CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Virtual Design and Construction: Themes, Case Studies and Implementation Suggestions

By

John Kunz & Martin Fischer

CIFE Working Paper #097
Version 8: January 2009

STANFORD UNIVERSITY

If you would like to contact the authors, please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
Terman Engineering Center
Mail Code: 4020
Stanford, CA 94305-4020

Virtual Design and Construction:

Themes, Case Studies and Implementation Suggestions

John Kunz and Martin Fischer
CIFE, Stanford University

Abstract

Virtual Design and Construction (*VDC*[1]) is the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives. This paper describes the theory and methods of VDC, and it includes specific examples of models and precise objectives as well as detailed suggestions on how to implement VDC in practice. VDC models are *virtual* because they show computer-based descriptions of the project. The VDC project model emphasizes those aspects of the project that can be designed and managed, i.e., the ***product*** (typically a building or plant), the *organization* that will define, design, construct and operate it, and the ***process*** that the organization teams will follow. These models are logically *integrated* in the sense that they all can access shared data, and if a user highlights or changes an aspect of one, the integrated models can highlight or change the dependent aspects of related models. The models are *multi-disciplinary* in the sense that they represent the Architect, Engineering, Contractor (AEC) and Owner of the project, as well as relevant sub disciplines. The models are *performance* models in the sense that they predict some aspects of project performance, track many that are relevant, and can show predicted and measured performance in relationship to stated project performance objectives. Some companies now practice the first steps of VDC modeling, and they consistently find that they improve business performance by doing so.

---

[1] Italics indicates that the glossary defines the italicized term

Virtual Design and Construction: 1
Themes, Case Studies and Implementation Suggestions 1
Abstract 1
Background 2
  VDC builds on traditional (20th century) practice 2
    Early History 3
  Example 4
  VDC maturity model 4
Themes 6
  VDC models are virtual 6
  VDC models represent the Product, Organization and Process (POP) 9
    POP models have different levels of detail 14
    Use Breakdown Structures to define generic POP models 15
  VDC product models show physical and abstract elements of a design 20
  4D animations visualize the product as it is built during the construction process 21
  Project models include the Organization and Process 21
  VDC supports public and explicit business objectives 22
    VDC Objectives Framework 22
  VDC emerges in stages 28
    Visualization shows the product, organization and process design 28
    Automation: automate some routine design and pre-fabricate to enable subassembly installation 29
  Integrated Concurrent Engineering (ICE) supports VDC 30
  VDC models support and require economic impact analysis 34
Summary 37
Discussion 37
  VDC strategy can enable companies to achieve significant breakthrough objectives 37
  Different stakeholders have different responsibilities 38
  Stakeholders collaborate by sharing visualizations 38
  VDC enables better project management 38
  VDC Limitations 39
Glossary 40
Acknowledgements 42
References 42

Background

This section gives an overview of VDC and relates it to the broader use of technology in AEC practice.

VDC builds on traditional (20th century) practice

Early in the 21st century, the facility design-construction-operations process has many admirable properties. The AEC design-construction process creates the world's fixed physical wealth such as homes, offices, schools, power plants, and fixed systems of our lives, including water, waste, transportation and power distribution. However, the process has problems. The process is fragmented so that it takes a long time to complete projects (usually far too long for the owner; although not long enough for critics). The fixed wealth is expensive for all and increasingly so for the world's least advantaged. The US construction process has measurably declined in its productivity per human hour invested over the past forty years, although sister engineering fields have dramatically increased their productivity during this period [Teicholz 04]. From an immediate engineering perspective, the process has maddeningly long latency in the sense that it often takes days or even months to get information or decisions. Many project stakeholders feel effectively disenfranchised from the design-construction process because it is so arcane and complex. Finally, participants complain that it is paper based and inflexible.

Figure 1 shows a photo of a construction planning office taken in 1998. We ask our students when the photo was taken. They guess the actual date fairly accurately and usually quickly recognize that it could have been taken in 1970 or yesterday -- except for some details. Some important methods of the construction planning process have changed during the past thirty years. For example, most of the paper documents shown in the photo are now printed computer documents, rather than copied hand generated documents. When asked if they expect an analogous photo to look similar thirty years from now, they uniformly say "no!" Interactive computer applications will replace most of the paper, and surely the roll of drawings on the table. One woman student suggested that there will be women in the picture.

Figure 1: This photo was taken in a construction planning office in 1998. Some important characteristics of this process are unchanged in the past thirty years, e.g., there are multiple participants in the process, although probably many other important stakeholders are absent from the meeting. We suggest that most such photos will look differently in thirty years, and some today already do -- those from construction management projects that are significantly more efficient and effective than most. The big change, which already has started to occur, is the emerging use of interactive computer-based visual project models to improve communication of project information, reduce latency and increase collaborative ownership of project plans.

Early History

We introduced the term Virtual Design and Construction (VDC) in 2001 as part of the mission and methods of the Center for Integrated Facility Engineering (CIFE) at Stanford University, and we explicitly have used the VDC methods in research since that time, e.g., [Garcia 04]. Both of us use the VDC method in teaching and research, and one of us has taught a formal VDC class since 2001 [Kunz 05]. Many of our current Ph.D. students now use the method.

Projects require developing and then relating design definitions, actual designs and design analyses, and then linking design, construction project management, with product management and financial management systems. In practice today, multiple teams perform most of this linking manually and socially, with great cost, interaction latency, and confusion. Motivated by these business drivers and technical work in concurrent engineering, which tried to integrate product, organization and process modeling and analysis tightly, the goal for *interoperability* emerged for multiple computer systems to exchange information and to use the exchanged information effectively. We now sharply distinguish social data exchange from technical or computer-based data exchange.

DARPA supported Concurrent Engineering research that led to an integrated Product – Organization – Process model and design methodology [Londoño 89]. Londoño et al used a blackboard for communicating and for control of information flow. The domain concerned engineering parts, and the blackboard database described the Product, Process and Organization. As we use VDC in an Integrated Concurrent Engineering environment (see below), all of a project's stakeholders can access the integrated project database, and individual designers can modify and analyze details of current designs in local data spaces. Many researchers address complementary or similar issues. Prasad anticipated “concurrent product and process organization” and many of the related VDC issues that we discuss, e.g., in [Prasad 96a and b], and he discusses “product and process organization.”

Industry Foundation Class (IFC) standards work of the International Alliance for Interoperability [IAI 05] and [Froese 02] both discuss semantic models for data exchange. More recently, the IFC and web XML data language and IFC communities collaborated to develop methods that provide web-based standards for sharing IFC data [aecXML 05]. The large Building Lifecycle Interoperable Software (BLIS) demonstration project defined hundreds of “views” and about 100 “concepts,” which were a “practical” subset of the IFC standard at the time [BLIS 02, 04]. The BLIS project was the first major demonstration by multiple software vendors to create an integrated set of project design models based on a shared IFC-based architectural model. The project had active participation from 1999 – 2002, and it demonstrated that real CAD and analysis applications could usefully share and exchange at least some of the data that a design team needed to create a design. While the BLIS project received lots of energy and attention, it had only limited success in its original hope to stimulate broad software developers’ support of IFCs and industry use of them. We have had mixed experience with use of computer application interoperability: it is possible to some extent, but difficult and limited [Kam 02], even in our own university teaching and research, as modest as they are. We find anecdotally that many AEC companies share similar concerns.

Our VDC work commits to making explicit the semantics of data that practitioners of different perspectives and applications need to share, and attempting to facilitate practitioners to define and use shared explicit representations. Like the IAI effort, we encourage the project team to identify and commit to a standard vocabulary. Further, we recommend being inspired by standards such as the IFC and pragmatic like BLIS, but even more modest than both. However, unlike the IAI standards, we do not propose standards for the semantic details of VDC models and method; we pragmatically assume that the long-term solution will take a long time to emerge, and in the short term, we want to support individual project teams to do as well as they can with modest incremental effort. Further, we encourage a strict discipline on both the level of detail of VDC models and the process for creating whatever detail the project team wants, which we describe below in the section **POP models have different levels of detail.**

Example

VDC maturity model

We find that users implement VDC in three distinct phases, each of which has its own value proposition, strategy for producing value and costs. Normally, organizations proceed sequentially through the steps in this maturity model, but some of the third step, Automation, often requires minimal and specialized, not general Integration.

1. Visualization *and Metrics*: In this first phase, project teams create models of the Product in 3D, of the Organization that performs design, construction and operations and the Process followed by organizational participants to do design, construction and operations and management, based on performance metrics that are predicted from models and tracked in the process. The results of the CIFE-CURT VDC use survey find that this stage is in common (although not yet widespread) use within the global AEC industry [Kunz and Gilligan 07]. For Visualization to work well, all stakeholder organizations need to develop the competence to interpret the visual models, and many need to develop core competence to develop them, which requires a strategic investment in the methods and their use. Similarly, for Visualization to work well for multiple stakeholders, multi-party collaboration contracts need at least to allow and ideally to incentivize data sharing, which may require strategic change in partnering arrangements. In the Visualization phase, projects:

- Routinely model and visualize the most expensive elements of the Product, Organization and Process (POP);
- Use a social process among project stakeholders to integrate multiple VDC models and model versions;
- Justify investment in VDC tools, methods and human resources based on the value proposition to the project, since this phase is (relatively) inexpensive and individual projects receive can significant benefit;
- Clarify project objectives, values, responsibilities, designs and expectations because good visualization enables many more stakeholders to participate in project review far more meaningfully than in routine practice.

2. **Integration** (computer based): In this phase, projects develop computer-based automated methods to exchange data among disparate modeling and analysis applications reliably. Some vendors support data exchange among different applications using proprietary exchange methods, which often works well for those applications made by the particular vendor. The results of the CIFE-CURT VDC use survey find some evidence that some projects now use computer-based integration of two or more applications [Kunz and Gilligan 07]. For Integration to work well, vendors need to agree on exchange standards, which may requires a strategic commitment to support cross-vendor data exchange. Similarly, for Integration to work well for multiple stakeholders, multi-party collaboration contracts need at least to allow and ideally to incentivize data sharing, which may require strategic change in partnering arrangements. In the Integration phase, projects:

- Share data meaningfully among Product, Organization & Process models and analysis programs using interoperation, i.e., reliable computer-based data exchange.
- Cannot justify investment in VDC tools, methods and human resources based on their project value proposition. Rather, the value proposition must support the

firm, since this phase is (relatively) expensive and multiple projects must use the same methods for the investment to produce significant benefit.
- IFCs are designed to enable this process, but there is little evidence that they are in significant use.
- Various vendors provide families of software applications that interoperate, often using proprietary exchange methods, which still limit exchange with other applications that might be useful to a project.
- Derive incremental value from integration per se because it can reduce modeling effort and time.

3. **Automation** In this phase, projects use automated methods to perform routine design tasks or to help build subassemblies in a factory. For Automation to improve design, project organizations normally need to dramatically change their processes to enable or perform more high-value design and analysis and spend much less time and billable effort for routine design. To support fabrication, the project needs to change from Design-Build or Design – Bid – Build to Design - Fabricate – Assemble, which takes strategic commitment to support a new partnering arrangement. Automation requires Integration, and good visualization helps make it work well. In the Integration phase, projects:

- Automate some aspects of routine *design* or Computer Numeric Control (CNC) *manufacturing* of assemblies for field installation
- Cannot justify investment in VDC tools, methods and human resources based on their project value proposition. Rather, the value proposition must support the firm, since this phase is (relatively) expensive and multiple projects must use the same methods for the investment to produce significant benefit.
- Enables dramatic increase in design efficiency and effectiveness;
- Enables dramatic decrease in construction duration, which in turn leads to breakthrough project performance in construction duration, e.g., the CIFE 2015 objective to be able to build most projects within 6 months from ground-break to high value use

Themes

VDC models are virtual

The current practice of AEC design and construction, as shown in Figure 1, obviously works for developing value-adding projects today. Computer applications generated most of the paper documents shown in this photo, such as the project schedule on the wall, which is the output of a scheduling program, and the drawings, which are the output of a CAD program. Paper documents today provide high-resolution descriptions of project elements including architectural designs and plans, and the vast majority of AEC projects in use today were created using these paper-based methods. However, the discrete paper based documents do not help integration of different disciplines and making even simple changes requires hours to days to make the initial change, print and review the updated documents and do even simple updates to related documents of functionally related disciplines. In addition, the format of today’s paper documents is often difficult for diverse stakeholders to understand: for example, users can rarely make meaningful comments about 2D architectural drawings or Gantt charts.

