New Information Technology Tools Enable Productivity Improvements

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Abstract

In this paper we argue that project information should be presented visually in 3D and 4D models to reach as many project stakeholders as possible as effectively as possible. When based on the input of many stakeholders, these models represent possible project alternatives completely, accurately and in an easy to understand manner. They enable all project team members to leverage their own project data and the data of others. The current document-centric paradigm, however, does not support the rapid and economical construction of these models. Hence the document-centric paradigm needs to be complemented with a model-based approach to create, share, and use project information. These project models will enable project team members to explore many design and construction alternatives rapidly to work out potential problems before work is put into place in the field. They will also enable e-commerce to improve procurement of materials and services. Electronic information exchange standards will greatly facilitate the creation and maintenance of these project information models throughout a project’s life cycle. The CIMsteel integration standards for the steel industry are the most advanced standard in the general building industry. Hence the steel supply chain is in a position to be the first supply chain to reap the aggregate benefits from model-based life-cycle engineering.

1. Introduction

1.1 You can’t always get what you want …

Walt Disney Imagineering (WDI), the design and construction management part of the Walt Disney Company (TWDC), derives part of its competitive advantage from creative and innovative shows and attractions - and from the safe, fast, and cost-effective construction of these designs. While WDI has been successful with today’s paper-based and file-based exchange of information between design teams and between design and construction, there is a growing realization that these methods will not continue to provide the rapid development and execution of design ideas necessary to sustain TWDC’s industry leadership. Therefore, it is a major concern that the project delivery processes and information sharing methods prevalent in the architecture, engineering, construction (AEC) industry today can not support TWDC’s long term competitive strategy. However, there is enormous optimism that the tools in development today will catalyze substantial improvements in productivity and profitability in the Architecture,

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Engineering and Construction (AEC) industry as a whole, as well as in WDI’s core business.

The document-centric storage and sharing of design and construction information makes it difficult for project team members to maintain consistent project information with respect to scope, cost, and schedule from the nuts and bolt level to the overall project level. Today, almost all information on projects is generated with software tools. However, most of the commonly used tools work only in a particular domain or discipline and function only at one level of detail. Furthermore, the two-dimensional representation of three-dimensional design information and the one-dimensional representation (bar charts) of four-dimensional schedule information\(^4\) make it impossible to communicate the scope and timeline of a project at all levels of detail to all affected stakeholders in a clear manner. In addition, today’s single-user tools do not support the quick generation of design alternatives in group settings. It is often difficult for AEC professionals to easily access project data stored in discipline-specific tools because there are no industry wide standards for most types of project data. This exacerbates the problem of creating, maintaining, and sharing consistent project data.

In recent years, several electronic visualization tools have become available (e.g., 3D CAD, 4D CAD, virtual reality). These tools communicate a project design and schedule more effectively than 2D drawings and bar chart schedules, but most of these tools are purely visualization tools. In other words, a project team can view the information from various vantage points and even fly or walk through it, but the team cannot interact with the 3D and 4D visualizations to collaboratively explore design alternatives and resolve design issues rapidly. In summary, the fast-paced work on design and construction projects requires tools that work at several levels of detail, that support interaction with visual models in a group setting, and that give users and other software tools easy access to project data in a commonly understood format.

This paper shows how WDI has collaborated with researchers from Stanford University’s Center for Integrated Facility Engineering (CIFE) to develop an interactive 4D visualization tool for design and construction. The tool allows design and construction professionals to review and change the design and corresponding construction schedule at several levels of detail and in variety of computing environments (desktop, web, and virtual reality (VR) cave). The tool was tested during the construction planning of one of TWDC’s new theme parks. The process of creating 3D/4D design and schedule information for this project highlighted the need for:

- effective electronic information exchange mechanisms since input from as many project stakeholders is critical to the success of the 4D model.
- tools and protocols that enable project participants to generate 'well-formed' design and schedule information. Although 2D and 3D design information and schedule information existed, the team had to generate a new set of 3D information and

\(^4\) A construction schedule combines scope information and spatial site constraints (3D information) with production information and activity durations (temporal information, the 4th dimension).
schedule information that was appropriately detailed and structured for the 4D modeling process.

