were able to communicate directly with the other team members to explain their design intent. Each team member had an incentive to provide the 3D models and this feedback because they could leverage their own 3D models and the designs created by others to support their project management functions throughout the design and construction processes. Therefore, this collaborative design process allowed the construction companies to reap the benefits from investments in information models.

In the following sub-sections, we describe the members of the team and how they leveraged 3D design information to support their work processes.

2.2.1 General Contractor - Hathaway Dinwiddie Construction Company (HDCC)

HDCC assembled the design-build team team in response to a request for proposal from Sequus Pharmaceuticals. They felt that a team-oriented design-build approach would provide a better project-delivery process that could meet the unique challenges of designing and building a pilot plant facility. Even though HDCC had no prior experience with 3D modeling, they wanted to see how they could leverage the 3D models of the architectural and MEP systems for their project management functions. Specifically, they wanted to use the 3D models for managing the MEP design coordination process, coordinating the day-to-day construction operations of the various sub-trades, and automating quantity takeoffs for cost estimating.

2.2.2 Architect - Flad and Associates (Flad)

Flad had extensive design experience on bio-tech facilities but had limited experience with 3D modeling. They hoped to use the Sequus project as a way to expand their design capabilities and to test the capabilities of commercial design software to support a 3D design process. Flad hoped a 3D design process would eliminate inconsistencies between their designs and improve the documentation of the design process. By modeling in 3D, Flad could create different views of the design from a single drawing. Traditionally, Flad would have created 2D plans and 2D elevations separately with no electronic link between the plans and elevations. Designing in 3D would allow Flad to create plans and elevations in one step. This link would be particularly useful when the design changed, as Flad could make all modifications in one model. Flad also hoped to improve the documentation of their designs by using 3D design objects rather than just lines and circles for designing their scope of work. 3D design objects would allow Flad to insert "doors", "windows", and "walls" into drawings rather than just drawing lines that represent these architectural objects. In summary, Flad wanted to leverage the 3D design process to create different design views of the facility design, to maintain the different views as the design evolved, and to document the design process.

2.2.3 MEP Subcontractors - Rountree Plumbing and Heating, Paragon Mechanical, and Rosendin Electric

The mechanical subcontractors Rountree Plumbing and Heating and Paragon Mechanical had previous experience with 3D modeling on bio-tech projects. They were extremely interested in participating on the Sequus Project, because they knew that if the critical subcontractors modeled their respective scopes of work in 3D, that they would be able to leverage this richer design information throughout construction. On the Sequus project, the MEP subcontractors were responsible for design and construction of their respective scopes of work. Consequently, the participants with the construction expertise that had the most to benefit from the models were actually designing and coordinating the 3D models. As a result, they could control the design process and create designs that considered the construction perspective and could be leveraged to support their project management functions throughout construction. Rountree and Paragon used discipline-specific design software that contained libraries of components for their scopes of work. This design software could export bills of materials to support their cost estimating and procurement processes and could export the component dimensions to automate the fabrication process. In summary, Rountree and Paragon planned to leverage the 3D models for design coordination, fabrication, daily coordination of work crews, and automated quantity takeoff. They hoped that by leveraging 3D models to support these processes, field productivity would be improved, rework would be eliminated, and field interferences would be avoided.

The electrical subcontractor Rosendin Electric, on the other hand, had never modeled their scope of work in 3D. In addition, there were no available discipline-specific software tools for electrical design to help them transition into 3D modeling. Consequently, Rosendin was forced to create their own 3D design objects of electrical components. Rosendin's main motivation for participating on the design-build team was to participate in the 3D design coordination process. They did not plan to fabricate their electrical components from the design models so that was not a benefit that could be realized. However, electrical systems are typically the last components scheduled for installation. Consequently, electrical subcontractors often get delayed and their activity durations get compressed if the preceding work is not completed as planned. Therefore, Rosendin had an incentive to participate in the design coordination process because they could benefit from a more efficient installation process. Rosendin hoped the 3D design coordination process would enable the project team to improve field productivity, reduce rework, and avoid field interferences, thus allowing them sufficient time and space to install the electrical system.

Therefore, the disciplines participating in the Sequus project team had various degrees of expertise in 3D modeling. However, each team member was committed to modeling their respective scopes of work in 3D and leveraging the 3D design information to support their design and construction processes.

2.3 Project Challenges

The Sequus Pilot Plant Facility was created to scale-up processes that have proven successful at the bench top level in the laboratory to a larger scale operation in a manufacturing environment. There were primarily three challenges to designing and building the pilot plant facility for Sequus Pharmaceuticals:

- Sequus did not have a clear idea about the scope of the pilot plant facility,
- Sequus had an extremely limited budget, and
- Pilot plant facilities typically have complex MEP systems.

Therefore, the nature of the pilot plant facility and the combination of challenges it presented made the Sequus project an excellent candidate for 3D modeling, 3D design coordination, and electronically integrating the 3D models with cost estimating and scheduling software.

The Sequus owner representatives did not have a clear idea about the scope of the pilot plant facility. Consequently, modeling the pilot plant facility in 3D would enable the owner to better visualize the facility design. The various owner representatives could use the 3D models in several ways as a visualization tool. The designers could create a "walk-thru" of the facility to help the users view the facility design as if they were inside the facility. The user groups could also view the locations of service drops and the location of electrical outlets. Finally, the operations and maintenance group could view the 3D models to identify the locations of access panels and verify access for maintenance purposes. Therefore, modeling the architectural and MEP systems in 3D would improve the visualization of the facility design and improve the project team's communication of the design to the owner representatives.

Sequus Pharmaceuticals had an extremely limited budget for design and construction of the pilot plant facility. This was the largest capital investment Sequus had ever made and cost minimization was their highest priority. Consequently, the combination of Sequus' uncertainty about the scope of the pilot plant and their limited budget heightened the need for electronically integrating the design and cost information. By electronically integrating the project's scope and cost, the project team would be able to explore the cost impact of different design alternatives quickly. Therefore, the project team would be able to deliver a facility that meets the owner's functional requirements while minimizing the project's cost.

Bio-tech facilities typically have very complex mechanical, electrical, and piping (MEP) systems. Consequently, a challenging aspect of this project was coordinating the design of the different yet interdependent MEP systems and installing the complex MEP systems within the confined space in the existing warehouse facility. Thus, designing the MEP systems in 3D with a collaborative and team-oriented approach would enable the project team to better coordinate their designs and avoid conflicts. Moreover, integrating the 3D designs with the project schedule would enable the general contractor to better coordinate the installation of the MEP systems. Therefore, by integrating each discipline's scope of work in 3D, each discipline could better visualize their relationships to other trades, identify and eliminate most design conflicts prior to construction, and explore alternative solutions in a 3D space. Moreover, by linking design and schedule information explicitly, project teams are better able to understand and evaluate the spatial needs of each discipline over time, thus improving communication and coordination between sub-trades.

Therefore, the challenging aspects of constructing a pilot plant facility made the Sequus project an excellent candidate for 3D modeling of the architectural and MEP systems, 3D design coordination, and electronically integrating the 3D models with cost estimating and scheduling software.

In the next section, we describe the technological challenges faced by the project team members as they modeled the facility design in 3D, coordinated the designs in 3D, and electronically integrated the designs with cost estimating and scheduling software tools.

2.4 Technological Challenges

A common goal for each member of the project team was to explore the use of commercial software tools to leverage 3D models for design coordination and constructability analysis, cost estimating, and construction planning. In the following sub-sections, we will describe the technological challenges that had to be overcome by the Sequus Project team when performing these tasks.

2.4.1 Design Coordination and Constructability Analysis

The primary challenges when performing electronic design coordination and constructability analysis were ensuring that the various disciplines' designs would fit together appropriately when integrated electronically in AutoCAD and be represented to support ease of manipulation during the electronic design coordination process. Figure 2.3 shows the software used to create each discipline's 3D models and the design information that was exchanged between applications. Each team member used discipline-specific design software that contained libraries of components for their scopes of work. The project team was able to share design information easily and view other disciplines' design drawings because AutoCAD was the common platform for all the design software. However, to support electronic design coordination and constructability analysis, simply sharing and viewing the different designs was not sufficient. The designs needed to fit together appropriately when integrated electronically in AutoCAD and be represented to support ease of manipulation during the electronic design coordination process.

To address these challenges, the project team developed design guidelines that each discipline followed to facilitate the design coordination meetings. These guidelines included instructions for setting the drawings' coordinate system to ensure the drawings would fit together when integrated electronically. In addition, the guidelines included instructions for layer and drawing naming conventions and drawing referencing to ensure the drawings would be in a useable form and could be easily manipulated during the coordination meetings.

In summary, to overcome the challenges of performing electronic design coordination and constructability analysis, the project team established design guidelines that ensured the design drawings would fit together appropriately when integrated electronically in AutoCAD and be represented to support ease of manipulation during the electronic design coordination process.

2.4.2 Design-Cost Integration

The main challenges of performing design-cost integration in a multi-disciplinary environment existed because the design-cost integration link was created for specific architectural design and cost estimating software. Design-cost integration was accomplished using the link Timberline and Ketiv Technologies created to integrate Timberline's Precision Estimating software and Ketiv Technologies' ArchT architectural design software. Figure 2.3 shows that the ArchT-Precision link extracts quantities from ArchT architectural drawings and inserts them into Precision Estimating for cost estimating. We used the ArchT-Precision link because it was the only such link available on the market at the time the Sequus project started. The ArchT-Precision link was the only solution that provided an off-the-shelf electronic link between design software and cost estimating software. However, a goal on the Sequus project was to integrate the MEP as well as the architectural models with cost estimating software. Unfortunately, we could not find any software that focused on 3D modeling of MEP systems with links to cost estimating software. Consequently, the project team had to confront the technological challenge of integrating design information that was not created using ArchT

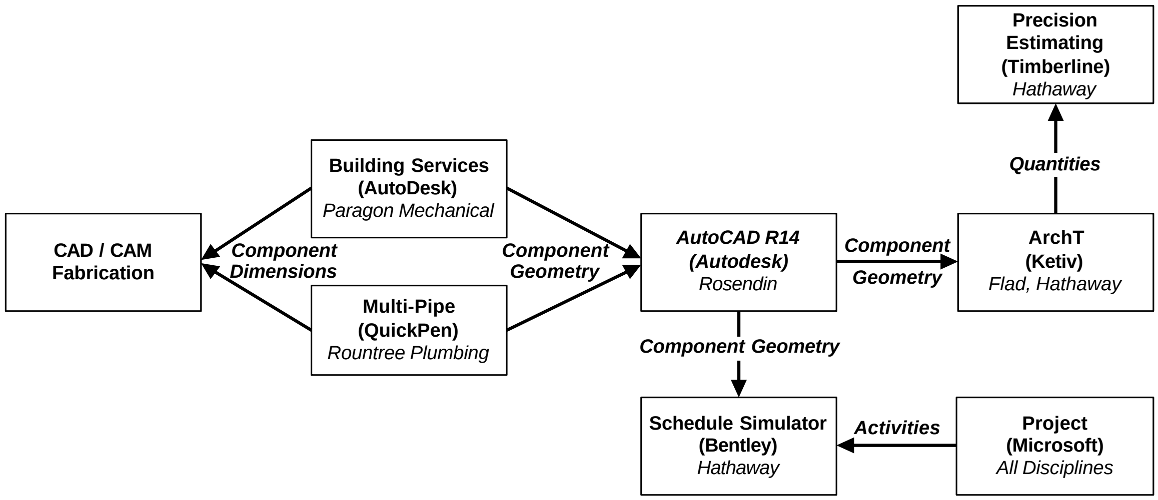


Figure 2.3: Software Used to Perform Design, Cost, and Schedule Integration and Information Exchanged Between Software Packages

with the electronic link created specifically for ArchT objects and Timberline estimating items.

Integrating non-ArchT design objects using the Precision-ArchT link was challenging because design objects generated using discipline-specific software solutions do not maintain their intelligence when viewed in other design software. For example, pipe objects created in Quickpen contain attribute information about the properties of the pipe but when the drawing file is viewed in ArchT, the pipe properties can not be accessed or manipulated. Consequently, to perform design-cost integration using the MEP design drawings, the project team had to develop "workarounds" to overcome this interoperability issue. The workarounds developed to electronically integrate the MEP designs using the ArchT-Precision link required the MEP designers to use specific drawing methods that were supported by the link or data manipulation techniques that transformed the data into a representation that was supported by the link. Therefore, to perform this link successfully, the user needed to understand the CAD model and how the graphical objects were drawn so that the correct quantity was extracted.

The design-cost integration process was further complicated by the fact that HDCC was the only company using Timberline's Precision Estimating software. Consequently, the project team had to manually input the estimating information for the MEP subcontractors into HDCC 's Precision Estimating database.

In summary, the technological challenges associated with an electronic design-cost integration process existed because the link was application dependent. The project team addressed the challenges by employing specific drawing methods and data manipulation techniques, and inputting all the cost information into a single Precision Estimating database.

2.4.3 Design-Schedule Integration

The lack of intelligent design objects when sharing design information across software applications made design-schedule integration challenging in a multi-disciplinary environment. Design-schedule integration (4D, 3D + time) was accomplished with Bentley's Schedule Simulator software, as shown in Figure 2.3. We used the Schedule Simulator because it seemed to provide the best solution available on the market at the time the Sequus project started. Bentley's Schedule Simulator imports component geometry from AutoCAD and activities from Microsoft Project (or Primavera). Then, we linked activities and design components in Schedule Simulator to create a 4D model of the facility design. Unfortunately, the properties of design objects created in the discipline-specific software are not maintained when the design files are shared between other design software. Consequently, most of the intelligence within the pipe, HVAC, and architectural design objects is lost when imported into Schedule Simulator through AutoCAD. For example, the material properties of the pipe objects created in Multi-pipe, such as copper or steel, could not be viewed in AutoCAD or exported to Schedule Simulator. The material properties are important because pipe objects with the same material properties are often installed concurrently. Yet this information could not be extracted from the design objects explicitly. To address this technological challenge, the project team had to put any information relevant for planning into the layer names corresponding to the design objects.

In the next section, we describe our role on the Sequus Project and the specific tasks we performed to support the project team and to further research. Our primary role was to support the project team in overcoming the technological challenges posed by coordinating design information and integrating design, cost, and schedule information in a multi-disciplinary environment.

2.5 The Role of Stanford Researchers

We supported the project team with the following activities:

- worked with project team members to develop design guidelines to aid the electronic design coordination process,
- identified drawing methods and data manipulation techniques to support design-cost integration of MEP designs using the ArchT-Precision link,
- tested ArchT-Precision link to integrate with the MEP designs created with the different discipline-specific design software using the specific drawing methods and data manipulation techniques mentioned above (refer to Figure 2.3),
- created a cost estimate using the ArchT-Precision link and the architectural model of the facility created with ArchT, and
- created a 4D model to assist with coordination of day-to-day construction operations.

The purpose of our involvement for research was as follows:

- to identify the benefits and shortcomings of existing integration software tools and the corresponding research issues,
- to document the impact of these tools on the project and project team's performance and organizational structure,
- to document the process and resource requirements necessary to accomplish these tasks on an actual project,
- to identify the functionality needed to create and maintain integrated scope-cost-time models on an actual construction project that addresses the limitations of today's tools,
- to produce this technical report so the experience could be shared with industry, and to present this material to industry practitioners (refer to Appendix A). In addition, our

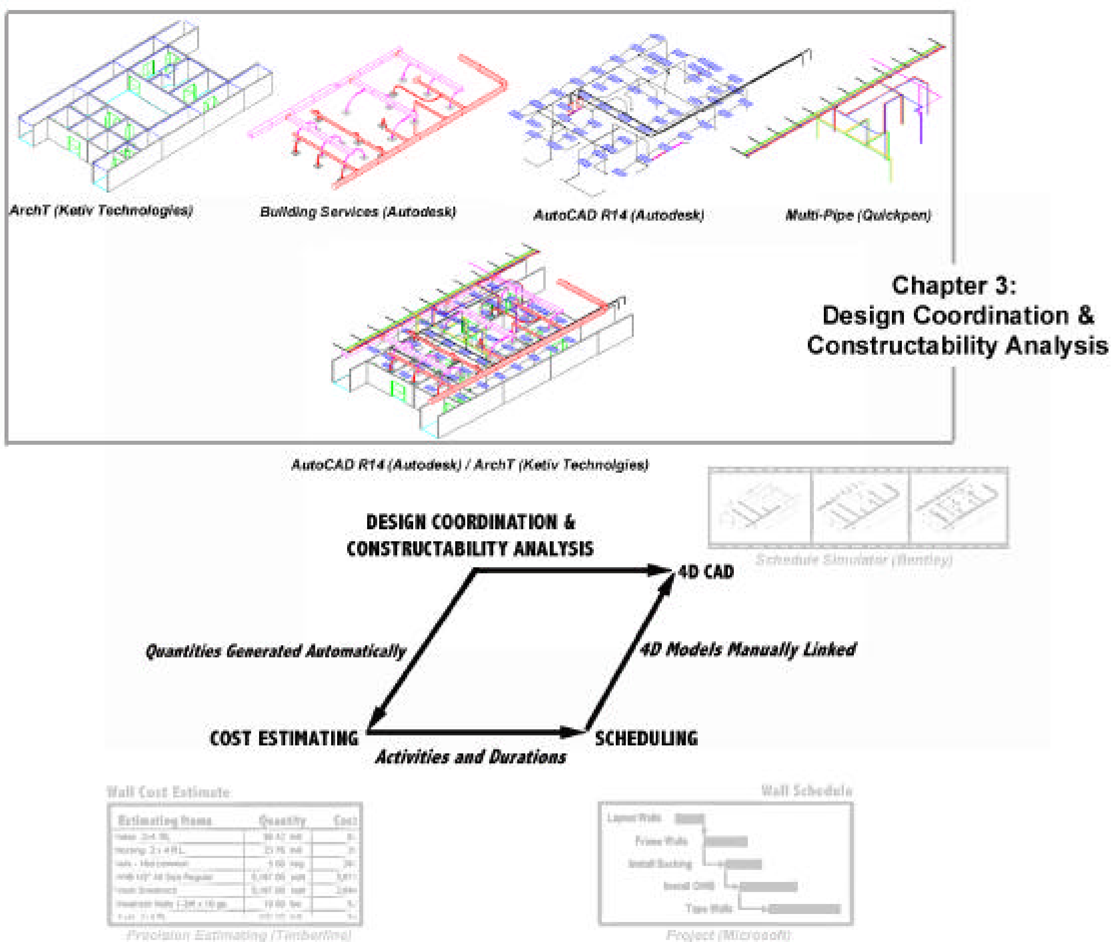
involvement on this project has provided the practical motivation for Ph.D. research on Feature-based Cost Estimating using IFC's (Staub-French and Fischer 2000).

In summary, the industry practitioners and the academic researchers benefited from this collaboration. Industry practitioners were exposed to the capabilities of current integration software, the effort required to make it work on an actual construction project, and the impact of the tools on the project performance and organizational structure. Researchers assessed the benefits and shortcomings of existing software tools, the functionality needed to maintain integrated scope-cost-time models on an actual construction project, and necessary research.

The next chapter compares the traditional paper-based method of performing MEP design coordination and constructability analysis with the electronic design coordination process used on the Sequus Project, the benefits and shortcomings of the 3D electronic design coordination process, and related research.

Chapter 3

Design Coordination and Constructability Analysis



Bio-tech facilities typically have complex MEP systems, and coordinating the designs of these different systems is a challenge for project teams. However, the current process of coordinating these systems is time-consuming, inefficient, and prone to errors as this process is performed using 2D paper-based design drawings. Consequently, many design conflicts go undetected, often leading to costly rework, reduced productivity, and schedule delays. The Sequus Project shows that performing design coordination and constructability analysis electronically with 3D models can enable a project team to identify most design conflicts and constructability issues prior to construction. This resulted in increased field productivity, less rework, 60% fewer requests for information, and fewer change orders compared to a traditional 2D paper-based process. However, additional functionality is needed to help project teams identify design conflicts quickly and reliably and develop conflict-free solutions, document and manage the coordination process, and share information between disparate systems.

This chapter describes the current practice of performing design coordination and constructability analysis and contrasts it with the electronic process used on the Sequus Project. It describes the specific steps the project team performed to create coordinated, nearly conflict-free designs and the benefits and limitations of the approach. The chapter concludes with a discussion of relevant research to address the limitations of the process and tools used on the Sequus Project.

3.1 Current Practice

Coordinating the designs of the many building systems in an industrial building is a challenging task for project teams, particularly for the complex mechanical, electrical, and plumbing/process piping (MEP) systems. In a design-build contract, such as was used on the Sequus Project, the architect prepares the layout of the building, and the engineering design-consultant prepares the specifications for the various MEP systems. The engineering design consultant specifies the required air flow to each room, the power requirements, the required flow rates to various locations within the building, and preliminary calculations of service loads in particular rooms (Korman and Tatum 1999). The specialty contractor for each of the MEP systems then uses the specifications, the schematic drawings, and the architectural layout to create detailed designs and route the systems. The general contractor usually coordinates the work of specialty contractors.

The design coordination process typically begins when the design and preliminary routing of the building systems are complete. The specialty contractors encounter common constraints that determine the system routing: the building structure, corridors, shear walls, fire walls, major equipment locations, and architectural requirements, such as ceiling type and interstitial space (Korman and Tatum 1999). Consequently, each specialty contractor routes their system to their advantage as they consider these constraints, which is reflected in the preliminary drawings. This includes minimizing the length of branches and number of fittings, choosing prime locations for major components, routing close to support points, and designing for most efficient installation by their own trade (Korman and Tatum 1999). The level of detail in the preliminary drawings often varies by trade. Typically, the HVAC and piping systems are sized at this stage whereas the electrical and fire protection are not. Consequently, some of the building systems are drawn to scale while others are drawn simply as lines with references to component sizes.

Design coordination is an iterative process that starts with the specialty contractors bringing their preliminary drawings to a coordination meeting. The drawings are typically created in 2D and printed on transparent paper at 1/4-inch scale. During the coordination meeting, each specialty contractor places their 2D drawing on a light table to compare the different building system designs. Figure 3.1 shows a typical view of MEP systems being coordinated using a 2D coordination process. The specialty contractors identify conflicts and develop solutions that are red-lined on the 2D drawings. This process continues until the coordination is complete and the specialty contractors sign-off on each other's drawings to signify their acceptance.

