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This article was originally presented at the:

5e Conférence spécialisée sur le génie de la construction de la Société canadienne de génie civil / 5th Construction Specialty Conference of the Canadian Society for Civil Engineering

Moncton, Nouveau-Brunswick, Canada

4-7 juin 2003 / June 4-7, 2003

https://csce.ca/en/publications/past-conferences/

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A CONCEPTUAL FRAMEWORK FOR REPRESENTING PROJECT MODEL INTERFACES

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ABSTRACT: Much of the current research and development in the area of information technology for architecture, engineering and construction is in the area of model-based tools and interoperability (also known as building information models, virtual design and construction, and Industry Foundation Classes). Within this broad area, practical solutions are beginning to emerge, yet many pragmatic problems remain in applying these technologies to the realities of building design and construction projects. This paper adopts the view that, at their core, model-based technologies provide the right solution for the next generation of construction information technology, but that much work is required to adapt these core technologies to many aspects of the practical environment found in construction projects. That is, the interfaces must be further developed between core model-based technologies and the design-construction environment. More specifically, this paper discusses the following types of interfaces: 1) interfaces between the models and model users (including individual and group model creators and consumers); 2) interfaces between the different discipline-specific models; 3) interfaces between the models and the actual construction site (including both data collection into the model and uses of the model for field applications); and 4) interfaces between the models and the project management process.

1. INTRODUCTION

Construction is characterized by complex and unique projects that are constructed in highly uncertain environments under intense schedule constraints. To meet these challenges, current project management practice typically divides design and construction processes into individual work packages that are assigned to different specialists who execute their tasks during the different phases of the project delivery process. This fragmentation has heightened the need for knowledge and information transfer between the different disciplines in a single phase of a project (e.g., different design engineers) and in different phases of a project (e.g., from design to construction). Although most project information is generated electronically, current methods of conveying information and knowledge in this multi-disciplinary environment are error-prone and inefficient, resulting in incomplete and contradictory information that is subject to multiple interpretations. The lack of meaningful information and knowledge transfer in the fragmented project delivery process has led to local suboptimization as each specialty group seeks to optimize their solution without thoroughly understanding or considering the effectiveness of the overall process made up of the combined tasks.

Emerging information technologies (IT) for the architecture, engineering, and construction industry (AEC) are addressing many of the problems found in the current process. Product and process modeling efforts and developments in data and transaction standards now support the sharing of information models between disparate systems. Automatic data collection technologies are improving and starting to gain use in the construction industry, and large scale displays to view information models are becoming economical. These advancements greatly improve information sharing and data reuse. They do not, however, support many of the interactions required for the multi-disciplinary design and construction environment. Specifically, they are limited by weak interfaces between the people creating and using the models, the information models themselves, the construction site, and the project management process. Consequently, project participants are not able to fully leverage their knowledge and information to identify the optimal design and construction solution.

This paper describes a conceptual framework for describing emerging IT trends in the context of the multi-disicplinary, multi-phase, and multi-objective design and construction environment. It focuses on building prototype models of the project and providing interfaces between the models, model users, and construction site to capitalize on the benefits of emerging IT. In this concept, design and management tasks work towards the creation of models, coordinate and refine the models as different alternatives are considered and issues resolved, and use the models to organize and manage the on-site production process. We identify the research needed to provide tools that support such multi-disciplinary interactions and we consider how the project management process should be set up to fully leverage these tools. This paper fits within the conference theme of “Building Our Civilization” by describing the interfaces required to leverage emerging information technology in multi-disciplinary contexts.

