



CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

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in Civil Engineering:
Experiences of the Center for Integrated
Facility Engineering at Stanford University**

By

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Integrated and Automated Project Processes in Civil Engineering: Experiences of the Center for Integrated Facility Engineering at Stanford University¹

John C. Kunz, Martin A. Fischer, John R. Haymaker and Raymond E. Levitt

Abstract

"It has often been said that a person really doesn't understand something until he teaches it to someone else. Actually a person doesn't really understand something until he can teach it to a computer, i. e., express it as an algorithm... the attempt to formalize things as algorithms leads to a much deeper understanding than if we simply try to understand things in the traditional way" [Knuth 73]

This paper summarizes some of the highlights of CIFE research since 1989 and summarizes some of our findings. We describe a case example of an integrated model of a project, including the product, a construction process, and the design-construction organization. Traditionally, concurrent engineering has focused on eliminating "over-the-wall" rework through integrated design of product and process. We have extended this focus by including the manufacturing facility, the project delivery process and the managing organization in the scope of concurrent engineering. We integrate the product-process model as a "4D" model, including xy-z and time. Product, process and organization simulation models provide decision support from a broad perspective. The process and organization models together describe the activities to design and construct the product and the groups that do the work. The results of our research suggest a number of open research questions that we introduce in the case example: how to represent models of facilities, processes and organizations so they can be both analyzed by the computer and viewed by stakeholders at multiple levels of detail; how to do automated interpretation of those multi-level models to support knowledge-intensive engineering activities; how to achieve interoperability among different software applications that typically are distributed; how to include all relevant project stakeholders in design review, analysis and development; and finally the grand question: Considering all the things that can (and cannot) be done with research today, which have the biggest potential impact on project cost, duration, quality and safety?

Introduction

Our research attempts to relax some of the fundamental limits on traditional civil engineering research methods by building computational models of engineering projects, i. e., *formalize integrated product, process and organization models*. Formalization is one step in taking engineering from a craft discipline, practiced by experts who teach apprentices at their side, to a scientific discipline with repeatable, predictable methods. Formalization involves building models that are both descriptive of the products and processes of the AEC industry, and that have procedures that enable prediction of the behavior of those systems under different assumptions. We review recent work of the Center for Integrated Facility Engineering (CIFE) at Stanford University, identify recurring research questions and issues, and speculate on the major research questions of the next few years.

As the name of the Center implies, CIFE focuses its research on improving the integration of information, processes, and organizations for capital facility projects through information and communication technologies. Many of the opportunities to improve the design, construction, and management of facilities lie at the interfaces between today's processes. A major center objective is to create a science base for integrated product, process, and organization design. This paper introduces a current example of our methods.

Our broad experience and the specific example both illustrate the way that integrated product-process-organization models can help to:

- Balance the design of the facility, schedule and organization,
- Support rapid prototyping and analysis of alternative design and management scenarios to identify bottlenecks in the delivery process, and
- Facilitate coordination among project participants.

¹ Published in *Computing in Civil Engineering Proceedings* from the Specialty Conference on Fully Integrated and Automated Project Processes, Anthony Songer and Paul Chinowsky (Eds.), ASCE, Reston, VA, 96-105, January 2002.

Motivating Case Example

The Walt Disney Concert Hall [DCH] will be the new 2290-seat home for the Los Angeles Philharmonic Orchestra [Disney Concert Hall, 2001]. Frank O. Gehry & Associates are recognized internationally for their daring designs, their innovative and advanced use of 3D modeling to represent their designs, and the integral role these models play in the construction process. Research at CIFE routinely uses ongoing projects as laboratories to motivate and test research [e. g., Kunz et al 1996, Collier and Fischer, 1996].

Figure 1 shows a view of the concert hall ceiling from above. The concert hall ceiling is an architectural and acoustical structure that hangs from the trusses that also support the concert hall roof. The ceiling integrates lighting, mechanical, and audio/visual systems into a curvilinear wooden ceiling finish. In this case, it was unclear how to frame the ceiling to make it constructible high above the seats of the concert hall and to integrate the many building systems (mechanical, electrical, acoustical, lighting, skylights, aesthetic, etc.) that occur in the tight space between the roof and the ceiling panels. The general contractor was in charge of completing the detailed design. The detailed design needed to consider issues like quality, structural reliability, Constructability for the various trades, sequence and methods of erection, overall schedule, availability of design, consulting and construction resources, and maintainability. Our observation on site was that even today's advanced computer tools (the site uses, e. g., 3D and 4D CAD models routinely) give little help for practitioners to elucidate the scope, cost, schedule and organizational tradeoffs of various alternatives. The rest of the example focuses on identifying two important conditions that may vary depending on the selected alternative and that have an impact on some of the issues listed earlier in this paragraph: walkable surfaces and cantilever conditions.