Like their forbearers in practice today, VDC models are computer based. In addition, however, the *use* of the VDC project models is flexible, visual and interactive, not document or paper-based. The engineer who generates the VDC schedule can project it and show it to other stakeholders who have responsibility for the CAD model or some area of the design or construction. They in turn can project their CAD models or project digital photos, ideally simultaneously with the schedule, each on a separate projection screen such as that shown in Figure 2, a photo of a project meeting taken in our CIFE lab.

Inexpensive computers and large, high definition and inexpensive projection devices enable social sharing of VDC computer models, and the modeling and simulation applications are now powerful and affordable.

Figure 2: Photo taken in the CIFE lab of a construction planning meeting using Virtual Design and Construction methods. As in the traditional method of Figure 1, there are multiple stakeholders in the meeting. Models of the product, organization and process can be displayed, explained and updated simultaneously on the separate displays. We find that *design team* performance improves dramatically compared with in the traditional method of Figure 1, and our goal is to simultaneously improve project team performance in schedule, cost and quality dramatically. Interactive computer models replace traditional paper documents.

The VDC model supports use by multiple stakeholders, as Figure 1 shows occurring in current practice and Figure 2 shows in the interactive VDC process. Since VDC is designed to support a multi-disciplinary project team, appropriate stakeholders include the multiple architects, engineers and general and multiple specialty contractors of AEC as well as owner representatives, users, suppliers, community representatives and government jurisdiction officials.

VDC creates an integrated framework and set of methods to manage the project, including those aspects of the project that must and can be designed and managed, i.e., the building, the design-construction process and the organizations that follow the processes to design, build and use the building. Building Information Modeling (BIM) focuses on the building elements of the VDC model, which we find useful but limiting because management issues usually involve building – organization – process interactions. BIM definitely appears to hold promise in practice [Bedrick, 05], [Haymaker 05]. BIM today is enabling many AEC professionals to improve performance. However, even using best BIM practices, projects do not normally model, visualize or analyze the organization and process accurately and effectively, and methods to manage and communicate multidisciplinary information and processes remain ad-hoc.

This paper includes a number of methodological recommendations on how to implement VDC in practice, which we enclose in boxes, such as the one below. Stakeholders can request the *visual* VDC models they need to participate effectively in the design, learn to understand all models as they evolve, and express their perspectives in a timely manner to other stakeholders throughout the project design.

Suggestion: Invite all relevant stakeholders to the project kickoff meeting, including an owner representative, architect, major contractors, and a potential user. In the meeting, identify the VDC models and visualizations for the project that will help stakeholders provide meaning and timely input to the project design and management. Define the project product, organization and process vocabulary in a generic POP model as part of the kickoff meeting.

Interactive VDC enables a very big change in the behavior of the design-construction process: dramatic reduction in decision latency, or the time between posing a question and having information with sufficient quality that it can be used to make a design decision. Questions can be formal "Requests for Information" or informal inquiries of fellow stakeholders. We repeatedly see latency change from days to hours and even minutes in integrated design sessions (see the section below on Integrated Concurrent Engineering).

Natural visual VDC models make the content of each model much more accessible than they are in traditional static paper descriptions. Specifically, most stakeholders find that interactive 3D models are vastly more understandable than static 2D plan and section drawings, and *4D* product-construction process animations are similarly much more understandable than traditional project schedule Gantt charts. Our interactive project models have started to become mutually *parametric* in the sense that change or highlighting any one will lead to very rapid or even instant change or highlighting in all others that are dependent. Because models can be examined with respect to each other, each grows to support the issues of others; time to get explanations and make decisions drops from days to seconds, likelihood of both design and construction rework drops because relevant stakeholders have increased ownership and timely participation in project decision-making. Since VDC models are visual, project team members who have different native languages can all reference the same graphic models, providing some support for the multi-cultural teams that are now common on many construction projects worldwide as well as some larger design teams. Some organizations have started to use multi-disciplinary VDC models as the focus of daily, weekly and major milestone design, planning and review sessions.

Suggestion: Hold project kickoff, major review, weekly and daily design and construction project meetings in a room with multiple computers, ideally with at least three projected screens that all participants can see simultaneously. Plan the agenda around description, analysis and evaluation of product, organization and process issues as shown explicitly in models. Invite all relevant stakeholders to the project meetings.

VDC models represent the Product, Organization and Process (POP)

We set the broad goal to create explicit models of those aspects of a project that a manager can manage. A project manager can control three kinds of things: the design of the *product* to be built, the design of the *organization* that does the design and construction, and the design and the design-construction *process* that the organization follows. We call this project model the Product-Organization-Process model, or the *POP* model.

The POP model is object-oriented in the sense that each P, O and P element has defined meaning (or semantics) to the stakeholders. For example, the Product model defines building elements such as Floors, Walls and Beams; the Organization model defines organizational groups, and the Process model defines activities and milestones.

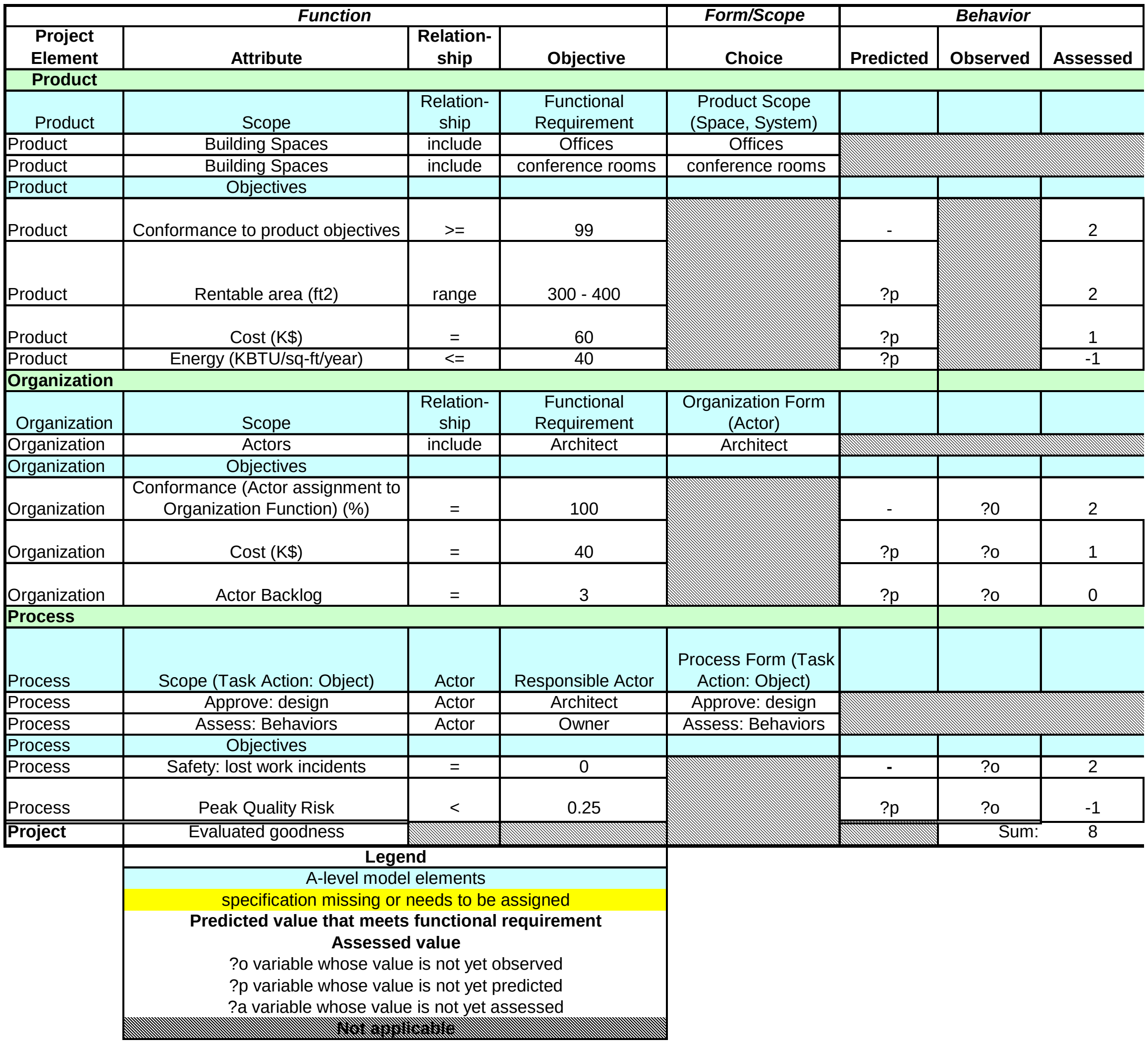
We define two related types of POP models: *generic* and *instance*. *Generic* models describe the conceptual vocabulary and thus can be very useful to define shared vocabulary for project stakeholders at the time of launching a project. More generally, generic POP models can define the vocabulary that a company or partnership uses to do a kind of work, allowing a community of organization professionals to define shared vocabulary that individual projects can customize as needed. Generic POP models define entity names, such as `column`, `Design Team` and *`activity`*. They may define associated attributes such as `height`, `team responsibilities`, and `planned duration`. However, generic models lack specific detail, i.e., have no values for their attributes, or names of individual instance elements. *Instance* models specialize the vocabulary as their generic relatives, naming individual elements, such as `Design Team A`. POP instances refer to corresponding objects in individual modeling or analysis applications, such as entities in a CAD, organization or process modeling application. They may refer explicitly to corresponding objects in modeling applications, or they may refer implicitly if POP model users understand the model naming correspondence. They may contain values of design variables such as planned dimensions when it is useful to share those values across multiple models.

The POP model specifies information that is shared among models, not a complete project model with which individual modeling applications send and retrieve information. Thus, the POP model describes the content of the individual P, O and P models, each which represents the details of designed conceptual elements with their attributes, attribute values and relationships. The individual P, O and P modeling tools have user interfaces that present the models using natural visual idioms that are appropriate for each relevant discipline perspective. The purpose of the shared POP model is to define conceptual elements that are shared and help the stakeholders to assure that the product, organization and process specifications are appropriate and mutually consistent. For example, the product model defines the physical elements to be designed and built, at some selected but necessarily incomplete level of detail. The Organization model defines the groups that design and build each defined physical element, and the process model defines the activities and milestones that stakeholders follow to do their work.

The product model, and hence the Product segment of the POP model, should represent the components and systems of the building. A well-designed POP model then also includes organization entities to design and build the systems and components, as well as the activities to do design and construction. The Industry Foundation Classes (IFC) define a large set of product components and systems -- such as Floors, Walls, Beams, and Equipment – as well as some definition of organizational and process entities [IAI 05, Tarandi 03]. The Scope section of coarse level of detail POP models will include only a small subset of the total IFC specification. Projects that find it useful to define POP models at several levels of detail may represent more of the IFC specification at the finer levels of detail of their generic POP models.

Suggestion: Whenever possible, create the vocabulary of the Scope segment of POP models using the names and definitions of deliverable element (such as components, spaces and systems) of organization entities, or “actors,” and process activities as defined in the IFC specification. Doing so will facilitate making the resulting models IFC compliant. Create a cross reference between the product vocabulary based on the IFC specification and the terms used in product marketing and design. Similarly create a cross reference between the IFC-based organization and process vocabulary and the vocabulary that is in common operational use.

At a high level, POP models represent the function, designed form or scope, and behavior of the project product, organization and process. Figure 3, for example, shows a generic POP model in the sense that it specifies the vocabulary used to describe a line of business. Related instance models represent specific projects, such as that to create an individual building.



Function				*Form/Scope*	*Behavior*		
Project Element	**Attribute**	**Relation-ship**	**Objective**	**Choice**	**Predicted**	**Observed**	**Assessed**
Product							
Product	Scope	Relation-ship	Functional Requirement	Product Scope (Space, System)			
Product	Building Spaces	include	Offices	Offices	▨	▨	▨
Product	Building Spaces	include	conference rooms	conference rooms	▨	▨	▨
Product	Objectives						
Product	Conformance to product objectives	>=	99	▨	-	▨	2
Product	Rentable area (ft2)	range	300 - 400	▨	?p	▨	2
Product	Cost (K$)	=	60	▨	?p	▨	1
Product	Energy (KBTU/sq-ft/year)	<=	40	▨	?p	▨	-1
Organization							
Organization	Scope	Relation-ship	Functional Requirement	Organization Form (Actor)			
Organization	Actors	include	Architect	Architect	▨	▨	▨
Organization	Objectives						
Organization	Conformance (Actor assignment to Organization Function) (%)	=	100	▨	-	?0	2
Organization	Cost (K$)	=	40	▨	?p	?o	1
Organization	Actor Backlog	=	3	▨	?p	?o	0
Process							
Process	Scope (Task Action: Object)	Actor	Responsible Actor	Process Form (Task Action: Object)			
Process	Approve: design	Actor	Architect	Approve: design	▨	▨	▨
Process	Assess: Behaviors	Actor	Owner	Assess: Behaviors	▨	▨	▨
Process	Objectives						
Process	Safety: lost work incidents	=	0	▨	**-**	?o	2
Process	Peak Quality Risk	<	0.25	▨	?p	?o	-1
Project	Evaluated goodness	▨	▨	▨	▨	Sum:	8

Legend
A-level model elements
specification missing or needs to be assigned
Predicted value that meets functional requirement
Assessed value
?o variable whose value is not yet observed
?p variable whose value is not yet predicted
?a variable whose value is not yet assessed
▨ Not applicable

Figure 3: Level-A generic POP model for design and construction of buildings. This most-generic level of detail specifies that POP models represent the Product, Organization and Process in terms of *functional* requirements or design intent, *Form* or *Scope* or design choices, and *behaviors* or predictions and observations. Level "A" models (shown) have about one form/scope element each for product, organization and process; Level "B" have about ten, level "C" about a hundred, etc.