In this paper we first discuss the development and testing of the 4D prototype and showcase the benefits accrued from its use on the Paradise Pier project. We then discuss the benefits that can be obtained from computer-based modeling and sharing of project information and outline the need for and challenges of standard information exchange mechanisms.

1.2 … but if you try sometime you can get what you need

The use of 4D models (3D + time) represents a fundamental change in project planning, design and construction management strategies. 4D models have the potential to dramatically reduce project costs, schedule and risk. This and the following sections describe an interactive 4D modeling system, comprised of three 4D environments—a VR cave, the desktop, and web—that fully enables this change. This software system vastly improves a project team’s ability to generate and maintain an up-to-date 4D model. It also improves and enhances the current benefits of commercially available 4D tools by enabling project team members to:

1) Better communicate the design and schedule of a construction project
2) Maximize the utility of the 3D and 4D models for other design and planning task
3) Quickly generate and revise 4D models to reflect design and schedule changes
4) Solicit feedback and input from all project participants without investment in expensive 4D tools for every project participant

This system facilitates evaluation, feedback, and suggestions from a range of project participants who can identify potential problems easily and rapidly explore and evaluate design and schedule alternatives. The following software innovations make these improvements possible:

- Integration of the VR, desktop, and web environments into an overall interactive 4D system
- Hierarchical representation of the 3D building models and schedule models to allow project participants to work with the 3D and 4D models at various levels of detail
- New display, interaction, and navigation functionality

These innovations extend the capabilities of commercial tools significantly.

WDI collaborated with researchers from Stanford University’s 4D research group to scale up a research prototype [McKinney et al., 1996] for use on the Paradise Pier section of the new Disney’s California Adventure park which is being built next to Disneyland in Anaheim, CA. This project involves the construction of seven attractions, four facilities, and land development work on a tightly constrained site and involves many project participants, from designers and architects, to ride vendors and mechanical engineers, to general contractors and specialty subcontractors, to operations and facility managers. This project was chosen as a test case for the use of the 4D project management system because the effective management and planning of this project demanded the ability to allow as many project participants to evaluate the design and schedule as often as possible. Furthermore, the project team needed a way to clearly communicate the
complexities of the site, schedule, and logistics. The following sections describe the motivation, background, innovations, development process and benefits in more detail.

1.3 Practical motivation for development of interactive 4D prototype

Research has shown that owner-led project teams are most successful in delivering projects faster and more cost effectively [Business Roundtable, 1997]. To realize these benefits, owners should have tools available that support quick modeling of design and schedule alternatives. Large project owners need to coordinate the opinions and requirements of many stakeholders in a timely manner, ranging from investors and community review boards to neighbors and casual users. New design tools should enable rapid and effective communication of insights gained while at the same time examining immediately the design and schedule impacts of those alternatives, comments, or suggestions. This allows interested participants to see changes to a project’s design or schedule while the decision-makers still remember the issues under consideration.

In addition, all project and construction managers should have project information available at the right level of detail and scope. The level of detail of a 4D model needs to support the wide range of ways in which a project manager organizes and coordinates the work. For example, zone and area managers coordinate work in a geographical area. They often find it difficult to quickly obtain project information at the right level of detail since it is typically organized by systems or by discipline and is not broken up by geographical areas or zones. Also, current schedules of the various subcontractors need to be incorporated into the general contractor’s (GC) and owner’s master schedule. A hierarchical 4D model easily accommodates these different levels of detail and elaboration.

Finally, such considerations as laydown areas, temporary works, and access roads, etc. can have a significant impact on the success of a project, particularly on spatially constrained sites, such as Paradise Pier. Effective staging and sequencing of work enables efficient use of resources and minimizes the waste of labor and materials. Interactive 4D models should respond to these practical needs by displaying not only the installation of components in the 3D model in their final position, but also by supporting a realistic evaluation of a proposed construction schedule.
Figure 1: Diagram of Interactive 4D Project Management System showing the three types of environments. The diagram also shows the flow of information from the initial input of a 3D model and schedule, to creation of a 4D model, to updates, revisions, and feedback for a 4D model.
2. The WDI – CIFE prototype 4D tool