2. PRACTICAL MOTIVATION

Vast amounts of information are generated by a multitude of disciplines throughout the project delivery process. This information is generated in a variety of formats (e.g., 2D/3D CAD views, spreadsheets, text, and timelines) by a variety of disciplines (e.g., architects, engineers, contractors, and owners) using a variety of discipline-specific tools (e.g., AutoCAD, Primavera, and Excel) to convey different types of discipline-specific knowledge (e.g., specifications, technical reports, and plans). Most design and construction professionals rely on and exchange paper-based views of this project-specific information and discipline-specific knowledge. For example, consider the two project scenarios shown in Figure 1:

(a) *Now that the concrete for the footings is in place, the rebar foreman focuses his attention on placing rebar for the slab. He wonders: Will the rebar arrive in time? Do I have enough labor to complete the rebar placement on schedule? Has my request for information (RFI) related to the design detail for the slab penetrations been answered? He refers to the paper-based set of design drawings and specifications found on the site (Figure 1a). He then goes to the job-site trailer to retrieve other relevant information, such as the construction schedule, procurement matrix, and RFI and submittal logs. He finds some relevant documents and manually relates the information in his head to assess current project conditions. At the end of the day, most of his questions remain unanswered.*

(b) *A project manager convenes the weekly construction meeting. The construction schedule hangs from the wall of the conference room and construction drawings are available on the table. Each meeting participant brings other relevant documents, such as cost estimates and contracts. The first item on the meeting agenda is “Confirm Schedule Status.” The project manager asks various questions: Are we on schedule? What if the slab concrete activity is delayed? What would be the cost impact of a schedule delay? Are we meeting the contractual milestones? What if the equipment arrives late? Throughout the meeting, many issues are identified and the participants search through their documents and scan the schedule on the wall to assess the possible impact of different project scenarios. Several potential problems are identified and discussed in this meeting but none are resolved.*

(a) Construction worker and on-site project information.

(b) Project team interacting with different project information during a meeting (photo from Liston et al. 2000a).

Figure 1: Two scenarios that show the different types of project participants and the different interactions they have with project information.

These scenarios demonstrate that project participants consider a wide variety of information when assessing project conditions and making project decisions. These scenarios also demonstrate that the current methods of conveying information and knowledge limit *the utility of project information* in the multi-disciplinary design and construction environment, which has the following implications:

- *Inaccurate information:* The rebar foreman noticed an error in the slab penetration detail that went undetected throughout the design review process.
- *Inconsistent information:* Cost reports and schedules reflect inconsistencies in construction progress.
- *Lack of integration:* The project participants had to identify, coordinate, and relate the various project information manually to answer any given question.
- *Lack of interactivity:* The rebar foreman and the meeting participants had to search for relevant information on their own to answer critical questions.
- *Limited "what-if" analysis:* The meeting participants were unable to explore the impact of alternative construction sequences during the meeting.

The overall efficiency of the project delivery process is significantly affected by the limitations of the current process, and often results in productivity losses, rework, and ultimately, cost overruns and schedule delays. The next section describes emerging IT that addresses some of the limitations of the current process.

3. TECHNOLOGICAL MOTIVATION

IT for AEC is the focus of much active research and development, and one of the most dominant themes is model-based systems. In one sense, any project information can be said to describe some aspect of an AEC project, and therefore to represent or abstract certain aspects of the physical construction project; thus the information forms a type of model of the project. However, current R&D is focused on a more specific form of information model, one in which various elements of the physical project are represented explicitly as software objects, with information and behaviour based on the type of element. Several names have been used for these project information models: semantic models, building information models, virtual building models, n-Dimensional models, etc.

Model-based technologies can be divided into two related categories: model-based tools and model-based interoperability. Model-based tools are software applications that use project models to provide richer and more powerful support for design and construction tasks, such as the following examples:

- *Object-based CAD systems*, for example, Autodesk's REVIT or Architectural Desktop products, which construct models of the 3-dimensionsal geometry as well as non-graphical information about a building and its physical components (products).
- *3D visualization and virtual reality,* which allow designers and users to virtually walk-through and experience buildings and spaces while they are still design concepts.
- *Parametric estimating systems,* which map information about the elements of a building project to quantity and cost information.
- *4-dimensional CAD,* which combines 3D geometry with a time dimension to plan, model, and visualize construction sequencing decisions.

