Strategies for Realizing the Benefits of 3D Integrated Modeling of Buildings for the AEC Industry

by

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ABSTRACT: We explore the reasons why advanced information technology applications have not been adopted by the AEC industry. Within the industry, however, some sectors have made significant moves toward adoption of advanced IT. By examining these areas of success, we propose a framework for the incremental conversion of the AEC industry to fully incorporate advanced IT.

KEYWORDS: knowledge-based applications, building models, information technology innovation, construction automation.

INTRODUCTION

The business models in each industrial domain provide different contexts for information technology innovation. Here, we focus on the building design and construction part of the Architecture, Engineering and Construction (AEC) industry. The building industry custom designs, engineers and constructs projects on varied construction sites. The components are either procured off-the-shelf, made-to-order or fabricated on-site. A variety of design and engineering specialists collaborate on a project, each bringing specific expertise and employing specialized software. In the US, the value of all construction work is 845 billion dollars (Economic Census, 2000), making it one of the largest industries in the nation.

Digital knowledge-based models of buildings have been advocated as the base representation for work in the construction industry for over twenty-five years (Eastman, 1999, Chapter 2). Here, we use "knowledge-based building models" as a shorthand reference for the integrated use of several technologies: (1) multiple heterogeneous computer applications allowing three dimensional representation, design, analysis and management of the systems and components that make up the proposed building, all incorporating significant domain knowledge, (2) the backend integration of workflow using one or more building product models; (3) associated Internet links to material supplies, delivery planning, operational controls and other such services needed for the building's procurement, fabrication and operation, and (4) expanded automation of all aspects of work, including design automation, automation of built-to-order components, and automation of on-site fabrication. We consider these technologies together to define current best practice use of advanced Information Technology (IT).

Although serious building model efforts have been carried on for ten years (e.g., CIMsteel – CIS/2 2001), national and international efforts in moving the AEC industries toward the use of advanced information technologies has shown little progress. Virtually all buildings designed today still rely on two-dimensional (2D) drawings as their principal representation. This is not to say that there has been no movement; rather, the particular conditions in the construction industry have not allowed it to proceed as fast as other product-oriented domains, such as manufacturing, electronics, aerospace and other industrial areas. It has also not even progressed as fast as art or entertainment industries, such as television, motion pictures, or music production.

This paper reviews why there has been so little movement and outlines a strategy for the incremental conversion of the AEC industry to the use of advanced IT applications. We build

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upon two examples, involving the structural steel and precast concrete sectors of the building industry. The issues and strategy may be useful for other industries, beyond AEC.

WHY THE CONSTRUCTION INDUSTRY HAS LAGGED

The commonly held assumption why building design, engineering and construction have not utilized knowledge-based building models is due to *fragmentation*. The construction industry has traditionally been craftsman-oriented, with many small participants. There are 656,000 construction-related firms in the United States alone. Of these, over 62 percent have fewer than 4 employees, while less than 1 percent have more than 100 (ICAF, 2000). Each firm carries out only a few steps of an increasingly complex process. No one organization has as much as five percent of construction dollars. These many organizations come together to execute construction projects in a very competitive setting, with each project typically involving a change of participants.

Within this fragmented setting, 2D architectural and engineering drawings have evolved over hundreds of years as the basic representation and physical artifact used by all construction industry participants. Business practices of all construction-related firms, financial and insurance institutions, standards and codes and reference materials are organized around 2D drawings and associated formatting conventions. However, it is generally recognized that it is not possible to verify the consistency of 2D drawings or to derive all the needed geometry for design and production automation. These are only possible with 3D modeling.

The very broad embedding of 2D drawings, combined with the fragmentation of the participants, is assumed to result in the situation where no single participant and no single project have enough economic impact to justify the investment – in technology purchases, in learning and in changing business practices – to convert to knowledge-based building models. No organization has the power to force conversion of the others (seemingly, not even the US government).