2.1 Background: Collaborative research between industry and academia

The Interactive 4D System (Fig. 1) illustrates a full research cycle from industry need, to research in academia, to development of technology and application in industry. Pilot projects in the late 1980s and throughout the 1990s demonstrated the value of 4D visualizations [Cleveland, 1989; Collier and Fischer, 1995; Retik, 1996]. Bechtel’s R&D Department demonstrated visual construction simulation in the late 80s, which led to the development of proprietary 4D tools, such as Bechtel’s 4D Planner [Williams, 1996] and the marketing of commercial 4D tools (e.g., Schedule Simulator by Bentley and Schedule Review by Intergraph). Studies of the practical applications of 4D models by the 4D-research group at Stanford identified two significant shortcomings of commercial 4D tools, which have limited the widespread use of 4D models in spite of their benefits:

- A new 4D model needs to be built for every new situation or for different levels of detail even though the basic project information is essentially the same.6
- 4D models are only visual models, and 3D and schedule data flow only from the original 3D CAD and schedule applications to the 4D model (in other words, it is not possible to make changes to the 4D model and simultaneously update the 3D model and the schedule.)

These applications also demonstrated that construction professionals want to interact with the 4D model. They want to be able to reorganize it on the fly and change the level of detail for some area or period. They also want to add new things to the 3D model or adjust the schedule quickly and see the effect of those changes right away in the 4D model.

To address these needs, WDI merged its research in interactive real-time 3D imaging with the hierarchical and interactive 4D modeling environment developed at Stanford’s 4D-research group. WDI selected Paradise Pier as its first test of the 4D approach to construction management. The particular design and management challenges for Paradise Pier included:

- Making sure that the design could be built on a physically constrained site with an aggressive schedule
- Involving many project stakeholders early in the design and construction planning process
- Merging multiple schedules of different contractors to check construction compatibility with each other and with WDI’s schedule
- These project challenges made 4D models a logical choice for the planning of the construction phase. They also required a far more interactive, easy-to-use 4D tool than any available today. These practical needs and the prior research in Stanford’s 4D-research group led to the improvements described in detail in the next section.

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5 See http://www.stanford.edu/group/4D/4D-home.htm for brief descriptions and illustrations of these applications.

6 Bechtel’s 4D Planner is the most advanced implemented tool in this respect because it supports two levels of detail in the schedule.
2.2 Multiple uses of 3D model

The same 3D model built for the visual simulation of the construction schedule was used for three purposes:

- To verify whether the design is buildable and whether it can be built according to the proposed schedule
- To visualize the finished project, including visual intrusion and sight line check, and
- To simulate rides (combining actual simulation data from ride vendors with the graphical 3D model)

Because these multiple uses leverage the 3D modeling effort, they made the development of a comprehensive 4D model for the Paradise Pier project much more economical. The multiple uses were enabled by newly developed translators and by Disney’s internal standard “egg” file exchange format. Our experience shows that with a little bit of foresight the information in a model developed for one purpose can be leveraged for other purposes.

2.3 Hierarchy

Hierarchical 3D CAD models and object-oriented representations for 3D information are emerging for the AEC market (for example, I-DEAS by SDRC, the IFC by the IAI, and the CIS/2 standard adopted by AISC). However, hierarchical 4D models are not yet available. A hierarchical 4D model requires the following functionality:

- Hierarchical product (design) and process (schedule) models leading to a hierarchical 4D model
- Links between any level of detail of the product and process models
- The ability to group product components by construction zones easily

This functionality allows a user to customize the content, view and level of detail for a particular 4D visualization session easily and quickly. The hierarchical representation of a design and construction schedule also allows users to update a 4D model efficiently because the changes can be made at any level of detail. The hierarchies allow users to group components into construction zones and to add temporary construction detail (such as laydown areas) to make the visual construction simulations more representative of the real situation on site. Users can also assign and update action types to activities easily so that multiple actions on the same components can be shown effectively in the 4D visualization (for example, test and adjust and torquing for steel structures).