As shown in Figure 3, we define the content of the POP models using the classic *function – form – behavior* taxonomy of design theory [Gero 90, Clayton 96]:

- *Function*, or design intent, represents the intent of the owner in making a requirement or the requirement of a critical stakeholder such as the code jurisdiction. Examples include that an auditorium seats 100; that an organization include a licensed structural engineer; and that the design process include certain specified review milestones.
- *Form*, or design choice – or designed *scope* -- represents the decision of a designer in response to a functional requirement or the designer preference. Examples include choice of specific spaces, the choice of a particular contractual relationship among the architect and contractors, and the construction plan.

- *Behavior*, or properties, including both predicted behaviors of the design and measured behaviors of the product, organization or process. Examples include the predicted deflection of a beam; measured hours spent by a contractor doing a task; and predicted CPM duration of the construction.

Figure 4 shows an example of a POP model that both specializes the generic model of Figure 3 for a university dormitory project and elaborates its level of detail. For example, the generic Level-A generic Product functions concern capacity and sustainability. At a greater level of detail, the instance Level-B Product functions include requirements to house 100 students, energy and water use that are stated fractions of 2002 comparables, specific noise, air quality open space, recycling and height objectives, the assumption of two-person dormitory apartments and a specific project budget. The generic Product form or scope represents systems and physical building elements, which remain unstated. As shown in
Figure 4, the Level-B instances include ten two-bedroom apartments per floor at 400 square feet each and elements that still need to be sized including solar panels, a foundation pad, laundry, corridor, lab spaces, etc. In the judgment of the designers at this (still early) design stage, these physical elements represented the top ten physical elements in terms of cost. Their management goal is to design, procure and build these elements with predictable and acceptable costs, thereby minimizing the overall project cost risks. The team will elaborate the level of design detail once the design team has significant confidence that the design of these physical elements, the responsible design-construction team and the associated activities are all consistently specified and acceptable. The generic Product behaviors include the predicted and observed (by post occupancy measurement and evaluation) Product functions – those listed in the function segment of the POP model – and periodic assessment during the design and construction process of the conformance of the design to the design functional requirements. Many researchers use model-based computational methods to predict behavior, such as [Dym 88], [Shea and Cagan 99], Flemming and Woodbury 95] [Stiny 80]. Additional product behaviors include design team assessment of the conformance of the prediction of design performance to each stated design requirement and measured observations of the final building performance for each stated requirement, by appropriate post occupancy evaluation (*POE*).

Similarly to the Product column of the instance POP model of
Figure 4, the Organization and Process Functions elaborate and specify details of the corresponding generic functions of Figure 3. The Organization and Process form or Scopes represent those that the design team judged to represent the top-ten in terms of cost. Although the POP model does not represent them explicitly, an external organizational modeling software application would, and the explicit POP model helps the project team understand the relationships of the Product, Organization and Process Scopes to each other (e.g., organization actor responsibility for design and construction and specific Product elements, and relationship between process activities and Product elements). Finally, the team will measure the Level-B organization and process behaviors and use those results in management.

Function				***Form/Scope***	***Behavior***		
Project Element	**Attribute**	**Relation-ship**	**Objective**	**Choice**	**Predicted**	**Observed**	**Assessed**
Product							
Product	Scope	Relation-ship	Functional Requirement	Product Scope (Space, System)			
Product	Building Spaces	include	Offices	Offices			
Product	Building Spaces	include	conference rooms	conference rooms			
Product	Building Spaces	include	public areas	public areas			
Product	Building Systems	include	HVAC	HVAC			
Product	Building Systems	include	telecom/network	telecom/network			
Product	Building Physical Elements	include	foundation	foundation			
Product	Building Physical Elements	include	above-ground steel	above-ground steel			
Product	Building Physical Elements	include	drywall	drywall			
Product	Building Physical Elements	include	skin	skin			
Product	Building Physical Elements	include	windows	windows			
Product	Building Physical Elements	include	roof	roof			
Product	Objectives						
Product	Conformance to product objectives	>=	99		-		2
Product	Rentable area (ft2)	range	300 - 400		?p		2
Product	Cost (K$)	=	60		?p		1
Product	Energy (KBTU/sq-ft/year)	<=	40		?p		-1
Organization							
Organization	Scope	Relation-ship	Functional Requirement	Organization Form (Actor)			
Organization	Actors	include	Architect	Architect			
Organization	Actors	include	City	City			
Organization	Actors	include	Concrete sub	Concrete sub			
Organization	Actors	include	Flooring sub	Flooring sub			
Organization	Actors	include	GC	GC			
Organization	Actors	include	MEP sub	MEP sub			
Organization	Actors	include	Owner	Actors			
Organization	Actors	include	Painters	Painters			
Organization	Actors	include	Steel sub	Steel sub			
Organization	Actors	include	Structural Engineer	Structural Engineer			
Organization	Objectives						
Organization	Conformance (Actor assignment to Organization Function) (%)	=	100		-	?0	2
Organization	Cost (K$)	=	40		?p	?o	1
Organization	Actor Backlog	=	3		?p	?o	0
Process							
Process	Scope (Task Action: Object)	Actor	Responsible Actor	Process Form (Task Action: Object)			
Process	Approve: design	Actor	Architect	Approve: design			
Process	Assess: Behaviors	Actor	Owner	Assess: Behaviors			
Process	Design: Building elements	Actor	Architect	Design: Building elements			
Process	Design: Building systems	Actor	HVAC/MEP designers	Design: Building systems			
Process	Predict: Predictable Behaviors	Actor	Owner	Predict: Predictable Behaviors			
Process	Build: Building elements	Actor	GC	Build: Building elements			
Process	Build: Building elements	Actor	Flooring sub	Build: Building elements			
Process	Build: Building elements	Actor	GC	Build: Building elements			
Process	Build: concrete elements	Actor	Concrete sub	Build: concrete elements			
Process	Build: Flooring	Actor	Flooring sub	Build: Flooring			
Process	Objectives						
Process	Safety: lost work incidents	=	0		-	?o	2
Process	Peak Quality Risk	<	0.25		?p	?o	-1
Process	Conformance (Actual schedule to plan) (%)	>	80		-	76	0
Process	Peak Predicted Schedule Risk (wks)	<	2		-	?o	1

Figure 4: an instance Level-B POP model represents the *Function* (intent), Form/*Scope* (design choices) and *Behavior* (properties) of a project *Product*, *Organization* and *Process*. The broad goals of the POP model are to help the stakeholder team to identify major requirements, the most expensive design choices made by the design team to meet those requirements, and the predictable and observable project behaviors early in the design process. The hope, and our experience, is that the POP model helps enable the most valuable possible modeling and analysis of a project during its entire lifecycle.

POP models have different levels of detail

Arbitrarily, we define POP model level of detail as a power of ten. For consistency with traditional product, organization and work breakdown structures (see **Use Breakdown Structures to define generic POP models** below), a *Level-A* POP model represents the product, organization and process as a single element, e.g., the building, design-construction team and design-construction process. Useful as a reference, this level of detail is too abstract to have managerial interest. A *Level-B POP model* represents P, O and P elements that each incur about 10% of the project cost, design-construction effort or schedule duration.

Figure 4 is an example. This initial *Level-B* POP model shows the P, O and P design elements that, in the judgment of the project team, represented the elements that will require the greatest cost, effort or schedule at this level of detail. The broad objectives of the POP model are to help the stakeholder team to identify these resource users explicitly early in the design process and to enable consistent modeling of those elements in the associated product, organization and process models. Having developed such a model and understanding its significance for managing the project, we can then elaborate its detail to a *Level-C POP model*, which represents those POP elements with about 1% of the cost, effort or duration. While AEC projects often define Level-D or greater level of detail, we focus our research and this paper on Level-A to –C models.

We borrow the convention of “ABC” from the method of Pareto analysis, or ABC analysis. With respect to the total cost, schedule or quality, we try to guild POP models that identify the ten most important factors in the “A” category. We try to identify the ten or so most important sub factors of each A category as the hundred factors in the “B” category, and in turn we will identify the ten sub factors of each B category as members of the relatively unimportant “C” category.

A measure of success or “goodness” of a POP model is that, for a particular level of detail, its elements are mutually consistent in detail, mutually refer to each other, and together describe the most important aspects of a project at a particular level of detail. For example, a Product element should relate to a design and a construction activity and to organizational parties (called “actors”) responsible for those activities. Similarly, a good POP model represents the product components with each modeled actor and activity related. Our early simple versions of the POP model do not explicitly represent the relationships among P, O and P elements, although the stakeholder team knows them.

The greatest value of the POP model comes when the project influence is greatest, i.e., at the schematic and early design development phases. At these early phases, by definition, only Level-A or –B and possibly -C details

Figure 5 shows a set of guidelines for how to create individual functions (design intent), form/scope (design choices) and behaviors (parameters) of a project. The modeling purpose might be to support understanding of architectural concepts, space management (i.e., how much space is planned and actually available for different spatial functions), cost estimation, energy analysis, schedule optimization, schedule impacts on stakeholders, structural analysis or mechanical system design and analysis. The choice of particular product, organization and process forms will depend on the choice of modeling purpose.

Use Breakdown Structures to define generic POP models

POP models represent three facets of the project, and the models start with generic Product, organization and Process (Work) *Breakdown structures*. A goal of a project POP model is to define the *PBS*, *OBS* and *WBS* so that they represent the important characteristic of their respective project models and are mutually consistent in both naming and references. The scopes of each row of a POP model should be consistent with the corresponding PBS, OBS or WBS.

> *Suggestion:* Create a Level-B instance POP model very early in the design process, at least by the end of the first day of a kickoff meeting. Start to elaborate the level of detail to Level-C only after the Level-B elements are defined, modeled, mutually consistent, acceptable and well understood.

> *Suggestion:* Choose Level-B POP model elements so that each represents about 10% of the cost, effort or schedule duration of the project. That is, model the physical product components, organizational actors and activities that represent about 10% of the cost, effort or schedule duration of the project, whichever is most important for project success.

The POP model represents breakdown structures hierarchically. Figure 6 - Figure 8 show a generic PBS, OBS and WBS, which represent a hierarchical decomposition of types of product elements, organization elements and work respectively. The individual product, organization and process models will use the names defined within the breakdown structures and shown together in the Form segments of the POP model. The relationships in each breakdown structure represent a class-subclass specialization hierarchy. That is, Product, Organization or Work elements at the top of each BS are abstract; lower levels become increasingly more specific and specialized.

> *Suggestion:* Include all the relevant stakeholders in defining breakdown structures and each major version of the POP model, at least including the owner representative, architect, contractor, and a potential user.

The PBS represents the physical and abstract components that together represent the physical and functional facility being built. The PBS represents both physical components to be designed and built, such as columns and slabs, as well as abstract systems such as egress and ventilation systems. The PBS shown in Figure 6 is based on the Industry Foundation Classes (IFC) specification [IAI 05, Tarandi 03]. In the simplest generic POP models, entities have only name; there is no explicit representation of their attributes. Generic POP models can also define the names of the most important attributes of each entity type. The relationships among P, O and P entities should be clear to the stakeholders, but they are normally implicit in simple POP models, as shown in Figure 5.