The current design coordination process of overlaying 2D drawings on a light table is time-consuming and inefficient. The following limitations exist with today's 2D paper-based design coordination process:

- Many design conflicts go undetected as 2D does not adequately represent the spatial requirements of the building components. Conflicts encountered in the

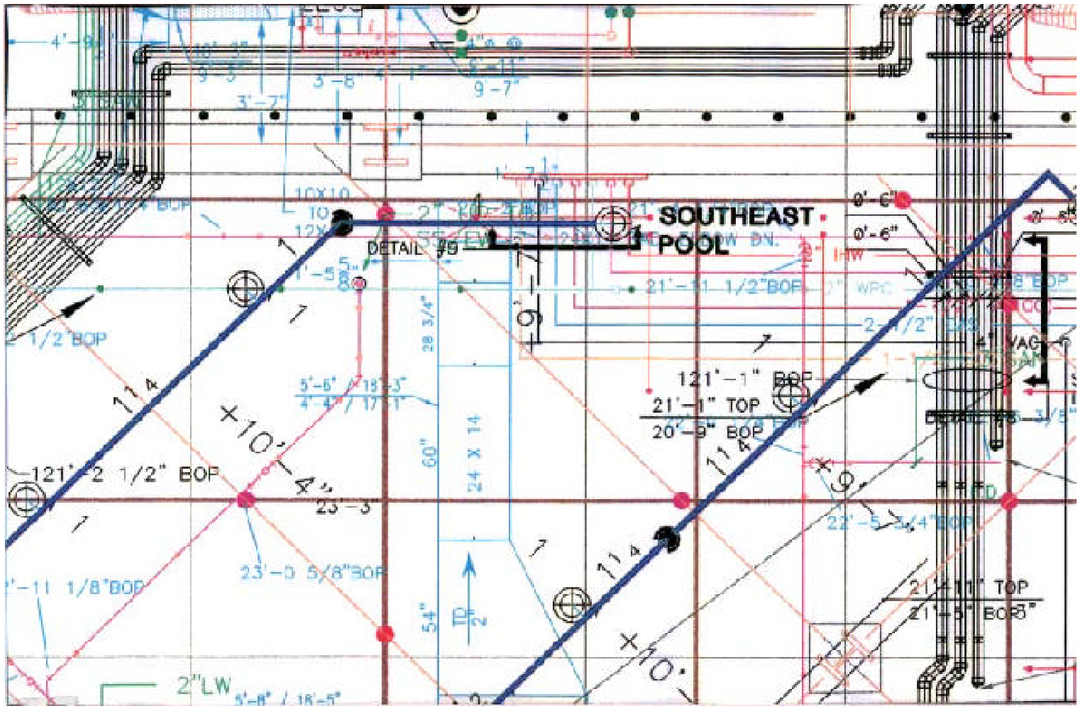


Figure 3.1: Typical View of MEP Systems Coordinated in a 2D Paper-based Process

field often have negative effects on the construction process, and can result in costly rework, reduced productivity, change orders, schedule delays, etc.

- Project teams can not easily create different design views or manipulate paper-based design information. Often, project teams need to focus on a certain area that requires extensive coordination, such as coordinating the many pipe and duct connections to an air handler unit. Using a static 2D representation, it is time-consuming and inefficient to print out all the possible views that may be needed for coordination.
- It is difficult to find conflict-free solutions because the 3rd dimension is not considered. Consequently, solutions that are generated based on 2D analysis of the MEP systems often have conflicts in the 3rd dimension that are not identified until the components are installed.
- Design information shared in paper-based form cannot be leveraged by other disciplines as they create their design solution. In the current process, each trade creates their designs electronically without considering the designs of the other

trades, prints the design on paper after the design is created, and then identifies conflicts in the weekly coordination meeting. Consequently, the opportunity to actually prevent design conflicts as the designs are created is not possible because the design information is not shared electronically.

- It is difficult for the MEP Coordinator to document and manage the coordination process because the designs are in paper-based form, the conflicts are identified on paper, and solutions are sketched out on paper. Consequently, the MEP Coordinator is often forced to document the coordination process rather than proactively manage it. The information gathered during the coordination meeting is not stored electronically and consequently, the project team could not easily retrieve or analyze it.
- It is difficult for the MEP subcontractors and MEP coordinator to track the rationale behind the design solutions proposed. If the rationale is tracked at all, it is usually just scribbled on the paper-based 2D drawing used in the coordination meeting. Consequently, if they need to know why a certain design configuration was chosen later in the design or construction process, they have to go back through all the paper-based 2D drawings and hope that it was noted somewhere.

Therefore, the current 2D paper-based design coordination is time-consuming, inefficient, and often leads to sub-optimal project performance as design conflicts are encountered and have to be resolved in the field. Creating and coordinating the designs in 3D allows project teams to integrate their designs electronically in the computer and identify conflicts in all three dimensions. Moreover, sharing electronic 3D models enables the project team to leverage the 3D design information throughout the design and construction process.

3.2 Electronic MEP Design Coordination and Constructability Analysis on the Sequus Project

Designing in a collaborative environment and utilizing design, cost, and schedule integration software enabled and forced the project team to share information electronically throughout all phases of design and construction. Thus, this collaborative approach enabled a completely new way of sharing and coordinating design information among the different disciplines. To facilitate this electronic sharing of information, the general contractor set up and maintained an FTP site so that all the disciplines could easily post and retrieve the latest design information. The project team created design guidelines to ensure that all disciplines' designs could fit together when integrated electronically and that the drawings would be in a useable form that could be easily manipulated during the coordination meetings. The disciplines shared their designs electronically throughout design development to enable *the project team* to leverage the models and create constructable and conflict-free designs. For example, Rountree Plumbing used the HVAC 3D model as a background while creating their design to avoid conflicts with the ductwork. Figure 3.2 shows a typical view of MEP systems being coordination using an electronic 3D coordination process.

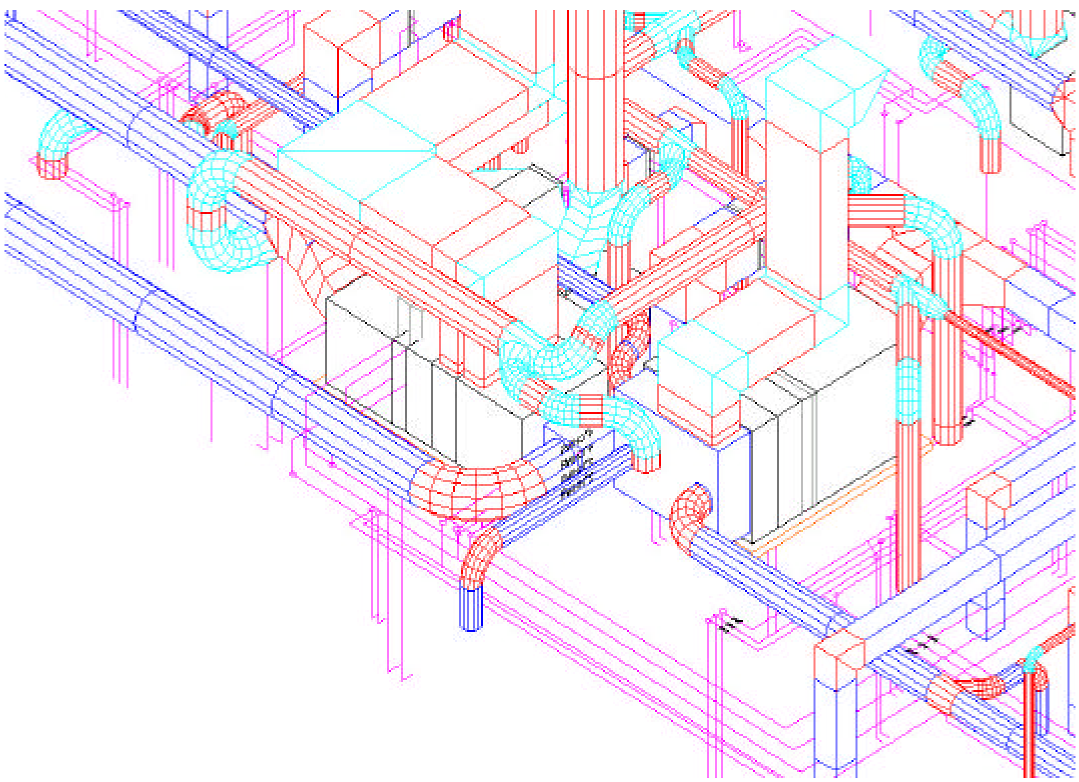


Figure 3.2: Typical View of MEP Systems Coordinated Electronically in 3D

Weekly coordination meetings were held for approximately two months during the early phase of construction. The coordination meetings were held at Rountree Plumbing's main office because they were the most experienced with 3D modeling. They purchased a high-end personal computer with a 21" monitor to facilitate the electronic coordination process. The weekly coordination meetings were attended by the MEP Coordinator and Technical Advisor for HDCC, the Project Manager and Detailer for Rountree Plumbing and Paragon Mechanical, the Engineer for Rosendin Electric, and the Project Manager for Superior Fire Protection (Superior). Superior was the only subcontractor in the coordination meetings who modeled their scope of work only in 2D.

Early in design development, we worked with the project team to establish several guidelines for design drawing management:

- Drawing file names will contain the company name and the date of the coordination meeting. This was necessary because when drawings are electronically integrated, the file name becomes the prefix for all the layer names. The layer names are used to navigate through the drawing. Also, the company name and the date of the coordination meeting were needed for version control.
- All drawings will conform to the project 0,0,0 set by the architectural model developed by Flad. This was convenient because the architectural model was used as the background for the building system designs. Moreover, it was necessary to ensure that the drawings created by the different specialty contractors would integrate appropriately within the architectural model.
- Each discipline's drawing to be coordinated at the weekly coordination meeting can not have any electronically integrated drawings (xref). This became a requirement after the first coordination meeting when the electrical drawing file to be coordinated was referencing other drawing files that were not available at the coordination site.
- All text must be on a separate layer. Text often hinders the visualization of the components being coordinated. Consequently, it was easier to identify conflicts between components when the text layers were turned off.

These guidelines improved the efficiency of the coordination meetings because they eliminated many of the technical difficulties that can be encountered when trying to electronically integrate multiple drawings. The next section describes the electronic MEP coordination process in detail.

3.3 Electronic MEP Design Coordination and Constructability Analysis - Process Description

Figure 3.3 shows the detailed steps and iterative process used on the Sequus Project to coordinate the multidisciplinary design development process.

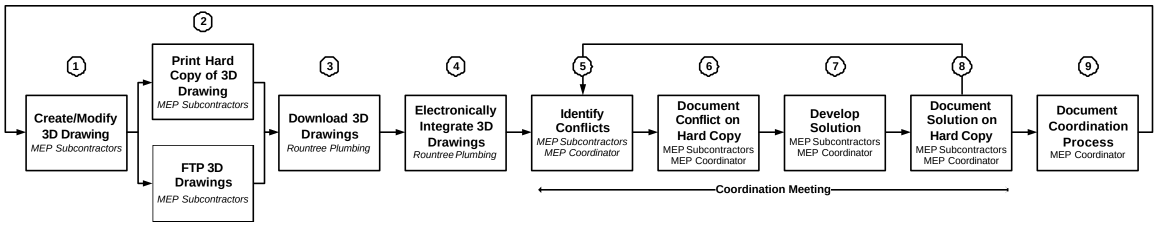


Figure 3.3: Steps for Electronic Design Coordination using 3D Models

1. **Create or Modify 3D Drawing**: Each MEP subcontractor created their respective 3D model using the design software used in their firm (Figure 2.3). The architect created the architectural model first. Then, the MEP subcontractors used the architectural model as the background when creating their 3D designs.

2 a. **Print Hard-Copy of 3D Drawing**: The MEP subcontractors printed a hard-copy of their 3D drawing prior to the coordination meeting to manually document the conflicts and proposed solutions on paper during the coordination meeting. The MEP subcontractors also printed an extra copy of their 3D drawing for the MEP Coordinator so that he could manually document the conflicts and proposed solutions on paper during the coordination meeting.

b. **FTP 3D Drawings**: The MEP subcontractors posted their respective 3D drawings on the FTP site the evening prior to the coordination meeting. The drawings had to be ready to be coordinated by showing only the work that was to be coordinated the following day. The filenames had to include the company name and date of the coordination meeting to make sure the project team was using the latest 3D drawing and for version control.

3. **Download 3D Drawings**: The morning of the coordination meeting, the project manager for Rountree Plumbing downloaded all the 3D drawings from the FTP site.

4. **Electronically Integrate 3D Drawings**: The project manager for Rountree Plumbing electronically integrated the 3D drawings that were scheduled to be coordinated in the meeting. This typically included drawings for the piping systems, ductwork, lighting, structural, and fire protection systems.

5. **Identify Conflicts**: The MEP subcontractors and MEP Coordinator spent a substantial amount of time in the coordination meetings trying to identify conflicts. They were primarily looking for conflicts between two design components, which were called "hard" conflicts. However, they would also look for conflicts between design components and access spaces or violations of clearances, which were called "soft" conflicts. To identify conflicts, the team focused on certain areas and building systems. Typically, the detailers and foremen for two companies would pair up and focus on a specific area. For example, in one meeting, the detailer and foreman for Rountree Plumbing met with the detailer for Paragon Mechanical to coordinate the piping and ductwork connections around the air handler units with the 3D models in the computer. Figure 3.4 shows a design conflict identified

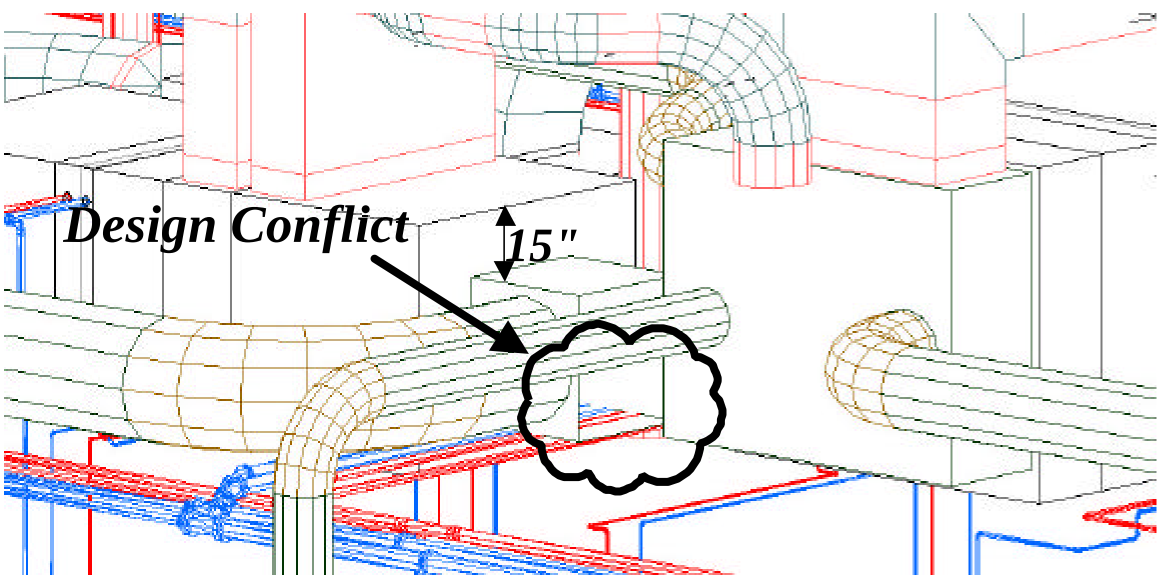


Figure 3.4: Original Design of Connection to Air Handler Unit and Conflict Identified

between the piping and ductwork at the air handler connection. Concurrently, the MEP Coordinator for HDCC, the project manager for Paragon Mechanical, and the project manager for Rosendin Electric were coordinating the location of lights and diffusers in the rooms with equipment requiring venting on the light table. Because the fire protection system was drawn in 2D, the design of the fire protection system could not be coordinated in the 3D coordination process on the computer. Consequently, the fire protection system had to be coordinated in 2D on the light table.

6. **Document Conflict on Hard Copy**: After a conflict was identified, the MEP subcontractors and the MEP Coordinator noted the conflict on the hard-copy printout of their respective 3D model.

7. **Develop Solution**: After conflicts were identified, the team would jointly develop a solution that worked for all parties involved. This step could take varying amounts of time depending on the conflict identified. Figure 3.5 shows the solution to the design conflict at the air handler connection shown in Figure 3.4. This design solution called for raising the air handler connection by 6" to avoid the piping. This design solution was detected early in the design coordination process and the AHU manufacturer implemented the change at no additional cost.

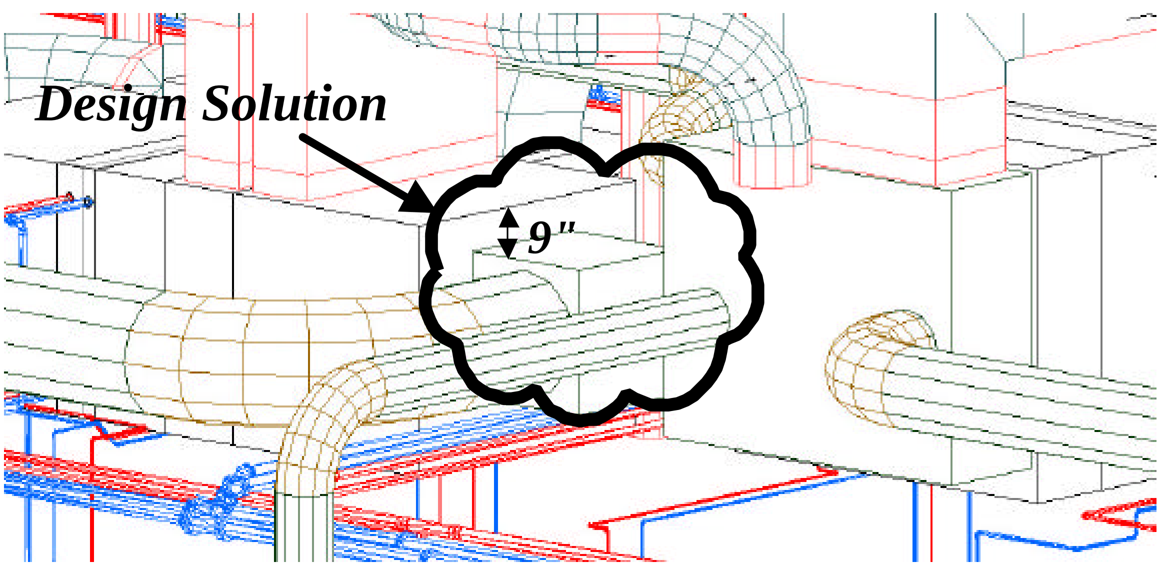


Figure 3.5: Revised Conflict-free Design of Connection to Air Handler Unit

8. **Document Solution on Hard Copy**: The MEP subcontractors and MEP Coordinator documented the design changes and proposed solutions on a hard-copy of the drawing being coordinated. The changes had to be made electronically prior to the next weekly coordination meeting. The MEP Coordinator also tried to document the rationale behind the solution, however, he did not do this consistently.

9. **Document Coordination Process**: Together with the MEP Coordinator, we compiled all the conflicts and proposed solutions identified during the coordination meeting. We saved all the electronic 3D drawings, and the MEP Coordinator maintained a log detailing the conflicts and solutions identified in each coordination meeting. The MEP Coordinator's goal for tracking this information was to make sure the MEP subcontractors updated their 3D models to reflect the solutions before the next coordination meeting. After some coordination meetings, we worked with the MEP Coordinator and faxed each team member a revised, dimensioned drawing showing the changes that were agreed to during the meeting. However, this confirmation process was only done for the coordination of the reflected ceiling plan.

Performing MEP coordination electronically in 3D was particularly challenging because the MEP subcontractors created their designs using different discipline-specific software and because of the file-based nature of the design tools. Moreover, the tools used did not help the project team to identify conflicts or document the coordination process. However, the Sequus project demonstrates that MEP coordination is improved if the critical disciplines model their scope of work in 3D and coordinate their designs in 3D.

3.4 Evaluation of Electronic MEP Design Coordination and Constructability Analysis

Electronically integrating the 3D models enabled the project team to identify most design conflicts and constructability issues prior to construction. This resulted in increased field productivity, less rework, 60% fewer requests for information, and fewer change orders compared to a traditional 2D paper-based process. The limitations were that the project team had to identify design conflicts and constructability issues manually, exchange design information inefficiently using an FTP site due to the file-based nature of the drawing tools, and document the design coordination process manually due to the combination of electronic and paper-based representations. The following sections describe in detail the benefits and limitations of the process and the tools used to electronically coordinate the MEP designs.

3.4.1 Benefits

- **Most "hard" and "soft" conflicts and constructability issues were identified prior to construction.** By modeling in 3D and electronically integrating the 3D models, design coordination and constructability analysis was performed with a more accurate representation of the building systems. Moreover, this process was further enhanced because the participants with the construction expertise that had the most to benefit from the models were actually designing and coordinating the 3D models. There was only one documented design conflict encountered in the field between the MEP subcontractors that modeled their scope of work in 3D.
- **The MEP subcontractors leveraged each other's 3D models for their own design creation process.** Consequently, the MEP subcontractors avoided design conflicts while creating their designs and as a result, created constructable and conflict-free designs. For example, the HVAC detailer used the piping 3D models as a background while creating the ductwork 3D model. The piping detailer also used the ductwork 3D model as a background while creating the piping 3D models.
- **60% fewer Requests for Information (RFI) than expected for a project of this complexity.** There are primarily two reasons why there were significantly fewer RFI's on this project: 1) the designs were coordinated and conflicts were identified early in the construction process (as described above), and 2) the MEP subcontractors were responsible for the detailed design of their scope of work. By creating detailed 3D models in the design phase, the MEP subcontractors were able to work out how

the components would fit together and how the building systems would interface. In a traditional process, these issues would often be resolved through the RFI process. On the Sequus Project, many of these issues were resolved through the design coordination process.

- **Significantly less rework than expected for a project of this complexity.** The MEP design coordination process eliminated most of the design conflicts and constructability issues prior to construction. Typically, many conflicts go undetected until they are encountered during installation, often resulting in expensive rework. On the Sequus Project, the only rework that was required occurred between trades that did not model their scope of work in 3D. In fact, the superintendent for the general contractor noted the "seamless" installation process for the 3D work.
- **Substantially fewer change orders than expected for a project of this complexity.** Rework is often a big cause for the many change orders that typically originate during construction. The project manager for HDCC expected change orders to range from 2%-10% of total construction costs, with 2% considered an indicator of a successful project. On the Sequus Project, the percentage of total cost for the MEP work that resulted from change orders was as follows: Paragon Mechanical (HVAC) = 1%; Rountree Plumbing = - 1% (negative because of a value engineering change order); Rosendin Electric = 1%. In addition, none of the change orders on this project resulted from unexpected design conflicts for the MEP work.

Therefore, electronically integrating the 3D models enabled the project team to identify most design conflicts and constructability issues prior to construction, resulting in increased field productivity, less rework, 60% fewer requests for information, and fewer change orders compared to a traditional 2D paper-based process. However, the tools used in the electronic 3D coordination process were limited in their ability to assist the project team in identifying conflicts and corresponding solutions and documenting the coordination process.

3.4.2 Shortcomings

- **The MEP subcontractors and MEP Coordinator identified "hard" and "soft" design conflicts and constructability issues manually.** It would be preferable if the computer could help the project team to identify both "hard" and "soft" conflicts and highlight them in the computer. It was particularly difficult to identify "soft" conflicts because the spaces for access and clearances were not in the 3D model. The MEP subcontractors spent a significant amount of time during the coordination meetings panning around the drawing simply trying to find conflicts. Bentley's Plantspace Interference Manager is a commercially available software solution that automatically identifies "hard" and "soft" conflicts and assists with documenting the resolution of the conflict (http://www.bentley.com/products/peproducts/).
- **The MEP subcontractors and MEP Coordinator identified conflict-free solutions manually.** It would be preferable if the computer could propose alternative conflict-free solutions. On the Sequus Project, manually identifying alternative solutions was a time-consuming process. For example, the detailer and project manager for both Rountree and Paragon spent an entire coordination meeting resolving the conflict between the piping and ductwork at the AHU connection.
- **The exchange of electronic design information was inefficient, and version control was prone to errors**. It would be preferable if the project team could access all design information from a *shared project model* rather than sharing electronic design files. A shared project model would allow them to create views of the design information that was scheduled to be coordinated. For example, it would have been convenient to simply query the project model to create a view that included the piping, ductwork, and air handler connection for the coordination meeting where this conflict was resolved. Moreover, a shared project model would help with design version control. On the Sequus Project, versioning was performed by renaming the drawing files to correspond with the coordination date. We believe computer tools should help the project team to maintain correct versioning of the design information residing in the *shared project model*.