The potential economic benefits of knowledge-based building models are varied in nature: some occur in isolated construction processes (e.g. CNC production of made-to-order components), while others depend on improving the process as a whole (e.g. reduction of rework resulting from errors). The motivations cited in most research have emphasized long-term system benefits without identifying measurable short-term payoffs (Moreau and Back 2000, Griffis and Sturts 2000). Because no one party to the building process seems to benefit, but the process as a whole improves, it is argued that the owners and clients of buildings are the beneficiaries and should financially support this IT transition. However, no effective business model has been implemented based on this premise.

We accept these conditions, in general, and conclude that *IT technology innovation must evolve based on local benefits*, not industry-wide ones.

SECTOR-LEVEL ADOPTION OF ADVANCED IT

Given the complex conditions cited above, it is apparent why current strategies have not moved the construction industry toward knowledge-based building models; there is no one business entity or financial incentive large enough to move the industry as a whole. (Griffis et al. 1995) and production (FIATECH 2001) indicates that the potential exists for significant process improvements in construction itself, and that these process improvements require IT support.

Despite this state of affairs, certain sectors of the construction industry have made strong steps to implement knowledge-based building models within their sector. We review two: structural steel and precast concrete.

Structural Steel

Structural steel fabrication and erection is a significant sector within the construction industry, with 8.5 billion dollars of production (Economic Census, 2001) and half a million workers (US Dept. of Labor 1999). Steel is used in a wide range of structures, including buildings, industrial facilities and process plants. Engineering companies, steel fabricators and structural engineers, as well as architects, are involved in aspects of the building structural steel sector. The processes in this sector include designing, detail engineering, prefabricating of pieces, shipping and erection of the pieces on the construction site.

Steel design and fabrication involves a significant amount of engineering that can benefit from knowledge-based design automation. Industry experts suggest that steel fabrication, which is dependent on engineering design, increases the value of raw steel sections by a factor of 2.5. The sector is supported by more than 30 commercial computer applications, providing computational services for design, analysis, detailing, bills of material and material tracking, scheduling and fabrication management (ERP) programs. A significant number of these applications are based on 3D modeling of the structure and pieces. The sector is also supported by a variety of production automation equipment -- for cutting, drilling, welding and other operations. Steel fabricators take different roles within the construction process. While the most common is as a sub-contractor, they sometimes serve as general contractor; in some cases, steel fabricators have embraced design-build and offer package services.

In the mid-1990s, the American Institute of Steel Construction (AISC), the main industry sector association, adopted the Structural Design Neutral File (SDNF) as a way to exchange data between the various applications. When limitations in SDNF were found that restricted its use, the AISC initiated an Electronic Data Interface (EDI) initiative to select a more robust and complete data representation for integration and exchange of structural steel data. In late 1999, they adopted CIMsteel Integration Standard, Version Two (CIS/2), developed at Leeds University, as part of a European Union automation effort. Major efforts have been directed toward its deployment, and at this time, ten applications have developed working CIS/2 interfaces. Several building projects have now been built using CIS/2 and it is coming into wide use within this industry sector (CIS/2 2001).

Precast Concrete

The precast concrete sector -- prefabricating concrete products off-site, often prestressed, then shipping and erecting them – is a fairly young sector of the construction industry. Compared to structural steel, the precast concrete sector in the US is smaller, with 2.6 billion dollars of annual work (Economic Census, 2001- non-building products omitted), about 200,000 employees. Industry experts suggest that the fabricated value of precast products is on the order of 6.0 times the raw material costs, again, with a large engineering component. In Europe, this industry sector is much larger; its share is above 15% while in the US, it deals with 1.2% of construction (Sacks et al. 2002). Like structural steel, careful design and coordination with the rest of the building design is required for the prefabricated pieces to fit correctly when erected. While the level of automation in the US is generally low, it is more advanced in Europe, providing both mature technology to draw upon and examples of its use. Precast concrete fabricators assume varying roles within the construction process: while the most common is as a sub-contractor, a significant number of precast fabricators provide design-build package services for specific structures, such as parking garages.