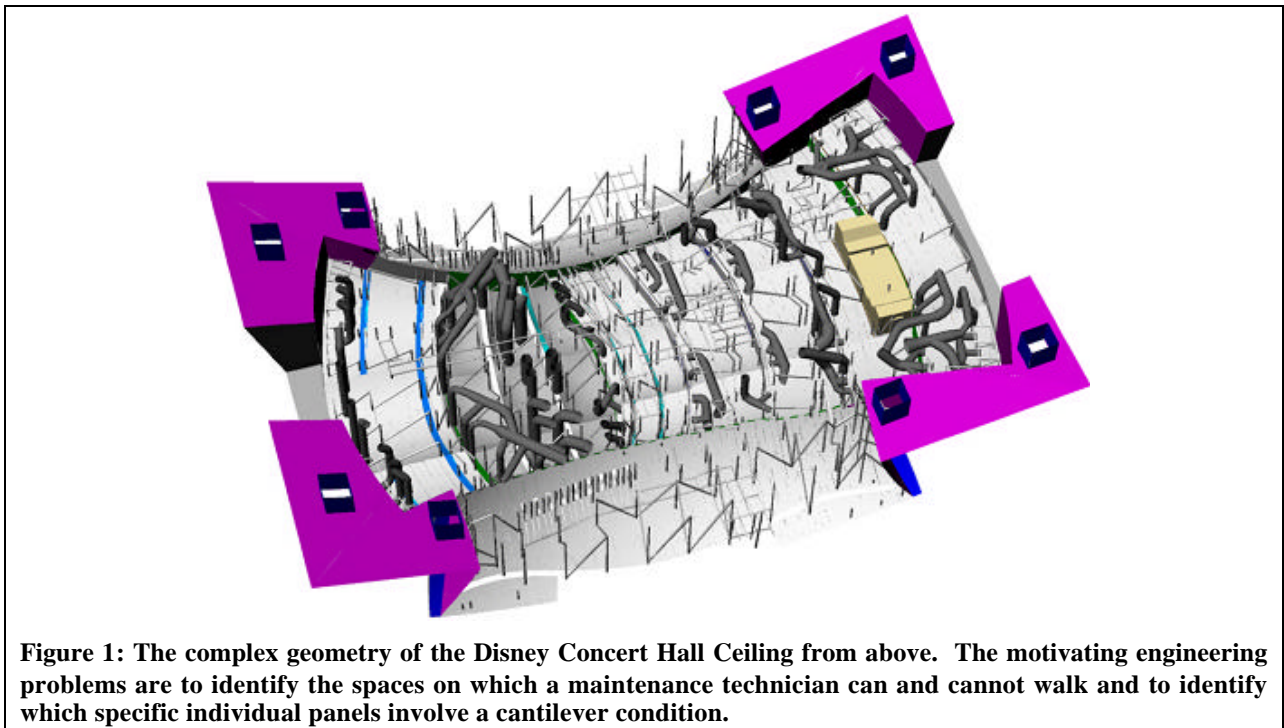
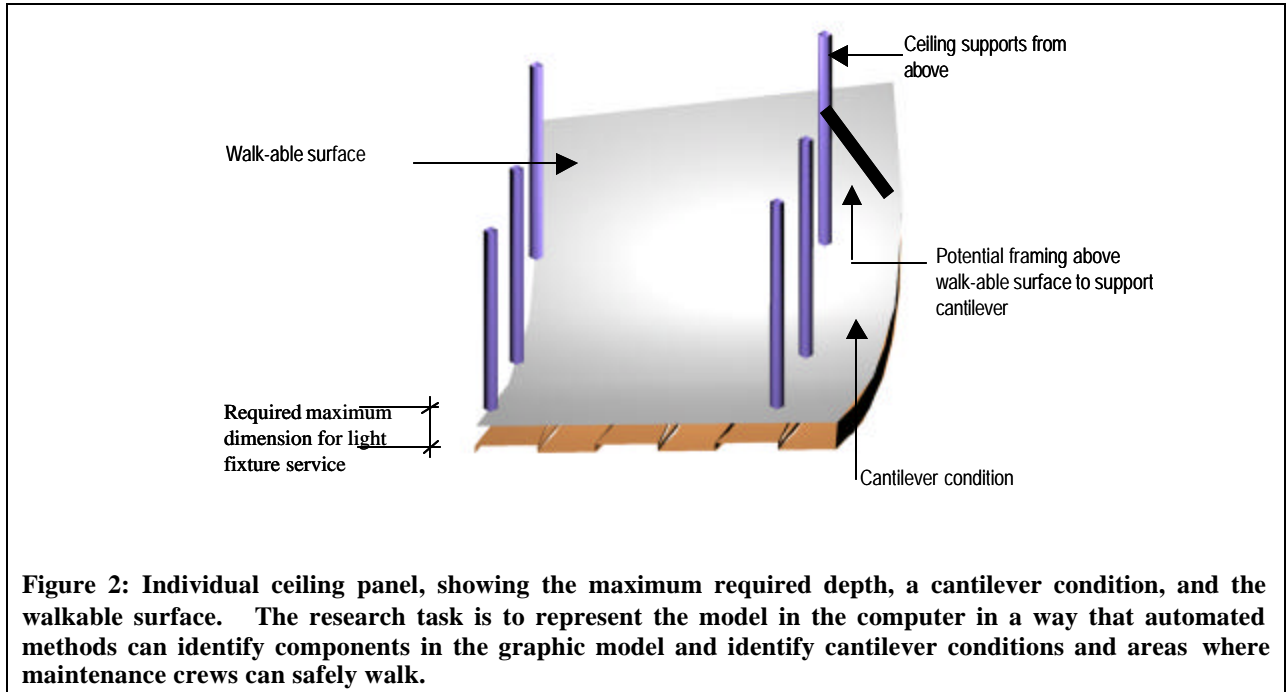