- **It was cumbersome and difficult for the MEP Coordinator to manage and document the coordination process**. The MEP Coordinator was responsible for making sure that the MEP subcontractors updated their 3D models as planned in the coordination meetings. Because the designs were generated electronically, stored as electronic files, and conflicts were documented on paper, it was difficult to manage these different representations. Ideally, each component would know how it evolved and changed, and the coordinator could view these changes by following the electronic links from the component object. However, this was not the case on the Sequus Project. The coordinator was forced to track files rather than the specific components. Consequently, to verify design progress, the MEP coordinator either had to compare the notes on the paper-based drawing from the previous meeting to the electronic drawing of the current meeting, or compare the two electronic files from each meeting. Both processes are time-consuming and inefficient. Bentley's ProjectBank is a commercially available software solution that provides component-level information management that provides a "journal" of changes to the component that allows users to "look back" through the journal to access project data as it existed at previous stages of development (http://www.bentley.com/products/projbank/).
- **It was difficult for the MEP subcontractors and MEP coordinator to track the rationale behind the design solutions proposed.** If the rationale was tracked at all, it was usually just noted on the paper-based 3D drawing used in the coordination meeting. Consequently, if a member of the project team needed to know why a certain design configuration was chosen later in the design and construction process, he/she had to go back through all the paper-based 3D drawings and hope that it was documented somewhere.
- **Designing and coordinating the designs in 3D increased the design time**. The piping and HVAC subcontractors, Rountree Plumbing and Heating and Paragon Mechanical, reported a 30% increase in design time and cost, while the electrical subcontractor, Rosendin Electric[2], reported a 300% increase in design time. The

[2] The increase in design time resulted because Rosendin did not benefit from the coordination meetings as much as the mechanical subcontractors, and yet still had to participate in all the meetings. Also, this was the first project that they modeled in 3D. They will be able to reuse the 3D design information and decrease their design time on future projects.

increased efficiency of the installation process, however, made up for the increased design cost and time.

- **To fully realize the benefits offered by this integrated approach, all the key disciplines should model their scope of work in 3D**. On the Sequus Project, the additional key disciplines that were needed for 3D design coordination were the structural and fire protection systems. This limitation could have been avoided if these parties were brought on board early, similar to the MEP subs.
- **The impact of design alternatives on the project's cost and schedule should be considered explicitly in the design coordination process**. The goal of the coordination process is to create designs that are optimally configured. Yet, without considering the cost and schedule impacts of different design configurations, it is difficult to determine the optimal design. We performed design-cost integration (Chapter 4) and design-schedule integration (Chapter 5), but that was not accomplished until the designs were coordinated. It would have been useful to have the link between design, cost, and schedule information throughout the MEP design coordination process as well.

The Sequus Project demonstrates that MEP coordination is improved if the critical disciplines model their scope of work in 3D and coordinate their designs in 3D. However, additional research is needed to enable the computer to assist with the coordination process. Specifically, project teams need computer assistance to partially automate the detection and analysis of design conflicts. Project teams also need computer assistance to automatically document the design coordination process and the evolution of the designs. Finally, project teams should be able to easily create different design views from a shared project model with automatic design version control.

3.5 Related Research

The limitations of the electronic design coordination and constructability analysis process used on the Sequus Project are being addressed in various research efforts. The following sections describe relevant research in the following areas: 1) Identification of "Hard" and "Soft" Conflicts and Corresponding Solutions, 2) Documentation and Management of Design Coordination Process, and 3) Shared Project Model.

3.5.1 Identification of "Hard" and "Soft" Conflicts and Corresponding Solutions

Korman and Tatum (1999) developed a software tool that identifies conflicts and corresponding solutions for resolving the conflicts. The tool considers design, construction, and operations and maintenance knowledge to assist with MEP coordination. Design function, construction, and operations and maintenance knowledge is represented as spaces relative to the component. Then, the tool identifies interferences between the spaces or design conflicts between components. When components in the model are found to be interfering, the tool determines what type of interference exists – "hard" interference, spatial incompatibility, or "soft" interference. Then, the type of interference determines what attributes of the components should be refined for the particular situation to determine the optimal rearrangement. Finally, case-based reasoning is used to determine the appropriate solution from a set of possible solutions that were used on previous projects.

Akinci and Fischer (2000) developed a software tool, 4D Workplanner, that identifies "hard" and "soft" conflicts and the corresponding problem that would be encountered during construction. 4D WorkPlanner models activity space requirements qualitatively and generically in construction method models. They modeled four types of spaces: (1) labor crew space, which is the space required by the labor crew to be productive; (2) equipment space, which is the space required by the equipment used during installation; (3) hazard space, which is the space allocated for the hazards generated during an operation; and (4) protected space, which is the space required to protect the components installed for a certain period of time. The spaces represented in such an integrated model know *when, where, why,* and *for how long* they exist. The output of 4D WorkPlanner is a list of time-space conflicts identified during certain periods of times, and categorized according to the problems they create. The system simulates the construction process and concurrently performs 3D geometric clash detection to identify time-space conflicts in all four-dimensions. Finally, the system categorizes the conflict based on a time-space conflict taxonomy and predicts the type of problem the conflict would create during construction. Project managers can use this information to modify their production models (e.g., change construction methods, re-sequence activities, etc.) to minimize spatial conflicts and to increase the reliability of their schedules.

3.5.2 Documentation and Management of Design Coordination Process

Garcia et al (1993) developed a system, Active Design Documents (ADD), that documents the design rationale for preliminary routine designs of HVAC systems. Garcia acquired knowledge about the design rationale for various preliminary designs of HVAC systems. The system uses this knowledge to document the design process and explain standard design decisions. This system monitors an HVAC designer performing HVAC design and uses the knowledge acquired to determine the expected design solution. If the HVAC designer selects the expected solution, then the system adds the design rationale to the HVAC design from the knowledge acquired and stored in the system. On the Sequus Project, this would have been useful because ADD automatically adds the rationale behind design decisions. Moreover, ADD stores the rationale electronically within the design, making it easily accessible and available to all members of the project team.

Fruchter and Reiner (1998) address the problem of capturing the design evolution in collaborative multi-disciplinary teams. They developed a prototype system, ProMem, that supports design evolution capture, visualization, and reuse of project information for the various perspectives within the AEC domain. The system addresses the limitations of current file-based management systems by capturing the team's design intents, interests, responsibilities, and the design evolution at different stages of design development. Specifically, it allows the designer to enter his/her perspective explicitly. For example, an engineer might view particular objects in terms of “beams” and “columns”, but a construction manager might be thinking in terms of “phases” and “zones.” The key point is that engineers and construction managers are both referring to the same physical objects but *framing* the situation in a subjective way from within their discipline. Therefore, project teams can query the system and extract graphic objects, discipline models, and project models from the project memory for documentation and reuse on future projects. On the Sequus project, ProMem would have been useful because it could capture the various disciplines' perspectives and allow them to organize and query the model.

3.5.3 Shared Project Model

On the Sequus project, information was shared between disciplines by posting electronic files on an FTP site or exchanging information electronically through e-mail. This process was application dependent in that the information was created in one application, transferred electronically as a file, and then viewed in another application. This worked on the Sequus project because each member of the project team agreed to use design software that relied on the AutoCAD platform. Therefore, the Sequus project relied on a *file-based* and *application dependent* process to share information. However, in an ideal world, the project information would reside in a shared project model where each member of the project team can easily extract design information they need *independent* of the application that the information was created in. To enable application independent information sharing through a shared project model, the project information needs to be represented using a standard representation.

The International Alliance for Interoperability (IAI) was formed in 1994 with the objective of defining standards for representing information for the AEC/FM industry. The intention of the IAI was to "specify how the 'things' that could occur in a constructed facility (including real things such as doors, walls, fans, etc. and abstract concepts such as space, organization, process etc.) should be represented electronically. These specifications represent a data structure supporting an *electronic project model* useful in sharing data across applications." (http://iaiweb.lbl.gov/) The IAI is defining these specifications in the form of Industry Foundation Classes (IFC's) that will enable information sharing throughout the project life-cycle and across all disciplines and technical applications in the building industry. Therefore, if the Sequus 3D design information had been represented in a shared project model using the IFC standard, the problems related to information sharing would have been eliminated. Specifically, each member of the project team could have easily extracted the design information they needed for each coordination meeting. Moreover, the MEP Coordinator would have also benefited from a shared project model because he would have been able to store all design coordination information in a central location that would have been easily accessible to the project team.

Therefore, previous research has addressed many of the limitations found in the electronic 3D coordination process on the Sequus Project. Systems developed in research support:

- automatic identification of "hard" and "soft" conflicts and corresponding solutions,
- automatic documentation of design evolution and design rationale, and
- application independent information sharing using a shared project model based on the IFC standard.

3.6 Research Needs

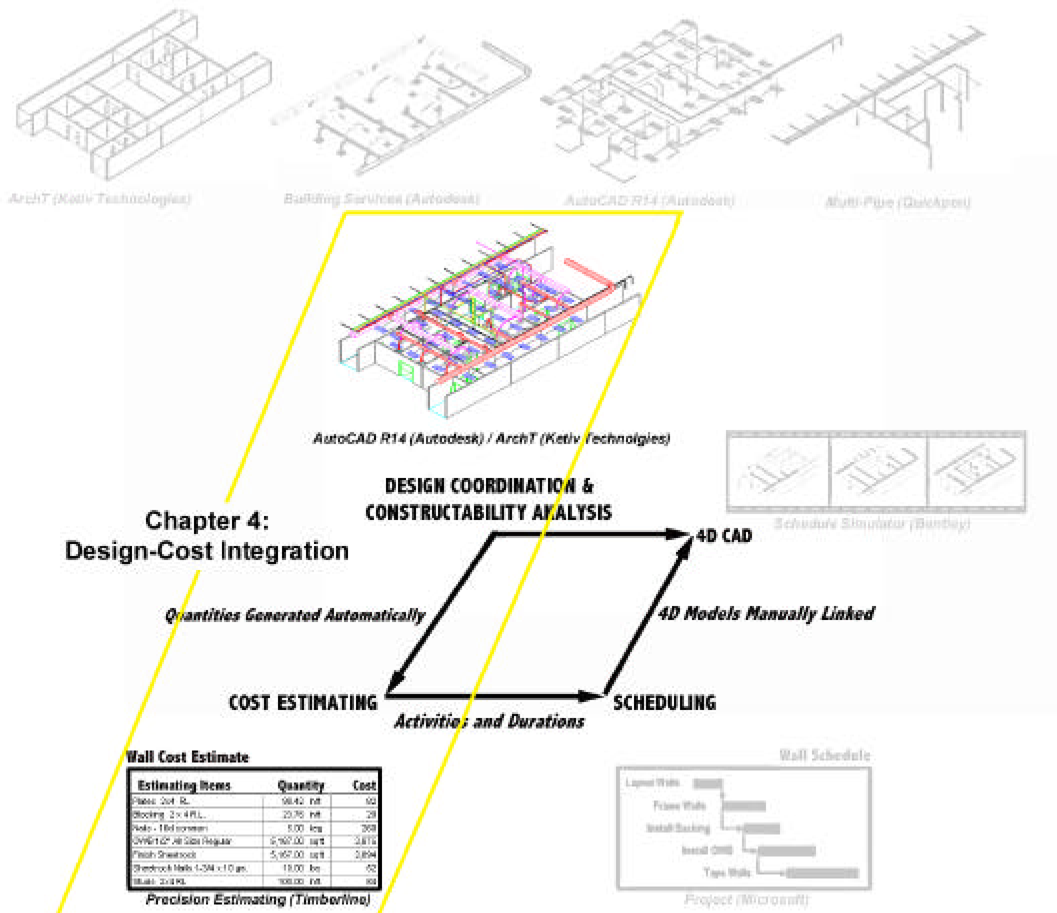
Research is needed to create the different design views needed during multi-disciplinary design coordination meetings (Haymaker et al 2000) and to analyze the designs to detect "hard" and "soft" conflicts over time. Today, project teams spend a lot of time panning around the electronically integrated drawings and manipulating the layering to create the view that is needed for that coordination meeting. For example, on the Sequus Project, it would have been convenient to simply query the project model to create a view that included the piping, ductwork, and air handler connection for the coordination meeting where this conflict was resolved. Current layering approaches are not flexible enough to support such queries. Therefore, research is needed to formalize the different types of views needed and the information required for each view, and mechanisms need to be developed to manipulate the data to create the views.

Research is also needed to detect "hard" and "soft" conflicts over time for MEP design coordination. Research by Korman and Tatum (1999) on MEP design coordination addresses the need for "hard" and "soft" conflict detection. However, this research does not consider the temporal nature of the construction process. Previous research by Akinci and Fischer (2000) identifies "hard" and "soft" conflicts over time. However, this research does not consider the unique needs of MEP. Therefore, research is needed to formalize conflict detection over time to support MEP design coordination.

The next chapter describes the current cost estimating process, the process used on the Sequus Project to electronically integrate design and cost information, an assessment of the benefits and shortcomings of the tools, and related research.

Chapter 4

Design-Cost Integration



Even though designs are generated electronically, current cost estimating processes do not leverage the electronic design information. Consequently, cost estimating remains a largely manual process - quantities are calculated manually, cost information is identified manually, cost estimates are validated and verified manually, and cost estimates are maintained manually - giving rise to inefficiencies in the estimating process that increase estimating time and decrease accuracy[3]. The unique challenges posed by the Sequus Pharmaceuticals Pilot Plant facility would not be overcome with a traditional paper-based estimating process. Sequus was uncertain about the scope of the project and was also under tight budgetary constraints. Consequently, they needed to explore a variety of design alternatives and quickly understand the cost impact of their design decisions.

The Sequus Project demonstrates that commercial design-cost integration software can help project teams to evaluate the cost impact of many design and specification alternatives rapidly. Moreover, commercial design-cost integration software can help estimators validate and document the completeness and assumptions of their estimates and calculate material quantities automatically. However, additional research is needed to help estimators create and maintain cost estimates throughout the project life-cycle.

This chapter describes the current practice of creating and maintaining construction cost estimates and contrasts it with the electronic design-cost integration process used on the Sequus Project. We describe the specific steps the project team performed to integrate design and cost information, the resource requirements to accomplish these tasks on an actual project, and the benefits and limitations of this technology. This chapter concludes with a discussion of relevant research that addresses the limitations of the design-cost integration tools used on the Sequus Project.

4.1 Current Practice

The typical estimating process involves four distinct steps. First, estimators analyze 2D paper-based design drawings and specifications to determine their scope of work and to identify critical design properties that affect construction costs. Second, they create the construction cost assemblies corresponding to the components they are estimating. Each cost assembly contains the estimating items needed to construct the component. For

[3] Laitinen (1998) reports that, on average, each building element is estimated seven times during a project.

example, a typical cost assembly to construct a concrete column would include the material unit costs, labor and equipment resources, and productivity rates for pouring concrete, installing rebar, and installing formwork. Third, they manually calculate the quantities of the items included in their scope of work, typically using a digitizer or scaling off the paper drawings. Estimators often use different color highlighter pens to document the design information and associated quantities that were assigned to the corresponding cost assemblies. Finally, the estimator calculates the costs for each estimating item. Then, if the design changes, the estimator repeats these four steps to maintain the estimate.

Even though designs are generated electronically, current cost estimating processes do not leverage the electronic design information. 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. Consequently, cost estimating remains a largely manual process, giving rise to inefficiencies in the estimating process that increase estimating time and decrease accuracy. In summary, the following limitations exist with today's 2D paper-based cost estimating process:

- The estimator calculates quantities manually.
- The estimator has to manually identify the relevant design properties that affect the construction cost information.
- The estimator has to manually identify the appropriate cost information.
- If the design changes, the cost estimate has to be manually updated. Consequently, the quantities have to be manually recalculated and the appropriate cost information has to be manually identified again.
- It is difficult for estimators to verify the completeness of their estimates. Often, estimators mark-up the paper-based drawings with highlighter pens to show that a particular scope of work has been estimated.
- It is difficult for estimators to recall the cost information that was used for a particular scope of work. Again, estimators often mark-up the 2D paper-based drawings with highlighter pens to show that a particular cost assembly goes with a particular component in the design.

- It is difficult to use or work on someone else's estimate. The estimator's assumptions about the design and rationale for selecting a particular estimating item is typically not explicit in the estimate.

Design-cost integration software improves the cost estimating process by leveraging existing electronic design information. Integrating design and cost information electronically 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 some design options quickly.

4.2 Electronic Design-Cost Integration on the Sequus Project

This was the first time that any member of the project team had performed electronic design-cost integration. Consequently, the project team had some concerns regarding the capabilities of the Archt-Precision link to integrate with the MEP designs, and the reliability of the computer generated quantities. To address these concerns, we tested the design-cost integration link on a theoretical pilot plant design prior to the design and construction of the Sequus Project. This theoretical project showed that although the link could extract the necessary quantities from the MEP drawings, the process was too cumbersome to pursue on the Sequus Project. In contrast, the link worked successfully on the architectural drawing and HDCC wanted to use the link on the Sequus Project. However, HDCC was still concerned about the reliability of the computer generated quantities. To address this concern, we performed electronic design-cost integration in parallel with a traditional 2D paper-based process performed by HDCC 's Project Engineer.

This study showed that the computer-generated quantities from the Archt-Precision link were more reliable than the manually calculated quantities from the 2D paper-based drawings. The computer-generated quantities were more precise and less prone to human error. Through a comparison of the estimates, we found several quantity takeoff errors in the traditionally generated estimate. Moreover, we were able to calculate the quantities for the architectural work in half the time. However, estimators may have to adjust their costs to account for the "exactness" of the computer-generated quantities. For example, in a traditional process, an estimator may calculate the quantity of flooring simply by calculating the building surface area. However, in the architectural model on the Sequus Project, flooring was drawn from the edge of the wall for each room. Consequently, the electronically generated flooring quantity did not include the area of the walls. Estimators will need to account for this difference in quantity takeoff when making the transition from a traditional estimating process to an electronic design-cost integration process.

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, Building Services, Multi-pipe, and Ketiv's ArchT Architectural Drawing software packages. Figure 4.1 shows an overview of these steps: the estimator attaches work packages to the objects in the CAD model, the system automatically calculates the quantities from within the CAD environment, and estimating items are then revised if necessary. This process

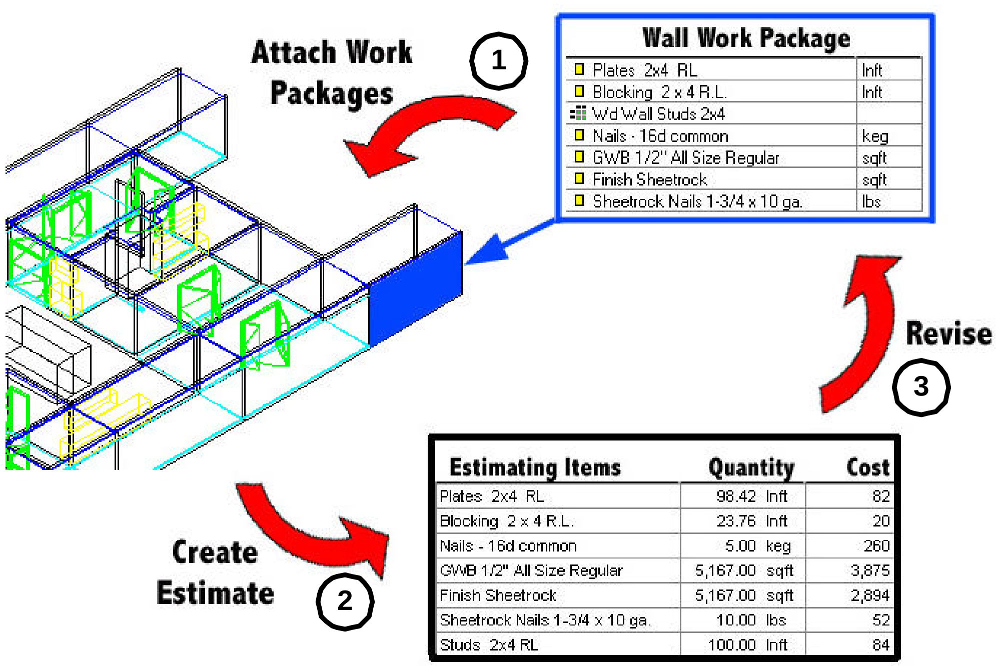


Figure 4.1: Overview of Steps for Electronic Design-Cost Integration

is repeated until the user is satisfied with the results. If the design changes, the user may have to repeat these same three steps. If the design change does not affect the applicability of the work package, then the estimator can skip step 1 and immediately create the cost estimate because the revised quantities are calculated automatically. However, if the design change requires a different work package, then the estimator needs to start at step 1 and attach the new work package before creating the revised cost estimate.

In Precision Estimating, the user initially performs setup procedures so that the estimating system extracts the appropriate quantity information from the CAD objects. Precision Estimating represents component dimensions, such as "length" and "height", using Precision Variables. Precision Variables reside in the item or work package formula and define the unit of measure that will be used in the cost calculation. The estimator has to link the Precision Variable defined in the estimating cost item with the CAD Variable that corresponds to the dimensional information in the CAD object. CAD Variables are the dimensions of the graphical objects, such as length and thickness. Table 4.1 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 4.1: 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

Figure 4.2 shows Precision Variables the estimator defined in a wall work package and relevant CAD Variables that could be selected and linked to those Precision Variables. The estimator has to link the Precision Variables with the appropriate CAD Variables for all work packages he/she wants to use to extract dimensional information from the CAD model. The CAD Variables available for a particular CAD object depend on the application and the drawing method used to create the CAD object. Therefore, 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.

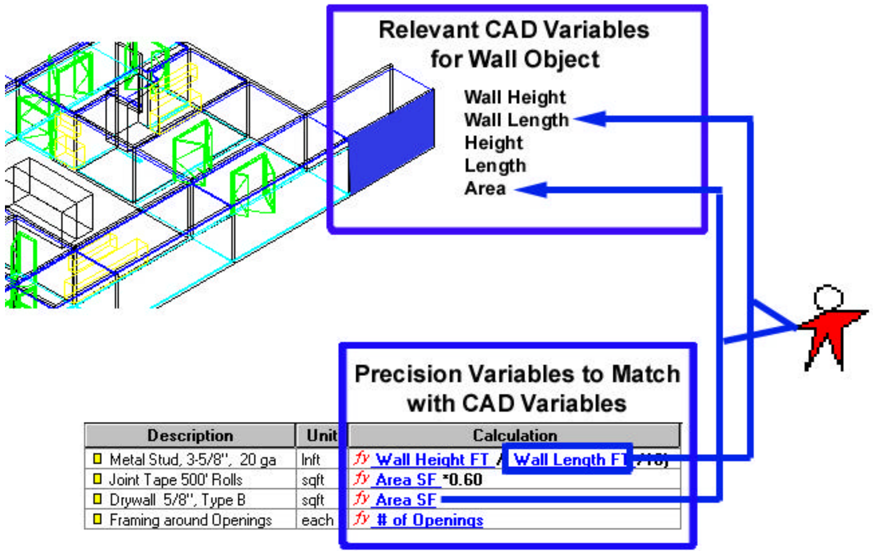


Figure 4.2: Estimator links Precision Variables with CAD Variables

On the Sequus Project, the integration of design and cost information was complicated because the project team consisted of different companies using different design and estimating software. There was no central Precision Estimating database with all the items necessary to create accurate and detailed cost estimates for the project team. 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 MEP subcontractors created their 3D models using discipline-specific design software, as described in Chapter 2.4. Consequently, the subcontractors had to draw their CAD objects with specific drawing methods to ensure that the dimensions necessary for electronic quantity takeoff would be available.