	Product	**Organization**	**Process**
Function	Design Intent		
	Measurable required functional project capability that is OK at each significant project milestone: qualitative or quantitative, e.g., specific spaces and specific systems, energy, lighting and egress, capacities and performance of spaces and systems, budget, assessed by responsible stakeholders	Intended skills and responsibilities of the project actors who are stakeholders	Major milestone dates, including start and finish
		Measured actor meeting participation timeliness: high participation of intended stakeholders > 90% of meeting possibilities	VDC modeling purpose and Level of Detail
			Activity schedule conformance: specific value and variance objective as well as measured values and variance
		Allowed predicted actor backlog, cost	Activity budget conformance: objective and variance
Scope	Design Choices		
	Physical spaces, components and systems; abstract deliverables to achieve Product functional objectives • **R:** each form implements one or more product functions • Each scope represents about 10% of the project *TCE*[2] (Level-B) • **R:** each physical element has process Task(s)	*Actors* to achieve Product, Organization and Process functional objectives • **R:** designed scope implements functions • Each actor has responsibility for about 10% of the project TCE[2] (Level-B) • **R:** actor has assigned activities	*Activities* to achieve Product, Organization and Process functional objectives • **R:** designed form or scope implements functions • Each activity represents about 10% of the project TCE[2] (Level-B)
Behavior	Properties: analysis predictions and observed performance		
	Measurement quality of designed or delivered product assessed by responsible stakeholders • **R**: Behaviors have quantitative objectives stated in functional requirements	Predicted, measured actor • **R**: Behaviors have quantitative objectives stated in functional requirements	Predicted risks, measured schedule delay • **R**: Behaviors have quantitative objectives stated in functional requirements
		Predicted, measured actor backlog	
	Measured architectural, construction, energy, etc. quality conformance	Predicted, measured organization costs	Predicted, measured schedule conformance
		Predicted, measured direct and hidden work volume	Measured Process cost conformance
		Measured direct and hidden work volume conformance	
		Measured actor meeting participation timeliness	

Figure 5: This table shows a set of guidelines for how to create individual Functions, Form/Scopes and Behaviors and how they appropriately relate to each other. Analysts can predict or measure behaviors by day, week, month, major milestone, etc. as appropriate. R: indicates relationships among POP elements, which normally are required for a consistent

POP and project model, although they are implicit in the model itself. For example, individual Product Form or Scopes specify spaces, components and systems, which the design team chose individually and collectively to satisfy product Functional objectives. TCE^2 is the total predicted Time, Cost, Effort or life cycle Energy use.

As shown in Figure 6, the generic PBS has multiple levels of detail, each of which can have one or multiple corresponding project instances.

Suggestion: Create the generic Product Form segments of the POP model to be consistent with the generic PBS at corresponding levels of detail. Design similar consistency between Organization and Process Form elements of the generic POP model and the OBS and WBS.

	Generic PBS Description	Project example
1	Project: (single element) project description. This LOD supports project Feasibility Studies. This generic project description links the design to the owner's business and the overall business case and project economics.	`Bay Street Project`
2	Buildings or Major Project Elements: This LOD supports project Conceptual Design. It supports decisions about overall form of major project components.	`Parking Structure`
3	Systems: This LOD supports project Schematic Design (SD). It supports decisions about form of major systems and space layout.	`Structural System`
4	Components: This LOD supports project Design Development (DD): It supports decisions about component types, dimensions and high-level construction methods.	`Wall 1`
5	Parts: This LOD supports project Detailed Design, Construction Documents (CD) and Shop Drawings: It supports decisions about specific parts.	`Rebar for Wall 1`

Figure 6: The left column shows the Level of Detail (LOD) in the *Product Breakdown Structure* (PBS), and the middle describes it. Each PBS element has a corresponding level of detail in the Product Form segment of the generic POP model, as in

Figure 4. The right column shows instances of each generic element for a specific project, each of which would be specified in an instance in the Product Form section of the instance POP model.

Project owners and designers normally use text documents to specify the form of a product, i.e., state the functional requirements. The project team often uses the Uniformat [ASTM 05] template to represent the PBS information based on defined elements and systems. The designer uses 2D or possibly 3D CAD to document the design in the levels 2-4 of the product breakdown, and the fabricator will use 2D or 3D to design parts.

The OBS represents the vocabulary to describe the organization design, specifying the organizational elements that do the work of the WBS to create the building of the PBS. Nodes higher in the OBS hierarchy have responsibility for management, oversight, and resolving the exceptions identified by lower-level organizational teams. The OBS should describe all the groups with responsibility for significant activities in the WBS; normally they will appear as lower nodes in the OBS. The relationships in the OBS specify information flow: lower-level (rightmost in Figure 4) organization elements pass issues that require executive resolution “up” the (or left and up) hierarchy to the next-higher level or supervising element, rising if necessary to the ultimate decision making element, which is at the top of the hierarchy. The generic OBS defines positions, not individual people, although an instance OBS might name individuals. Each position in the OBS might include one or more than one individual, each working part or full time on the project. The project management system records the separate assignment of people and other resources to organizational groups.

	Generic OBS Description	Project example
1	Project Sponsor / Executive	`Developer`
2	Project Manager	`Construction Project Manager`
3	Area / Discipline design or construction Manager	`On-site construction superintendent`
4	Design group leader / Construction crew Foreman	`Concrete Foreman`
5	Teams of Design Engineers, Crews of construction Workers	`Concrete crew` (composed of multiple individual laborers)

Figure 7: The left column shows the Level of Detail (LOD) in the Organization Breakdown Structure (OBS), and the middle describes it. Each OBS element has a corresponding level of detail in the Organization Form segment of the generic POP model, as in Figure 5. The right column shows instances of each generic element for a specific project, each of which would be specified in an instance in the Organization Form section of the instance POP model.

Suggestion: The generic OBS elements at each Level of Detail (LOD) have responsibility to design or construct the deliverable Product elements in the PBS at a corresponding LOD. POP Organizational Form elements have similar responsibility for POP Product Form elements.

The WBS represents the work design, i.e., the activities that the organization performs to design, build and manage the project of the PBS. The generic Work Breakdown Structure defines the types of project design and construction deliverables. The deliverables may be physical products such as built elements of the product, abstract products such as designs or reports, or services such as continuing supervision. The WBS describes the work to be done to create the product, not the functions or attributes such as cost of those product elements.

Figure 8 shows a generic WBS and some representative instances of those generic elements. The WBS elements at Levels 1-3 have corresponding elements in the process Form/Scope segment of a typical POP model, and individual activities and operations specified generically by WBS elements 5–7 constitute the typical construction master schedule.

	Generic WBS Description	Project example
1	Design, construct and manage the project	`Construct the Bay Street Project`
2	Design broad kinds of systems or physical elements or Construct specific areas	`Construct the Parking Structure`
3	Design specific kinds of systems or physical elements or Construct specific Sub areas	`Construct Area (Zone) AP4 Level 1`
4	Design specific systems or physical elements or Construct types of Building units	`Construct Piles`
5	Activities to specify, design, review and approve specific systems or physical elements or Construct, approve or commission specific types of Building units	`Construct Build Wall 1 in AP4 Level 1`
6	Activities to design or construct specific objects defined in the PBS	`Build Wall 1 in AP4 Level 1`
7	Detailed design or construction activities	`Place Rebar Wall 1`

Figure 8: The left column shows Levels of Detail (LOD) in the Work Breakdown Structure (WBS), and the middle column explains each. Each has a corresponding level of detail in the Process column of the generic POP model. The right column shows instances of each generic work element for a specific project, each of which would be specified in an instance in the Process Scope section of the instance POP model.

VDC product models show physical and abstract elements of a design

Traditional CAD models of products are composed of a set of lines, which the human eye interprets as elements such as columns, doors and windows. Historically, these traditional models are in 2D, although some are now in 3D. These drawings can be immensely helpful or even crucial for understanding design of a physical product. Traditional models of organizations and processes show the organizational actors and activities and sometimes their relationships, but not their relationships to the elements of the product.

Modern 3D CAD product models look to a viewer the same as their traditional counterparts, but they are built using “objects” that the computer modeling system recognizes as physical elements such as columns, doors and windows and that appear in the user interface as meaningful visual representations of the modeled element. The modeling tool understands the number, location and properties of each such object, and the tool can export a project model in a computer readable format that other computer applications can interpret meaningfully. VDC models of products, organizations, processes and the integrated POP models all are object-oriented in the sense that each can represent a set of project elements using a vocabulary that the modeler specifies. Using a VDC methodology, the project will build these product, organization and process models using consistent vocabulary and mutually consistently with each other, to enable concurrent management of the people, the work, and the unfolding project itself.

VDC models show the physical elements of the product and the abstract elements of the organization, i.e., the teams or "actors" and the abstract elements of the work process, i.e., the activities. The POP model lists these physical and abstract project elements, and the individual VDC models show them in a visually meaningful way, describe their attributes and attribute values, and describe the dependencies among them.

4D animations visualize the product as it is built during the construction process

4D models link a 3D design with a construction schedule [Koo and Fischer 00]. Using time-based animation, 4D models show the construction of a project over time. Diverse project stakeholders can view a planned construction sequence as a 4D animation, and stakeholders such as users and neighbors can understand it even though they do not understand 2D drawings or Gantt charts, and construction professional consistently find that the 4D animations enable their finding time – space interferences more effectively than they can using traditional drawings and Gantt charts.

Suggestion: Use 4D animations to optimize the construction plan or schedule, to engage all stakeholders to look for and understand constraints on the construction process due to space-time interferences (when one construction activity will interfere with another), find interferences of the construction with ongoing facility operations and user activities, and find interferences between work of different subcontractors.

Project models include the Organization and Process

The organization model shows the teams involved in design and construction, and it shows the specific responsibilities of each team [Kunz 98]. In addition, the organization model shows reporting or "exception handling" paths, i.e., which another actor is to be notified when issues emerge. Normally, the actor receiving such an exception has responsibility to decide what to do in the presence of the problem, generically to seek a definitive solution to the problem, find a quick work around, or to ignore the problem and proceed.

Based on organization theory, the "Virtual Design Team" method creates a computational model of a project organization and the process followed by the organization to build the project [Jin et al. 95, Kunz 98, Levitt 02]. The VDT organizational models consistently describe and predict the behavior of both organizations and processes, including task and project durations and the volume and distribution of direct work by actors and of "hidden" work, which is the sum of coordination effort, rework and wait time for information or decisions. It also predicts the time-varying actor backlog due to the cumulative time demands on an actor of direct and hidden work in excess of available time. Finally, it also predicts risks that task durations will exceed the nominal (conservative) Critical Path Method (CPM) predicted task durations due to the impact of "hidden" work and actor backlogs.

Suggestion: Explicitly describe the process performance metrics as part of the Process Functions of the POP model. To create the Process Scope, start with a "process map" or diagram of the activities to perform [Hunt 96]. For the Process Form/Scope, describe work activities at a consistent level of detail, e.g., ten activities that each represents about 10% of the effort or 100 activities that each represent about 1% of the effort.

Most issues of latency involve organization design and management. One actor asks information or decisions of another, and the dependent actor lacks time, knowledge, information, authority or motivation to reply promptly. Meanwhile, the first actor must wait on the issue at hand before proceeding. A project can reduce latency dramatically by making the requirements for coordination and the objectives on timeliness both explicit.

Suggestion: Use organization models to document the organization so all stakeholders understand it clearly, to predict organizational backlogs, and predict the volume and distribution of both direct and hidden work. Attempt to mitigate the greatest predicted organization backlog, coordination, time and cost risks.

VDC supports public and explicit business objectives

This section describes a family of business objectives for which we see significant demand from practitioners and owners. We find that VDC methods support all these objectives, and many of them require something like VDC.

VDC Objectives Framework

Senior corporate managers can set specific major objectives for projects, which the project team can measure and report at the end of the project. The specific breakthrough objectives of Table 3 are project objectives of this type. We explicitly encourage senior management of owner and AEC project companies to set such objectives and hold themselves and their project development teams responsible for the vision, strategy and operational plans that will achieve those specific objectives and broad objectives that each company finds valuable yet achievable.

From the perspective of a field manager, however, the project objectives are like the sound coming from an AM radio; they are the final observed outputs, not the decisions a line manager can make or the "knobs" that the operator might turn. Thus, we identify a set of factors that a manager controls day by day, as well as a set of *process performance metric*s that the project team can measure and use to judge how well the management choices are moving toward the final *project outcome* objectives.

We conceptualize three levels of objectives:

- ***Project** controllable factors*, which a manager sets for decisions that are made daily, as shown in Table 1. Like how far to depress a car gas pedal, a project team typically can make only a few decisions, such as what product, organization and process elements to choose. These controllable factors influence process performance and, finally, project outcome.
- ***Project process objectives***, measurable weekly or bi-weekly, such as those shown in Table 2. Like a driver monitoring car speed and RPMs, a Project team can measure many progress indicators, which individually and collectively have values affected by controllable factors and that influence but do not determine final outcome.
- ***Project outcome objectives***, measurable at the end of the project, such as final project cost, schedule, quality and safety, assessed with respect to explicit budget, schedule, quality and safety objectives, such as those shown in Table 3.