2.4 Use of World Wide Web

Access to the WWW is quickly becoming ubiquitous. However, most web sites simply display information in pre-defined ways and do not allow users to reorganize and broadcast the information in new ways. Users and interested parties can interact with the 4D model via the WWW/internet at three levels of interaction with:

- An Internet-Enabled 4D tool: allows parties who are given project access to the 4D information to create, revise, and view 4D models. This gives the team members direct access to the 4D project database via the Internet.
- A Java 3D/4D view: allows parties to create and interactively view 4D models without downloading any software, but does not allow them to update the project database
• **HTML 4D view**: show 4D models to other interested participants as movies (.avi or QuickTime files) or as a series of snapshots of a 4D model to show planned milestones. This set of 4D Viewers does not require most team members to install new software on their computers because a web browser is all that is needed. In contrast, today’s commercial 4D tools require that every viewer of a 4D model install a license of the 4D tool.

### 2.5 Interaction and navigation

Each audience has different interests when viewing a 4D model. In the VR “cave” environment, on the desktop and over the web the user can, on the fly:

- Select views, define new views, or move to pre-defined views
- Change the 3D model (e.g., adjust the laydown areas), schedule (e.g., re-sequence activities), and links between 3D components and activities (e.g., split up an activity into several subactivities and associate them with the corresponding 3D components) in the 4D environment
- Define and edit action-types to communicate the types of construction activities being performed, e.g., define an action-type for laydown areas and assign 'yellow' to that action-type (Fig. 2-1)

**Figure 2**: Snapshots of 4D Model showing the project site at various stages of construction. Highlighted are the various types of construction activities that are communicated with the 4D model.
These innovations make it possible to tune the visualization of 3D and 4D models to the particular needs of the current audience. The fully hierarchical 4D environment enables this functionality.

3. Impact on industry performance

3.1 Impact of interactive 4D model on Paradise Pier project in the pre-bid construction planning phase

3.1.1 Much better and faster consensus on project design and schedule and on potential problem areas

Many more people than typically possible today have reviewed the design and construction schedule. About 400 people from the CEO to the project engineer on an adjacent project, to city planners have viewed and understood the 4D visualization of Paradise Pier. The shared experience in the VR cave and the common visual language allow each group of project stakeholders to experience “what it will be like to ride the roller coaster” and “what the site will look like in a year.” This common experience externalizes many people’s preconceptions of project issues and supports a more objective resolution of potential conflicts. For example, the project team spent several hours trying to resolve some potential problems with the construction of a wave machine, which is located under the pier in the lagoon, across from the roller coaster. The team then went to the VR cave and was able within 10 minutes to resolve and achieve a consensus on how to solve those problems. Instead of trying to defend their ideas, individuals tend to talk about the model and focus on how to improve the design and construction schedule. In short, we found that “a problem discovered together is solved together.”

3.1.2 Much shorter 4D modeling and remodeling time and faster construction planning

It is easy to develop several schedule scenarios and have them checked by many professionals in an environment that ensures a common understanding of the pros and cons of each scenario. With commercial tools, it typically takes several hours or even days to create new 4D models incorporating design and schedule changes. During schedule review sessions, the interactive 4D system allowed the scheduler for the Paradise Pier project to update the schedule and the 4D model simultaneously. This was particularly useful to synchronize concurrent activities on adjacent attractions including the corresponding laydown areas. For example, over a two-week period, the scheduler was able to consider 20 different design and schedule scenarios. He was able to explore the effect of changes in level of detail of the schedule, different placement of laydown areas over time, addition of activities to the 4D model (such as turnover, area development, interior work, test and adjust).

3.1.3 Much more detailed and thorough analysis of a construction schedule in a short time

The construction management team believes that the schedule resulting from the 4D planning process is much better than normally possible in an equivalent time. The team was able to analyze spatial constraints between components and activities and check the
realism of a sequence much more thoroughly than possible today. They were able to propose more complete schedules. Many more people were able to understand the flow of work and provide constructive input, which allowed the project team to consider many more aspects of the schedule. For example, the staging of work for the lagoon involved input from the construction team, environmental engineers, ride vendors (since the rides are located adjacent to the lagoon). Since the lagoon is prime space for laydown, the goal was to stage the work in such a way as to maximize laydown space for ride construction. The planning of this work involved developing various spatial configurations of the stages of lagoon construction as well as spatial configurations of the laydown areas and relating these various spatial configurations to alternative schedule sequences. With the interactive system, the planner could make all of these changes simultaneously, optimizing the laydown and staging areas for the construction of the various attractions in Paradise Pier.