Model-based interoperability addresses the problem of information sharing among the many computer tools used throughout the lifecycle of an AEC project. In order to allow information to flow freely between different software, there must be some form of standard language or data structure that is common to all applications. This standard data structure again takes the form of semantic object-oriented information models of AEC projects. Significant progress has been made in developing these standard data models, and numerous commercial software systems (e.g., CAD, various forms of engineering analysis, cost estimating, etc.) are now capable of importing and exporting these standard data model files (as discussed later in this paper).

Model-based technologies have lead to very powerful and promising software for AEC projects. However, very little of this model-based technology is used in common practice. In particular, the long-term goal of a collection of powerful model-based applications that can share information seamlessly through standard data models appears to suffer from many practical challenges. For example, model-based applications and interoperability rely on each other: the applications require the interoperability in order to assemble the large amounts of data they work with, while the interoperability relies on the model-based applications as the producers and consumers of data. Thus, neither of these technologies can be applied unless there is a fairly complete network of project participants that all share this type of advanced software.

The potential advantages of model-based approaches are significant and we believe that these technologies will be critical to future generations of AEC software. However, we also believe that to date, the development of these technologies has remained largely "in the test tube"; they have received only minimal exposure to full scale implementations and many of the difficulties in applying these technologies to the complexities and practical challenges of real construction projects have yet to be addressed. We conceptualize this situation as one in which the core model-based technologies are reaching a level of maturity, but many of the critical ***interfaces*** between these models and their target project environments require much additional work. The next section discusses some of these key interfaces and their central research issues.

4. INFORMATION MODEL INTERFACES

To fully realize the benefits of computer-integrated project models, we believe more research is needed to understand the interfaces between the models and the rest of the design and construction environment. Figure 3 graphically communicates the different interfaces that are the focus of this paper:

(1) Interfaces between the models and model users including individual and group model users and model creators,
(2) Interfaces between the different discipline-specific models,
(3) Interfaces between the models and the actual site including both data collection into the model and uses of the model for field applications,
(4) Interfaces between the models and the project management process, and
(5) Interfaces between other types of project information or processes that we have not yet identified or that have not yet emerged.

The next sections describe each of the four interfaces in detail, related research, and the additional research needed to support them.