Figure 1: The complex geometry of the Disney Concert Hall Ceiling from above. The motivating engineering problems are to identify the spaces on which a maintenance technician can and cannot walk and to identify which specific individual panels involve a cantilever condition.

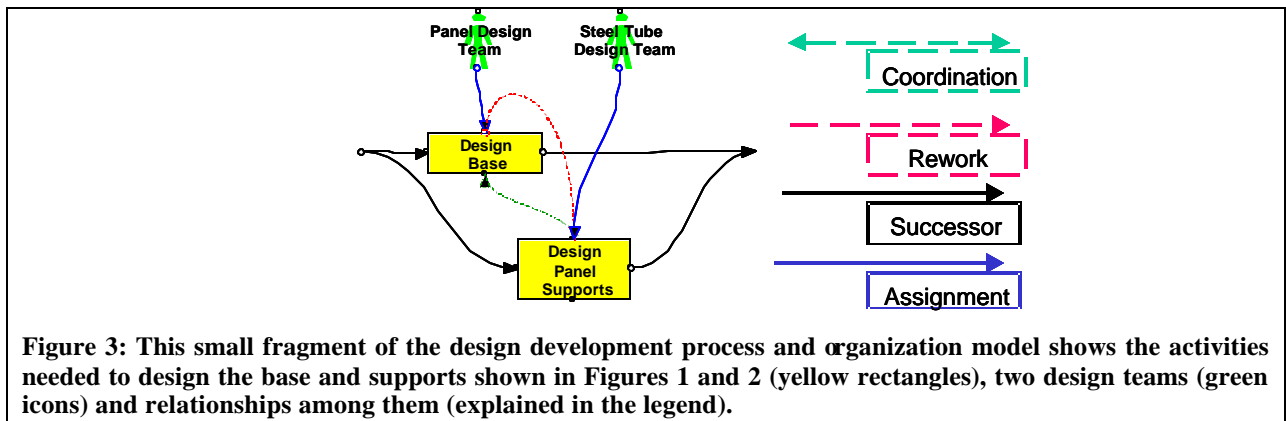
Figure 2 shows a simplified portion of the ceiling and annotates a walkable surface and a cantilever condition.

The design of the panels and their support involves considering a number of issues, including the walkability and cantilever conditions. We built a model of the *process* to design larger ceiling system and the *organization* that performs the process, a small fragment of which is shown in Figure 3. This model includes activities for various design, procurement, construction, and procurement tasks including more tasks, and some

organizational relationships. It also represents the precedence between activities, the anticipated requirements for coordination and rework between activities, the engineering teams that perform the activities, and the responsibility relationships among teams and activities.