3.1.4 More effective transfer of information and insights gained by the owner’s team to the construction team

WDI construction managers used the 4D model on the Paradise Pier project in pre-bid meetings to illustrate the project’s challenges to the invited GCs. The owner’s project management team was able to answer the GC’s questions very quickly and clearly. For example, it was easy to show the tight site with restricted laydown space and access routes and to make clear the challenges of installing a wave machine in the lagoon next to the roller coaster. Additionally, the GC’s could clearly understand site access constraints and how their access to parts of the site changes over time. The GCs realized that many project risks had been identified and mitigated in the 4D model and asked to use the 4D model to show the project’s scope and challenges to their subcontractors.

The bid results on Paradise Pier and other sections of the park, which were planned with traditional means, provide further evidence of these impacts. The Paradise Pier project has, so far, been the only bid package on the whole theme park that has come in right on target, i.e., the owner’s estimate and the bids were very close.

3.2 Potential impacts on industry

The benefits listed in the previous section have already been realized in the project’s pre-construction stage. We anticipate the following benefits during construction. These benefits should be common to any construction project of comparable size and complexity.

3.2.1 Addressing impacts and developing workarounds caused by late or early delivery of steel sections for the roller coaster

If the on-site and off-site schedules diverge at some point the site management team will be able to assess quickly how a delayed or early shipment will affect the schedule and adjacent work. The 4D model will allow the site team to develop and communicate recovery schedules quickly and to verify that a recovery schedule does not make the situation worse for related work.
3.2.2 Merging schedules from the subs with the GC’s and owner’s schedules to assess the schedules’ compatibility and to identify schedule and space conflicts prior to construction

Today, the work of related subcontractors is typically coordinated through 2D overlays. These overlays allow a project team to identify some spatial conflicts in the design. The construction period can introduce entirely new spatial conflicts that are very difficult to identify with 2D overlays. This is particularly true for today’s aggressive schedules with many concurrent activities. The interactive 4D prototype allows the project team to merge schedules quickly and to visualize them as 4D models. Hence the interactive 4D prototype acts as a tool for 4D overlays.

3.2.3 More productive resource use

The 4D model coordinates not only the spatial aspects of a project, but also the temporal aspects. This will improve fabricators’ ability to fabricate steel just in time for erection without risking delays on site. Inventories of work in progress will be vastly reduced requiring less temporary storage space, less handling and re-handling of materials, and less working capital. It also allows crews to get on site and complete their work quickly and efficiently, reducing the risk of accidents and minimizing rework.

3.2.4 More learning on a project and from project to project

Because each 4D model simulates how a design could be built the project team can learn more quickly and early in the process how to approach the construction phase. Each 4D model documents the design and construction very clearly, which will allow project teams on future projects to understand the approach taken on past projects.

**Figure 3:** Evolution of design and construction tools from abstract, document-based representations to realistic, model-based representations of project information.
4. What comes next?

So far the paper has demonstrated the need to improve design and construction tools and has summarized recent developments in this area at WDI. This section shows how these developments were a logical evolution from today’s commercially available tools and briefly introduces the next step WDI is planning to take. The following sections then detail corresponding technological developments and challenges and business opportunities.

Figure 3 shows how today’s commonly used 2D drawings and schedules in bar chart or CPM format do not relate scope and schedule information explicitly. Commercially available 3D and 4D tools relate scope and schedule information, but do not provide the hierarchical (multi level) representations necessary for project work and do not offer the interaction functionality and portability necessary to allow multiple participants to collaborate on improving a project design and corresponding schedule. As described above, hierarchical and linked 3D and 4D models enable project participants to work at multiple levels of detail and make changes to project information in a visual and interactive environment. As a next step, a shared project model will enable owners, designers, and builders to extend the usefulness of their data through all phases of a project, from blue-sky conception to operations and maintenance and retrofit. The next sections describe some of the essential developments necessary to support such a shared project model and highlight several of the business opportunities and benefits that will arise with the implementation and use of project models.

5. 3D product modeling supports design and construction

CAD tools are often seen as design tools. In our view they should also be seen as construction tools, since a good, detailed 3D CAD model is in essence a complete virtual replica of the real project. As could already be seen from Sections 2 and 3, viewing CAD as a construction tool in addition to a design tool requires entirely new user and system interface functionality. To warrant the development of this functionality it is important, however, to develop the business case for the extended use of 3D and 4D tools.