We worked with the MEP subcontractors to determine the dimensional information that was needed for estimating the cost of the MEP systems. Then we identified the specific drawing methods for the corresponding MEP CAD objects. Figure 4.3 shows the CAD objects for HVAC ducts, pipe, and electrical conduit, the dimensions that were extracted, and the drawing method used. Normally, HVAC ducts, pipe, and electrical conduit would be drawn as 3D solids. However, the only CAD dimension that can be extracted from a 3D solid is volume, which is not useful for estimating ductwork, piping, and electrical conduit. Therefore, HVAC ducts and electrical conduit had to be drawn as polylines with thickness to provide the desired graphical representation and CAD dimension for estimating purposes. To estimate pipe objects, length was extracted from the attribute line.

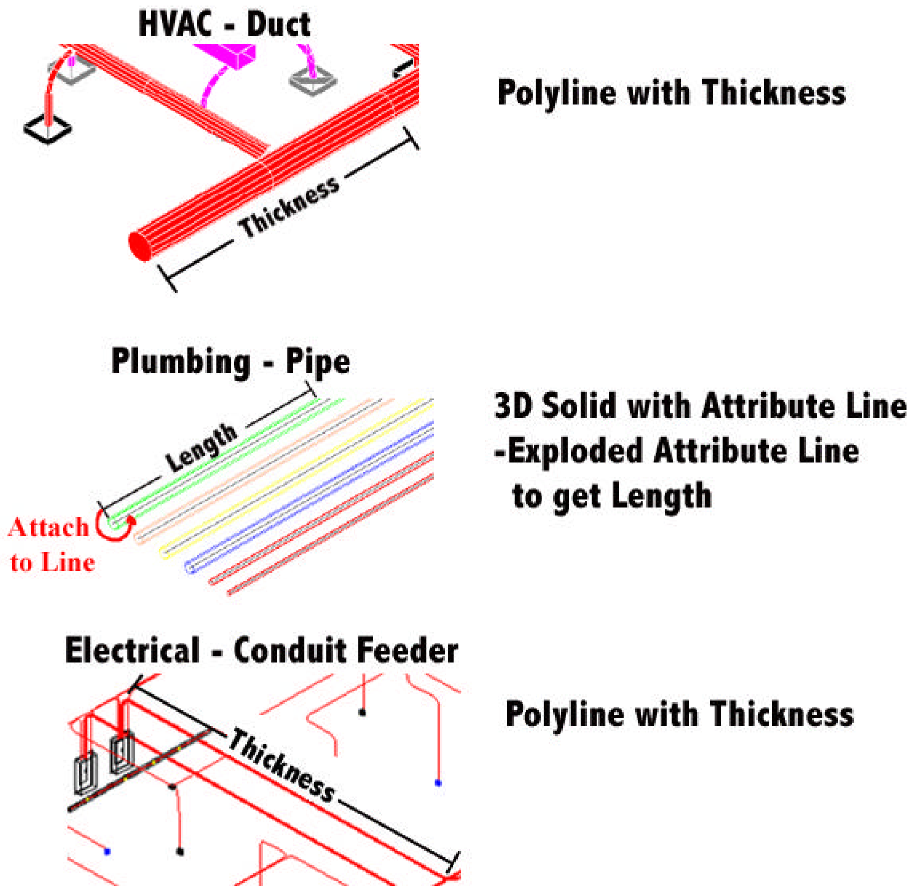


Figure 4.3: Typical MEP CAD Objects and Associated Drawing Methods

Therefore, to integrate design and cost information in a multi-disciplinary environment, the MEP CAD objects had to be created using a specific drawing method to leverage the link provided by ArchT and Precision Estimating.

In the following section, we describe the specific tasks we performed to integrate design and cost information.

4.3 Electronic Design-Cost Integration - Process Description

We performed electronic design-cost integration in parallel with a traditional 2D paper-based performed by HDCC 's Project Engineer. We created estimates using both approaches to evaluate the capabilities of electronic design-cost integration with respect to estimating duration, estimating accuracy, and estimating functionality in contrast to a traditional paper-based process. This section describes the steps and the resource requirements necessary to accomplish electronic design-cost integration. Figure 4.4 shows the eight steps required to perform electronic design-cost integration on the Sequus Pharmaceuticals Pilot Plant. However, it should be noted that steps 2-3 are also required in a traditional paper-based process.

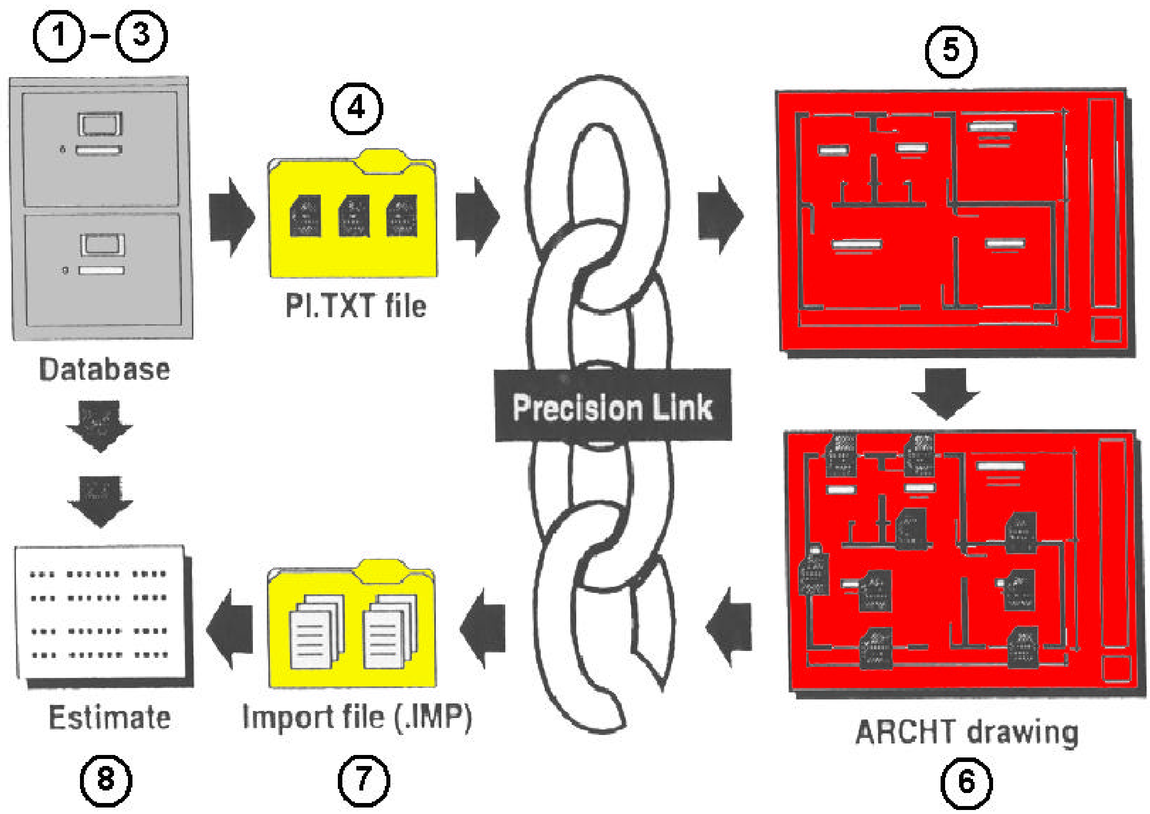


Figure 4.4: Specific Steps Required to Integrate Design and Cost Information using the Precision-Archt Link

1. **Add MEP subcontractors' estimating items to the general contractor's estimating database for all the disciplines.** We gathered crew production rates whenever possible to leverage the quantity information extracted from the CAD models for calculating accurate labor durations and corresponding costs. The average duration to create this database was three hours for each subcontractor. We added a total of 314 items to the general contractor's Precision 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, which is described in step 4. 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. **Create pi.txt file and link Precision Variables with CAD Variables.** We selected all the estimating items or work packages that were going to be linked to CAD objects in ArchT. For each item, we linked the Precision Variables defined in the item formula with the appropriate CAD Variables. Then, we created the pi.txt file that contained all the estimating information for the items selected. The estimating information in the pi.txt file is used by ArchT to link the cost information to the CAD objects. The total duration for this task was four hours.

5. **Modify CAD model, if necessary, to correspond to estimating items.** 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. The total duration for this task was 4 hours.

6. **Attach work packages and items to the CAD objects in each design model in ArchT.** ArchT provides useful functionality to aid the user in performing this step. We queried the model to determine what CAD objects had specific estimating records attached. This functionality was useful for making sure the appropriate work package or cost item was attached to a particular CAD object. We also queried the model to make sure all the CAD objects had an estimating record attached. This functionality was useful for making sure the estimate was complete and that all the CAD objects had an estimating record attached. 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. Figure 4.5 shows the three sub-steps and the user interface to attach work packages or cost items in ArchT. The total duration for this task was 12 hours.

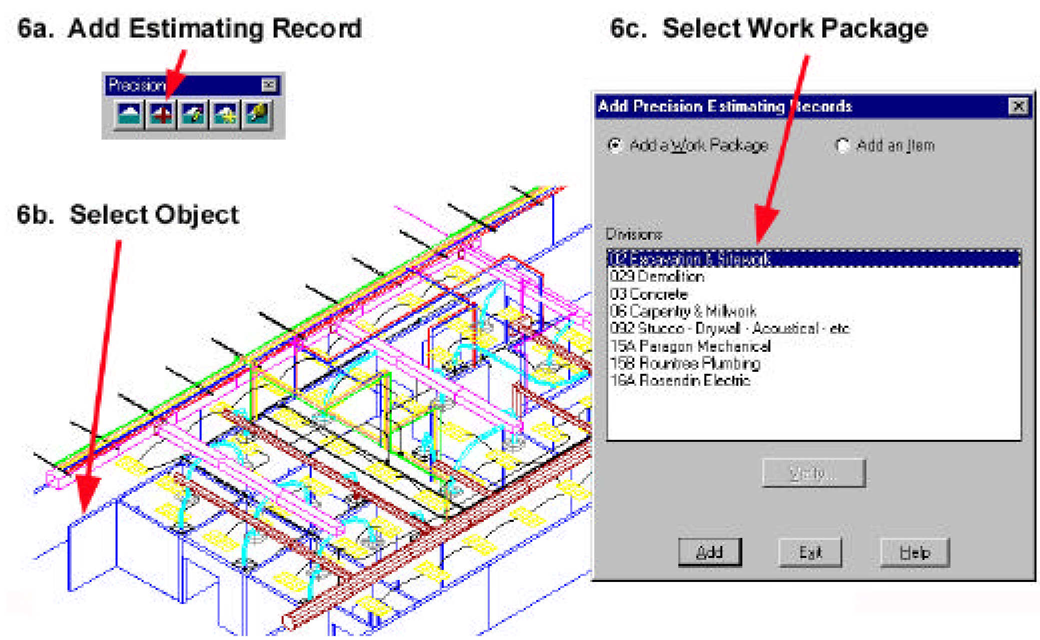


Figure 4.5: Steps to Add Estimating Records

7. **Create and evaluate estimates.** After all the work packages and cost items were attached in ArchT, we simply had to select the "Create Estimate" button and the

estimate was automatically created and the quantities were automatically inserted into each cost item in the estimate. The total duration for this task was about 10 hours.

8. **Update estimate if the design changes.** We did not perform this step formally during the Sequus Project, although we tested the functionality to determine the capabilities of the link to handle design changes. The ArchT-Precision link deals with design changes in two ways depending on the type of change:
   a. *component geometry changes*: For example, if the wall height changed from 8' to 12', the estimator simply has to hit the "Create Estimate" button and the quantities will be updated automatically in the revised estimate. However, if this design change requires a change in the cost information in the work package, the estimator has to change the work package, regenerate the pi.txt file, and re-attach the work package to the CAD object.
   b. *component specification changes*: For example, if the wall paint type changes from latex to epoxy, the estimator would have to revise the work package, regenerate the pi.txt file, and re-create the cost estimate by selecting the "Create Estimate" button. Alternatively, the estimator could create a new work package that includes epoxy paint, regenerate the pi.txt file, attach the new work package, and then re-create the estimate by selecting the "Create Estimate" button.
   c. *Insertion of building component*: For example, if a door is inserted into the drawing, the estimator would have to attach the work package to the new component, and re-create the cost estimate by selecting the “Create Estimate” button.
   d. *Deletion of building component*: For example, if a door is deleted from the drawing, the estimator would simply have to hit the "Create Estimate" button and the quantities will be updated automatically in the revised estimate.

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 for cost estimating with Precision Estimating. However, as project teams apply 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.

4.4 Evaluation Of Design-Cost Integration Software

Electronic design-cost integration provided many benefits to the project team when compared with the traditional paper-based process. Specifically, electronically integrating design and cost information enabled the project team to validate and document the completeness and assumptions of their estimates, to calculate material quantities automatically, and to evaluate the cost impact of some design alternatives quickly. However, a primary goal on the Sequus Project was to explore a variety of design alternatives and quickly understand the cost impact of their design decisions. Unfortunately, the tool is limited in its ability to provide this functionality because only changes in quantities are reflected in the costs. Consequently, the costs for many design changes cannot be evaluated much more quickly than with the traditional paper-based process. Finally, the Sequus Project showed that the tool is limited in its use in a multi-disciplinary environment where the designs were created with different discipline-specific software.

4.4.1 Benefits

- **The quantities are automatically calculated and inserted into the estimate**. Using the traditional process, HDCC 's Project Engineer spent about 40 hours to complete the estimate for architectural features on the Sequus Project. We reduced the estimating time by 25% by using the automated process. This was the first time HDCC used this technology and in the future they expect even greater time savings. Others have reported time savings up to 80% with an automated takeoff process (Laitinen 1998).
- **Some what-if scenarios can be handled quickly**. Project teams can quickly explore and compare the cost impact of different design and specification alternatives. This option can be particularly useful during value engineering or in the programming phase when different design options are being considered. The ArchT-Precision link works

particularly well for component geometry changes because the quantities are automatically recalculated and inserted into the revised cost estimate. The ArchT-Precision link is less efficient in dealing with component specification changes because the estimator has to revise the cost information before the estimate can be updated.

- **ArchT provides electronic verification that all objects in the CAD model have been included in the estimate**. It is a difficult task for an estimator to verify that all the design objects are included in the estimate when using the traditional paper-based process. Typically, estimators will use highlighter pens and color in the portions of the design that have been added to the estimate. This is a time-consuming and error prone method of performing this verification process. When using the design-cost integration tools, the user simply selects the ArchT option to identify "All Objects Not Having a Record" to verify the completeness of the estimate. We used this option extensively when creating the estimate with the ArchT-Precision link.
- **ArchT documents the work package or item used for each CAD object**. This is a very useful feature when creating estimates or communicating about estimates that have been created. The estimator is able to query the CAD model and know exactly what design objects are related to a specific estimating item or work package. We used this feature extensively to verify the accuracy of the estimate. For example, there were ten different wall types on this project and this feature made it extremely easy to verify that the appropriate estimating work package was attached to each wall type. In addition, this feature was also useful when communicating the estimate to other members of a project team or other estimators. During pre-construction, the estimator of the Sequus Project left the company, which is not uncommon in this business. Using the traditional paper-based method of estimating, it was very difficult for the new project manager to understand what design the estimate was based on and what estimating item related to each design object. In contrast, the integrated approach provided an integrated document that allowed the new project manager to pick up where the previous manager left off.

Therefore, electronic design-cost integration software can help project teams to evaluate the cost impact of some design alternatives rapidly, to validate and document the completeness and assumptions of their estimates, and to calculate material quantities automatically.

However, the tools used to perform electronic design-cost integration are limited in their ability to integrate design information in a multi-disciplinary environment and to calculate the cost impact of all design changes.

4.4.2 Shortcomings

- **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 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, as discussed in Section 4.2.
- **The link between the CAD information and the cost information is not intelligent**. For example, the estimator can attach a door cost assembly to a wall object and the system will not identify or prevent this inconsistency. However, in this situation, the system will most likely not be able to calculate the appropriate quantity, which would signal a problem to the estimator.
- **The estimating information must reside in a central Precision Estimating Database**. It was time-consuming to add all of the MEP subcontractors' estimating information to HDCC's Precision Estimating database. Moreover, it is unlikely that subcontractors will be willing to share their cost information on future projects. The only reason that the MEP subcontractors shared their cost information on the Sequus Project was to assess the ArchT-Precision link. Electronic design-cost integration should be performed by each discipline using their company's design and cost estimating software.
- **If the design changes, the system is limited in its ability to detect whether the cost information selected is still applicable.** For example, if the wall height was changed from 8' to 12', the system would calculate the cost impact by revising the quantity. In

reality, however, the productivity rate would also be affected by this design change. Today, estimators have to manually update all the electronic links between cost information and 3D components in these situations. It is possible to add more intelligence to the links so that the system can but it requires extensive knowledge of Precision Estimating[4].

- **The user almost always has to select the estimating item that is associated with each CAD object**. Ideally, estimating items would be selected automatically based on specific Precision Variables and corresponding CAD Variables. For example, the appropriate work package should be automatically selected for pipe objects based on the "pipe diameter" and "pipe material." However, the ArchT-Precision link could only extract geometric properties from CAD objects to automatically select estimating items. Consequently, most cost information had to be selected manually[5].
- **There is no explicit relationship between the schedule and cost information as the design evolves**. Consequently, the system can not detect the cost impact of different planning strategies or sequencing alternatives.

The Sequus Project has demonstrated that design-cost integration software can help project teams to evaluate the cost impact of some design alternatives rapidly, to validate and document the completeness and assumptions of their estimates, and to calculate material quantities automatically. The main limitations of the software resulted because the link was application dependent and could not easily integrate design information in a multi-disciplinary environment. Other limitations of the software were based on the link's ability to recognize when a work package is no longer valid if the design changes and to provide computer assistance with the maintenance of the cost information.

[4] Precision Estimating allows the estimator to add intelligence to the link that enables the system to automatically select a different cost estimating item in some situations. However, this functionality is limited to certain geometric design changes. Consequently, this functionality is not available for most design changes. Moreover, setting up this link requires extensive knowledge of Precision Estimating.

[5] It is possible to attach work packages or cost items to wall, door, or window styles. Then, when designers draw CAD objects using a specific style, the CAD object will automatically have the work package or cost item attached. However, this functionality is only possible if the contractors share their cost information with the designers. Consequently, this option was not used on the Sequus project.

4.5 Related Research

The limitations of current design-cost integration software used on the Sequus Project are being addressed in various research efforts. Standards are being developed for the AEC/FM industry to enable information sharing between disparate systems *independent* of the application used to create the information. Moreover, research has also been developed to enable estimating systems to help estimators to identify the impact of design changes on the cost information selected and to maintain cost information as the design evolves. Therefore, the following sections describe research in the following areas: 1) Adoption of Standards for the AEC/FM Industry, 2) Maintenance of Cost Estimates.

4.5.1 Adoption of Standards for the AEC/FM Industry

The IFC's formalize the objects and relationships between design, cost, schedule, and resource information. The standards defined by the IFC's will eliminate many of the limitations found in current design-cost integration software. The design-cost integration software used on the Sequus Project worked best for objects created in ArchT because the link was specifically created between ArchT and Timberline. Consequently, design objects created in other design software, such as the discipline-specific software used by the mechanical and piping subcontractors, did not link easily with the cost information. This limitation forced the MEP subcontractors to use specific drawing methods, as shown in Figure 4.3. Standards would eliminate this problem because the design objects and associated properties would be represented consistently and with a single accepted representation. Therefore, standards would enable the design objects and associated properties to be consistently represented independent of the software and drawing-method used to create the design object.

Although the IFC's will improve the level of integration possible by formalizing the relationships between design, cost, schedule, and resource information, they will not solve all the problems encountered when integrating design and cost information on the Sequus Project. In fact, if a contractor had explicitly linked the project's design, cost, and resource information using the IFC's and the design changed, the process would not be much better than is possible with today's design-cost integration tools. The quantities would be updated because there is an explicit relationship between the cost element and its corresponding quantity, but it would not help the estimator to determine whether that relationship is still applicable. The IFC's formalize the relationships but they do not provide the *context* for the relationship. Consequently, software tools relying on the formalized relationships defined by the IFC's will be limited in there ability to determine the situations in which the relationship is appropriate for a given design, and when the relationship becomes inappropriate in the case of design changes. Therefore, additional research is needed to maintain design-cost integration as the design evolves and changes.

The next section describes research that investigates the effects of design changes on the cost information selected to help estimators with the maintenance of cost estimates.

4.5.2 Maintenance of Cost Estimates

A critical limitation of commercial tools is that they don't help estimators maintain cost estimates by signifying when cost information is no longer applicable in the case of design changes. On many projects, designs change often and there are thousands of links or relationships between cost items and design objects. Therefore, it is unlikely that estimators will be able to manually update all the electronic links between cost information and design objects in a timely and complete manner to maintain an accurate computer model with linked cost and scope information throughout a project's life cycle. Hence, estimating tools will need to provide additional functionality to aid the estimator with the maintenance of cost estimates throughout the project life cycle.

Staub and Fischer (2000) investigated the usefulness of the IFC's to create and maintain construction cost estimates and found that additional functionality needs to be added to estimating software to leverage IFC product models. Specifically, they found that formalisms need to be developed to represent the *context* for the relationship between design and cost information, and mechanisms need to be developed to enable the computer to help estimators create and maintain cost estimates. Staub and Fischer formalize the context for relating design and cost information as consisting of design properties, conditions, and effects. Their goal is to provide a generic relationship template that captures this context in a formalized and systematic way using a computer-interpretable representation. The system can then use the context of the relationship between design and cost information to assist an estimator in selecting the appropriate cost information for a given IFC product model and notifying the estimator if the cost information selected is no longer applicable in the case of design changes. To provide this computer assistance, mechanisms need to be developed to identify design properties and their effects on construction costs.

Many other research efforts identified design properties and their affect on construction costs for specific scopes of work. Fischer (1991) identified the design properties that affect method selection of formwork in reinforced concrete parking structures. For example, he identified that the applicability of flying forms for concrete slabs is limited by a 20' maximum floor-to-floor height. Sanders and Thomas (1991) identified the design properties that affect masonry labor productivity. They gathered data from multiple projects and found that repetitive designs can improve productivity by 30% and designs that require extensive layout can negatively affect productivity by as much as 40%. Hanna et al (1993) identified the factors that affect the selection of vertical formwork systems. This knowledge was then implemented in an expert system that assists the formwork selector/designer in selecting formwork systems. Therefore, these research efforts made substantial progress in identifying critical design properties that affect construction costs for specific scopes of work. This is an important step in developing computer tools that help estimators to maintain cost information.

Therefore, previous research has addressed some of the limitations found with current design-cost integration technologies. Specifically, standards are being developed for the AEC/FM industry to enable information sharing between disparate systems *independent* of the application used to create the information. Research has also been developed to enable estimating systems to help estimators to identify the impact of design changes on the cost information selected and to maintain cost information as the design evolves.

Finally, research efforts have identified critical design properties that affect construction costs for specific scopes of work.