During construction, the walkable areas change, both as permanent structure is added and as workers add and remove temporary supports. “4D” models animate the construction of a building and thus enable analysis of such as issues as safety, interference, congestion and walkability during the construction process. While we cannot show the time-varying animation of a construction process in a paper, we repeatedly find that 4D models provide value for construction planning [Staub, McKinney and Fischer, 1998]. The 4D model links the product and schedule models, and the visualization system shows product objects in the scheduled sequence and rate.



Research Questions

This paper discusses our approach to two related basic research questions:

- How can the computer analyze engineering issues in an engineered product (in this test case, determine where cantilever conditions occur and how this condition interferes with the ability of maintenance crews to walk around the ceiling to do routine service);
- How can the computer analyze the schedule, workload, cost and quality impacts of changes in the design-construction process (in this test case, different ways to assess the cantilever and walkability issues); and
- How can the computer support integrated analysis of product, process and organizational issues?

Research Methods

In order for the computer to analyze the cantilever and walkability issues, we built a symbolic (i. e., non-graphical and non-numerical) *product* model, i. e., the ceiling system that represents, for the entire ceiling, the content shown in Figure 2. We used the Industry Foundation Class (IFC) model as the basis for our product model [IAI (2000), Yu et al., 1998]. Thus, the product model identifies the components, e.g., panels and steel-tube supports. However, the architect did not (and routinely does not) identify the attributes and relationships of interest, i. e., whether individual panels involve a cantilever condition and whether they have access that allows walkability. Thus, the initial product model does not represent these attributes explicitly. As suggested in Figure 4, the *Perspectors* system, currently working as an early prototype, identifies the panels and steel-tube supports in the product model and performs simple reasoning that adds the *walkability* and *cantilever* attributes appropriately.

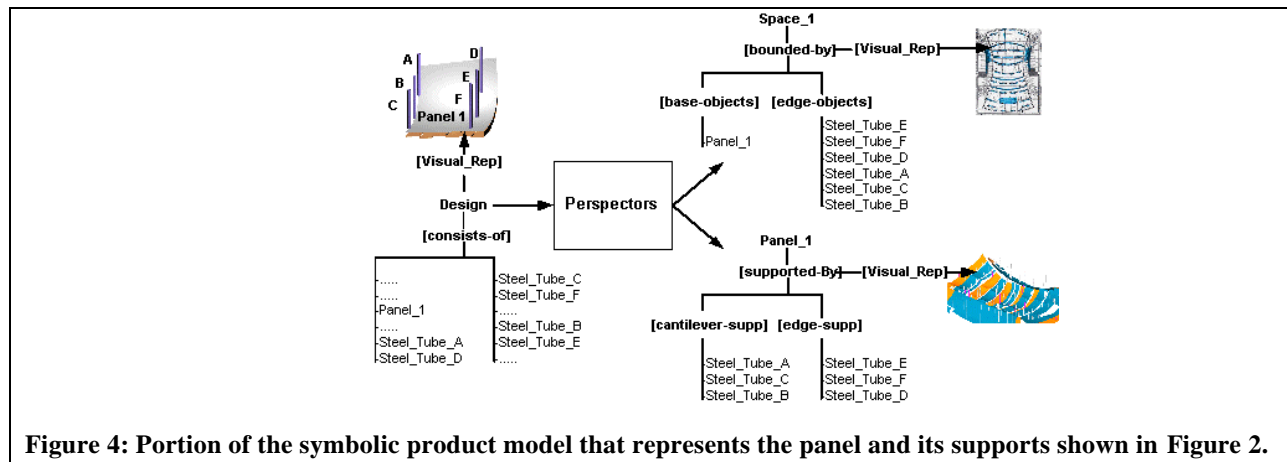


Figure 4: Portion of the symbolic product model that represents the panel and its supports shown in Figure 2.