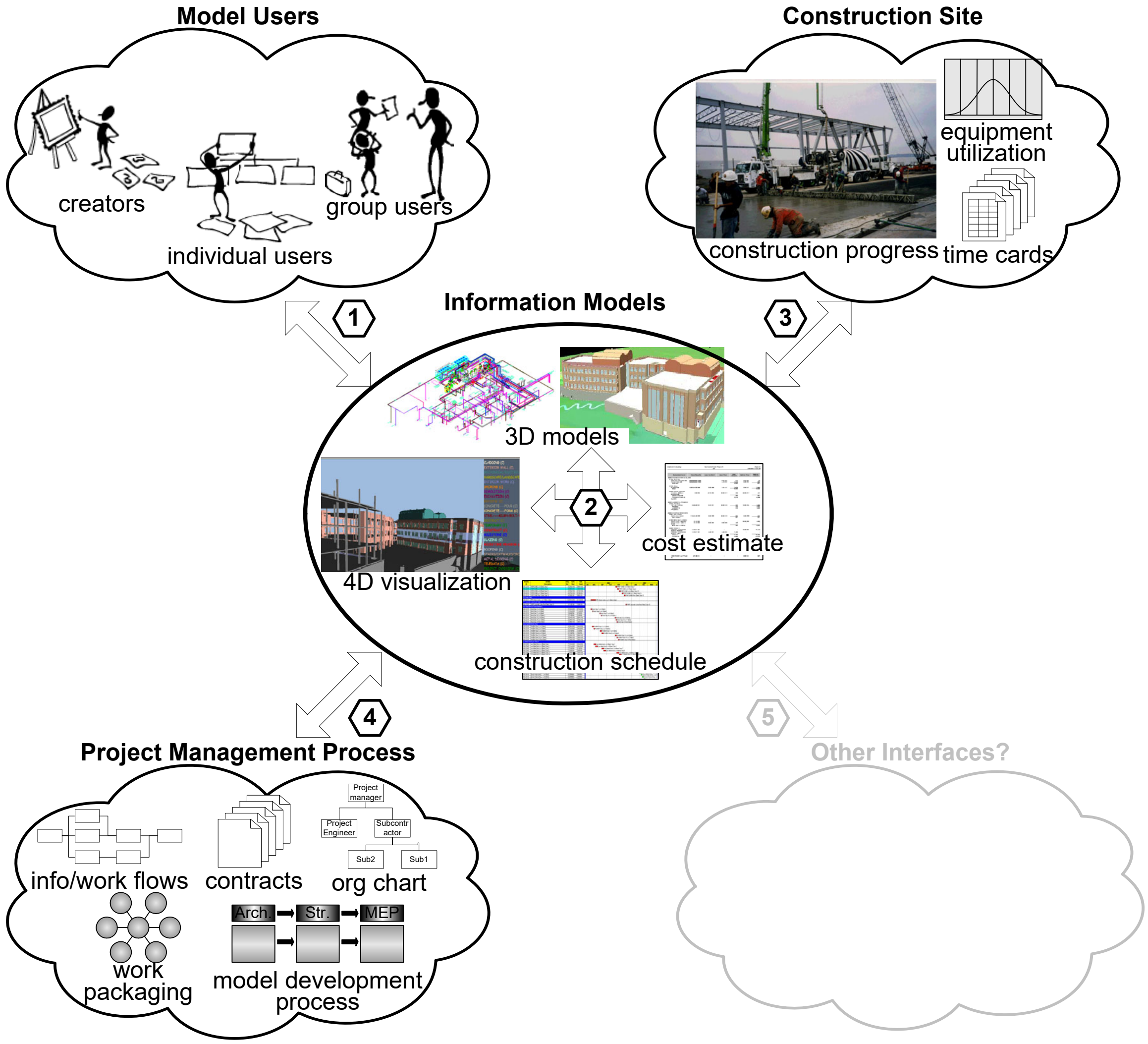

Figure 3: A conceptual framework for describing emerging IT trends that represents interfaces between model users, information models, the construction site, and the project management process.

4.1 Interfaces Between Models and Model Users

The two project scenarios demonstrated that different types of model-users perform different types of interactions with the different project models and require different types of model views. Liston et al. (2000a) observed project meetings and found that project teams today spend the majority of their time describing, explaining and evaluating project information (40%, 20% and 30% respectively) and very little time performing the critical predictive tasks (10%) that lead to better decisions. They also found that current 4D (3D + time) workspaces do not improve the project teams' abilities to perform predictive tasks, although they improve the distribution of time spent explaining, describing, and evaluating information. They predict that improvements in visualization tools and techniques will enable project teams to spend significantly more time on predictive tasks (as much as 50%) and less time having to describe, explain, and evaluate information. To accomplish this, additional research is needed to understand how users interact with emerging integrated information models and how information should be displayed to improve the efficiency with which this information is communicated.

<u>User Interactions</u>
Project participants interact with the project information in different ways. Research is needed to formalize the different types of user interactions that are performed by individual users (e.g., the rebar foreman),

user groups (e.g., the team in the project meeting), and model creators (e.g., architects, engineers, and contractors) when interacting with different project information during the different phases of the project life cycle. User interactions specify the user(s), the purpose of the interaction, the visualization technique, and the view required for that user. Liston et al. (2001) investigated multi-disciplinary, multi-device interactions with multi-format information and found that the combination of interactive information access, data sharing, and simple visualization techniques help project participants to focus on specific information relevant for a particular issue. Additional research is needed to understand the requirements of visualization tools and how to match user interactions with visualization techniques and information views for different types of users.