5.1 3D modeling benefits in design

Participants at a workshop on 3D and 4D modeling in design and construction at WDI and Stanford University in May 1999 identified the following benefits from 3D and 4D modeling for designers:

- Increase and improve information available for early project decision making through pre-visualization or “3D sketching”
- Plan site and space use better
- Enable look and feel through photorealistic rendering
- Reduce design time
- Reduce design effort
- Speed up evaluation of design

• Reduce time needed to model an alternative
• Improve coordination between design disciplines
• Improve evaluation of design (functional sensitivity analysis)
• Share work around the world (model-centric project teams)
• Eliminate design production work (no or fewer construction documents needed)

Designers can control the generation of the information that allows them to reap these benefits. The participants identified several other benefits, such as reduced rework, more productive field crews, less wasted materials (see next section), that can best be accrued through the collaboration of professionals across current organizational and project phase boundaries. Many designers often wonder how to pay for 3D CAD modeling on top of everything else they already have to do. It is noteworthy that many participants mentioned that they would do a design in 3D CAD even if clients were to ask them to deliver 2D drawings. The lesson here is that 3D CAD should not be an extra thing to do, but the new way to document a design. Several design-build firms reported that they were able to eliminate the traditional 2D construction documents because they are now fabricating directly from the 3D model.

5.2 3D modeling benefits in construction

Owners will, of course, not only benefit from the design benefits listed in the previous section. They will also benefit from a more efficient construction period. The participants at the workshop identified the following benefits from 3D and 4D modeling, which accrue mostly during construction:

• Shorten design and construction period
• Increase productivity of crews
• Reduce wasted materials during construction
• Reduce rework
• Create complete set of information from which to plan and build the project
• Improve (verify, check) constructibility
• Verify consideration of site constraints in design and schedule (sight lines, access,…)
• Avoid (minimize, eliminate) interferences on site
• Maximize off-site work (prefabrication)
• Increase schedule reliability
• Verify executability of GC and sub schedules
• Shorten construction period
• Speed up evaluation of schedules
• Increase site safety
• Minimize in-process time in supply chain
• Shorten site layout/surveying time
• Improve site layout accuracy
• Reduce RFIs (Request for Information)
• Improve portability of design
• Improve learning and feedback from project to project
• Improve effectiveness of communication
• Coordinate owner, GC and sub schedules
Many contractors are already building 3D models to accrue these benefits even if the design information is produced in the form of traditional 2D documents (Zabelle and Fischer 1999). It would, of course, be much more efficient if the 3D models were built jointly between designers and builders or if builders could at least start their planning and estimating work with an electronic 3D model. As can be seen from the many benefits in design and construction, the information in 3D models can be leveraged for many purposes, including 4D modeling, which allows joint consideration of temporal and spatial constraints on projects. The construction benefits show that projects could be delivered more efficiently if electronic information were shared between participants in a project phase and across project phases.

6. Importance of information exchange

One way or another, all the participants in a complex major project must exchange data relevant to the completion of the project. Current methods combine a complicated mixture of traditional paper, discipline specific software, and universally portable text and spreadsheet files. This paper has described a new tool to coordinate and manage the process of project delivery, but 3D models will only be helpful to the extent that data can be exchanged easily and accurately between users and software tools. The use of 4D models likewise requires effective exchange of data between the same users and tools. This section discusses several issues and opportunities related to information exchange.

6.1 Information exchange is an enabling technology

Common standards are the acknowledged technique by which data are exchanged between software tools. Because not all software tools use the same data for the same purpose, standards that are intelligent enough to recognize the different uses of the same data and react accordingly are the long-term goal of many standard-setting organizations. For example, information about the geometry of a steel beam might need to be shared between procurement, scheduling, finite element modeling, and detailing software packages. In a perfect world of unlimited computer bandwidth, storage and processing speed, the FE analysis software might be able to get the geometry from the procurement software, perform a complete analysis and forward it to the scheduling software. In today’s world we are a long way from this ideal, and in fact, such a system would be very conservative in the retention of data, for which there would be a penalty in terms of file and database size, not to mention revision coordination requirements.