Operationally, each organization must identify the factors to control, process metrics to monitor and use in management and outcomes by which to evaluate project success. From this story, which is difficult but extremely useful to develop, companies can then identify a strategy and annual plans for making the changes that it judges will help realize its future breakthrough objectives. Each company is completely in control of its VDC vision, measurable objectives and implementation strategy.

Suggestion: Each project should set, track and manage against a small (2 – 3) set of explicit objectives of each type:

- *Controllable factors*, including the VDC modeling and analysis strategy, process objectives to measure and one or two additional factors (see Table 1).
- Measurable *process performance parameters*, such as schedule conformance and response latency (See Table 2).
- Measurable *project outcome objectives*, such as safety, schedule, cost and functional quality as assessed by post occupancy evaluation (See Table 3).

Suggestion: Make objectives public, specific and aggressive yet realistic. Review them each project meeting. Allocate resources to collect, manage using them and meet them. Predict them, ideally using well-founded computational methods, otherwise using professional stakeholder judgment. Manage using them by reporting and reviewing their performance frequently, identifying the causes of large variances and intervening to improve identified problems. Celebrate when the project meets objectives.

Table 1: This table shows *controllable* project factors that can be made strategically by organizations and line managers on a daily basis. Performance of these factors can be measured, reported to the project team weekly or bi-weekly, and used in management. The theory of VDC is that attention to the controllable factors leads to improved process performance, which is measurable, and in turn to improved project performance that can be reported to the owner and senior management.

VDC strategy and plan	The plan and strategy concern: • *Visualization* involves showing elements of the product, organization and process in a way that different stakeholders can understand and relate to them. A project can choose modeling level of detail and focus considering contribution of the elements to total estimated project Time, Cost, Effort or life cycle Energy use (*TCE*[2]). • *Integration* includes definition and support of relationships among modeled product, organization and process elements that enable the computer to update values of dependent elements when an independent value changes as well as make parametric change, cross reference and appropriate highlighting of related elements in different models. Considering their respective capabilities and limitations, a project team can choose the tools to use and methods to use them to enable different levels of social and technical, i.e., computer-supported, integration. • *Automation* is support by the computer for elaborating design details, checking consistency, doing analysis, moving and processing materials as part of prefabrication and assembly at the work face. A project can choose the amount of automation to perform given business objectives and the capabilities and limitations of different tools.
Process objectives to measure, track and use for management	Of the candidate process objectives, as shown in Table 2, select about two to measure, track and use for management.
Decisions and rationale recorded	Objective is to record descriptions of and decision choice rationale for 100% of POP items with > 10 (or 2)% of the budged time, cost, effort or energy TCE[2]
Coordination requests	Objective is that >= 90% of all actual coordination activity among project participants is planned (weekly), explicit, informed, public and tracked
Coordination support	Objective is that 90% of all planned coordination activity is reported (weekly) by intended recipients to have been timely and suitable
Prediction basis	Objective is that >= 80% of all predictions by project designers are made by theoretically founded and automated methods
Design versions	Objective is 2 or more for >= 80% of all decisions that affect more than 10% (or 2%) of cost, effort or schedule
Risk management strategy	There is an explicitly defined risk assessment and management strategy that is followed on 100% of POP items with > 10 (or 2)% of TCE[2]
Globalization strategy and plan	Objective is that >= 50% of project purchased components and services can be acquired from global suppliers
Lifecycle cost factors considered	Objective is that project lifecycle costs explicitly model financial costs and value returned, natural resources consumed, and emissions generated

Table 2: This table shows quantitative project *process* performance measures that can be measured, reported to the project team weekly or bi-weekly, and used in management. Achieving these process objectives makes it more likely that projects will reach aggressive overall project objectives.

Performance Factor	Typical 2005 practice	ICE Potential
Detailed Schedule conformance: fraction of time that scheduled activities start and finish within one day of schedule, where design-construction activities are measured at whatever level of detail the project chooses for planning	Often not measured; usually well less than 70% in practice.	>= 95% of all design and construction activities started and completed within one day of their planned start and finish dates, usually based on a 2-3 week lookahead schedule
Decision latency (Decision-making promptness): time between when information is available to make a decision and the time that it is announced	Two days in a good project to a month or more in many projects; high variance	<= 60 seconds during critical design and construction activities @ > 98% reliability; <= 2 days max
Meeting effectiveness: fraction of stakeholders who self-report that they have timely and meaningful participation in project meetings.	Unknown since not routinely measured, but generally not high on average although variance across projects is high	> 90% Meeting effectiveness requires careful attention to meeting participation, excellent attendance, and highly relevant meeting content so that appropriate stakeholders can have timely and meaningful participation in project design decisions.
Response latency: time between asking a question or issuing an RFI and receiving a useful response (Decision-making no earlier than necessary)	Same as decision latency.	Same as decision latency.
Stakeholder involvement: degree to which intended stakeholders have timely and significant participation in task review and approval	Little formal definition of appropriate stakeholder involvement; wide variance in practice	90% of intended stakeholders have appropriately timely and participation that is self-assessed as significant in input to review and approval of major activities.
Detailed Cost conformance: fraction of estimated cost items that cost within 2% of their budgeted cost	Often not measured; often well less than 90% in practice.	>= 95% of budgeted items cost within 2% of their budgeted costs
Field-generated Requests for Information	Many	None for questions related to issues that could have been identified before construction
Rework volume: volume of work that must be redone because of unanticipated conditions	Significant, but largely unknown because often not measured explicitly	None for field construction work; Objective is 20-40% of virtual work. Note that design alternatives have value.
Field material delivery: fraction of all field material deliveries made 24 or fewer hours ahead of scheduled use	Usually << 80% in practice	>= 95% of all field material deliveries

Meeting efficiency: fraction of meeting activities that concern value-adding activities of Evaluation, Prediction, Alternative formulation or Deciding vs. non-value adding activities of Description, Explanation and Negotiation	Normally not formally measured, but anecdotally very low	>= 70%
Meeting agenda appropriateness: fraction of agenda items that are acceptable as topics of conversation for a majority of meeting participants; meetings cover 100% of agenda items that were voted onto agenda by a majority of invited participants	Normally not formally measured, but anecdotally very low	>= 90%
Model (or drawing) coordination consistency: fraction of multi-disciplinary models or drawings that are found to contain conflicts, interferences or inconsistencies at major project milestones	Normally not formally measured, but anecdotally very low	0 coordination inconsistencies at Construction Document review, during construction
Budget estimate conformance: fraction of budged items within 5% of budgeted cost in the Guaranteed Maximum Price (GMP) estimate with $0 contingency	Normally not formally measured, but anecdotally low	During design phase: 95% of budged items are within 5% of budgeted cost at relevant *DD* & *CD* milestones During construction phase: 95% of budgeted items within 2% of budgeted cost

Table 3 defines a set of specific breakthrough business objectives to give AEC professionals a vision and a specific set of measurable objectives that appear to be aggressive and highly valuable in practice. Each of these objectives includes quantitative, measurable outcomes. We chose the quantitative objective values to be representative of many AEC organizations, although each organization and project needs to set specific objectives. For example, some high-rise buildings will take longer than six months to create in 2015, but houses will often take only a few days or weeks. In our judgment, success in any of these objectives will improve the effectiveness and value of the industry dramatically. Each individually and all collectively appear achievable with the VDC methods and significant design-construction process change. However, none can be reached with simple incremental improvements in the current design-construction process.

The breakthrough objectives are “reach” objectives in the sense that they will be achievable only given success in practice of VDC visualization and metrics, integration and automation, plus significant but necessary enabling changes in the processes of design and construction.

Viewing current practice, we see opportunities to improve AEC performance in several areas, which we list in Table 3, where the mean performance is less than what is possible or would be valued by clients, and the variance is high.

Table 3: This table summarizes a number of important project-level *outcome* performance objectives for AEC projects, each of which is measurable. The second and third columns respectively suggest the typical practice in 2005 and our proposal for possible and highly valuable breakthrough performance one decade in the future. We suggest that our breakthrough performance objectives are possible in practice with effective use of VDC methods and will not be possible without effective use of such methods.

Performance Objective	Typical 2005 practice	Breakthrough Performance
Safety	Good	Better
Function: support of the operating facility for planned and actual user and owner objectives	Actual functional performance: not well known because of infrequent formal post occupancy evaluation (POE)	*Objective is 100%* satisfaction by systematic POE. Variance: +-5% by routine formal POE. The senior management of the owner organization must explicitly commission a POE or it will not normally happen. Unfortunately, owner management teams often are reluctant to commission a POE because it will identify problems in projects that the organization just spent so much money to develop, thereby disappointing the board that approved the project and embarrassing the senior managers who are paid to do well.
Cost: 1. Unit cost, e.g., per square foot or per unit of product produced 2. Conformance of actual final project cost with corporate management approved budget	Variance: +100%, -5%	1. Reduced 20% for similar or improved function, quality and schedule Early in the 2000s, some companies set this objective at a high level of management. 2. Companies deliver *98%* of their AEC projects with less than *2%* of unbudgeted change. Achieving this kind of goal requires that companies appropriately define the time at which the board-level cost objective is set.
Schedule: actual duration of project design and construction phases as well as variance with respect to approved schedules across the project portfolio	1. Design duration: 1-6 years; Construction duration: 1-3 years; 2. Variance: +100%, -5%	1. Design: 1 year 2. Construction: ½ year 3. Variance: +-5% Some companies have already established dramatic schedule improvement as 2008 objectives.
Sustainability: lifetime use of energy and water and materials; long-term suitability of the facility to support changing client needs with minimal retrofit costs	Lifetime energy use not systematically predicted during design phase	Lifetime energy use >= 25% better than 2005 comparables, as predicted during design phase and observed in practice. Many organizations now demonstrate significant commitment and achievement in this area.
Globalization: global sources of products and services; global	Wide variance in fraction of components and services potentially obtained from	1. >= 50% of components and services potentially obtained from global supply chains;

market	global supply chains. Wide variance in fraction of products and services potentially sold to global markets.	2. >= 50% of products and services sold to global market. These related objectives are important for many companies already, and inevitably global companies will find new opportunities for market growth, cost management and, perhaps most important, sources of innovation. Globalization goals are also important for regional companies that face or will soon face global competitors.

Table 3 suggests our view that there are opportunities to achieve breakthrough performance in the measured effectiveness of AEC practice as provided to clients. Achieving breakthrough objective performance, however, requires commitment to the objectives by clients and the providers of AEC services and products. We suggest that breakthrough performance objectives – such as these we give for 2015 – are possible in practice with effective use of VDC methods but will not be possible without effective use of such methods.

VDC emerges in stages

Organizations need to develop their own value proposition for VDC. The process of implementing it normally unfolds incrementally, partly by natural evolution but ideally following a broad strategy designed to obtain maximum organizational value from VDC. Initially, someone has a vision. The visionary creates a coalition, usually informally, that creates one or often several pilots, usually funded by individual projects, often with minimal upper management attention. Once project stakeholders perceive significant benefit, they work with senior management to obtain significant resources to implement selected VDC methods broadly across the organization or to implement one of its aspects that cannot be supported by an individual project because of its form, breadth of impact or long time to develop.

Normally, as discussed above in the **VDC maturity model** section, we find that VDC emerges in *three stages*: visualization, which is easily justified and implemented by a project; integration of multiple models and segments of the business; and automation to perform some significant portion of design or construction far more rapidly and reliably than in traditional practice. The latter two stages require corporate commitment, as does implementing the visualization stage consistently throughout an organization.

Visualization shows the product, organization and process design

Visualization is the first stage of VDC. Current PC technology makes it relatively easy to implement. Hardware is readily available, and there are a number of highly capable commercial software tools, all acceptably (though not cheaply!) priced.

Suggestion: As a measure of maturity of *Visualization*, use the number of intended stakeholders who report that they have timely and meaningful participation in project reviews. Use Schedule Conformance, Latency or Meeting Effectiveness as additional process objectives of *Visualization*. As shown in Table 2, set a quantitatively precise objective, such as at least 95% of all design, construction and coordination activities started and completed within one day of their lookahead schedule milestones. Measure process performance and intervene if the project team can improve performance in a way that adds value for the client.

Thus, in addition to careful attention to meeting participation, excellent attendance, and highly relevant meeting content, meeting effectiveness requires that stakeholders be able to explain their concerns so that others understand and to understand and react constructively to the designs of their partners. We find that visualization is, by far, the most effective way for stakeholders to describe and explain themselves accurately and to analyze in their minds their own work and that of others.

Suggestion: As a measure of VDC development capability maturity, use the extent to which projects have at least four principals who are skilled enough to develop Level-B and Level-C Product, Organization and Process models and manage effectively using models.