4.6 Research Needs

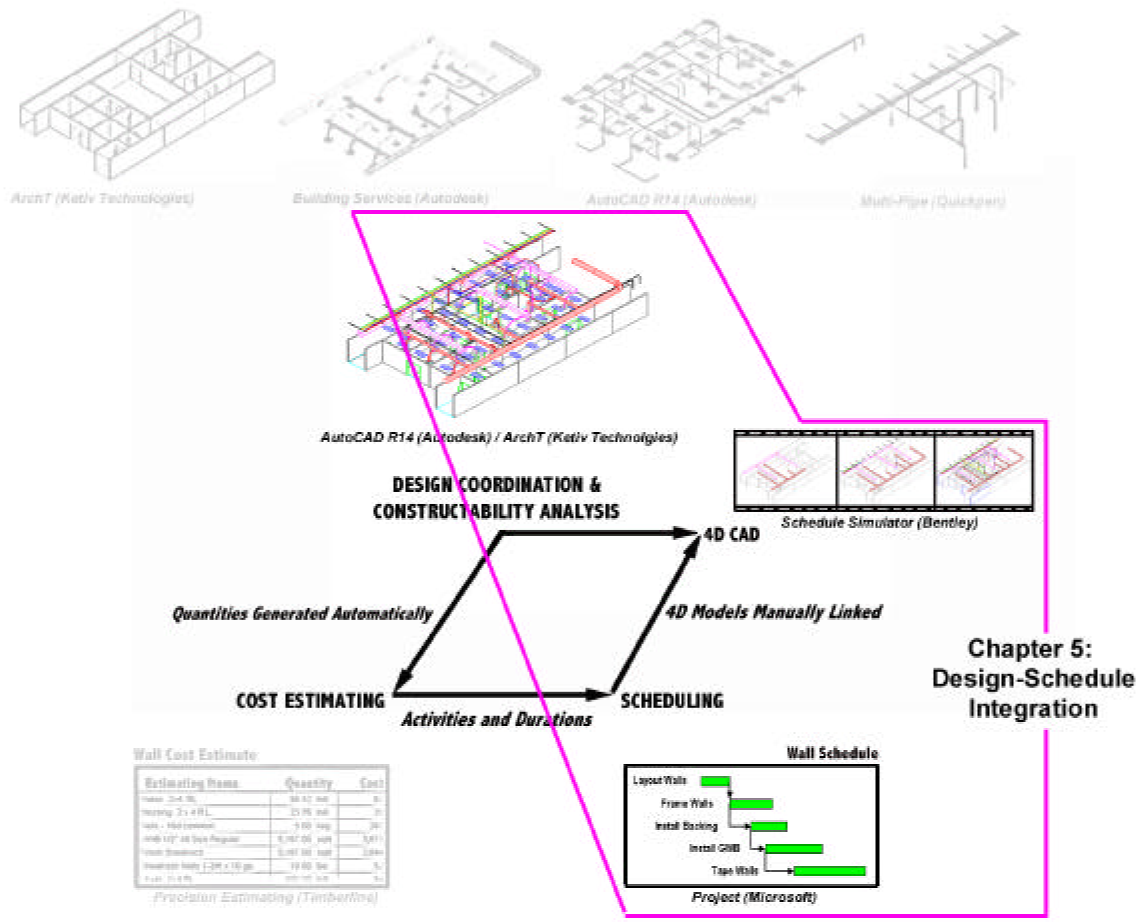
There is still research needed to help project teams understand the impacts of their decisions on construction costs in real time, and maintain cost estimates over the life of the project. Specifically, research is needed in the area of cost-schedule integration. There is a need for a formalized approach for modeling the effect of schedule sequencing, installation time, schedule compression, and planning strategies on construction costs. Thus, research needs to be developed to analyze 4D models and the costs associated with the temporal nature of construction.

Research is also needed to track design evolution and reconcile the corresponding construction costs. Cost estimates are often created prior to detailed design, and estimators often make assumptions about the design details. However, there is no methodology today to help estimators maintain estimates at multiple levels of detail over the course of a project. Thus, tools need to be developed to help estimators reconcile their estimates and estimating assumptions as the detailed design is completed.

The next chapter describes the current practice of creating schedules, the process and tools used on the Sequus Project to electronically integrate design and schedule information (4D modeling), an assessment of the benefits and shortcomings of current 4D tools, and related research.

Chapter 5

Design-Schedule Integration (4D Modeling)



Current project management practice uses CPM (Critical Path Method) schedules to coordinate sub-trades and show the dependencies between activities. However, CPM schedules do not provide a link between the three dimensions of space and the fourth dimension of time, and yet the interdependency between this information is critical for coordinating the construction process. Coordination of the sub-trades was a key concern for the project team during construction of the Sequus Pharmaceuticals Pilot Plant facility. The pilot plant facility had complex MEP systems that needed to be installed in the confined space in the existing warehouse facility. Consequently, the Sequus project team used commercial 4D tools to help coordinate the installation of the MEP systems.

The Sequus Project demonstrates that 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. However, additional research is needed to improve the efficiency in which 4D models are created and maintained, to assist with the analysis of 4D models, and to improve the visualization capabilities of 4D models.

This chapter describes the current practice of creating and maintaining construction schedules and contrasts it with the electronic design-schedule integration (4D) process used on the Sequus Project. We describe the specific steps the project team performed to create 4D models and the benefits and limitations of this technology. This chapter concludes with a discussion of relevant research that addresses the limitations of the 4D tools used on the Sequus Project.

5.1 Current Practice

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 fourth dimension of time. Yet the interdependency between this information is critical for planning, evaluating, monitoring, and coordinating the construction process.

Most construction managers, through years of experience, are able to visualize the construction process in their heads. Communicating that conceptualization of the construction process, however, is ineffective with traditional CPM networks and bar charts, resulting in differing perceptions about how the work will actually be installed in the field. Consequently, many problems go undetected resulting in reactive project management and sub-optimal project performance as problems get resolved *during* construction. To proactively mange the construction process, project teams need to be able to visualize the four dimensional nature of the construction process.

In summary, the following limitations exist with the current bar-chart and network representations of construction schedules:

- Communicating the schedule intent is difficult and often leads to differing perceptions about how the work will be installed in the field.
- It is difficult for project teams to visualize how the work will flow through the site and understand the dependencies between the trades.
- Constructability issues are difficult to identify prior to construction and often go undetected until field installation.
- It is difficult to detect potential field interferences that often result when activities are scheduled concurrently at the same location.

4D-CAD (3D + time) is a tool that links 3D CAD objects with construction activities and allows project teams to visualize the construction process as a computer animation. As a result, project teams are better able to evaluate the spatial needs of each discipline over time, thus improving communication and coordination between sub-trades.

5.2 Electronic Design-Schedule Integration (4D Modeling) on the Sequus Project

We performed design-schedule integration by linking activities created in Microsoft Project with graphical 3D objects created in AutoCAD R14, Building Services, Multi-Pipe, and Ketiv's ArchT, as shown in Figure 5.1. First, each discipline finalized the content of the

Schedule model and the CAD model in their respective programs. Then, we exported each model in a format compatible with Bentley's Schedule Simulator and created a 4D model by linking the CAD objects with the Schedule objects.

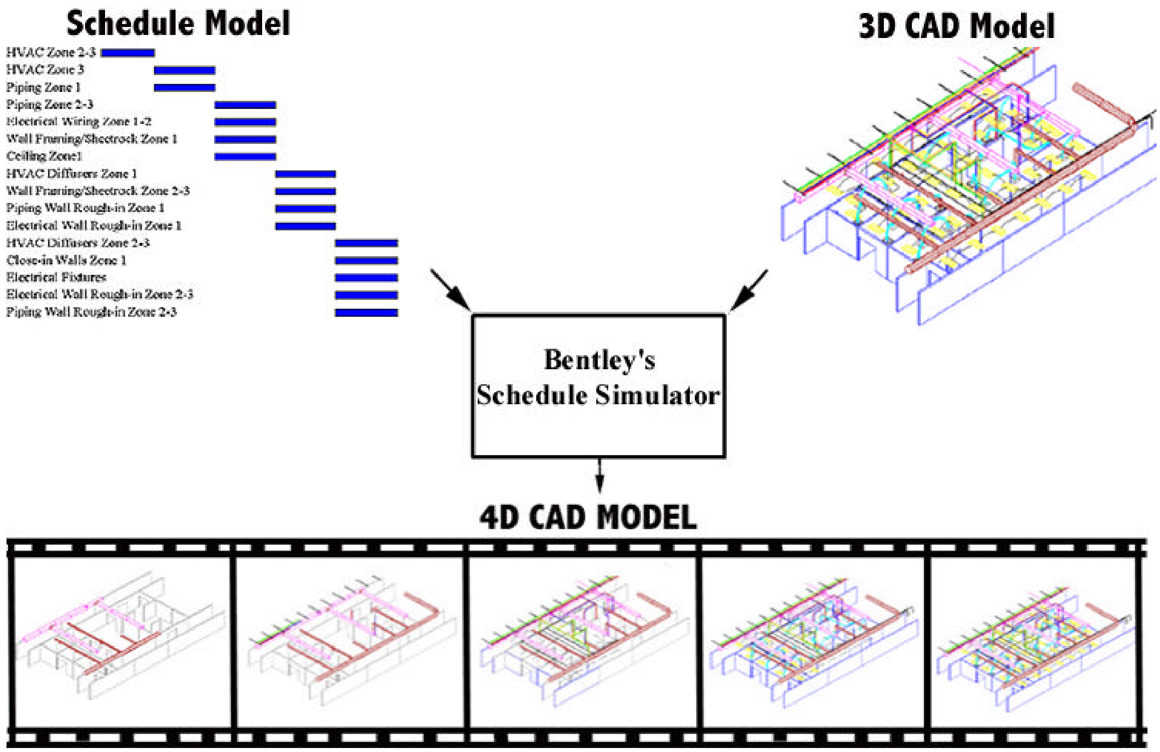


Figure 5.1: Overview of Design-Schedule Integration

Coordination of the sub-trades was a key concern for the project team during construction of the Sequus Pharmaceuticals Pilot Plant facility. The pilot plant facility had complex MEP systems that needed to be installed in the confined space in the existing warehouse facility. The MEP systems were designed such that the majority of the work was placed on an equipment platform. The platform was necessary because the existing structure was not capable of supporting the increased loads from the MEP systems and related equipment. Figure 5.2 shows the MEP systems and related equipment on the equipment platform. Completing the installation of these systems was further complicated by the late arrival of the Air Handler Units (AHU's). The AHU's were not scheduled for arrival until one month after the MEP system installation started. Consequently, a goal of the coordination process was to limit the interaction between the subcontractors installing the different systems and to avoid the installation path for the AHU's. The coordination of the MEP systems and equipment installation on the equipment platform was modeled in 4D to ensure it could be executed effectively.

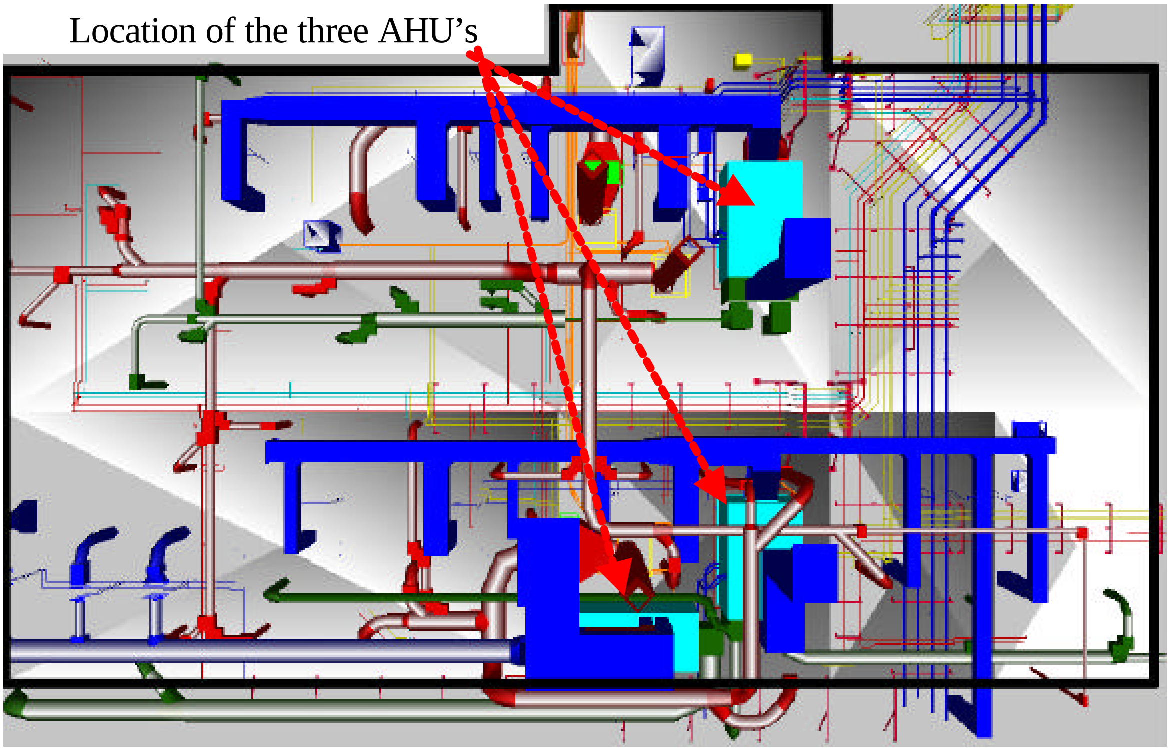


Figure 5.2: MEP Systems and Related Equipment on Equipment Platform

In the following section, we describe the specific tasks we performed to create a 4D model of the MEP systems and related equipment on the Sequus Project.

5.3 Electronic Design-Schedule Integration - Process Description

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 (MEP) work with the equipment installation on the mechanical platform. Consequently, the general contractor needed a detailed 4D model to coordinate the MEP subcontractors. To build a detailed 4D model, we first added activities to the schedule model to reflect the work breakdown in zones. Next, we structured the CAD model such that the layering corresponded to the breakdown of work that existed in the schedule model. Because the CAD drawings were not organized to represent the constructor's perspective, we had to modify the CAD models to reflect how the project will be built. Finally, we manually linked the schedule activities and CAD objects. Alternatively, we could have performed this link automatically. To automatically link schedule activities and CAD objects, the activity names within the schedule model must be identical to the layer names in the CAD model. Then, a program provided by Bentley as part of the Schedule Simulator creates the link between the schedule model and the CAD model by matching the activity names with the layer names.

Figure 5.3 shows the three steps used on the Sequus Project to create the 4D model: 1) Elaborate Schedule, 2) Group and Break Up 3D Objects, and 3) Create 4D model:

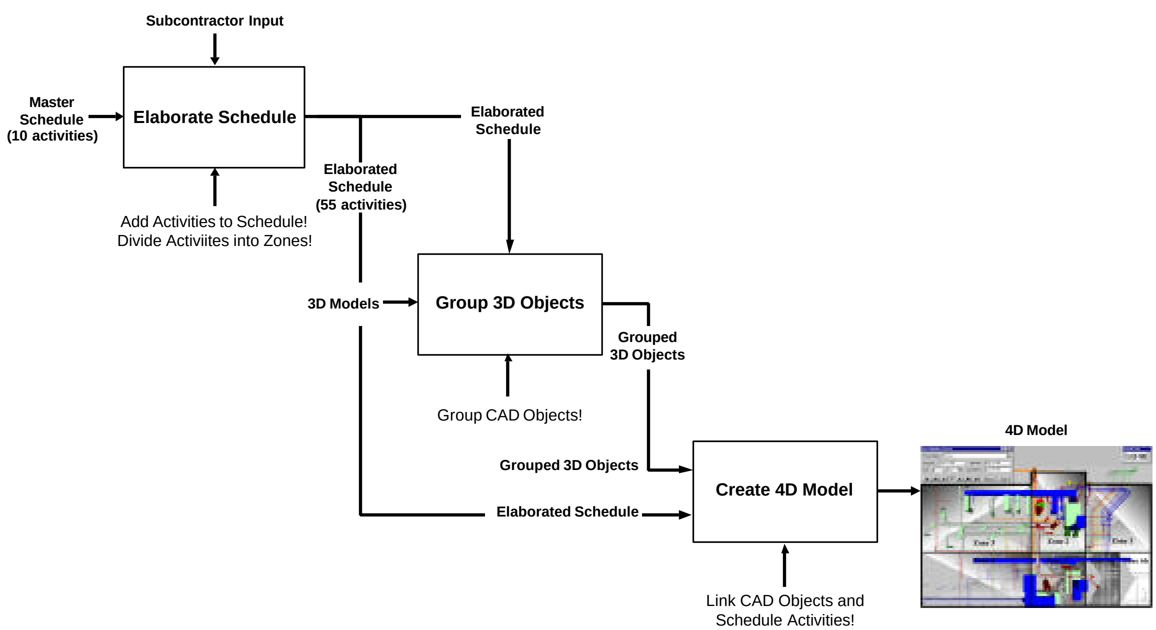


Figure 5.3: IDEF0 Diagram of 4D Model Generation Process for Work on Equipment Platform

1. **Elaborate Schedule:** First, we expanded the master schedule created by the general contractor to the level of detail required to represent the day-to-day operations of the various subcontractors. We consulted the foreman for each of the three MEP trades and the superintendent for the general contractor to determine what activities were necessary, how the work would be sequenced, and how work would flow through the

equipment platform. We then added the necessary detail to the schedule and divided the activities for the MEP work into seven zones to represent the work flow planned by the MEP trades. Consequently, the schedule showed when each of the subcontractors would be working in each zone on the equipment platform. The schedule originally contained ten activities for the MEP work and equipment installation on the equipment platform while the final schedule for this work contained approximately 55 activities. The total duration for this task was eight hours.

2. **Group 3D Objects:** We used the 3D models created by the architect and MEP subcontractors to create the 4D model. However, the 3D models represented the designers' perspective and needed to be transformed to represent the construction perspective. Essentially, each layer in the 3D model needs to be organized so that it corresponds to an activity in the schedule. Consequently, we created new layers, renamed old layers, and moved CAD objects to the appropriate layer. 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". In addition, the 3D CAD models also had to be transformed to incorporate the work flow through the equipment platform. Consequently, the 3D CAD models had to be reorganized so that the scope of work related to each of the seven zones was assigned to a separate layer, as shown in Figure 5.4. To illustrate the extent of changes required for this step, the HVAC design model originally contained six layers. After the model was modified to correspond to the schedule activities, there were 22 layers. This process was performed on five piping drawings for the different process piping and wet-side mechanical systems, the HVAC drawing for the ductwork and AHU's, and the structural drawing containing the concrete decking. If any one of these designs changed this step had to be repeated, which was a time-consuming task. The total duration for this task was 16 hours.

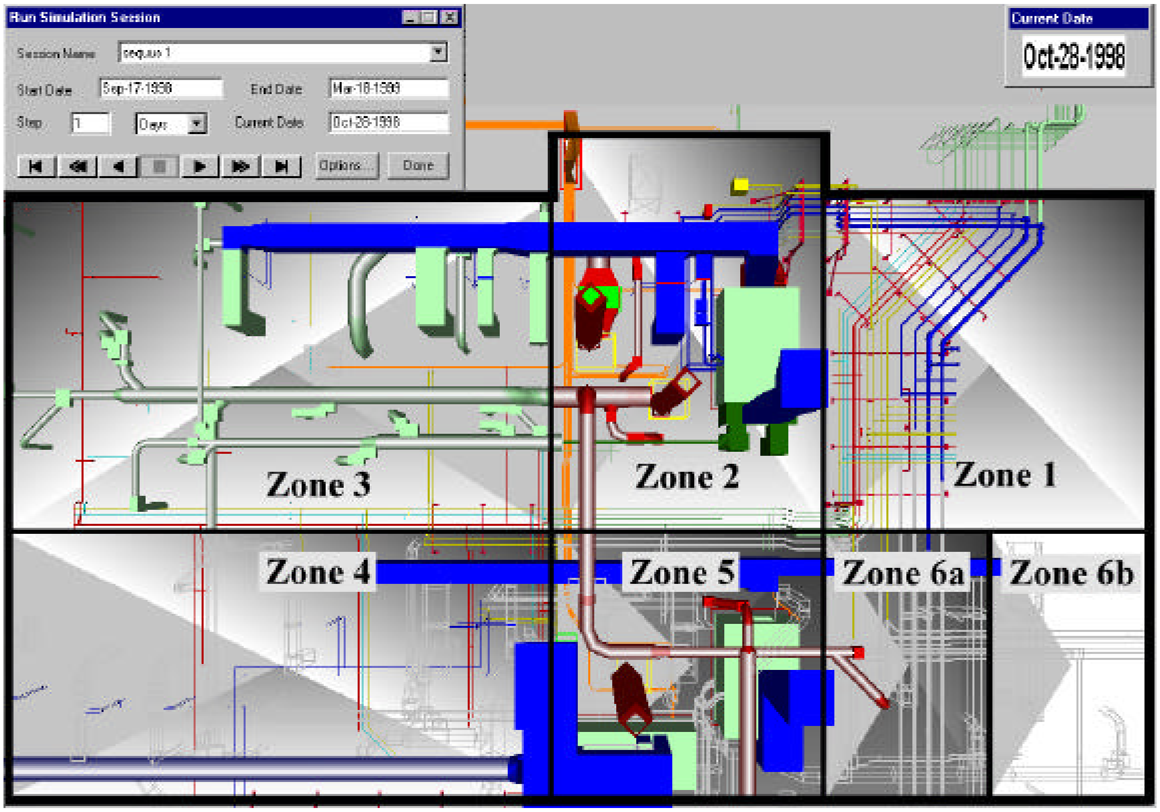


Figure 5.4: Snapshot of 4D Model of the MEP work and Equipment on the Equipment Platform (viewed from the top)

3. **Create 4D Model:** To create the 4D model, we used Bentley's Schedule Simulator. This software imports CAD models and schedule models and transforms them into object-oriented models. We imported each of the CAD models as separate files so that we could easily focus on specific systems. Consequently, eight[6] CAD files were imported into the Schedule Simulator, which allowed the project team to view any combination of the different systems in 4D. After the CAD models and schedule model were imported, we manually related the grouped CAD objects created in the second step with the appropriate schedule activity created in the first step. For example, one grouped CAD object was the cold water piping system in zone 1 and the corresponding activity was "Install cold water piping in zone 1." If the design

[6] The eight 3D design models imported into Bentley's Schedule Simulator included: five process piping models, one HVAC model, one architectural model, and one structural model of the equipment platform. Rountree Plumbing created separate 4D files for each of the five piping systems because the files were too large.

changed, we had to repeat both step 2 and step 3. This step took approximately four hours.

The 4D model was primarily used as a communication tool between the general contractor and the owner and between the general contractor and the subcontractors. The 4D model of the work on the equipment platform demonstrated to the owner that the equipment could be installed as planned and wouldn't result in any rework for the MEP subcontractors. Moreover, the 4D model also helped identify access issues for equipment installation and identified what areas needed to remain clear to ensure that equipment could be installed as planned. Specifically, it showed the piping subcontractor that it would not be possible to install the different pipe runs continuously as planned. Rather, he had to postpone the installation of the piping that ran between the AHU's because it interfered with the path required for their installation. By building the 4D model early, the project team was able to coordinate the equipment installation and MEP work weeks in advance and avoid rework that often results when work in place conflicts with the path needed for equipment installation.

The process of creating the 4D model also proved to be beneficial for the Sequus team. The project team identified several design conflicts resulting from design changes that occurred after the MEP design coordination process was complete. In one instance, a steam generator had been added to the scope of work late in design development. The proposed location for the steam generator directly conflicted with the compressed air piping run. As a result of the building 4D model, this conflict was resolved prior to pipe fabrication and installation. We also identified a design error that could have potentially caused substantial rework. The AEC chiller was incorrectly designed in 3D at about 20% its actual size. When this mistake was corrected, the AEC chiller no longer fit in the space allocated requiring the piping to be re-routed to a new location. This conflict was also resolved three months before the AEC chiller was scheduled for installation.