In contrast to steel, the precast concrete industry sector has been supported by only a small number of commercial software applications, with small sales volumes. Many of these have been custom-programmed and paid for by individual precast producers. Some software has been funded by industry associations, primarily the Precast Concrete Institute. A significant percentage of precast fabricators have implemented Enterprise Resource Planning (ERP) systems.

In 2000, the North American precast industry initiated an information technology initiative (see http:// usa.arch.gatech.edu/pci/), using a limited liability corporation called the Precast Concrete Software Consortium (PCSC). The first step of the PCSC was to undertake careful process modeling by the member companies, to gain understanding of their current workflow and identify opportunities for IT (Eastman et al. 2002). They then developed a plan that included specification for design and engineering software of precast concrete building assemblies and also individual pieces (Eastman et al. 2001) and for the development of a precast concrete building model. The software specification defines a knowledge-based CAD application for the precast concrete industry. The specification was completed in December

2001 and distributed to twenty-six software organizations; twelve proposals were submitted. Today, they are negotiating with two candidate companies to develop and implement software. Definition of the precast concrete building model was begun in the Spring of 2002.

It is clear that the internal conditions within these two sectors of the building industry were appropriate to make significant investments to develop and implement knowledge-based building models, as we have defined that term. The benefits were not industry-based, but rather for their own sector and companies. The authors propose that given these initiatives in IT and their different situations, it may be possible to generalize and posit a framework for IT development that lays out the necessary conditions for IT innovation. If such a framework was developed, it would allow us to identify necessary conditions for particular types of IT innovation to be made, and to recognize whether an industry sector was "ready" (or not) for various innovations leading to knowledge-rich building models.

Below, we propose such a framework of technology innovation within a complexly structured industry, focused on IT innovation in construction.

A FRAMEWORK FOR IT INNOVATION IN THE CONSTRUCTION INDUSTRY

The adoption of knowledge-based building models by companies in the construction industry is obviously dependent on many factors. We have identified seven conditions, organized hierarchically:

Pre-conditions; only if these conditions exist, or are perceived to exist by industry leaders, will there be motivation to take risks and expend intellectual development effort to undertake industry sector change:

(1) an economic situation with a significant value-added component to the sector's activities, allowing capital and knowledge-based investments;

(2) perceived benefits from technology innovation, in possible gains in market share, in capturing profits of an outside but closely related sector, or other business incentives;

Leveraging conditions; these conditions provide the use benefits of knowledge-based building model technology:

(3) the availability of automation technologies that require rich digital project data; the automation may be at the production level, supporting computer controlled machining, welding, concrete mixing, conveyors, finishing, etc.; it may be at the erection planning or erection level; it may be at the analysis and simulation level;

(4) computer integration in the internal business environment, which would benefit from integrating project level automation with enterprise level data management, for scheduling, procurement, manpower planning, etc. Many of the capabilities are provided by ERP systems;

(5) computer integration of aspects of the external business environment; this includes building code checking, web-based bidding for services, web-based procurement, web-based project management or other business activities with outside organizations;

Information generation conditions; knowledge-based data throughout the industry sector must be generated by specific applications:

(6) the availability of knowledge-based 3D modeling CAD software, capable of providing the rich digital data needed to support design or production automation within that industry sector; development of such software requires embedding much of the codified engineering knowledge in that sector into the CAD software, automating conventional design practices; data-rich CAD also provides the detailed engineering data used for production, purchasing, scheduling and other activities;

Information integration and exchange; the final step, in this view, allows the knowledge-based data to be fully utilized throughout the industry sector, for automation, enterprise integration and web-based e-commerce:

(7) development of a product data model for the industry sector, that supports the integration of the above aspects of the business with enterprise and web-based applications.

We consider these conditions to define a cascade or waterfall set of conditions, where previous conditions must be met before others below can be successfully implemented. These conditions are being met in the structural steel industry, and are rapidly developing in the precast concrete industry.