Integration: automated methods can relate the product, organization and process models

VDC project models are, by design, multi-disciplinary. For example, they include product, organization and process models, and the product model often includes physical component models and systems such as structures, egress and energy. The organization model represents all the parties with significant project responsibilities, and the process model represents the milestones and tasks of the organizational entities to develop the project. In the Visualization phase, designers manually create consistency among different models. The costs include effort and calendar time to build models and often reenter data from one model into another, time and effort to check for consistency, to analyze and use in management, and time and the design, construction or operational costs of the inevitable failures to maintain consistency. Although automated systems integration remains elusive in practice, some software vendors provide reliable and useful automated data exchange within the family of models they sell and high level of consistency among models. In addition, some software vendors support the Industry Foundation Class (IFC) data standard, which is designed to enable automated integration and interoperability. Ideally, automated Integration assures that the content of one model is propagated appropriately to other models, including both the choices of designers and the predictions of models.

Suggestion: As a measure of *Integration* capability maturity, measure assessed Model (or drawing) coordination consistency. Use Latency as an additional process objective.

Automation: automate some routine design and pre-fabricate to enable subassembly installation

We see that automation is the fundamental enabler of the breakthrough schedule objective identified in Table 3. The usual design-bid-build process probably cannot be compressed to building major projects within six months successfully. However, we suggest that many major projects can be built within about six months if major subsystems have a good integrated assembly design and manufacturing method, the manufacturing has carefully crafted and controlled supply chain management, and the construction process becomes design-fabricate-assemble for schedule-determining components.

Today, for example, the Heathrow Airport project detailed and pre-assembled rebar cages on a cycle time of one week or less, including detailing, fabrication, assembly, delivery, installation, and concrete pour [Kunz A and Ballard 04]. Many projects now do rapid design and pre-assembly of common large systems such as bathrooms for offices, kitchens for homes, and equipment spools for process plants. The job site installs these pre-assembled systems far more rapidly than it ever does field construction, with gain in schedule performance, final product quality, cost reliability, and often of base cost.

Suggestion: As a measure of *Automation* capability maturity, measure schedule conformance or design and construction phase productivity and cost.

Integrated Concurrent Engineering (ICE) supports VDC

VDC brings multiple stakeholders together. Different stakeholders all have specific business objectives, including standards of their fields such as architecture, engineering, construction or finance, which, although different, can provide complementary perspectives for a project. Different stakeholder perspectives and experiences build impediments to effective stakeholder collaboration, including vocabulary that often is not shared, differing methods and cultures, and they lack of experience working intimately together. Additional impediments to effective collaboration arise because stakeholders often have conflicting objectives, such as maximizing profitability of their own organizations and maximizing utilization of their own organizational assets.

Since the middle 1990s, a Jet Propulsion Laboratory (JPL) design group called “TeamX” has created conceptual stage designs of space mission within a few weeks, down from the year or so in its traditional practice [Mark 02]. Their method defines the functional objective, design response and makes many predictions about the cost, schedule and performance of the proposed mission project. The project design explicitly considers the physical and systems design of a physical vehicle, the organization to do the design, manufacturing and operations, and the processes of the design – manufacturing – operations team. The cost for a design study also dropped markedly; and the reported quality of designs improved – although of course there is continuing effort to improve design quality [Chachere 04].

The JPL TeamX has evolved a culture and set of methods to design space missions at a vastly accelerated pace in comparison with traditional design methods. Researchers now call this technology-mediated method *Integrated Concurrent Engineering* (*ICE*) [Chachere 04]. While the engineering details of space missions for JPL and building projects for AEC are different, both use projects to build new capabilities, and the projects involve collaboration among multiple disciplines and multiple stakeholders with a mixture of shared and competing objectives and methods.

We had the goals to develop multi-discipline project models collaboratively and very quickly that support highly effective multi-stakeholder design review and approval. Based on careful observation of the JPL method, we formalized, extended, specialized and then implemented the ICE method in our VDC work and practices. We find that it provides an exceptionally effective methodology for teaching and applying VDC methods.

Researchers at JPL and independently at Stanford built multi-screen interactive environment, such as one at Stanford shown in Figure 2, and we find that multiple displays are is necessary to allow disparate design teams to describe and explain their own models and to interpret those of their colleagues both effectively and quickly. The environment has two parts: technology and methodology. The example of Figure 2 implements and specializes the Interactive Room (iRoom) technology first established by the Stanford Computer Science Department [Johansson 02]. The environment includes multiple touch-sensitive displays, each showing the projected screen of a computer. The computers have low-level Internet Protocol message exchange methods and a shared database. The CIFE implementation of the iRoom also includes some methods to enable time synchronization of different applications running on networked iRoom computers.

The ICE method attempts to remove most non-value adding diversions from the attention of the design staff as they participate in an ICE session, such as clarifications of goals, methods or vocabulary, secondary responsibilities and waiting for responses to questions from fellow stakeholders. In the absence of diversions for designers and with technology, methods and skills to do very fast design and analysis, the design team achieves response latency of about a minute in greater than 99/100 inquiries by all members of the design team, which in comparison with routine practice is both very fast and very reliable. Independent observers report that CIFE ICE teams achieve rapid design project completion and generally high quality design product.

We found that a set of complex, interrelated factors enable high level ICE performance as shown in Table 4.

Table 4: Factors that enable Integrated Concurrent Engineering. In our experience, each factor must be well managed to achieve high performance ICE. Coordination latency is an observable but non-specific indicator of failure to achieve high-level performance of any of these factors, resulting in ineffective or slow engineering design process.

Critical Factor	Success Target	Risk factors	ICE solution
Design staff focus	**100% available during meetings:** Design session participants focus exclusively on project work during design sessions;	Designers have other responsibilities during design sessions	Management support of focus; short meetings make enable managers to free valued staff; Culture and management practice, dedicate all participants during design

			sessions
Discipline-Specific Modeling. Visualization Tools	**Strategic:** Balanced so all potentially modeling and analysis tasks are very fast	Manual design activities bottleneck project schedule; One stakeholder fails to understand the model of another	Modeling, visualization, analysis and decision support tools enable all critical path activities
Information Network of designers	**Closed**: All activities' requisite knowledge, procedures, options, and authority are immediately available.	Delay to access design interpretation or decision-making	Heavy reliance on collaborative design sessions; designer collocation during sessions; careful pre-planed participant selection; appropriate participant training in modeling, analysis, interpretation of other models and collaboration
Communication Media Richness and Fidelity	**Rich**: Shared and personal, visual, multi-disciplinary, showing functional requirements, design choices and predicted behaviors	Slow process to describe models, explain rationale, evaluate choices, make predictions, create alternatives	Mature modeling and analysis tools; Personal workstations; shared iRoom displays
Independence of Management Structure	**High**: do design work with minimal management oversight.	Staff solicits or waits for management decisions	Exclude projects whose uncertainties or complexities require high oversight; staff selection and training to work independently; culture of autonomy; analysis and decisions visible to all
Organizational Hierarchy	**Flat**: Minimal organizational barriers or management overhead	Decision making slows awaiting exception resolution	One facilitator, no managers; culture of working with minimal management supervision
Goal Congruence	**High**: Participants aspire to project success; commitment to project success over functional goal optimization	Debates on process; decision flip-flops; large amounts of rework; hidden agendas	Culture; facilitator attention; discuss objectives and design process at session start; persistent shared view of formal objective metrics; culture of congruence; analysis and decisions visible to all
Process Equivocality	**Low**: Procedures and objectives are well understood and accepted	Extended debates about process or priorities	Pre-plan for process clarity; culture of autonomy; analysis and decisions very visible to all; team experience; excellent process facilitator
Integrated Conceptual	**Semantically rich:** Separate models use	Inflexible, coarse, or confusing	Careful design of the project ontology; simple

Models	consistent naming and level of detail; data stored in only one place but readily available to all relevant models (via data automated sharing) or visible to stakeholders (for shared understanding)		POP database to define conceptual entity names, references to values stored in databases of specialized applications
Topology of Stakeholder Social Network	**Pooled**: Actors resolve problems in small self-formed groups	Formal or inflexible coordination requirements;	Collocation; Projection screens; sidebar culture
Topology of Computer Applications	**Scale[2]-free network:** most applications access a shared database, which thus has very high network centrality	Inconsistent data definitions or levels of detail, missing data, participants or applications that do not understand or reference the shared project model	Shared database uses a POP format designed and understood by the project team members and, in support of automation, reliably accessible by the most critical design and analysis applications
Design subtask duration	**Less than 10 minutes:** participants decompose their activities into subtasks of short duration so that they can ask questions that can be answered easily, minimizing the duration of potential rework	Significant effort is required to appropriately decompose the activities of traditional practice, which often have duration of a day or two and little structured subtask decomposition.	Careful activity decomposition into subtasks, training of designers, and design of appropriately supportive software design and analysis applications

Based on theoretical analysis and observation, we find that ICE teams at JPL manage ten enabling factors that lead to exceptionally low information response latency, and consequently to a dramatic improvement in project duration over traditional methods. A carefully designed network of knowledgeable participants who have the skills and culture to work independently of much central management direction, along with rapid, precise, and semantically rich communication of design intent, choices and predictions, are two features of the ICE approach that shrink response latency to near zero. We present response latency as a unifying theoretical principle to describe, evaluate and manage engineering design collaboration, whether using traditional or ICE methods.

Suggestion: Measure latency for both traditional and existing co-located cross-functional teams, and assess the value to the organization of reduction in latency during design and construction reviews, to create major project deliverables, and more generally in design and construction management.

Suggestion: Implement ICE incrementally by extending ongoing traditions

---

[2] *Scale-free* networks have an exponential distribution of network links density, i.e., a few highly centralized nodes and most with low connectivity, while *Scaled* networks have a normal and generally more even link density distribution.

such as use of a co-located highly experienced cross-functional team to create project proposals in a short period of time and use of co-located cross-functional construction management review and value engineering teams.

Suggestion: ICE teams should establish the specific measurable goal of latency of minutes during ICE sessions and no more than two days outside of design sessions.

VDC models support and require economic impact analysis

The culture of AEC development considers costs carefully. Most universities teach cost accounting; companies have departments to do cost estimation, and projects budget, track and manage costs. Each project has a value proposition that justifies the owner's commitment to the project. In addition, in principle, designers, contractors and the owner could consider incremental changes to the product, organization or process design to evaluate the value to the owner as well as the first costs for the project.

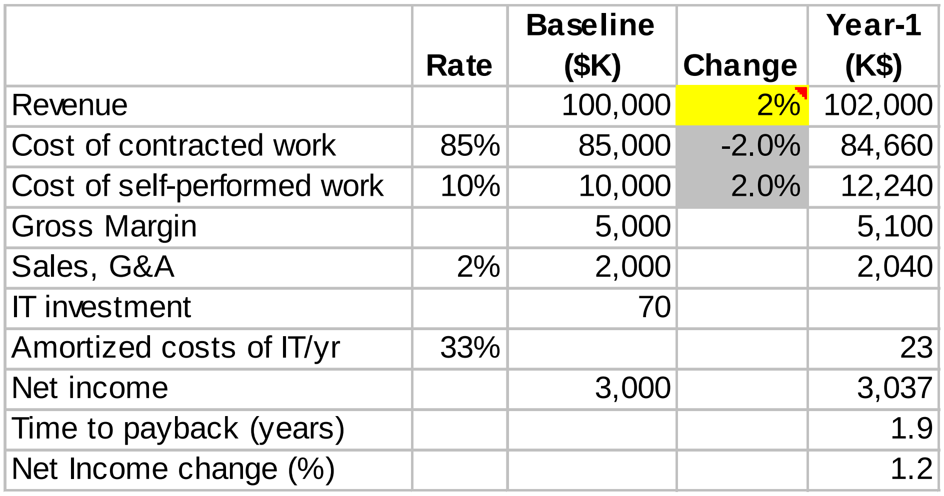
Giga Consultants developed the Total Economic Impact^{TM} (*TEI*) to allow analysis of both the value and the cost of software system investments [Cormier 02, Gliedman 03]. Macomber described its use in AEC [Macomber 03]. The method makes the value proposition explicit and quantitative, not just the costs, and it establishes quantitative assumptions and goals for business performance that responsible parties can track and manage to achieve. The method considers the anticipated effects on owner value and costs of investments. Values include revenues due to increase in market size as well as reduction in costs due to increased operating efficiency. Costs include the immediate and support costs of the investment.

We apply the total economic impact method to elucidate the value proposition of technology investments, specifically for investment in use of VDC for individual projects and for companies. The method requires estimating any change in revenue or cost of subcontracted work, plus cost of an investment and service of it. Thus, the method requires making assumptions about both how a new investment will be used and its impact on the business. While many engineers and managers resist making such assumptions, doing so creates a coalition in favor of an investment, which is good.