5.4 Evaluation Of Design-Schedule Integration Software

Coordinating the work on the equipment platform using 4D models allowed the project team to better coordinate the installation of the complex MEP systems and corresponding equipment. The project team was very concerned about completing the installation of the MEP systems in light of the fact that the AHU's were scheduled for arrival one month after the MEP system installation started. Consequently, a goal of the coordination process was to limit the interaction between the subcontractors installing the different systems and to avoid the installation path for the AHU's. The Sequus project showed that 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, the ability of 4D tools to deal with design changes, and the lack of automated analysis of 4D models.

5.4.1 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 work of the different sub-trades. The 4D model was specifically used to coordinate mechanical, electrical, and piping trades 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 a month after the duct work, piping, and conduit work had already started. Figure 5.4 shows a snapshot in time of the 4D model created for the work on the equipment platform.
- **The 4D model clearly communicates schedule intent**. The 4D model of the equipment platform communicated the schedule intent to the owner and the MEP subcontractors. The 4D model of the work on the equipment platform demonstrated to the owner that the

equipment could be installed as planned and wouldn't result in any rework for the MEP subcontractors. The 4D model showed the MEP subcontractors where and when they could and could not work on the equipment platform.

- **The 4D model showed how the MEP work flowed through the equipment platform over time.** The scheduling strategy was to divide the equipment platform into zones to determine the optimal installation path for the installation of the air handlers and work sequences between trades. To accomplish this task, the general contractor worked with the MEP subcontractors to determine how their work would flow through the equipment platform. The subcontractors' workflow was used to determine how the equipment platform should be broken up into zones (Figure 5.4).
- **By virtually building the facility on the computer screen, 4D models help identify constructability issues and sequencing problems prior to construction.** Constructability analysis is typically performed during pre-construction by reviewing 2D drawings. However, there are many constructability issues that depend on *when* components are installed. 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.
- **4D models show the status of construction at any time in the project.** The project team used the 4D model to view the status of construction at any time in the project. This was particularly useful for coordinating equipment and material deliveries, determining the path for equipment installation, and communicating to the various parties how the facility would look at different phases during construction.

Therefore, 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, the ability of 4D tools to deal with design changes, and the lack of automated analysis of 4D models.

5.4.2 Shortcomings

- **The link between the CAD objects and the schedule activities was not intelligent**. Consequently, we could have linked the "install piping" activity with the graphical object for the door and the system would not detect an inconsistency.
- **If the design changed, we had to re-create the 4D model**. This is a significant limitation as designs change frequently throughout the project life-cycle. To re-create the 4D model, we had to modify the revised CAD model to represent the construction perspective and then link the CAD objects with the appropriate schedule activities, as described in steps 2-3 in Section 5.3.
- **A schedule needed to exist before a 4D model can be built**. Many team members would have liked to create the schedule right in the 4D system.
- **We needed to modify the CAD model to represent the construction perspective**. When creating the CAD models, the designers did not focus on how the constructors would assemble the building components. As a result, we needed to modify the CAD model so that the CAD objects could be related to the associated schedule objects.
- **Zones had to be added manually to show work flow**. It was a time-consuming process to add zones to the CAD models and corresponding schedules. Consequently, it was difficult to explore multiple zoning options.
- **The communication capabilities of the 4D model would be enhanced if other information was also shown in the 4D visualization**. For example, it would be useful to show temporal information, such as lay-down areas. It would also be useful to communicate the different operations that are occurring on a given design object. For example, the 4D visualization of the interior work shows the wall objects being acted upon three different times corresponding to the framing, drywall, and painting activities. Unfortunately, when viewing the 4D visualization, it was not clear what operation was actually occurring on the wall object at a given time.
- **The system did not help the project team to evaluate the feasibility of the proposed schedule or identify potential conflicts or problem areas.** For example, many activities may be occurring at the same time and place resulting in congestion problems and decreased productivity, the path required to install a piece of equipment may be blocked

by the execution of a concurrent activity, or the zones implemented to coordinate work flow may not adequately reflect the spatial needs of the various trades. Problems such as these must be manually identified using current 4D tools.

- **The system did not show supporting information that may be needed to describe the 4D simulation**. For example, cost growth over time would have been useful supporting information to view in parallel with the 4D simulation. Other supporting documents might include contracts, phasing plans, or move-in schedules. Being able to view these various information sources through a 4D medium would allow project managers to quickly access relevant information for planning decisions and make more informed decisions.
- **There was no explicit relationship between the cost and schedule information**. Consequently, the system could not detect the cost impact of different planning strategies or sequencing alternatives.

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. The main limitations pertain to the effort required to set up the CAD and schedule models, the ability of 4D tools to deal with design changes, and the lack of automated analysis of 4D models.

5.5 Related Research

The limitations of current design-schedule integration software used on the Sequus Project are being addressed in various research efforts. The following sections describe research in the following areas: 1) adoption of standards for the AEC/FM industry, 2) transforming design models into construction models, 3) 4D analysis, and 4) 4D Visualizations.

5.5.1 Adoption of Standards for the AEC/FM Industry

As stated previously, the IFC's formalize the objects and relationships between design, cost, schedule, and resource information. If 4D information was represented using the IFC standard, some of the problems with existing 4D tools would be eliminated. Specifically, the IFC standard would help with the maintenance of 4D models because each design component would have an explicit relationship to the schedule activity, *independent* of the application the link was created in. Consequently, when the design changed, the link between the design object and the schedule activity would not be affected. Today, 4D models are created by importing 3D models into Bentley's Schedule Simulator. Thus, if the design changes, it has to be re-imported into PlantSpace Schedule Simulator and the design objects have to be re-linked to the schedule activities. The IFC's would eliminate this manual change management by maintaining an explicit link between the design objects and schedule activities throughout the design evolution.

IFC's won't solve all the problems with current tools as planners would still need to transform the design models into construction models and manually analyze the 4D models to detect constructability problems and assess the feasibility of the schedule.

5.5.2 Transforming Design Models into Construction Models

Using today's tools, it is a time-consuming process to manually adjust the design models to represent the construction perspective. Design models need to be manually manipulated to represent work flow and zoning. During the planning of the scope of work on the equipment platform, the general contractor decided to break up the platform into seven zones with work flowing counterclockwise. As a result, we had to manually change all the CAD models to correspond with this plan. However, this may not have been the optimal work flow. If this transformation could have been automated, the project team could have explored a variety of zoning options to optimize the installation process.

Akbas and Fischer (1999) formalized product model transformation mechanisms to automate the transformation of design models into construction models. They formalized three different types of transformation mechanisms needed to create construction zones:

aggregation mechanisms - group components into a zone. For example, grouping several pipe objects into one zone on the Sequus equipment platform.

decomposition mechanisms - decompose a component into several zones. For example, decomposing the equipment platform slab into several zones for placing concrete.

productivity-based mechanisms - decompose a component into zones based on productivity deviations that result from component properties or methods used. For example, decompose the concrete placement for the equipment platform slab into zones based on productivity differences that occur around the edges and center of the slab.

Therefore, Akbas' and Fischer's research addresses the limitations of current tools by automatically transforming design-centric product model information to represent construction zones and the corresponding work flow.

5.5.3 4D Analysis

Notwithstanding the above limitations, 4D CAD models allow design and construction professionals to test different design and sequencing alternatives in the computer prior to construction[7]. However, analyzing 4D models is a manual and time-consuming process. For example, on the Sequus Project, we identified the conflict between the pipe runs and the installation path for the AHU's through visual inspection of the 4D model. Improving the constructability of a facility design has become a key concern for owners, designers and builders of facilities as decreased construction duration and costs and improved construction operations benefit everyone. Recognizing constructability issues early in the project delivery process can help to identify design constraints which limit a constructor's ability to plan and perform construction operations effectively. These design constraints often cause improper construction sequencing which can result in construction delays, re-design, or decreased crew productivity, ultimately leading to higher costs and a sub-optimal project performance. It

[7] On a project in Chile, Bechtel created 80 sequencing alternatives and visualized them with 4D models (Rischmoller et al. 2000).

would be very useful if the computer could identify such constructability problems automatically.

Staub and Fischer (1998) describe how a 4D model can help expose constructability problems prior to construction. Through case examples, they show how different design and sequencing alternatives create constructability problems related to access, temporary support, availability of work space, and completion of prerequisite work. McKinney and Fischer describe how 4D models can be used to analyze 'temporary support' of building components during installation. They describe the requirements of the information model that provides the reasoning mechanisms to support 4D analysis of 'temporary support'. Through case studies, they identify five different types of support that affect constructability and describe the component attributes needed to detect constructability issues related to temporary support.

To improve the constructability of the facility design, it is important to identify conflicting spaces prior to construction to proactively manage the construction process. For example, on the Sequus Project, the space required for the installation of the Air Handler Unit interfered with the pipe runs. However, the space required for installation was not represented explicitly and the conflict detection was performed manually. Akinci and Fischer (2000) formalized generic space representations for micro-level spaces and mechanisms that automatically identify conflicting spaces. Their system, 4D Work Planner, analyzes a 4D production model to identify spatial conflicts and classifies the conflicts based on the problems they cause.

5.5.4 4D Visualizations

Today, a schedule needs to exist before a 4D model can be built. Consequently, project teams must wait for the completion of the 4D model before they can visualize their planning decisions. On the Sequus Project, many team members would have liked to build the schedule right in the 4D system. Consequently, there is a need for an environment where project teams can create 4D models interactively. The Responsive Workbench (RWB) displays computer-generated stereoscopic images onto a horizontal tabletop surface using a projector and mirrors system (http://www.graphics.stanford.edu/projects/RWB/). The users of the RWB wear shutter glasses to view and interact with the 3D objects. The system tracks the users' heads to render the correct perspective. In addition, users wear a pair of gloves and stylus that are used to interact with the objects in the tabletop environment and assemble or disassemble the 3D models. Users can manipulate the components and view the related schedule sequence in an integrated environment. The RWB provides an interactive 4D system that allows project teams to interactively and easily create and communicate different construction sequences (Fröhlich et al. 1997).

McKinney and Fischer (1998) developed an environment in which planners can visualize various types of planning information to better support decision making. Today's tools primarily document planning decisions. There is a need for tools to visually communicate the context of the planning decisions in order to explain the decision making process. The 4D Annotator uses 4D CAD as a medium to explain planning decisions and the impacts of those planning decisions. The 4D Annotator generates 4D annotations that visually explain the context of planning decisions by not only communicating descriptive information, but also communicating information that would help to explain and predict the impact of those decisions. Therefore, 4D annotations enrich the information content of 4D models and, as a result, greatly increase the communication capabilities of 4D models.

Therefore, many research efforts have addressed many of the limitations of 4D models in the areas of standards development, transforming design models into construction models, 4D analysis, and 4D Visualizations.

5.6 Research Needs

The Sequus project team would have benefited from the progress made in research in the area of 4D modeling described above. These research efforts have addressed many of the limitations of commercial 4D tools found on the Sequus project. Specifically, research addresses the problem of transforming design models into construction models. Research is providing analysis tools that automatically detect time-space conflicts in 4D simulations and representation and reasoning requirements to support 4D constructability analysis. Finally, research is improving the interactivity of 4D models and the information content conveyed through 4D simulations.

However, there is still research needed to improve the planning process and analysis of construction schedules. Specifically, as discussed in the previous chapter, research is needed in the area of cost-schedule integration. There is no formalized approach for modeling the effect of schedule sequencing, planning strategies, and installation time on construction costs. Moreover, research is also needed to help planners analyze and create construction plans that optimize the construction process across all disciplines on a project.

In the next chapter, we summarize the results and lessons learned from the post-construction analysis of the effects of the integrated approach on project performance and provide detailed accounts of each discipline's perspective on the benefits and limitations of this integrated approach.

Chapter 6

Evaluation of Integrated Approach

The Sequus Project showed that early and simultaneous involvement of project teams including designers, general contractors, and subcontractors in the design and construction of a capital facility coupled with the use of shared 3D models allows project teams to deliver a superior facility in less time, at lower cost, and with less hassle. The following summarizes each team member's evaluation of this integrated approach:

- Owners benefited from this approach through improved visualization, cost and schedule control, and planning for post-construction use of the facility. However, this approach imposed increased demands on the owner's engineering department because they had to address design and construction issues simultaneously.
- The architect benefited from Archt's 3D object libraries that allowed them to insert door, window, and wall objects into the drawings, rather than having to draw lines to represent architectural objects. Moreover, 3D modeling allowed them to create plans and elevations in one step, and make all modifications in one model. However, the architect had to work more closely with the general contractor to ensure that the architectural 3D model could be leveraged for cost estimating and 4D modeling. Finally, this integrated process required the architect to do less detailed design and more management of the design development process.
- The general contracted benefited from this approach because designing and coordinating the work in 3D enabled most design conflicts to be identified prior to construction. Moreover, they were able to leverage the 3D models to automate the quantity takeoff process, improve the coordination of the construction process through 4D modeling, and communicate the schedule intent to the various disciplines.

- The piping and mechanical subs reported increased field productivity, less rework, and fewer change orders and requests for information than expected for a job of this complexity. Most design conflicts were identified and resolved prior to construction enabling a more efficient and productive installation process. They reported a 25-30% increase in design time and cost for 3D design and coordination. The electrical subcontractor, on the other hand, reported an increase in design time and cost of about 300% and didn't note any improvement in field productivity.

This chapter describes the project team's evaluation of this integrated approach and integration software tools. We describe each discipline's perspective in detail and review the specific benefits they realized on the Sequus Project. We conclude the chapter with an analysis of the cost savings realized by leveraging the 3D design information throughout construction and by applying a team-oriented approach to design and construction. Refer to Appendix C for the written comments of the project team.

6.1 Summary of Lessons Learned

Construction for the scope of the work designed and coordinated in 3D (mostly the mechanical, electrical, and piping work) went together seamlessly in the field. The most challenging parts of the work, which was the MEP work on the equipment platform and in the interstitial space, had been coordinated well ahead of installation time. Most spatial conflicts had been eliminated in the combined 3D model in weekly coordination meetings prior to construction. In addition, all work for the most intensive and difficult construction period had been coordinated and sequenced with a detailed 4D CAD model that showed each sub what to do (and what not to do) the next day, week, etc. For the scope of work modeled in 3D, there was only one contractor-initiated change order, which is unheard of for work of this complexity. There were about 60% fewer Requests for Information on this project compared to a project using a traditional paper-based process.

To our knowledge, this is the first project where multiple firms have collaborated using an integrated suite of design and project management software. As such, the project team learned many valuable lessons that were critical to the success of this integrated approach and should be incorporated on future projects. These lessons learned are summarized below:

- Project teams should determine the level of detail in 3D to model each discipline's scope of work prior to design development. This is necessary because there are varying levels of detail that components can be modeled in 3D. For example, a transformer can be modeled simply as a 3-dimensional box, or it can be modeled to show all the switches, access points, indentations, etc. Moreover, some work may only require 2D modeling because there may not be any substantial benefit or because the benefits may not be worth the investment. For example, project teams would need to determine if the light switches should be modeled in 3D or 2D. To resolve this issue, project teams should consider all the possible benefits of 3D modeling, including visualization, constructability analysis, design coordination, cost estimating, and scheduling.
- Project teams should determine the stage in the design development process when a specific scope of work should be modeled in 3D. The sequencing and timing of the design development process needs to coincide with the design coordination process, the procurement process, and the construction process, particularly in design-build environments.
- Project managers and executives committing to a team-oriented approach should carefully assemble their project staff. It is critical that each discipline's project team understands the goals of the project, the level of information sharing needed, and the level of 3D modeling required.
- Assemble teams so that the designs are created by the participants who have the construction expertise to create constructable designs, and who are responsible for installation and can leverage the designs throughout construction. A collaborative design approach also provides incentives for team members to provide feedback on the other discipline's designs because they can leverage the designs created by others

to support their project management functions. Therefore, a collaborative design process allows the construction companies to reap the benefits from investments in information models.

- It is important to set up a design protocol early in the design process. This includes setting the coordinate system, file naming, layering, and file sharing standards.
- Every essential trade on the project should put their design (scope of work) into the 3D model to leverage the benefits of electronic 3D design coordination. The structural work was only partially modeled in 3D and the fire sprinkler work was not modeled at all in 3D on the Sequus Project, resulting in the only design conflict problems during construction.
- Project teams modeling in 3D require increased design and coordination time. Although this is offset by benefits in construction, it does need to be addressed in each discipline's estimate and contract.

In the next sections, we describe each discipline's perspective on the benefits and limitations of this integrated approach.

6.2 Owner's Perspective

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, improved cost and time control during construction, and the potential for post-construction use of the 3D CAD models for operation and maintenance and budgeting for future remodels or expansion. The main benefits received are as follows:

- **Improved Visualization** - The owner representatives benefited greatly from the improved visualization provided by modeling the facility in 3D. Early in design development, the architect created a "walk-thru" of the facility to help the owner visualize what the facility would look like after construction. The subcontractors presented their 3D models to the user groups to show the locations of user drops and the location of electrical outlets. The

3D models were also used to identify the location of access panels and verify access for maintenance purposes.

- **Improved Cost Control** - The facility was constructed within budget. The owners were impressed with the minimal number of design conflicts encountered during construction and the minimal amount of rework. Cost control was extremely important to Sequus as they were working with a very limited budget. Typical cost growth on projects of this complexity range from 2% - 10%, with 2% considered extremely successful, according to the project manager for HDCC. In contrast, the cost growth on the Sequus Project averaged 1% for the MEP subcontractors, which was mostly due to owner initiated design changes. This translates into cost savings of approximately $250,000, assuming a 7% cost growth was avoided.
- **Improved Schedule Control** - The facility was constructed within schedule and the time it took from the start of construction to turnover was shorter than a typical project of this complexity. The use of 3D and 4D allowed the project team to better communicate the design intent to the owner and allowed the owner to better visualize the facility design, thus eliminating design changes that result late in the design process from misinterpretations about what the facility will actually look like. On the Sequus Project, the 3D design coordination process led to better coordinated designs and more efficient installation with less rework. Moreover, the 4D model was also a powerful tool for communicating the schedule intent, providing assurances that the work could be constructed in the time allotted and validating that the equipment installation and MEP work was coordinated and achievable as sequenced.
- **Post-construction Use** - The owners intended to use the detailed 3D CAD models for operation and maintenance and budgeting for future remodels or expansion. However, Alza Corporation purchased Sequus Pharmaceuticals after the facility was substantially completed in February 1999. Consequently, the facility has been unoccupied since February 1999 and is finally being commissioned and started-up for Alza Corporation. The facility was opened in June 2000.

The owners were challenged by some aspects of this integrated approach and felt that certain capabilities of the software integration tools were not utilized.

The owner representatives were challenged by the increased demands on engineering. Because this project was being constructed in a design-build environment, they had to address construction and design issues simultaneously. Small companies like Sequus need to account for these issues when deciding what approach to use in constructing their facility.

The owners expected more use of the design-cost integration tools with respect to exploring different what-if scenarios. Several different designs were explored during the programming phase and the owner expected the contractor to be able to produce cost estimates for these changes on the spot. However, as discussed in Chapter 4, current off-the-shelf design-cost integration software does not support this type of functionality.

6.3 Architect's Perspective

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. Another benefit of this technology was its ability to model objects rather than just lines and circles. ArchT allows designers to insert "doors", "windows", and "walls" into drawings rather than just drawing lines that represent these architectural objects, as shown in Figure 6.1. In addition, properties can be attached to the objects to enable architects to use the CAD model to generate wall schedules and door schedules.

The project architect for Flad worked closely with HDCC in the development of the architectural design. This collaboration allowed HDCC to utilize the design information to perform design-cost integration. HDCC provided input that included suggestions on how to model certain CAD objects and what objects to include in the CAD model. For example, HDCC advised Flad to draw polylines for the ceiling and flooring so that the area could be extracted for estimating purposes. Flad needs to include this information in some form when designing in the traditional process, but through collaboration was able to create design information that allowed the constructors to better utilize the design.

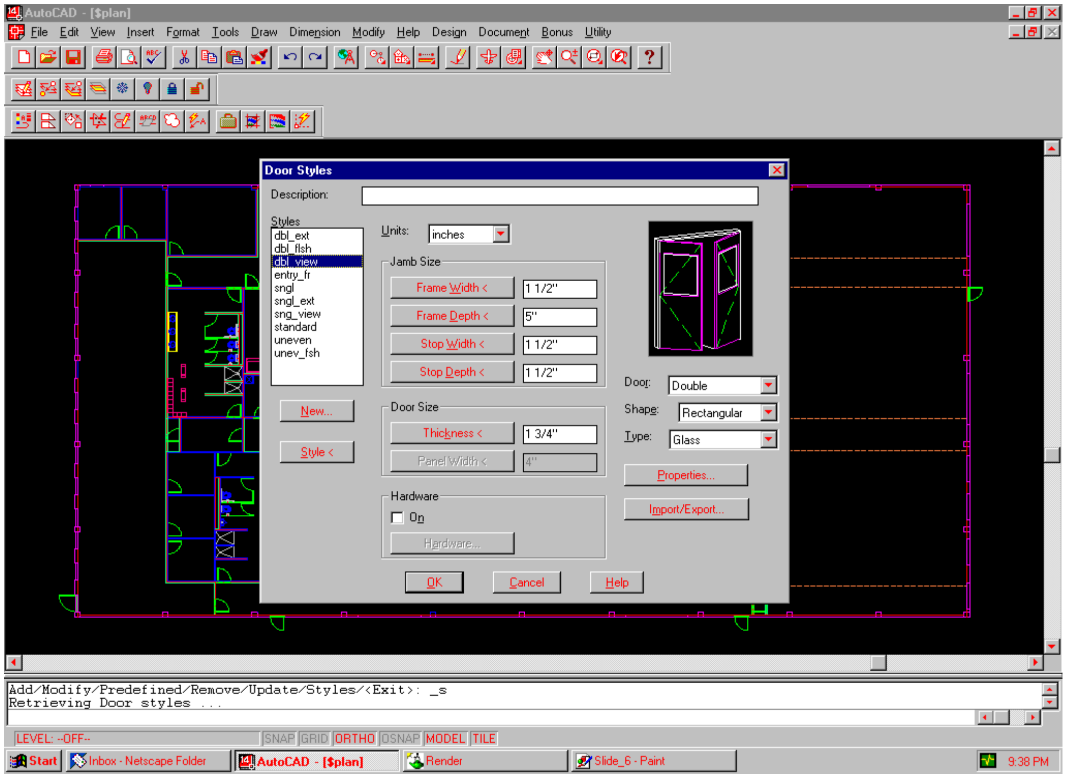


Figure 6.1: Example Door Object created by Flad for the Sequus Project

Finally, the architect had to do less detailed design and more management of the design development process. For example, the coordination of the reflected ceiling plan was performed by the general contractor and the MEP subcontractors rather than the architect. However, they also had to coordinate the design development process. The benefit of this change in responsibility is that there were 60% fewer RFI's than expected on a project of this complexity.