Visualization Techniques

Project participants today often have to search through vast amounts of information to find the relevant information required to answer a particular question. Electronically integrated environments will improve project participants' abilities to find related information but they will not help them to focus on the specific piece of information that is critical. Liston et al. (2000b) investigated the usefulness of two visualization techniques – highlight and overlay – for graphically communicating the relationships between information. They developed a prototype that highlights information by emphasizing related sets of information within a view and across multiple views, and overlays one set of information onto another set of information that results in one merged view. They identify fits between visualization techniques and decision-making tasks for project teams. Additional research is needed to identify visualization techniques that explicitly consider the different types of users interacting with the information (e.g., individuals vs. groups and designers vs. builders), the different formats of project information (e.g. tables, graphs, and diagrams), and the different types of project information (e.g., design, cost, and schedule information).

User-specific View Generation

Most project information today is generated for a domain-specific purpose using discipline-specific tools. Consequently, current views of project information are often inappropriate for sharing and utilization in multi-disciplinary contexts. User-specific view generation requires different types of information translation. Users may require information filtering (e.g., filtering the construction schedule to show certain types of tasks), information synthesis (e.g., synthesizing a cost report), information conversion (e.g., converting a tabular view, such as a cost estimate, into a graphical view), or information generation (e.g., creating new 3D/4D models to represent alternative construction workflow scenarios). Several research efforts are addressing this issue in specific application areas. For example, Haymaker et al. (2002) formalize mechanisms to construct semantic views from building product models by inferring the existence of spatial relationships between building components and instantiating them in building product models. However, most of this research has focused on developing the mechanisms that create a particular view rather than identifying the most suitable view. Additional research is needed to test the appropriateness of the views created and to generate other user-specific views from project information that improve the efficiency of information communication.

4.2 Interfaces Between Discipline-specific Models

The two project scenarios demonstrated the need for relating the different discipline-specific models (e.g., relating the design, procurement schedule, and RFI's to help the rebar foreman find relevant information), sharing information between the different models (e.g., sharing schedule status information between cost and schedule models to eliminate inconsistencies), and analyzing the validity of information and the impact of information changes (e.g., analyzing the impact of schedule changes on construction cost to support what-if analysis in the project meeting). To provide this type of functionality, additional research is needed to understand how and what information is exchanged between the different systems, and how to represent and analyze the different discipline-specific models in a multi-disciplinary context.

Exchanging Information:

Sharing information between disparate systems requires the development and use of standard information structures and transaction standards. Studies have shown that the removal of information re-keying would enable savings of 16% of construction costs (as reported by Jeffry Wix and Thomas Liebich at an IAI Meeting in April, 1999). The International Alliance for Interoperability (IAI 2002) has taken up the challenge of developing data standards for the AEC industry in the form of Industry Foundation Classes (IFC). The IFC's have reached a level of maturity and stability to provide basic interoperability in a number of core project areas, such as architectural design, cost estimating, and code checking analysis (BLIS 2002). However, the IFC's are far from offering a complete solution and require additional development and extension as described by Froese (2003), which includes the following:

- The scope of the IFC's should be extended beyond buildings to include a broad range of civil infrastructure, such as roads and bridges, and the building surroundings, such as landscaping and municipal services. Some of the challenges in developing these extensions include developing the detailed product models, developing representation schemes for linear-based projects (e.g., roads) and area-based projects (e.g., earthworks) rather than the component-based approach underlying the IFC building product model, and managing the growth of the overall IFC model. Several research groups are pursuing some of these extensions.
- Sharing information between disparate systems requires a series of data exchanges or "transactions" between computer applications or other software components. While the IFC's standardize the content of an information exchange transaction, they do not standardize the context of the transaction, including the specific data exchanged in the transaction, the purpose of the transaction, constraints on the transaction, and obligations of the participants in the transaction. We are pursuing research related to the standardization of data exchange protocols to support IFC-based transactions in distributed and heterogeneous environments (Halfawy et al. 2002: Pouria et al. 2002).