CURRENT EFFORTS TOWARD IT INNOVATION IN THE AEC INDUSTRY

Most of the conditions outlined above have not been met in the architectural or general contracting sectors. Yet, the majority of research in the building construction product-modeling arena has focused on integration at the front-end architectural design part of the process, because these activities are the primary information generators. The current major effort in developing a knowledge-based building model is centered around the International Alliance for Interoperability (IAI) and its Industry Foundation Class (IFC) building model (IFC 2001). In the IAI, a wide range of construction industry organizations have come together to fund the development of the IFCs.

However, architects and engineers have been expected to make equally significant investments in adapting their business practices to new software tools required of the IFC integration technology. Effective implementation of large IT systems requires not only vision and investment, but also significant process changes, which imply organizational restructuring (Egan 1998). While design activities have a large value-added component, architects and engineers receive a small and relatively fixed percentage of the construction dollar. No effective business plan has been implemented to pay for the additional work that populating a building model would require. Also, personnel issues and training often stand at the forefront of such restructuring.

Currently, only a few architectural or building design software applications exist that claim to be able to fully populate a building model. No set of applications, as of 2001, was able to support all the design detailing typically involved in architectural practice. Thus the software needed to take advantage of a building model has been lacking.

On the software side, the large software companies whose products are widely used in the AEC industry stand to reap relatively small and uncertain benefits from developing new generations of software technology. Such changes may even result in their losing market share when new selection criteria and lack of track records in the new functionality open the market to new competitors. On the other side, small software companies that are naturally interested in displacing the established ones, do not have the financial backing needed to educate designers to new technologies and new ways of doing design.

Because there have been few serious efforts at deployment, many technical problems have not been resolved (Amor and Faraj 2001, Eastman and Augenbroe 1998). Among the issues needing further work are: integrating applications and data exchange with productive workflows, system architectures to support integrated data models, and data management and integrity issues where many organizations and individuals contribute to a building project, with various levels of involvement and over differing segments of a project life-span. Hurdles also exist in software able to deal with the datasets associated with large, complex production-oriented 3D models. Even medium sized projects are likely to require models with on the order of a half a million objects. These issues are among those that have stifled taking advantage of recent developments regarding web-based project coordination.

While there are significant analysis and simulation applications that could be integrated, their benefits have not been viewed as significant by architectural practitioners (as evidenced by current investment). Benefits from integration with enterprise-level computer systems in architectural firms appears not to be significant. One under-developed potential benefit of knowledge-based building modeling for architects is for design automation support of design development and contract drawing preparation.

Similarly, contractor services have not been computerized beyond project estimating and billing, often because of the claim that none of their subcontractors are ready. Again, strong knowledge-based CAD systems have not been available for either industry sector.

However, the framework above suggests that different sectors of the downstream building production process, certainly including precast concrete, structural steel, but also possibly curtainwall and window wall fabricators, elevator and vertical circulation systems, HVAC systems, and others, may have better business reasons to implement advanced IT. If this happens, then the context for general contractors will change, leading to opportunities for them also to adopt advanced IT.

SUMMARY

We have developed a simple framework based on the above seven issues. The framework suggests a sequence of undertakings within each AEC business sector, based on the current situation of that sector. It can be used to identify, for any AEC industry segment, the economically beneficial IT development steps and the potential benefits of those changes. It avoids predicating computer integration on any single design, construction or IT technology, in favor of a systems approach, using contextually based implementation criteria.

We are using this model to evaluate AEC industry business sectors, with two goals: measuring their potential to derive benefit from knowledge-based building modeling; and proposing incremental strategies for achieving the benefits of advanced IT, with each step providing distinct payoffs. Assuming that additional industry sectors will follow the lead of the steel and precast concrete sectors in incorporating 3D modeling in their business practice, multiple critical masses may be reached, leading larger segments of the construction industry to move to integrated IT. These may percolate through the whole AEC industry, which will eventually make the transition to integrated 3D modeling.

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