6.4 General Contractor's Perspective

HDCC received many benefits from using the software integration tools. HDCC believes the benefits offered by this technology justify further commitment to this technology and plans to use this technology on future projects. The benefits are as follows:

- **MEP Design Coordination** - MEP design coordination is typically performed by overlaying 2D drawings over light tables, as described in chapter 2.1 and illustrated in Figure 6.2a. In the typical coordination process, each discipline huddles around the light table and tries to identify design conflicts. This process is time-consuming, prone to errors, and makes it very difficult to identify design conflicts and determine conflict-free solutions. Figure 6.2b shows how MEP design coordination is accomplished by using an integrated approach. MEP design coordination on the Sequus Project was accomplished by electronically integrating each discipline's 3D CAD model in the computer. By integrating each discipline's scope of work in 3D, each discipline could better visualize the relationships of their work to that of other trades, identify design conflicts early and easily, and explore alternative solutions in a 3D space. This allowed the project team to identify and eliminate most design conflicts prior to the start of construction. As a consequence, conflicts in the design were identified early, which reduced the amount of design work wasted by each discipline. The traditional, sequential process often leads to a large inventory of design information in each discipline that has not been cross-checked. The MEP coordinator for HDCC was so encouraged by the process of performing MEP design coordination in an electronically integrated environment, that he plans to take classes on AutoCAD to better understand the potential of this tool.

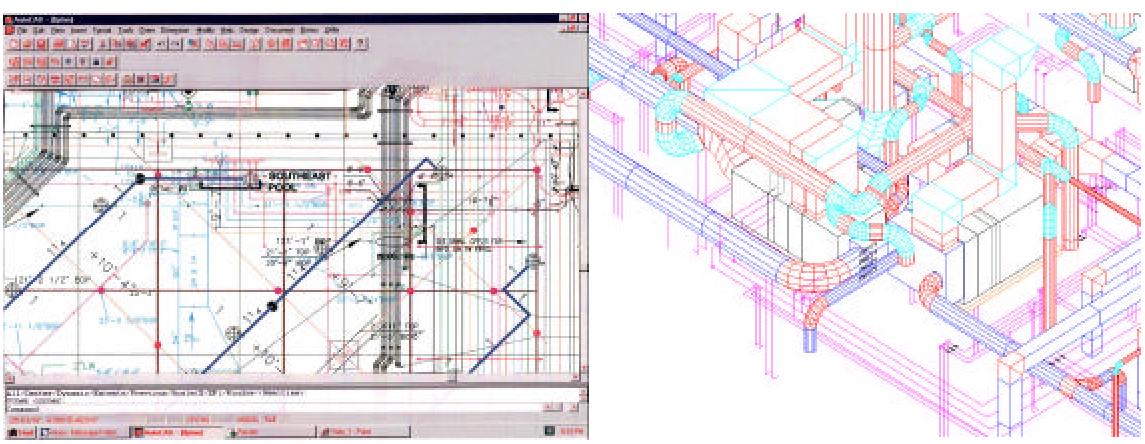


Figure 6.2a: MEP Design Coordination Process using Traditional Process

Figure 6.2b: MEP Design Coordination Process using Integrated Approach

Figure 6.2: Comparison of MEP Design Coordination Processes

- **Estimating -** HDCC 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%. HDCC 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 in completeness and accuracy. 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. When HDCC estimates similar projects in the future or gets involved in the retrofit of this facility, estimators will be able to easily access estimating information from the CAD model and understand what estimating record was chosen and what design object it is related to.
- **Scheduling/4D Modeling -** The 4D model was particularly helpful with the coordination of the equipment delivery and installation and the on-going MEP work on the equipment platform. Specifically the contractor was concerned about the installation of the three Air Handler Units (AHU's) because they were scheduled to arrive over a month after the MEP work on the platform had started. Figure 6.3 shows a plan view of the equipment platform and the location of the three AHU’s. The goal was to build a 4D model to demonstrate that the AHU's could be installed as scheduled and yet allowed the MEP subcontractors access to work productively. In building the 4D model, the contractor divided the equipment platform into six zones, as shown in Figure 6.3. The contractor then worked with the subcontractors to understand the sequence for how they planned to install their work in these zones and incorporated this work flow into the construction schedule. Finally, the contractor linked the construction schedule to the 3D CAD model creating a detailed 4D CAD model. The 4D model then showed what each subcontractor was doing (and not doing) on a daily basis on the equipment platform. The 4D model showed that the AHU's could be installed as planned but certain parts of the mechanical and piping work would have to wait until after their installation, such as the piping between the AHU’s in zones 2 and 5 shown in Figure 6.3. By building the 4D model prior to construction of the MEP work on the equipment platform, the project team was able to coordinate the equipment installation and MEP work in advance and avoid rework that often results when work in place conflicts with the path needed for equipment installation.

The superintendent for HDCC emphasized how "cleanly" the installation was executed because of this technology. Therefore, by creating and coordinating 3D CAD models prior to construction and combining them with detailed construction schedules, HDCC was better able to manage and coordinate the construction process.

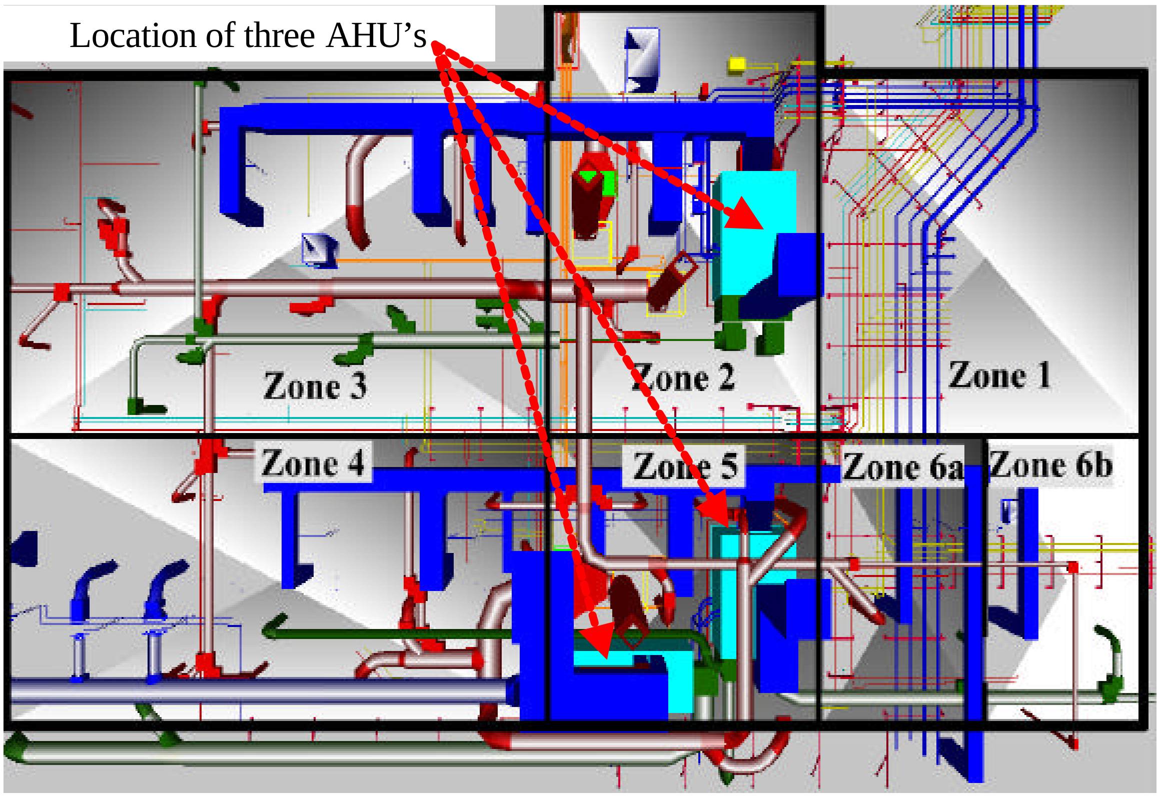


Figure 6.3: Plan View of MEP Work and Equipment on Equipment Platform

- **Communication -** The 4D model was also a powerful tool for communicating the plan for installing the MEP work and equipment on the platform to the owner. Through improved visualization, HDCC was able to assure the owner that the equipment would be installed as planned and that the subcontractors would be able to work productively.

6.5 Mechanical, Electrical, and Piping Subcontractors' Perspectives

The piping and mechanical subs reported increased field productivity, less rework, and fewer change orders and requests for information than expected for a job of this complexity, as shown in Table 6.1. Most design conflicts were identified and resolved prior to construction enabling a more efficient and productive installation process. Because the subcontractors were responsible for creating the 3D models of their scopes of work and they have the construction expertise, they were able to create designs that were constructable and could be leveraged throughout the construction process. Specifically, the subcontractors leveraged the 3D models for design coordination, fabrication, and daily coordination of their crews.

	Rountree Plumbing Process Piping/HVAC Wet	Paragon Mechanical HVAC Dry	Rosendin Electric Electrical
Contract Value	$2,018,937	$1,071,237	$488,414
Increased Design Costs and Time	30% Difficult to find trained designers with installation experience File size with Solid Pipe Designer	20-30% Went from 2D to 3D	300% Engineering costs typically 4% Engineering costs - 12%
Number of Change Orders	6	1	3
Reason for Change Orders	4 - Owner Requested 1 - Value Engineering 1 - Unforeseen Condition	1 - Owner Requested	3 - Owner Requested
Percentage of Total Cost	-1.00%	1.00%	0.97%
Number of RFI's	40	23	-
Expected RFI's	100	50	-
Example Conflict Avoided	Routing of chilled water and heating water to AHU	Relocate reheat coils to avoid ductwork conflict	Coordination of Reflected Ceiling Plan and Register Location
Productivity	Significantly increased	Much more Productive	No Difference
Rework	Dramatically reduced - Only occurred on non-3d portions	Minimal	No Difference
Profitability	Same Expects greater return with increased use	Same Expects greater return with increased use	Less Increased design time with less benefit from coordination when compared to other trades.

Table 6.1: Summary of MEP Subcontractor’s Experience

It is difficult to quantify the cost savings that resulted from this improved design and construction process. According to the project manager from HDCC, typical cost growth on a project of this complexity ranges from 2% -10%. On the Sequus Project, the cost growth averaged approximately 1% for the MEP subcontractors, and these costs were a direct result of owner initiated design changes. Riley (1999) researched four complex building projects and found that the costs due to material conflicts ranged from $500- $3,500 and increased for minor rerouting to $2,000 - $25,000. Nylen (1999) investigated one project that reported a cost growth of 8% and found that 95% of those costs could have been avoided with better modeling and coordination. Morris and Hough (1987) investigated project overruns that occurred on major military, civil, energy, and information-technology projects completed in the US, UK, and less developed countries and found that these projects demonstrated excessive cost overruns ranging from 40% - 500%. Hayes et al (1986) investigated 900 projects financed by the World Bank between 1974-1983 and found that all of the projects had a cost growth ranging from 7% - 56%. Therefore, we conservatively estimate a cost savings of approximately $250,000 for the scope of work performed by the MEP subcontractors that totaled $3,578,588, assuming a 7% cost growth was avoided.

6.5.1 Piping Subcontractor - Rountree Plumbing's Perspective

Rountree Plumbing was responsible for all of the piping work, including plumbing, process piping, and HVAC wet. The project manager for Rountree, Chris Crouse, stated that "profitability was in line with our expectation for a project of this type. We would expect to obtain greater return with increased use of this technology." Rountree has substantial experience in 3D CAD modeling and is able to derive many benefits from 3D models throughout the construction process. During the design and construction of the Sequus Project, Rountree utilized the 3D models to obtain the following benefits:

- **Design Coordination** - As stated previously, the 3D CAD models were used for electronic MEP design coordination. The project manager cited the following example where the technology helped identify a potential conflict in routing the chilled and heating water piping to an air handler. "During the 3D coordination, we could not find a suitable route to connect piping to the coils of this piece of equipment. Since the unit had not yet been built, we were able to have it modified slightly to allow our piping to pass under the plenum, solving the problem". As a result of this coordination process, Rountree reported that "rework was dramatically reduced". They noted that some field changes were necessary but these resulted from the fact that the existing structure was not completely modeled in 3D and because the fire sprinkler contractor did not create 3D models of their scope of work. Rountree also reported that there were fewer change orders as a result of this integrated approach. They had six change orders on this project, none of which were for coordination issues.

- **Fabrication** - Rountree was able to fabricate many of the different pipe runs from the 3D models, resulting in time and cost savings and fewer errors. Figure 6.4 shows an example cut-sheet generated from Rountree's 3D model. This was particularly useful for the extremely expensive piping that is used in Sequus' manufacturing processes. For example, stainless steel pipe can cost approximately $400/LF in cramped spaces, such as mechanical rooms, and $125/LF in open spaces, such as laboratories. If one measurement is off in such complicated piping systems, it could cost approximately $700 to fix each mistake. In addition, installing stainless steel piping systems is an extremely labor-intensive process. Consequently, Rountree was able to reduce labor time substantially by fabricating the stainless steel pipe in the shop rather than in the field. The project manager for Rountree Plumbing, stated that "Virtually everything prefabricated from the 3D model was installed as planned."

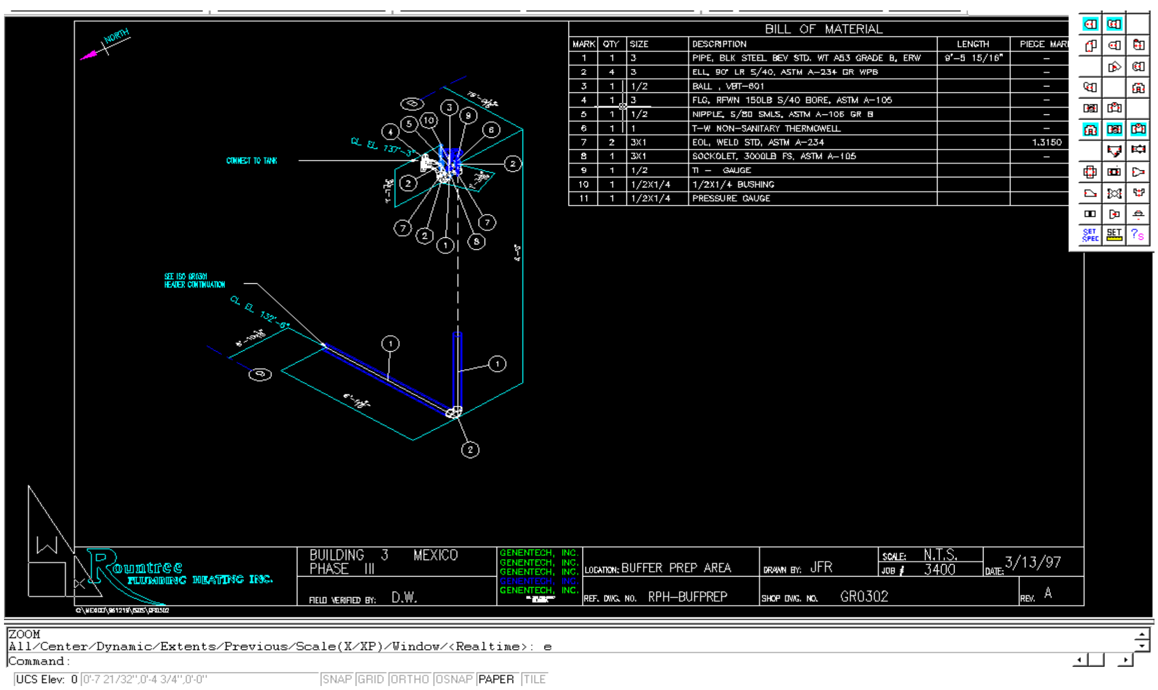


Figure 6.4: Example Cut-sheet of Pipe created from Rountree's 3D Model

- **Field Coordination** - Rountree used the 3D models extensively for field coordination. The superintendent for Rountree, Dan Waters, had a laptop on site and used the 3D models for daily planning of construction activities. He would dimension the 3D CAD model for the specific pipe components that would be installed for each day and print them out for his field crews. This resulted in a substantial increase in field productivity. As stated by the project manager: "Field productivity was improved. Even on a system where we did not attempt to do any prefab, the installers were able to refer to small area isometric drawings to facilitate installation." Figure 6.5 shows a comparison of the 3D model with the actual installation of a portion of the piping on the equipment platform.

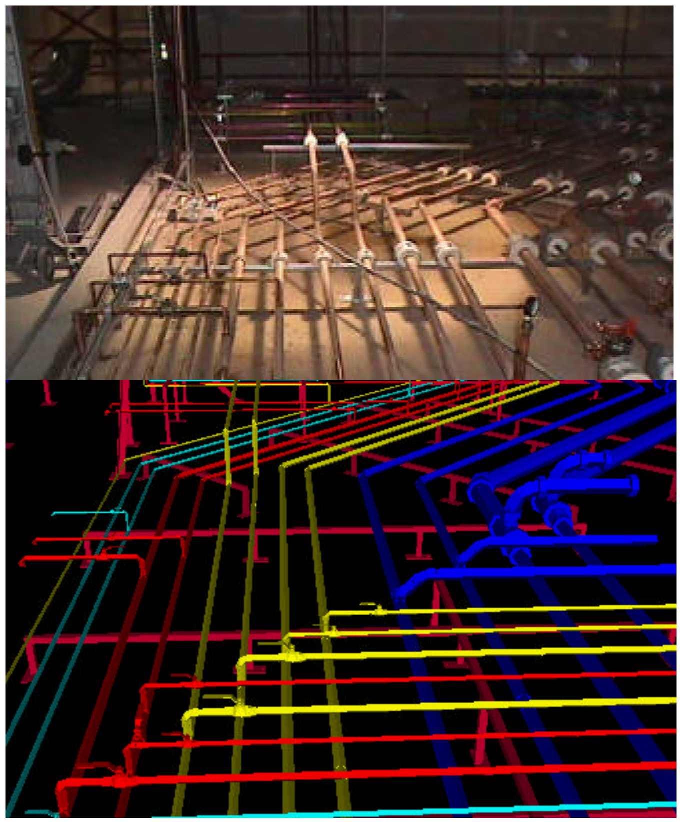


Figure 6.5: Comparison of 3D Model and Actual Installation

- **Estimating** - The detailed 3D models created by Rountree could also be used for estimating. Rountree used the 3D modeling software called Solid Pipe Designer (UHP Process Piping, Inc 1998). This software is able to generate a complete bill of materials, which provides the quantities necessary for estimating purposes. Ideally, Rountree would link their estimating software, QuickPen (http://www.quickpen.com/), with their 3D CAD software, Solid Pipe Designer. However, these software programs currently do not support electronic integration. On the Sequus Project, Rountree was unable to utilize these benefits because they were required to submit a price for their work prior to the creation of the 3D models.

6.5.2 Mechanical Subcontractor - Paragon Mechanical's Perspective

Paragon Mechanical was responsible for the ductwork in the HVAC dry system. The project manager for Paragon, Jim Brady, emphasized that this project was both successful and profitable from his perspective. He contributes part of this success to the good working relationship between project team members. In his words, "the team worked together and everyone was willing to get behind each other for the good of the project. That is what made this project successful and profitable." He also emphasized the importance of the technology in their success. "This project was very successful from the HVAC aspect…the use of CAD drawings in 2D and 3D were, without a doubt, an asset to this project." Paragon experienced many of the same benefits as Rountree Plumbing, which included the following:

- **Design Coordination** - Paragon benefited greatly from the electronic MEP design coordination process. The project manager cited the following example to illustrate how this integrated approach helped to eliminate a potential problem. During 3D design coordination, a conflict was identified between the reheat coils and a run of ductwork. Using the integrated 3D models, they were able to quickly and easily identify an alternative solution. Consequently, this conflict was identified and a solution was found before any duct or pipe had been detailed or fabricated. Paragon also emphasized that there were no change orders resulting from the 3D coordination. The project manager stated that this "is a true credit to the design/coordination/construction teams. Projects of this size without this concept would probably have between 10 and 15 major changes."
- **Fabrication** - Paragon used the 3D models for most of the duct routings and for the shop drawings. The 3D shop drawings were then used "to fabricate and install all the ductwork and equipment for this project." This resulted in significant time and cost savings in the field.
- **Field Coordination** - Paragon reported substantial improvements in productivity due to this integrated approach.

6.5.3 Electrical Subcontractor - Rosendin Electric's Perspective

Rosendin Electric was responsible for all the electrical and controls work on this project. This project was not considered a success financially by Rosendin's project manager, Chris Sorauf. This was primarily due to the increased design and coordination time required by this integrated approach. This was the first time that they had designed their work in 3D, and they reported an increase in design time of about 300%. The project manager stated that "electrical did not benefit from the meetings as much as the other trades but understood that we had to be there for the project to be successful. In the future, this additional cost will have to be figured into the total cost of the project." Electrical subcontractors benefit less because they do not fabricate from the 3D models and because they simply install their wiring by going around the other trades. The library of 3D components built up on this project, however, could be reused on future project projects.

- **Design Coordination** - The main benefits derived by Rosendin Electric were based on the coordination of the light fixture locations. Substantial time was spent on coordinating the locations of the light fixtures and the air diffusers being installed by Paragon Mechanical. Rosendin did report that this coordination "resulted in fewer conflicts than normally encountered in the field."

In the next section, we describe the process changes and organizational impacts that are necessary to successfully apply these software integration technologies and this integrated team approach.

Chapter 7

Process Changes and Organizational Impacts

The Sequus Project 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.

In this chapter, we describe the process changes each discipline will need to make to capitalize on the benefits offered by these technologies and this integrated approach. We also describe how these process changes will have organizational impacts and change the roles of each discipline within the project team.

7.1 Owners

Owners will need to bring an integrated 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 ensure that each member is on the same page.

7.2 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. The project architect for Flad worked closely with HDCC in the development of the architectural design. This collaboration allowed HDCC to utilize the design information to perform design-cost integration. HDCC provided input that included suggestions on how to model certain CAD objects and what objects to include in the CAD model. For example, HDCC 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.

7.3 General Contractors

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. As demonstrated earlier, these skills are essential to support MEP design coordination, field coordination with 4D models, and automated quantity takeoff. 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. General contractors are also likely to become the keeper and coordinator of the models during design and construction. 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.

7.4 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 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.

Chapter 8

Conclusions

This chapter provides a summary of our conclusions from the Sequus Project case study. We describe the benefits that were achieved on the Sequus Project and the impact of this integrated approach on the organizations involved. Finally, we conclude the chapter by describing our vision for integrating design, cost, and schedule information.

8.1 Conclusions

Construction professionals need software tools that enable them to leverage the 3D design information throughout the project's life-cycle. Such integration tools 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 the following:

- shorter estimating time,
- fewer takeoff errors,
- better documentation and reproducibility of the estimating process,
- improved coordination of the construction process,
- improved communication of the schedule intent,
- construction completed on time and under budget,
- less rework,
- increased productivity,

- fewer requests for information,
- fewer change orders,
- less cost growth, and
- decrease in time from start of construction to facility turnover.

To our knowledge, this is the first project where multiple firms have collaborated using an integrated suite of design and project management software. As such, the project team learned many valuable lessons that were critical to the success of this integrated approach and should be incorporated on future projects. These lessons learned are summarized below:

- Project teams should determine the level of detail in 3D to model each discipline's scope of work prior to design development. This is necessary because there are varying levels of detail that components can be modeled in 3D. For example, a transformer can be modeled simply as a 3-dimensional box, or it can be modeled to show all the switches, access points, indentations, etc. Moreover, some work may only require 2D modeling because there may not be any substantial benefit or because the benefits may not be worth the investment. For example, project teams would need to determine if the light switches should be modeled in 3D or 2D. To resolve this issue, project teams should consider all the possible benefits of 3D modeling, including visualization, constructability analysis, design coordination, cost estimating, and scheduling.
- Project teams should determine the stage in the design development process when a specific scope of work should be modeled in 3D. The sequencing and timing of the design development process needs to coincide with the design coordination process, the procurement process, and the construction process, particularly in design-build environments.
- Project managers and executives committing to a team-oriented approach should carefully assemble their project staff. It is critical that each discipline's project team understands the goals of the project, the level of information sharing needed, and the level of 3D modeling required.