<u>Analyzing Information</u>

Studies have shown that better modeling and analysis prior to construction, and greater integration within the industry could eliminate many of the inefficiencies found in the current process (Howard et al. 1989, Nylen 1999). The IFC's take an important step in providing standards for representing design and construction models and identifying the necessary relationships between the models to support information integration. They do not, however, represent the context for when and how information should be related, which is critical for assessing the validity of a model and its relationship to the overall project model. Project participants need analysis tools that recognize inconsistencies between models, identify the impact of model changes on related models, and predict the impact of alternative design and construction scenarios (what-if scenarios). To provide this type of functionality, additional research is needed to understand domain-specific knowledge and the relationships between domain-specific models. For example, Akbas et al. (2001) formalize domain knowledge about construction zone generation and developed a tool that leverages this knowledge to automatically generate construction zones from 3D CAD models. Additional research is needed to understand the domain knowledge behind the information models and the relationships between the different information models to fully leverage these models in a multi-disciplinary environment.

4.3 Interfaces Between Information Models and Site

Ideally, information models of a project would drive the construction process and the status of construction would drive the development and maintenance of information models. This concept is consistent with the lean construction concept of pull-driven scheduling which advocates that real-time feedback regarding the status of progress on site be used to re-sequence process steps opportunistically (Tommelein 1998). To provide this type of functionality, research is needed to better understand how information models can be used to drive the construction process and how the construction site can link back to the information models in the context of the dynamic and multi-disciplinary construction environment.

<u>Using Information Models to Drive the Construction Process</u>

Information models are being used in many different applications to improve on-site management and execution. Several projects have used 4D CAD models to help project teams in a variety of on-site construction contexts, that includes evaluating construction sequences, coordinating subcontractors, visualizing workflow, etc. However, most evidence to date on the use of information models for on-site construction is anecdotal and specific to a small subset of the entire project model. Information models have received limited exposure to full-scale on-site implementations and the challenges associated with the dynamic, complex, and uncertain construction site. Additional research and testing is needed to better understand the different types of project information and the different types of applications of these models for on-site construction.

Linking data collection technologies to information models

Automatic identification and data collection (AIDC) technologies are emerging and starting to gain use in the construction industry. The following highlights some of these AIDC technologies based on Construction Industry Institute (2003) findings:

- *Bar Codes:* an automatic identification technology that allows data to be collected quickly and transmitted to a computer. In construction, bar codes are primarily used for timely identification and tracking of construction materials.
- *Radio Frequency Identification (RFID):* an automatic identification technology, similar to bar code technology, with positive identification and automatic data transfer between a tagged object and a reader. It is able to both read and write information to and from the tags. With Radio Frequency Identification (RFID) technology, no line of sight or direct contact is required between the reader and the tag because RFID does not rely on optics (as with bar codes), making it ideal for dirty, oily, wet or harsh environments. Similar to bar codes, RFID technologies are primarily used for timely identification and tracking of construction materials.
- *Light radar (LIDAR):* a technology used to track the state of components at construction sites that are of an amorphous nature, such as earthwork, that is currently done by surveying. LIDAR performs real-time construction progress measurements and earthwork calculations of the construction site. The gathering of data is non-intrusive and will not impede the construction progress.
- *3D Laser Scanning:* a scanning technology that obtains as-built geometry information for large structures and sites by collecting "point clouds" of 3D measurements. As 3D measurements are collected and points accumulate, detailed graphic images quickly emerge. You can then export the 2D or 3D models to popular CAD and rendering software.

Although these technologies are being used efficiently in their particular application areas, they have had very little exposure to emerging model-based technologies and information models. We don't yet understand how the data collected on-site should be linked into emerging information models. For example, how should the 3D models abstracted from 3D laser scanning technologies relate to the 3D design models and 4D process models? Additional research is needed to understand how to integrate these different types of emerging technologies and how to leverage them to optimize on-site construction management.