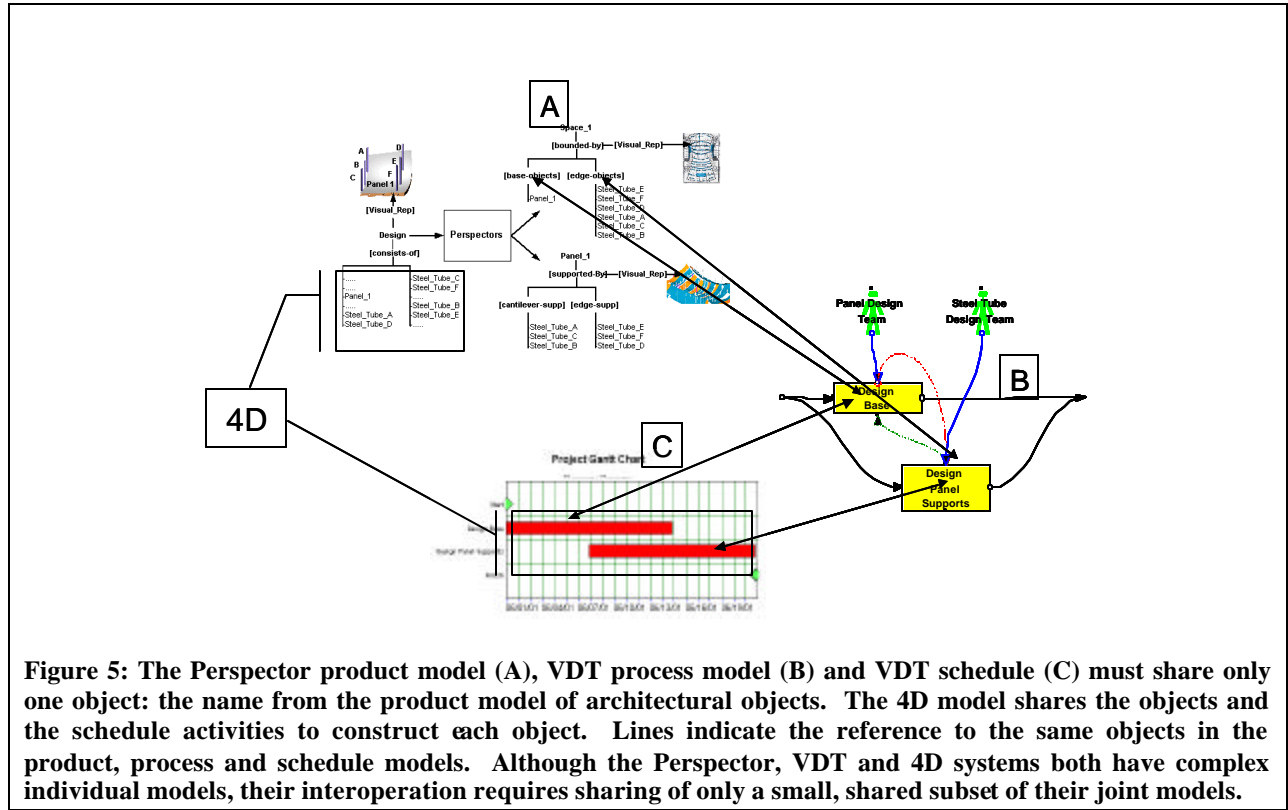
In order for the computer to analyze the project performance and organizational issues, we built a symbolic model of the *process*, i. e., the process to design the entire ceiling. As with the product model shown in Figure 4, the process and organizational models use software objects to represent the activities and project teams. We built the process and organization model in the Virtual Design Team (VDT) system [Kunz et al, 1997; Levitt et al, 1999].

The product analysis (i. e., the *Perspectors* system in this test case) needs to coordinate with the process and organization models (i. e., the *VDT* system in this test case). The IFC model in principle supports the requirements of the product, process and organization models required for this test case. In CIFE integration work, we have repeatedly observed, however, that heterogeneous applications such as the *Perspectors* and *VDT* systems share only a tiny fraction of the total information models that together they require [Kunz et al. 1996, Arnold et al., 1999]. In analyzing the requirements of this test case, we identify only one kind of information that is necessary to share between the *Perspectors* and *VDT* applications: the Object, i. e., the identity of each architectural object in the product model. The *Perspector* and *VDT* models both have additional attributes and relationships, but these other data need not be shared between these two applications.

Discussion

The process of designing and building a new facility now involves a team of several to more than a hundred contractors collaborating with a number of owner representatives over a period of one to several years. The

documents around the edges and the leftmost photo in Figure 6 illustrate the current document-centric reality of project practice. The rightmost photo suggests the potential of interoperability and new visualization methods to enable stakeholders to collaborate. By tradition and in current practice, AEC project development involves creation of a large set of project documents. The fundamental focus of CIFE integration research is to represent models of different aspects of the project -- in the computer -- in a way that the models can be stored, distributed, shown to users and used to enable some AEC process such as planning. Interoperability allows different applications to share data, and our new visualization research allows many stakeholders, potentially distributed in space and in time, to view many integrated and consistent project views at different levels of detail.