- Assemble teams so that the designs are created by the participants who have the construction expertise to create constructable designs, and who are responsible for installation and can leverage the designs throughout construction. A collaborative design approach also provides incentives for team members to provide feedback on the other discipline's designs because they can leverage the designs created by others to support their project management functions. Therefore, a collaborative design process allows the construction companies to reap the benefits from investments in information models.
- It is important to set up a design protocol early in the design process. This includes setting the coordinate system, file naming, layering, and file sharing standards.
- Every essential trade on the project should put their design (scope of work) into the 3D model to leverage the benefits of electronic 3D design coordination. The structural work was only partially modeled in 3D and the fire sprinkler work was not modeled at all in 3D on the Sequus Project, resulting in the only design conflict problems during construction.
- Project teams modeling in 3D require increased design and coordination time. Although this is offset by benefits in construction, it does need to be addressed in each discipline's estimate and contract.

The Sequus Project also demonstrates that owners, designers, and builders of facilities will need to develop new skills and implement organizational changes to take advantage of these benefits, as described below.

- 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.
- 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.

8.2 Vision

Our vision is to provide an integrated project model that allows project teams to create, manage, and maintain the project's scope, cost, and schedule throughout the project life-cycle. Figure 8.1 shows that off-the-shelf software tools allow project managers to perform the following tasks: (1) coordinate and analyze designs electronically in 3D, (2) link cost assemblies to design objects to automate the quantity takeoff process, (3) create schedule activities and calculate activity durations automatically, (4) link design objects with schedule activities to create 4D visualizations. However, the current tools used to perform design coordination and constructability analysis, cost estimating, and

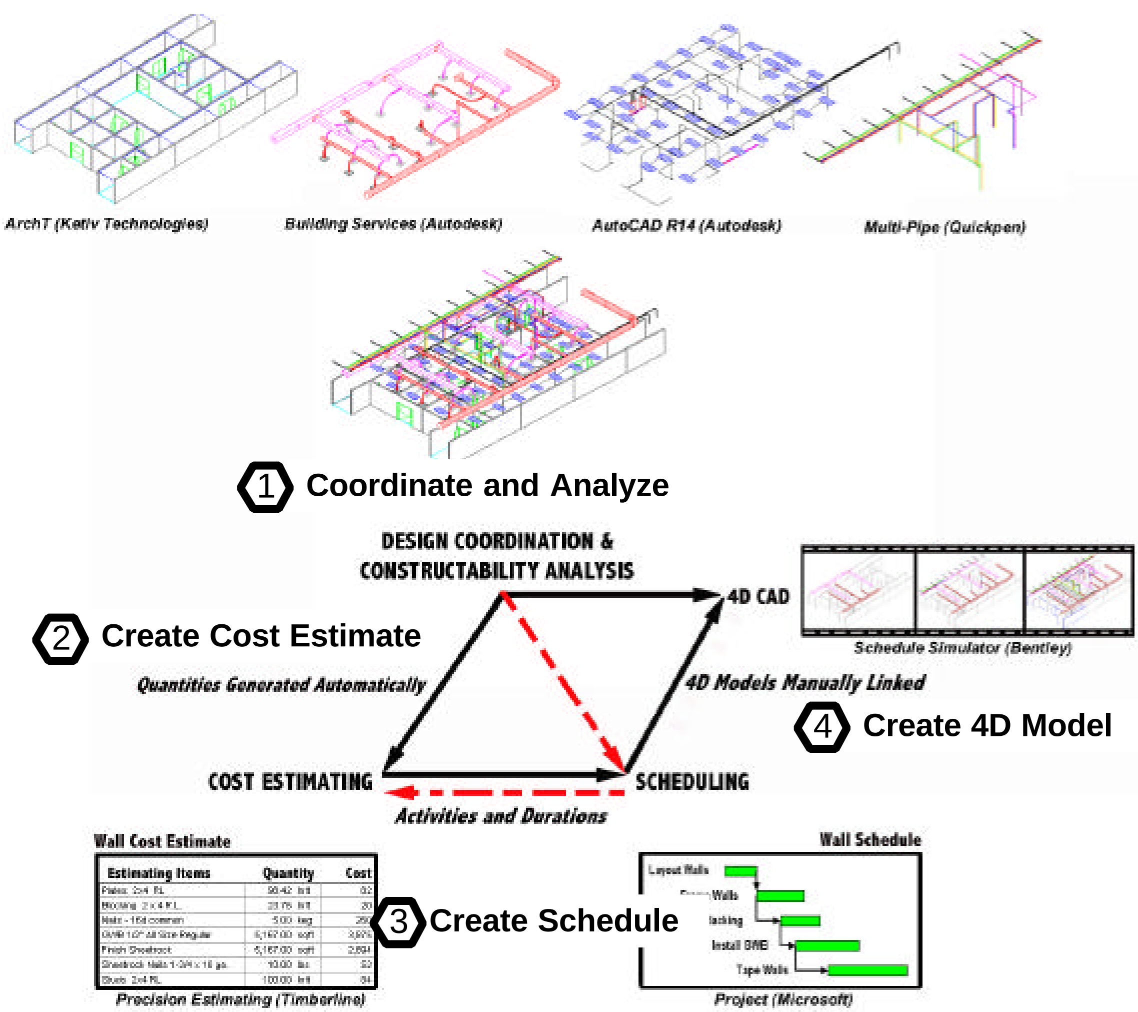


Figure 8.1: Capabilities of Current Tools to Integrate Design, Cost, and Schedule Information and Relationships Needed (shown as hatched arrows)

construction planning do not account for the interdependencies between this information. Figure 8.1 shows the missing links in today's tools that must exist to provide computer assistance in maintaining the project's scope, cost, and schedule throughout the project life-cycle (shown as hatched arrows). Design coordination affects the constructability, construction costs, and activity sequencing of a facility design. Similarly, construction sequencing affects the corresponding construction costs and method selection, and decisions made during cost estimating affect the activity requirements and sequencing in construction schedules. Therefore, it is not only important to explicitly represent the relationships between this information, but also *how* one view affects the other.

Ideally, a project's scope, cost, and schedule are in sync and changes in one correctly propagate to the other. The arrows in Figure 8.1 show the relationships that need to exist to enable this synchronization. Project teams should be able to change the design, construction method, planning strategy, and activity sequencing and the system should help the design or construction professional to identify the related information affected and the potential impacts of that change. We do not believe this could be completely automated. However, we believe that without computer support to help project teams store and use these relationships, the designers and contractors will need to remember when to adjust the information so that the cost estimate, schedule, and project scope descriptions are in balance. On many projects, however, there are thousands of relationships between cost items, schedule activities, and product model components and it is unlikely that designers and builders will be able to manually update all the electronic links in a timely and complete manner. Therefore, we believe project management software tools must provide the necessary functionality to help project teams to represent the context of the relationships between this information and to maintain the information as the project evolves. A company's knowledge and data are one of its most valuable assets and computer tools need to help companies to leverage their product and project information on current and future projects.

Appendices

Appendix A - Presentations

Appendix B - Company Information and Contacts

Appendix C - Project Team Evaluations

Appendix A - Presentations

Fischer, Martin and Staub-French, Sheryl (2000). "Integrating CAD, Scheduling, Cost, and Document Management." AEC Systems Show, Washington D.C., June 5.

Fischer, Martin and Staub-French, Sheryl (2000). "Feature-based Cost Estimating - Current and Future Software Functionality." Annual Meeting of the American Association of Cost Engineers (AACE), Monterey, CA, March 26.

Fischer, Martin and Schwegler, Benedikt (1999). "Information Technology Tools for Integrated Teams." Advanced Techniques in Design-Build Project Delivery and Finance." Design-Build Institute of America (DBIA), San Francisco, CA, Sept. 17.

Staub, Sheryl; Spradlin, Melody; Mickow, John (1999). "Cyber-Construction: Integrating Design, Cost, and Schedule Information." Tutorial, AEC Systems Show, Las Vegas, Nevada, March 22.

Staub, Sheryl; Spradlin, Melody (1999). "Designing the Construction Process Using 3D Models." Timberline User Conference, San Antonio, Texas, February 26.

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Design-Build Institute of America & The American Institute of Architects, Chicago, IL, October 15-16.

Spradlin, Melody; Mickow, John; Fischer, Martin; Ramsay, Mike; and Staub, Sheryl (1998). "Case Study #2: Sequus Pharmaceuticals, Inc. 3D Modeling of a Pilot Plant Project." Gene Acres 1998: Scaling Up for the New Millenium, Sixth Annual Conference on Life Sciences Facilities, Bay Area Bioscience Center, Foster City, CA, Sept. 29.

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Staub, Sheryl; Spradlin, Melody; Mickow, John (1998). "Designing the Construction Process Using 3D Models." Tutorial, AEC Systems Show, Chicago, Il, June 3.

Fischer, Martin; Staub, Sheryl; Spradlin, Melody; Mickow, John; Reis, Jim; Sorauf, Chris; Johnson, Mark; Ramsay, Mike (1998), "Design, Cost, and Schedule Integration." Stanford University, March 14, 1998.

Appendix B - Company Information and Contacts

OWNER:	
SEQUUS PHARMACEUTICALS, INC. (Now Owned by ALZA CORPORATION)	
1900 Charleston Road **Mountain View, CA 94039-7210**	**Tel: (650) 564-5319** **Fax: (650) 564-5656**
www.alza.com	
Name	***Title/Project Role***
Mike Mainini	Assoc. Director of Facilities / Project Representative
Mike Ramsay	Sr. Director Of Operations / Corporate Representative
Anantha Annapragada	Development/Alternate Development
Kenny Brown	Engineer 1 / Validation Process
John De La Fuente	Director QA / Validation Regulation
Angela Kwong	Manager Mfg. / Mfg. Representative
Jamie Rashleger	Operations Administration/Project Coordination
Tom Suess	Mfg. Supervisor / Mfg. Alternate
Harry Wong	Sr. Engineer / Development Representative

GENERAL CONTRACTOR:	
HATHAWAY/DINWIDDIE CONSTRUCTION COMPANY	
565 Laurelwood Road **Santa Clara, CA 95054-2419**	**Tel: (408) 988-4200** **Fax: (650) 988-1958**
www.hdcco.com	
Name	***Title/Project Role***
Melody Spradlin	Project Manager / Executive
Gregg Thoman	Superintendent
David Gerber	Project Engineer
Rick Lasser	MEP Coordinator

ARCHITECT:

FLAD & ASSOCIATES

650 California Street 8th Floor
San Francisco, CA 94108

Tel: (415) 398-1600
Fax: (415) 398-1606

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Name	***Title/Project Role***
John Mickow	Project Manager
Christopher Stewart	Project Architect
Bob Jochnowitz	Senior Technician
Kay Kornovich	Process Architect
Jim Gazvoda	Process Consultant

MECHANICAL ENGINEER:

PARAGON MECHANICAL, INC.

3370 The Alameda
Santa Clara, CA 95050

Tel: (408) 241-3441
Fax: (408) 244-2936

Name	***Title/Project Role***
Jim Brady	Project Manager
Dave Fazekas	Detailer / CAD Operator
Paul Lee	Project Architect

ELECTRICAL SUBCONTRACTOR:

ROSENDIN ELECTRIC, INC.

880 N. Mabury Road
San Jose, CA 95133

Tel: (408) 534-2800
Fax: (408) 295-6423

www.rosendin.com

Name	***Title/Project Role***
Chris Sorauf	Project Manager / Estimator
Michael Albright	Project Engineer
Vish Mahajan	Project Engineer
John May	CAD Operator

PLUMBING/PROCESS PIPING SUBCONTRACTOR:

ROUNTREE PLUMBING, HEATING, INC.

1027 Bransten Road
San Carlos, CA 94070

Tel: (415) 637-1580
Fax: (415) 637-1586

Name	***Title/Project Role***
Jim Reis	Project Manager / Estimator
Chris Crouse	Project Manager
Dan Waters	Field Foreman
Terry Bauer	Detailer / CAD Operator

Appendix C - Project Team Evaluations

Chris Crouse - Rountree Plumbing and Heating Perspective

Rountree had only six change orders. None were for coordination issues. Four were owner requested revisions to equipment connection details. One was to correct a hidden deficiency in the existing building condition. One was a credit to furnish a less expensive fixture in lieu of a more expensive one we had proposed.

We had about 40 RFI's. This is considerably fewer than we would expect on a job of this complexity. Most were to document the owners requirements. It would not be unusual for a job of this type to generate 100 RFI's.

The technology helped us to identify a potential conflict in routing of chilled and heating water to an air handler. During 3D coordination, we could not find a suitable route to connect piping to the coils of this piece of equipment. Since the unit had not yet been built, we were able to have it modified slightly to allow our piping to pass under the plenum, solving our problem.

Field productivity was improved. Even on systems where we did not attempt to do any prefab, the installers were able to refer to small area isometric drawings to facilitate installation.

Increased field productivity was offset somewhat by a lengthy and difficult design/detailing process. The technology is still evolving, and remains hard to use. Trained designers with installation experience are required, but are difficult, if not impossible to find. File size with Solid Pipe Designer remains a problem which tests the limits of the Intel based workstations which dominate the industry. (Total file size of As-Built drawings was about 150 MB.) Overall, profitability was in line with our expectation for a project of this type. I would expect to obtain greater returns with increased use.

Rework was dramatically reduced. Virtually everything prefabricated from the 3D model was installed as planned. There were some field changes necessary to coordinate with the existing structure. On this project, the structural engineer and the fire sprinkler contractor did not produce 3D models.

Chris Crouse
Project Manager

Jim Brady – Paragon Mechanical Perspective

First of all let me state that this I feel this project was a very successful project from the HVAC aspect. I came on to this project just prior to the start of construction. The use of CAD drawings in 2D and 3D were without doubt an asset to this project. In the Sequus project 3D drawings were used for most of the duct routings and shop drawings. These shop drawings (3D) were used to fabricate and install all the ductwork and equipment for this project. The 2D drawings were used in the engineering and for the contract drawings because 2D are much quicker for application. Once the coordination and engineering was complete then the 3D drawings were generated and used. When all the information is correct with regards to architectural and structural then they make the field labor much more productive, and in this case it did. The one thing lacking at the start of this project was the structural drawings. This I feel was error in judgement, because it caused us to have to create the structural to ensure proper installation. All parties need to work off the same backgrounds. 3D are a very powerful tool for demonstrating to the owner what the construction will really look like.

The amounts of change orders for these jobs resulting from the 3D coordination were zero. That is a true credit to the design/coordination/construction teams. Projects of this size without this concept would probably be between 10 and 15 major changes. RFI's were to a minimum and most of the RFI's did not concern the drawings, but dealt with the owner-furnished equipment and issues. No costs were incurred due to RFI's. Three items come to mind that were identified and solved with the 3D coordination.

- The return opening and the WFI piping had a conflict that was identified and the air handler manufacturer was able to raise the opening 6" during production without cost increases for the piping.
- The reheat coils had to be moved to avoid a ductwork conflict and this was identified before any duct or pipe had been detailed or fabricated.
- Location of the AEC chiller on the mechanical platform was located and placed for maximum space and services before construction started.

To summarize this project, is to say that this job was success and was profitable. The profit was probably about the same as with a non-CAD project due to the amount of time spent on the drawings. It did take more time than anticipated but the results in the field made up the difference. The CAD programs are still not there when it comes to going from 2D to 3D, because each have to be drawn separately. The technology was part of this, but the team was the main part. The team worked together and everyone was willing to get behind each other for the good of the project. That is what makes this project a successful and profitable. We have learned a lot from the experience and on the next project of this type and with the increasing technology constantly upgrading I feel we can perform and be much more productively which results in profitability.

It was a pleasure work with you and good luck in the future

Jim Brady
Project Manager
Paragon Mechanical, Inc.

Chris Sorauf – Rosendin Electric

This was a very interesting project in regards to the design approach taken.

1. Productivity was unchanged with this approach. The integration on of the customer equipment and large equipment, such as WFI, RO/DI systems into the construction drawings would have been a benefit.

2. Rework was less with respect to coordination issues with fixtures and duct work. Time was spent on coordination with fixtures and overhead duct work and the result was fewer conflicts than normally encountered in the field.

3. The engineering cost for this project tripled in cost. A design build project of this size would have engineering / CAD cost about 4% of the total cost. This project exceeded 12%, almost 13% of the project cost. This high cost can be attributed to the numerous coordination meetings, as many as 2 a week during the design phase. Electrical did not benefit from the meetings as much as the other trades but understood that we had to be there for the project to be successful. In the future this additional cost will have to be figured into the total cost of the project.

4. Financially this was not a successful project. This can be traced to many reasons, at the top of the list was excessive engineering cost. Other factors had to do with the labor availability, which is not a factor in this analysis.

5. Change orders were about the same as most projects. The change orders resulted in the customer changing specs and unsure of the equipment to be utilized in the pilot plant.

6. The technology was not much of a benefit to the electrical trade but required input from us so plumbing and HVAC could utilize our requirements for their total coordination.

I hope to see you on the final debrief of this project.

Regards,
Chris Sorauf

Chritopher Stewart – Flad and Associates

Stanford University Research Project

Flad recently participated in a joint research project with the Stanford University Civil and Environmental Engineering Department, SEQUUS Pharmaceuticals, Inc., and Hathaway Dinwiddie Construction Company . The research component included the ARCHT drawing program from Ketiv Technologies and Precision Estimating from Timberline Software Corporation. Both technologies were used in the design and construction of the SEQUUS Pharmaceuticals Pilot Plant in Menlo Park, California, a design/build project completed in March 1999. The research component of the design and construction of the Pilot Plant was coordinated by Stanford University, and construction was coordinated by Flad. The results of the research project were compiled by Stnaford University and disseminated to industry professionals through magazine articles, seminars, and conference presentations.

Ketiv Technologies is the Autodesk –authorized dealer in the Pacific Northwest promoting AutoCAD software, mechanical and architectural software solutions, training, and support. Founded in 1983, Ketiv Technologies employs mechanical engineers and licensed architects with industry knowledge and experience. AutoCAD has been the leading drawing tool for architects and engineers for several years. Timberline Software Corporation has been involved in the construction industry since 1971 providing construction and property management firms with accounting, estimating and information management software.

The overall objective of the research project was to demonstrate the effectiveness and efficiency of Timberline Precision Estimating, and information gathered from practical application is being used to improve the software, and consequently, the methods of construction cost estimating. A secondary objective was to demonstrate that ARCHT is an effective tool for bridging the gap between drawing and estimating. Flad was fortunate to be selected for this research project because use of this technology appears to be the direction in which the industry is heading, and Flad is among the first architects to have practical experience applying the technology. The experience permits us at Flad to market ourselves as being involved in cutting-edge technology particularly in light of the fact that Flad services the biotech industry that is by nature on the cutting-edge of technology. Stanford University gained valuable information to develop their academic programs to provide exposure to the latest trends in the construction industry. To the best of our knowledge, the relationship between Stanford University and the software developers was purely in the interest of research and not for financial gain for the parties.

The Project

The SEQUUS Pharmaceuticals Pilot Plant project is a FDA-validated facility for bulk manufacturing of drug products for clinical use. The project renovated 16,000 square feet of a 20,000 square foot, 1940’s tilt-up concrete building. 4,000 square feet remained undeveloped for future expansion. The plant includes GMP compounding labs, process development labs, offices for manufacturing operation and QA, and the potential expansion to Fill and Finish capabilities. Other features include custom walk-in fume hoods, WFI and RO/DI water systems, lyophilization, and the provision for the removal of large volumes of liquid and dry hazardous waste. Flad provided services from Programming through Construction Administration.

Ketiv ARCHT and Timberline Precision Estimating software

Ketiv ARCHT is a drawing program specifically designed for use with AutoCAD that expands AutoCAD's drawing tools to produce traditional 2D Design and Construction Documents as well as relatively-detailed 3D models in less time and labor than AutoCAD's standard 3D capabilities. ARCHT is the architect's primary tool for drawing and compliments AutoCAD drawing commands, seamlessly integrating the production-drafting process with 3D design tools into the production environment. It permits the architect to associate or "attach" information to drawn objects which can then be extracted by another software, Timberline Precision Estimating, the contractor's primary tool for estimating.

Timberline Precision Estimating extracts the "attached" information from the drawn object and translates the drawing information into a spreadsheet of construction cost estimates and scheduling. It streamlines the estimating process, from conceptual estimate to final bill of materials. It offers accurate take-off tools, a variety of ways to view and analyze the estimate, and presentation-quality reports. The ability to link the estimate directly with the drawing allows the design team to more efficiently explore design options, as well as provide a more precise estimate of the construction cost throughout the design process.

Example

In traditional AutoCAD, a double line is drawn in 2D to represent a wall. Construction information such as height, length, thickness, finishes, trim, structure, insulation, fire-rating, etc. associated with that wall is noted in the Specifications and on the drawing to indicate requirements and design intent to the Owner and the Contractor. The same double line drawn with ARCHT, represents the same wall, but ARCHT "attaches" the construction information to the two lines: height, length, width, finishes, trim, structure, insulation, fire-rating, etc., When the lines are drawn, a dialog box appears prompting for the wall information. The contractor takes the drawing and links it to Timberline Precision Estimating which then reads the construction information and builds a spreadsheet with accurate costs for the individual wall components. The costs is based on traditional method of "doing take-offs" from the drawing but instead pulls the information from a database of unit costs and labor created by the contractor. Once the information is attached to the drawn object, it remains attached and can be reviewed and modified by selecting the drawn object. Because the drawn objects are linked to the estimating software, changes to the design or construction components is automatically updated and reflected in the latest estimate and schedule.

ARCHT has an extensive library of standard blocks such as doors, windows, and plumbing fixtures organized by CSI classification and detailed in both 2D and 3D. Selected from a menu, the blocks can be customized and contain construction information like the drawn object. The information attached to the blocks can also be extracted by Timberline Precision Estimating to generate a construction cost estimate

An additional component of the research project included the Mechanical, Electrical, and Piping engineers subcontracted to Hathaway Dinwiddie. The engineers employed drawing programs similar to ARCHT to produce their respective Design and Construction Documents. The drawing programs, specific to the respective disciplines, enabled the engineers to generate 2D/3D drawings similar to the architectural drawings. The 3D drawings were then combined and used to identify conflicts prior to fabrication and installation.

3D Presentation Tool

In addition to providing accurate, up-to-date construction cost estimates, ARCHT uses the attached construction information to simultaneously “build” the wall in three dimensions and permits the architect to produce simple perspective drawings. The perspectives are a valuable tool to illustrate the design to a client. Although the drawn object can be viewed in 3D, it appears as 2D until the 3D command is invoked. The drawings appear as traditional Construction Documents and can, for example, be modified, xref’ed, or plotted.

Conclusion

The use of both the Ketiv ARCHT drawing program and the Timberline Precision Estimating software provided accurate, up-to-date construction cost estimates for the Pilot Plant project. They provide value to the client by providing fast, accurate take-off tools to reduce estimating time, and a variety of ways to view, analyze and present the estimate. In addition, they allow more time for creating and less time with design software. Productivity and accuracy of design are based on a true model of the physical building, enhancing while preserving the proven production-drawing process.

Flad is among the few industry leaders with practical application of this technology. The experience permits us at Flad to market ourselves as being involved in cutting-edge technology, and expands our foundation of services that we are able to offer our clients. For more information about this software and research project, please contact Christopher Stewart at the San Francisco office.

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