4.4 Interfaces Between Models and Project Management Process

As discussed above, there are many ways in which the available model-based technologies are not an ideal fit with current AEC practice. In part, this may be because of the relatively minor role that shared information resources and integrated processes play in current practice. In addition to trying to fit the IT solutions to current practice, it may be useful to also consider how current practice could be changed so that it will be able to take advantage of the new integrated solutions that are available. We are developing the concept of Unified Project Management (UPM) as a project organization and management technique that is better able to accommodate integrated processes and information technologies. Unified Project Management draws from several key reference areas:

- Trends in integration and model-based information technologies.
- Integration techniques in software engineering, in particular, the Unified Modeling Language (UML) (Object Management Group 2002), and UML-based software development methodologies (Unified Process, Kendall 2002)
- Concepts of value chains, lean construction (Lean Construction Institute 2002), etc.

In current project management practice, the overall design and construction project is broken into individual work packages that are assigned to different groups within different companies. The predominate focus for these groups is then on carrying out their work packages, with relatively little focus or structure for how the results of the work integrate with other work packages into the complete project. In contrast, Unified Project Management introduces a framework that emphasizes the way that each work package fits within the overall project lifecycle and value chains, that makes explicit the relationship between work packages and the collective body of project information, and that emphasizes the cyclical, repetitive nature of work tasks rather than their "one-off" nature.

The Unified Project Management approach defines three dimensions for organizing project work:

- The Project Lifecycle dimension organizes the project into well-defined project phases, which are further refined into iterations. Although projects are currently thought of as passing through typical phases, this is an informal notion that is not explicitly used in organizing the work.
- The Workflow dimension organizes the work into the various work disciplines required to complete the project. This is somewhat like the normal division of work into work packages, but rather than describing the tasks as discrete work packages, the work is organized as ongoing workflows, which can be further broken down into sequences or networks of sub tasks.
- The product/deliverable dimension organizes the results of work. These results are described as parts of the product being constructed: initially, the results are information about the physical facility, which make up the virtual product, while during the construction phase, the results are the construction of the physical components themselves. These deliverables, flowing from the virtual facility to the physical one, form a continuum that makes up the product of the project.

Given these three dimensions, the work can be further organized along the intersection of each pair of dimensions:

- Workflows along the project lifecycle: most workflows span several project lifecycle iterations/phases, but different amounts of work are required at different times. By considering the workflows vs. the project lifecycle, the amount of each workflow that should be carried out in each iteration can be planned.
- Product/Deliverables along the project lifecycle: similarly, different amounts of the various deliverables are developed during different project iterations/phases.
- Product/Deliverables vs. Workflows: The organization can also define which workflows should collaborate on each of the project deliverables.

With the Unified Project Management framework dimensions are planned explicitly and used as a primary organizational vehicle during the project, participants still carry out their individual work tasks, but their inter-dependencies with other tasks, other project phases, and a combined product model are much more evident and easier to attain. This approach should improve the interface between project models (plus other information resources) and project management processes.

Although the three dimensions seem appropriate for the overall organization of all project participants, the management specialists responsible specifically for the overall management of the project could consider additional simultaneous dimensions, such as costs, risks, resources, etc. We are continuing to develop the concept of Unified Project Management, based on the underlying premise that new project organization and management frameworks may help work practices better fit the emerging technological tools.

5. CONCLUSIONS

In summary, this paper suggests that model-based technology will be central to future information technology solutions for AEC. However, the interfaces between the core technology and the AEC project environment are currently very weak. Several critical interfaces require significant research and development, including the following:

- Interfaces between the models and model users
- Interfaces between the different discipline-specific models
- Interfaces between the models and the actual construction site
- Interfaces between the models and the project management process.

This paper has introduced the concept of interfaces to model-based technologies and has presented some trends and issues relating to these interfaces. This has been done as part of an effort to formulate a new research program, and will lead to specific research projects addressing one or more of the interface challenges that have been identified.

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