For this reason it is likely that information exchange will grow in specific domains more easily than in the industry as a whole. Those domains which share a common focus (like steel construction) and can recognize a common hierarchy in data should be able to formulate standards which do not attempt to be “all things to all people” and in so doing can make relatively more progress towards standards than purposefully general tools.

6.2 Be aware of different types of information

Information exchange between stakeholders and specific disciplines on a large project has been identified as a significant concern. As was discussed in the previous section the use of standards is a functional method for achieving this exchange. Although the previous
discussion emphasized the exchange of identical information used in common by different stakeholders, there are also qualitative differences in information, which are a function of the origin and use of the data. These qualitative data types include data from construction, schedule, financial, resource, operational, maintenance, vendor, etc. sources. Each of these information types has its own characteristics such as geometry, physical properties, time sequences, etc., only some of which are identical between stakeholders. The development of data structures to deal with these qualitative data types is a secondary goal of information exchange efforts.

6.3 Structure of information relationships
In addition to the standards and the qualitative data types discussed above, the structure of project data can make an important difference in ease of exchange and utility of the shared information. Relational databases are powerful tools for data that can be stored as character strings or individual files. However, 3D models offer the potential of navigating data for large complex projects in a visual and intuitive manner. The WDI-CIFE tool has the potential for each item in the 3D scene to be linked to a background database which does not depend on naming conventions, even though the naming conventions are one of the first level of data exchange standards typically addressed. This approach to “data navigation” is an important first step in creating relationships between project information. These relationships can be as simple as one-to-one or as complex as many-to-many as are common in large enterprise software database applications.

6.4 Rising importance of company data - beyond construction
The creation of 3D models in the WDI-CIFE project has catalyzed an increased awareness of extending the lifetime of design and construction data. While the 3D model has benefits like the data navigation discussed above, there are other more subtle benefits, which might be explored. For example, the 3D model can be used to confirm a wide variety of operations assumptions, from fire access to emergency evacuation of buildings and attractions. When coupled with emerging tools like autonomously behaving characters, the potential for the re-use of data beyond construction has far reaching implications.

6.5 Benefiting from e-commerce
Web-enabled project management tools and e-commerce applications in construction are rapidly emerging. For e-commerce, business-to-business and auction models are currently the most prevalent e-commerce approaches. E-commerce allows buyers to aggregate demand to demand better terms by offering sellers more volume and more insight into future demand for certain products. E-commerce also allows sellers to


\[\text{http://www.metsite.com or http://www.esteel.com for steel related e-commerce sites, \text{http://www.buildpoint.com for a general e-commerce site for construction, and http://www.partsnet.com for an e-commerce example in the automotive industry.} \]
promote their products and services more widely in an easily accessible form. E-commerce should enable architects, engineers, general subcontractors, subcontractors, construction managers, distributors, and manufacturers to strike deals more quickly because information posted on the web is instantly available to all interested parties. In spite of its name, the world wide web does not necessarily make everything posted on a web site available to everybody. Access to certain information and sites can, of course, be limited to particular companies or people. In any case, the increased speed of transaction and the potentially wider web for demand and supply aggregation should lead to improved procurement terms for project materials and components.

Since many of the expensive items that are procured for facility projects are customized components, the amount of information that needs to be exchanged for a e-commerce transaction in the AEC industry will likely be larger and unique for each case than in other industries. While e-commerce certainly supports the current project delivery processes and information exchange approaches it would be vastly more efficient if the information exchange between specifiers, buyers and suppliers were based on standards. Implementations of CIS/2 will therefore not only enable the sharing of project data between traditional software applications but also enable more efficient e-commerce.

E-commerce will most likely be the default tool for procurement in the near future. Every e-commerce transaction will need to include “how much of what needs to be shipped when and where.” Today, specification, quantity, location, and timing information typically exist in disparate documents. Discrepancies in information status may exist between these documents, and it often takes significant effort to assemble these data items from the various documents. 4D models combine scope and quantity information with temporal and location information and could be ideally suited to leverage e-commerce or be leveraged by e-commerce. The availability of industry standards will likely speed up the realization of benefits from e-commerce services. In the food industry, for example, instill.com is proposing a standard vocabulary to make it more efficient for restaurants and suppliers to engage in e-commerce. If each restaurant and each supplier used slightly different names for the same thing the benefits from e-commerce would not nearly be as great as they would be with a common vocabulary or ontology (standards).