Issues

CIFE research results have given us the sense that there is indeed a nascent science of the use of computational methods in design and analysis of construction products and processes, a field we call *Construction Engineering Informatics*. We feel that CIFE research has demonstrated to us, to some colleagues, and to some industrial partners, that there is a scientific field behind the art and craft of design and analysis of the products and processes of construction. We find that this science has a consistent conceptual framework, the core of our recurring research issues:

- **Symbolic product, process and organization models:** Research issues concern ontologies that support description, analysis and prediction of specific engineered systems [Clayton, Akinci, Aalami, Levitt, Kunz].
- **Reasoning methods,** or processes to analyze product, process and organization models: research issues concern development of specific methods that analyze a large variety of design and construction related processes [Akibas and Fischer, Akinci et al., Levitt et al., Kunz et al. 96].
- **Scientific foundation of specific facility design and construction-related products and processes,** including models of plans and organizations, 4D (3D plus time) CAD, e-commerce, visualization of design and construction information, and collaboration methods.

- **Interoperability:** Fundamental research issues concern purpose, content and parsimony. We have investigated inter-disciplinary interoperability, i. e., interoperability between software applications that support different engineering activities such as architectural design and cost estimating. Repeatedly, we find that only small amounts of data need to be shared, obviating the need and value of a rich shared product-process-organization model [Kunz et al., 1996, Arnold et al., 1999]. Recent work, such as we describe in this paper, suggests that the OARPLAN (Object, Action, Resource) formalism [Darwiche et al., 1988] provides a sufficient basis for inter-disciplinary interoperability models.