We use the method not to say what the revenue and cost changes will be but rather as a mechanism to set explicit, specific and public objectives. The investment advocate must identify individuals within the team who will "sign up" for specific revenue and cost numbers assuming a technology investment. Using the TEI method, the advocate and the management team can then identify the total economic impact of making those numbers. The method will predict the pay back time for the investment, given the assumptions. The development, business, and management teams can then make a collective decision to invest because the payback period and risks in the estimates are acceptable, or choose not to invest.

Suggestion: Stakeholder coalitions that support technology or method innovation should build a TEI model to explicitly represent their business assumptions about what value an innovation contributes to the business and their explicit measurable process and financial objectives for their work. The coalition can use the assumptions to help set functional objectives for projects and process performance measurements to make to support management.

Consider the example of Figure 9. This model assumes that IT costs are amortized and paid in the three years after the investment. The model further assumes that cost of contracted work drops due to the investment, because of better designs and cost management, but that the cost of self-performed work increases because of using the system. The TEI modeler adjusts the revenue change so that the payback period is acceptable for the company. If the marketing team will commit to the revenue change number (2% in this case), and the contract management and self-performed work teams also commit to their numbers, then management can predict that the investment will pay for itself in about two years. If these commitments have acceptable risk in the eyes of the team and management, and the payback period is sufficiently short, the investment is justified. The method identifies the team that must take responsibility for the business success of the investment, the commitment each subteam must make, and specific quantitative business objectives for each subteam. In addition, the model suggests some of the measurements the team should make and use in management, i.e., its costs of contracted and self-performed work.



	Rate	Baseline ($K)	Change	Year-1 (K$)
Revenue		100,000	2%	102,000
Cost of contracted work	85%	85,000	-2.0%	84,660
Cost of self-performed work	10%	10,000	2.0%	12,240
Gross Margin		5,000		5,100
Sales, G&A	2%	2,000		2,040
IT investment		70		
Amortized costs of IT/yr	33%			23
Net income		3,000		3,037
Time to payback (years)				1.9
Net Income change (%)				1.2

Figure 9: Simple Total Economic Impact^{TM} model applied to a simple pro forma financial summary of a representative General Contractor (GC). This model assumes typical revenue, costs of business and a relatively comfortable baseline net income for a typical GC. With the assumptions given, following the investment, the company must both predict and commit to increasing revenue by at least 2%, reducing cost of contracted work at least 2% and increasing cost of self-performed work no more than 2%. The team making this commitment constitutes the coalition in favor of the innovation. If the team makes its numbers, the investment will pay for itself in slightly less than two years.

Simple analysis of TEI models for AEC leads to a number of important conclusions. First, assuming that the investment level is modest (e.g., $70K as we assumed), VDC technology investment can be a feasible goal for a technology *leading* company in a relatively good market. In fact the revenue increases we see due to VDC can be dramatic, and the savings of contracted work can also significantly exceed the usual GC profit. However, as the model indicates, an investing company requires superb execution to make its commitments and simultaneously to preserve its margins on other work. Assigning the best staff may make the investment successful but make the rest of the business falter. Second, VDC investment is unlikely to make business sense in a bad market. Third, if a new VDC method becomes established in a market, low-cost companies will need to invest to stay in business as competitors grow. While their costs of investment will be marginally lower because they are late in acquisition, their market growth might actually be negative due to the earlier success of their competition.

iRoom			
hardware			
PC	2,500	4	10,000
Projector	3,000	3	9,000
Smart Board	2,000	3	6,000
installation	2,000	1	2,000
Software			
4D	10,000	1	10,000
CIFE infrastructure	0	1	0
MS Project	1,000	1	1,000
Organization model	10,000	1	10,000
Training (days)	2,500	4	10,000
Internal staff development	500	20	10,000
Total			68,000
Budget			70,000

Figure 10: Representative costs to implement basic VDC capabilities in a company. These costs assume purchase of a three-screen iRoom, such as that shown in Figure 2, purchase of 4D and organizational modeling software at certain assumed prices, some staff time, and availability of good CAD modeling software. The TEI analysis of Figure 9 assumes this bottom line number as the investment cost.

The most important conclusion of analysis of TEI models for AEC concerns the crucial role of slack resources. The numbers of Figure 10 highlight the issue. If a good engineer is available for assignment to support a discretionary investment, the staff cost is the sum of direct plus indirect cost. In this example, at $62.50/hour loaded cost, the internal staff cost represents a significant but not a dominating fraction of the total investment cost. However, many AEC companies work with virtually no slack resources. In this case, the cost of an internal staff member becomes the marginal cost of taking that engineer off a critical project. Those costs can easily be $10K per day on projects with liquidated damage risk. If the cost of the staff engineer changes from loaded to opportunity in a fully committed company, almost no investment will ever reach a reasonable payback time hurdle rate. The AEC industry is nearly universal in its culture of running with negligible resource slack. This simple TEI analysis suggests that it is indeed rational for companies to resist almost all investment, in the absence of slack. This simple example also suggests the opportunity for companies that will make small pools of slack resources available to support promising investments.

Summary

The theoretical basis of VDC includes several major components, which we discussed above in the Themes section:

- *Engineering modeling methods* to represent the product, organization, and process;
- *Model-based analysis methods* to predict the project schedule, cost, effort, hidden work, organization, process, and schedule risks, 3D and 4D interferences;
- *Visualization methods* to present views of the product, organization and process in ways that are clear for professionals and a broad class of interested stakeholders;
- *Business metrics and methods* to manage project processes using measured performance; and
- *Economic Impact*, i.e., quantitative models of both cost and value of capital investments, including the project as a whole, individual project elements, and incremental investments to change the process.

We emphasize this theoretical framework because we feel that it is an appropriate subject for careful design, academic research, and potential and rigor if applied consistency and appropriately. The tempting alternative is to approach these issues differently for each project. Our experience is that developing and applying a theoretical framework leads to better, less expensive and more predictable project processes and outcomes.

Discussion

VDC strategy can enable companies to achieve significant breakthrough objectives

Some organizations now find significant competitive advantage from their facilities or their timeliness of developing new facilities. Other companies find that unbudgeted changes to new facility development significantly impact corporate profitability. For all these reasons, senior management has started in some organizations to place dramatic “breakthrough” objectives on the capital development process. Some companies now have senior management objectives to lower cost (say per square foot) by 20% while improving quality and schedule; others want to reduce unbudgeted change to a few percent. Others want to develop new facilities – from project approval through to high value occupancy – in dramatically less time while preserving or improving quality, schedule and cost performance. Uniformly, project delivery organizations accept that they cannot make these objectives with incremental changes to their traditional development processes. Repeatedly, companies find that a VDC strategy and implementation plan is a crucial element of their plan to achieve breakthrough organizational goals.

With hardware and software vendors and service providers all selling their offerings aggressively, there is a technology push for VDC models today, and project members often find them very appealing. In our experience, the biggest driver for VDC methods is demand-pull: senior management of some AEC providers and some owners see the value in a competitive market of “faster, better, cheaper” products and services, and they pursue VDC methods as the best way to achieve such competitive advantage.

Different stakeholders have different responsibilities

A building design project will include multiple participants, such as architecture, structural engineering, interior design, landscape design, energy analysts, lighting consultants, heating and ventilation consultant, construction planning and scheduling, cost estimation, users and owners. Representatives of each of these specialties will reference the evolving project POP model and contribute to its detail as the team increases detail from Level 2 to Level 3. Each of these specialists has specialized models for the purposes of each specialty. The stakeholders can come together and do systems level analysis and design slowly in a traditional design process, or they can work quickly in an ICE environment in which each has responsibility for one or more specialty models. All these stakeholders can participate in the VDC method of modeling to support business objectives, and they can benefit from the shared vision, models and methods.

Stakeholders collaborate by sharing visualizations

The VDC method strongly emphasizes use of models that can be described to and evaluated by multiple stakeholders. In our experience, only visual models have the power to support description to and evaluation by a broad class of stakeholders. Thus, we emphasize use of visual product modeling tools, i.e., CAD; visual organization models, i.e., use of visual organization charts; and use of visual activity network diagrams and schedule bar charts – which have some meaning to professionals – and 4D schedule animations that most stakeholders can understand. The multi-screen iRoom allows presenting, describing and evaluating different project perspectives simultaneously, as well as using them to explain the reason for analyses and evaluate design quality.

VDC enables better project management

Once started, projects always face severe time, cost and quality constraints. The integrated focus on all the aspects that can be managed, -- product, organization and process -- at least enables projects to find integrated solutions to complex interrelated problems. In addition, because projects change continuously, change management is a major issue in projects. Current AEC modeling tools easily enable creation of multiple versions of design documents, although they have very limited capability to identify change dependencies among the contents of related models. VDC gives an integrated project framework to describe, track and manage changes in the product, organization and process over time, which today can be visualized and managed socially. The multi-screen iRoom already makes the display, comparison and management of different versions feasible.

VDC Limitations

The theoretical framework suggests limits of VDC, each of which we see in practice. Important limits include:

- **Owner management:** VDC non-users report that lack of owner request or initiative limits their interest and willingness to use VDC in practice [Kunz and Gilligan 07]. Apparently, owners take a limited view of the potential value of VDC, carefully assessing the costs but not its potential value for projects. Because cost minimization is comparatively easy and relatively straightforward managerially, owners frequently establish minimal apparent risk and minimum first cost as crucial selection criteria for new projects, and they use similar restrictive criteria as crucial criteria in deciding on incremental changes to a base project design. Unless asked and encouraged, designers will not even ask the question of life cycle value of projects or incremental changes to projects. In the absence of asking about the value proposition seriously, the cost-value tradeoff defaults to a cost minimization exercise.
- **Project-orientation of the AEC industry:** owners, designers and contractors all have a culture and practice of project work. It is difficult, and often not advisable, to make investments to improve processes when individual projects cannot justify them. Even if successful, it is difficult to institutionalize the lessons learned about how to use innovative methods effectively on subsequent projects.
- **AEC industry culture: A**rchitects, engineers and contractors all have a culture and methods that minimize cost. With notable exceptions, many lack a culture that seeks to maximize value. This culture follows owner preference, but it also represents a culture that some AEC players accept in order to minimize their short-term project risks.
- **Sharp theoretical basis for VDC methods:** The VDC modeling and particularly the model-based VDC analysis methods are still undergoing theoretical development. In an industry that appropriately values risk mitigation, the changing theoretical foundation provides a handy and often an appropriate excuse to avoid use of the methods.
- **Learning:** The AEC industry has several practices that limit the ability of individuals, teams and companies from learning from experience. The ever-changing project basis of the industry contributes to diffusion of experience, rather than systematic learning [Taylor 04]. Owners systematically fail to commission post occupancy evaluation of new projects and recently completed project development processes, and AEC providers do not do such studies on their own.
- **Tools that are capable and integrated:** Users consistently report that VDC modeling and analysis tools are difficult to use, support limited business objectives, and do not integrate easily or well with other tools that the project wants to use. The National Institute of Standards and Technology recently published a report that attributes nearly a $16B annual cost to the lack of interoperability in US capital facilities development [NIST 04]. Anecdotally, individual projects incur real costs as developers recreate or reenter the same information in their models, often developing design details several times though different stages the design process. However, users report that they use VDC

methods and receive value from its use in spite of the limits that they acknowledge.

Glossary

4D model: a model that links the 3D description of a product to be constructed with the plan and time-based schedule to build it. A 4D animation shows the construction of a project.

Activity: identifiable work to be performed by an actor using a set of resources to complete an identifiable activity in a process. Actors and a process together define an organization-process model.

Actor: a project group or individual stakeholder with responsibility for an activity in a process. Actors and a process together define an Organization-Process model.

Behavior: predicted or observed measurement about an aspect or element of a design, such as cost, schedule or capacity. Behavior is a major segment of POP models.

CD: See *project phases*

Conformance: percentage agreement of planned and measured schedule, cost or quality data. A good project has high measured daily or weekly conformance (> 80%) of planned 2 or 3-week lookahead schedule to actual schedule performance. “Plan Percent complete” (PPC)” is another term for schedule conformance.

Controllable factor: a condition that a designer or manager can actually control, such as a design choice about a product, the choice of what teams and people to hire, and the design of a work process. *Controllable factors* affect *process performance* and project outcomes.

DD: See project phases

Form, or *Scope:* the choice made by a designer in response to a *function* requirement, including physical elements such as a door and abstract elements such as design teams and activities. Scope is a major segment of POP models.

Function: requirement for a project that must be met because it is intent of an owner or comes from a municipality or usual design practice. *Function* drives choice by the design team of designed *form* or s*cope.* The designed and ultimately the built scope in turn affect the behaviors of design, construction processes, such as schedule and cost, and the then operations, such as energy use. Function is a major segment of POP models.