7. Conclusions

7.1 Effects of e-commerce and information modeling on project execution

Lessons from the manufacturing industry indicate that large improvements in the performance of supply chains are possible if the demand and supply forecast windows could be lengthened. This requires improved forecast accuracy which, in turn, can only be achieved by making site assembly processes more reliable. Ultimately it is the construction site that drives the need for information and materials. Studies have shown that inaccurate information is by far the most frequent source of construction problems and rework. Information may be inaccurate because it is out of date or simply inconsistent with related information. Faster information exchange will reduce the amount of information that is out of date and my help AEC professionals spot information
discrepancies. Building 3D and 4D models for a project vastly improves information quality and consistency.

On a recently completed biotech facility in Northern California the 3D model allowed the mechanical, electrical, and piping contractors to work out all the problems in the computer model [Staub et al. 1999]. There was not one field interference during construction for the scope of work modeled in 3D and 4D. Faster distribution of more accurate project information should allow buyers and suppliers to extend their planning horizons.

More certain product and timing information should enable manufacturers to shorten the time required from order to delivery of materials. This, in turn, will enable owners to spend more time exploring alternative design, procurement and construction scenarios and to get the project built in a short time once they decided what they want. We would like to stress, once again, the importance of visual models at the appropriate levels of detail to enable decision makers to understand the proposed design(s) and construction plan(s) fully so that they are comfortable committing to a particular design and corresponding execution strategy.

In summary, e-commerce and electronic project models should enable a concurrent engineering process by helping to improve the definition of design criteria and by supporting the simultaneous involvement of cross-functional teams organized from the beginning of a project.

7.2 Research needed

This section briefly mentions a few important research issues. Note that this is only a partial list.

Abstracting construction concepts and their relationships
We are lacking useful abstractions of construction concepts and their relationships. Without such abstractions, there is no scientific basis for the development of software applications that are general enough to be useful from project to project yet specific enough to automate engineering tasks in the context of a particular project.

Integrating data, workflow, and business modeling
The successful adoption of the technologies described in this paper requires the concurrent consideration of data, workflow, and business issues. Simply figuring out the data modeling issues will not be sufficient for an efficient utilization of the technology. The benefits from these new technologies will likely be far greater if system wide (or at least supply chain wide) adjustments are made to the current workflow models and if new business opportunities are created. Integrating data, workflow, and business modeling is still a research issue.

Accounting for partially complete models
The information models supporting e-commerce, visualization, data exchange, etc. will need to be created over time by all the project participants. Hence, for most of a project these models will only be partially complete. Good, generally accepted methods to handle partially complete models with computers still need to be developed.
Maintaining sets of alternatives

Most owners will likely want to maintain sets of alternatives for as long as possible to study the business issues related to the various alternatives as precisely as possible and to wait to the last possible moment to commit to an alternative. Reducing the time from the final “go” decision to facility utilization will allow owners to use the latest market data in their facility design. Better approaches to maintain sets of alternatives and to evaluate and compare them are needed.

7.3 A possible migration path

The on-going adoption of web-based collaboration tools (for design and project management) will help work out the social issues of collaboration. It will also improve the quality of documents because fewer data re-entries are necessary and the quick and widespread accessibility of documents will allow others to comment on a document quickly. The web-based collaboration will increase the speed of information delivery and improve information quality to some extent. Some firms will then exploit the benefits of project information models, which, as already discussed, will greatly improve the quality of information.

7.4 The opportunity for steel

3D modeling and electronic information exchange benefits will arrive in the steel industry sooner than in the rest of the construction world. The component-based nature of steel structures makes it easier to build 3D and 4D models for steel structures. Intelligent CAD component libraries will make it possible to assemble and change detailed 3D models rapidly. 3D will enable more work to be done off-site, with fewer on-site re-work and fewer workers exposed to hazardous site conditions for shorter periods. If the participants in the steel supply chain work together they might be able to cut significant in-process waiting time out of the steel specification, design, order, detailing, fabrication, and erection schedule. As a result, steel should become a more competitive material.

8. References