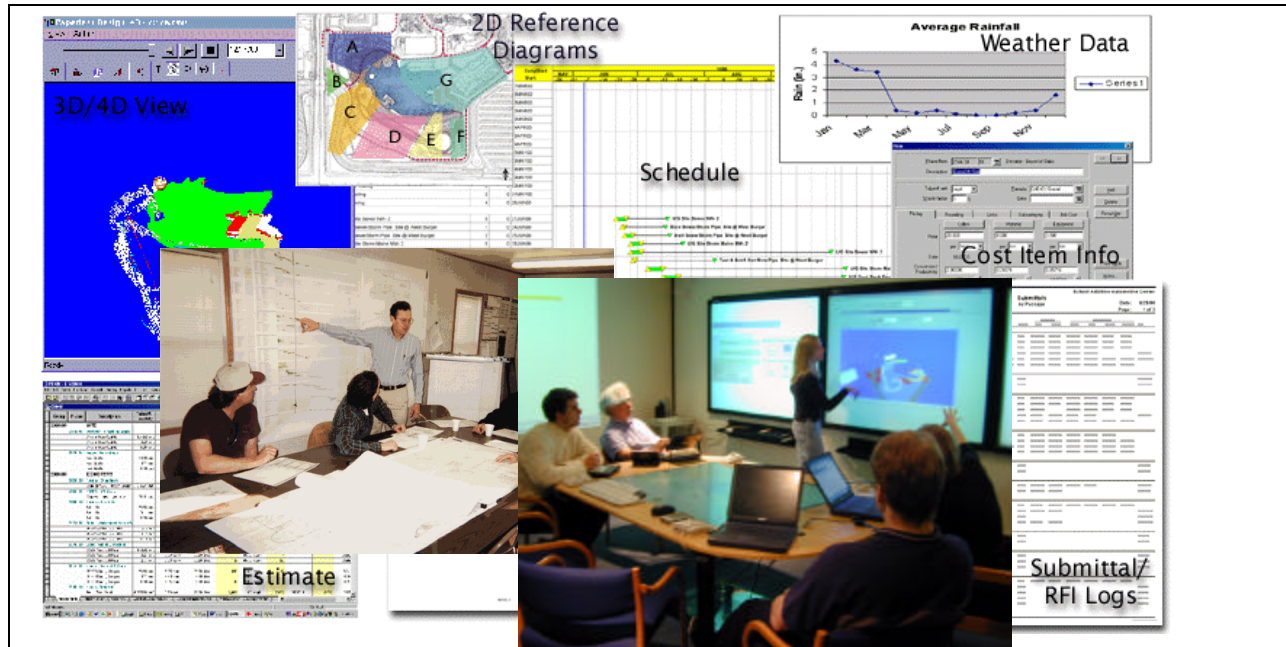


Figure 6: Design and construction today involves creation of multiple views of the project by numerous AEC discipline professionals and then continuing meetings among them to clarify and reconcile their designs and actually build or operate the facility. As suggested by the multiple figures around the photos, current AEC practice is largely document-based, either on paper or computer-based. Thus, in general, the human professional must create and assess the relationships among the documents. The opportunity of interoperability is to create and support some of these relationships computationally, and the opportunity of visualization is to allow project stakeholders to explain their own work and understand the work of others. The leftmost photo shows current practice; the rightmost shows the Stanford interactive workspace [Fox et al., 2000] in which multiple displays show different project views provided by interoperable applications

- **Validation methods:** Fundamental research issues concern methods of validation that consider real (i. e., industrial) applications, and methods to develop evidence for the power and generality of research contributions. Universally, our research projects consider industrial test cases. We have developed and used a controlled study method (the charrette method [Clayton et al., 1996]), retrospective [Katz, 1998], prospective [Thomsen et al. 1999] and intervention studies [Levitt et al., 1999, Haymaker and Fischer, 2001]; and the “milk-stool method” that seeks three-way consistency among the predictions of theory, practicing experts and our models².
- **Visualization** of project information for multiple stakeholders who frequently are distributed in both space and time [Fröhlich et al., 1997]. As shown in Figure 6, the Stanford Interactive Room (iRoom) has multiple large and small displays driven by computers linked via the Internet. Fundamental research issues

² The method takes its name from the design of the 3-legged stool traditionally used by American farmers to milk cows, a design that provides a stable seat on an uneven barn floor. One of us (Fischer) observes wryly that the Swiss milk stool has one leg.

concern design and evaluation of the effectiveness of different display modes and technologies, methods to show and relate different discipline views and different levels of detail, and methods to validate the effectiveness of different visualization methods [Liston et al., 2000].

Benefits and Limits

The CIFE experience has led to a number of practical benefits to industry, research and students.

Industrial members of CIFE have continued to provide support over a number of years. Several companies have taken specific CIFE technologies and incorporated them into new product offerings. Spin-off companies have started to commercialize CIFE technologies for organization modeling, 4D, collaboration and pipe routing. Companies have directly benefited by the ability of newly hired students to apply their research. Industry representatives say that they learned specific methods to address IT and integration issues from the CIFE focus on IT and integration and some specific integration research.

The CIFE students universally report after graduation that their CIFE experience provided a unique and far-reaching view of the practice and issues in use of IT in construction engineering and research. Students appreciate the opportunity to develop their own practical test cases, use modern computer methods, and validate their work in industrial settings. Surprisingly to the faculty, the graduate students enthusiastically embrace the integrated view and scientific methods practiced at CIFE, taking significant time to learn and to apply systematic research and validation methods. For example, one of us (JRH) developed the 3D and 4D models summarized in this paper during a 6-month internship. He initially formulated the research questions on the job and later clarified them back at the university. He designed, built, analyzed and tested the symbolic building model at the university, as shown in this paper, returning periodically to the job team to test preliminary results and validate the relevance of the work to engineering problems found on the job site.

Naturally, we have found that many barriers stand in the way of developing the science of construction informatics, providing value to industrial practice and educating students who will go forward and create meaningful careers and contribute to societal welfare. Although industry relatively readily adopts incremental improvements to existing processes, the industry has few organizations that can do the hard work of identifying and commercializing any novel developments of the university laboratory. Software vendors in the AEC industry tend to have a strong focus on a traditional discipline, e.g., on architectural design or energy analysis or cost estimation. Most vendors seem to find it difficult to sell products whose appeal lies outside of the mainstream of current practice. CIFE's focus cuts across the current organization of the construction industry. Technology transfer is challenging because CIFE's work does not closely match with established markets and business practices. Thus, although some leaders have interest, companies find it difficult to create and sustain significant energy on commercializing novel products and methods that provide, support or even use integration. Finally, CIFE and related departmental activities are committed to the principle of teaching and doing research on the science of the field, yet the field is so new, novel and embryonic that it is difficult to recruit and hire new staff

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