ICE: Integrated Concurrent Engineering, a way to organize a design team that enables stakeholders from multiple disciplines to participate concurrently to develop integrated project designs very rapidly.

LOD: Level of detail, which is a measure of the complexity of a model. The most abstract (“Level-A”) have about one element in each major section; about ten elements in each major section in Level-B, and increasing in detail in higher levels.

OBS: Organization Breakdown Structure, the definition of the names of generic teams that design and build a product.

Organization: a team of people that does the work specified in a *process* to create a *product*. POP models represent the Functions, Scopes and Behaviors of project Organizations.

PBS: Product Breakdown Structure, the definition of the names of generic physical elements in a physical product design.

POE: Post occupancy evaluation of the quality of a project by affected stakeholders

POP: Product – Organization – Process, the integrated perspective of VDC models, representing the integrated *functions*, scope and *behaviors* of each.

Process performance metric: an aspect of project performance that a team can measure frequently (hourly, daily or every week or two) and use to judge how well past management choices (see Controllable factors) are moving toward the final project outcome objectives.

Process: Activities and procedures followed by an *organization* team to create a *product*, i.e., the work the organization does, or a statement of "what we plan to do." Plan activities are statements of the work to do including precedence relationships among activities, and Schedule activities have a planned start and end. Activities have responsible actors; they may have coordination and rework dependencies that identify the other activities with which they must coordinate or that must initiate rework if an individual activity encounters some sort of failure. POP models represent the Functions, Scopes and Behaviors of project Processes.

Product: the physical or abstract deliverable of a project as the organization follows the process, typically a building, facility or design. POP models represent the Functions, Scopes and Behaviors of project Products.

Project outcome: an aspect of a project that is important and normally can be known only at the project completion, such as final quality, cost, schedule and safety. Outcome follows *process performance* and in turn *controllable factors*.

Project phases: traditional AEC phases include pre-project planning, which obtains budget and initial zoning approvals; early Schematic Design (*SD*), Design Development (*DD*), which adds system issues to the design, and Construction Document preparation (*CD*), which is the final design phase. Design is followed by *Construction*, *Commissioning* and *Occupancy*.

SD: See project phases

Stage of VDC implementation: VDC emerges incrementally. Normally the first stage is *visualization* to support understanding and decisions of an individual project team, then systems based *integration* of multiple models to facilitate description, explanation, evaluation and prediction of their behaviors, and finally as *automation* of significant portions of design and construction activity.

TCE^2: Total estimated project Time, Cost, Effort and life cycle Energy use.

TEI: Total Economic Impact®, a simple pro forma financial model that shows both the value added to a business and the costs incurred of a technology investment.

VDC: Virtual Design and Construction, the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives.

Virtual model: a model in the computer of some aspect of a project. Virtual models can complement and often replace physical models, and they can be built long before the actual product, organization or process emerges in real life. Our experiences are that if a team cannot build a project in the computer, it cannot build it in real life, and that building virtual models can significantly decrease project risks.

Visualization: presenting a model in a way that is meaningful to diverse stakeholders, which is normally visual, such as a 3D model of a *product*, a network of actors and activities for *organization* and *process* models, and time-based (*4D*) animations of product construction as well as time graphs of building performance.

WBS: Work (or Process) Breakdown Structure, the definition of the names of generic activities to design and build a project.

Acknowledgements

We appreciate the encouragement, technical help and financial support of the CIFE member companies over the years that we have taken to develop this work. CIFE has provided the majority of the financial support to do this work. We also appreciate the passion, skill and hard work of dozens of our wonderful students, and specifically Calvin Kam who developed the models in our test case example with the help of his colleagues and sponsors at the US General Services Administration.

References

[aecXML 05] North American International Alliance for Interoperability (IAI) chapter web site, last accessed 5 October 2005, http://www.iai-na.org/about/resources.php

[ASTM 05]: American Society of Testing Materials (ASTM): Standard Classification of Building Elements and Related Sitework - UNIFORMAT II, last accessed 26 September 2005, http://www.uniformat.com/

[Bedrick 05] “BIM and Process Improvement,” *AECbytes* Viewpoint #20
December 13, 2005, http://www.aecbytes.com/viewpoint/issue_20.htm, last accessed 23 December 2005.

[BLIS 00] BLIS Software demonstrations: IAI International Council Summit, October 2000, website last accessed 6 October 2005, http://www.blis-project.org/demos/index.htm, 2000.

[BLIS 02] BLIS project website, last accessed 6 October 2005, http://www.blis-project.org/index2.html, August 2002.

[Chachere 04] Chachere, John, Kunz, J., and Levitt, R., “Observation, Theory, and Simulation of Integrated Concurrent Engineering: Grounded Theoretical Factors that Enable Radical Project Acceleration”, CIFE WP 87, also available at http://cife.stanford.edu/online.publications/WP087.pdf, 2004.

[Clayton 96] Clayton, M. J., J. C. Kunz and M. A. Fischer, “Rapid Conceptual Design Evaluation Using a Virtual Product Model,” *Engineering Applications of Artificial Intelligence*, Vol. 9, No. 4, Elsevier Science Ltd., pp. 439-451, 1996.

[Cormier, 02] Cormier, Bob, "The Total Economic Impact^{TM} (TEI) of Deploying Network Appliance’s NearStore Product for Backup and Recovery," Giga Consulting Group, last accessed 6 October 2005, http://www.netapp.com/tech_library/ftp/analyst/ar1010b.pdf (September 2002)

[Dym et al. 88] Dym, C. L, R. P. Henchley, E. A. Delis and S. Gonick, “A knowledge-based system for automated architectural code checking,” *Computer-Aided Design* 20(3): 137-145, 1988.

[Flemming and Woodbury 95] Flemming, U., and Woodbury, R., “Software Environment to Support Early Phases in Building Design (SEED): Overview,” *Journal of Architectural Engineering*, Vol. 1, 147-152, 1995.

[Froese 02] Froese, Thomas, Current Status and Future trends of Model Based Interoperability, eSM@rt Conference Proceedings Part A, pp. 199-208, University of Salford, 2002, ISBN 0902896415.

[Garcia 04] Garcia, A.C.B., Kunz, J., Ekstrom, M., and Kiviniemi, A. 2003], Building a Project Ontology with Extreme Collaboration and Virtual Design and Construction, *Advanced Engineering Informatics*, Volume 18 # 2, April 2004, Pages 71-83, also CIFE TR152, http://cife.stanford.edu/online.publications/TR152.pdf

[Gero 90] Gero, J.S. (1990). “Design Prototypes: A Knowledge Representation Schema for Design,**”** *AI Magazine*, 11(4), 26-36.

[Gliedman 03] Gliedman, C., “the total Economic Impact^{TM} of Deploying the Sun-Sybase Enterprise Data Warehouse Reference Architecture,” Giga Consulting Group, http://www.sun.com/products/architectures-platforms/wp/GigaInformationGroup_TEI_Sun-Sybase.pdf (August 2004)

[Haymaker 05] Haymaker, John; Ayaz, Engin; Fischer, Martin; Kunz, John; Kam, Calvin, Ramsey, Marc; Suter, Ben and Toledo, Mauricio, “Methodologies to Manage and communicate multidisciplinary design processes and information for the Stanford University Green Dorm Feasibility Study, *ITCON*, Fall 2005

[Hunt 96] Hunt, Daniel V., **Process Mapping: How to Reengineer Your Business Processes,** John Wiley and Sons, 1996.

[IAI 05] IAI international web site, last accessed 26 September 2005, http://www.iai-international.org/Model/IFC (ifcXML) Specs.html

[Jin et al. 95] Jin, Yan, Raymond E. Levitt, Tore Christiansen, and John C. Kunz, “The Virtual Design Team: A Computer Simulation Framework for Studying Organizational Aspects of Concurrent Design,” SIMULATION Journal, Vol.64, No.3, pp. 160-175, March 1995.

[Johansson 02] Johansson, B., Fox, A., and Winograd, T. “The Interactive Workspaces Project: Experiences with Ubiquitous Computing Rooms,” IEEE Pervasive Computing Magazine 1(2), April-June 2002.

[Kam 02] Calvin Kam and Martin Fischer, PM4D Final Report. CIFE technical Report 143, Stanford University 2002, also available at http://www.stanford.edu/group/4D/download/c1.html

[Koo and Fischer 00] "Feasibility Study of 4D CAD in Commercial Construction", Journal of Construction Engineering and Management, ASCE, 126(4), 251-260, 2000.

[Kam 04] Kam, Calvin and Fischer, Martin, "Capitalizing on early project decision-making opportunities to improve facility design, construction and life-cycle performance POP, PM4D and decision dashboard approaches", *Journal of Automation in Construction*, 13, 1, pp. 53-65, Elsevier, 2004.

[Kunz and Gilligan 07] Kunz, John and Gilligan, Brian "Value from VDC / BIM Use," last accessed 13 April 2007, http://cife.stanford.edu/VDCSurvey.pdf

[Kunz 05] Stanford Civil and Environmental Engineering class CEE243, last accessed 26 September 2005, Virtual Design and Construction, http://www.stanford.edu/class/cee243/.

[Kunz, A and Ballard 04] Kunz, Alex, and Ballard, Glenn, "Opportunities Offered by Computer Modeling for Restructuring Construction," *Proceedings of the 2004 CIB World Congress*, May 2004.

[Kunz 98] Kunz, John, Christiansen, Tore R., Cohen, Geoff P., Jin, Yan, Levitt, Raymond E., "*The Virtual Design Team:* A Computational Simulation Model of Project Organizations," *Communications of the Association for Computing Machinery*, pp. 84-92, November, 1998.

[Levitt 02] Levitt, Raymond and Kunz, John, "DESIGN YOUR PROJECT ORGANIZATION AS ENGINEERS DESIGN BRIDGES," CIFE Working Paper #73, 2002.

[Londoño 89] Londoño, F., Cleetus, K. J. Reddy, Y. V. "A Blackboard Scheme for Cooperative Problem-Solving by Human Experts", *CERC-TR-TM-89-001*, Concurrent Engineering Research Center, West Virginia University, last accessed 26 September 2005, http://www.cerc.wvu.edu/cercdocs/techReports/1989/cerc-tr-tm-89-001.pdf.

[Macomber 03] Macomber, John, "Follow the Money: What really Drives Technology Innovation in Construction", ASCE Construction Research Congress, Proceedings of Construction Research Congress, March 19-21, 2003, Honolulu, Hawaii; Sponsored by Construction Institute - Construction Research Council, American Society of Civil; Engineers Construction Engineering and Management Program, University of Colorado at Boulder, edited by Keith R. Molenaar, (E) and Paul S. Chinowsky, *Reston, VA*, 2003

[Mark 02] Mark, G., "Extreme Collaboration" *Communications of the ACM*, Volume 45, Number 6, pp. 89-93. 2002.

[NIST 04] "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry," NIST GCR 04-867, last accessed 26 September 2005, http://www.bfrl.nist.gov/oae/publications/gcrs/04867.pdf (August 2004)

[Prasad 96a] Prasad, B., Concurrent Function Deployment – an Emerging Alternative to QFD: Conceptual Framework, Advanced in Concurrent Engineering: Proceedings of CE96 Conference, USA, pp. 105 – 112.

[Prasad 96b] Prasad, B., Concurrent Engineering Wheels, in *The RASSP Digest* - Vol. 3, 1st. Qtr. 1996, last accessed 26 September 2005, http://www.eda.org/rassp/documents/newsletter/html/96q1/news_6.html

[Shea and Cagan 99] Shea, K. and Cagan, J., “The Design of Novel Roof Trusses with Shape Annealing: Assessing the Ability of a Computational Method in Aiding Structural Designers with Varying Design Intent,” *Design Studies*, Vol. 20, 3-23. 1999.

[Stiny 80] Stiny, G., “Introduction to Shape and Shape Grammars,” *Environment and Planning B: Planning and Design* 7, 343-351, 1980.

[Tarandi 03] “Editorial: IFC - product models for the AEC arena,” **ITcon** Vol. 8, Special Issue IFC - Product models for the AEC arena, pg. 135-137, http://www.itcon.org/2003/11, last accessed 3 January 2006.

[Taylor 04] Taylor, J. and Levitt, R.,. “Understanding and Managing Systemic Innovation in Project-based Industries.” In: Slevin, D., Cleland, D. and Pinto, J. (Eds.), **Innovations: Project Management Research** 2004, pp. 83-99. Project Management Institute, Newton Square Pennsylvania, 2004.

[Teicholz 04] Teicholz, Paul, “Labor Productivity Declines in the Construction Industry: Causes and Remedies” **AECbytes** Viewpoint #4, April 14, 2004, http://www.aecbytes.com/viewpoint/issue_4.htm, last accessed 3 January 2006.