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Framework & Case Studies Comparing Implementations & Impacts of 3D/4D Modeling Across Projects

By

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FRAMEWORK AND CASE STUDIES COMPARING IMPLEMENTATIONS AND IMPACTS OF 3D/4D MODELING ACROSS PROJECTS

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Extended Summary

Today few project teams avail themselves of the continued and widespread use of 3D/4D modeling to the extent effective and efficient. Due to this limited practice, the implementation of 3D/4D modeling is mostly based on anecdotes from a few past projects. However, ad-hoc experiences from individual projects are not sufficient for AEC professionals to guide implementations of 3D/4D modeling. In addition, we found a number of general beliefs (p.2) about what has been learned from implementations and impacts of 3D/4D modeling. These beliefs are tacit knowledge and hence might be valid or could be wrong when AEC professionals apply them from one situation to another. Therefore, the goals of our research were to:

- develop a framework to capture, describe, and organize the characteristics of 3D/4D modeling implementations so that AEC professionals can document 3D/4D modeling experiences and compare them across projects; and
- provide researchers with a framework for cross-case pattern analysis that supports the generation of insights and guidelines.

To gain a grounded understanding of important characteristics of 3D/4D modeling implementations, we studied 3D/4D modeling practices on thirty-two case projects.

- The thirty-two projects were completed from the 1997 to 2008.

- Fifteen projects are located in the U.S., twelve projects are located in Finland, three projects are located in other European countries, and two projects are located in Asia.
- The thirty-two projects range from a few million dollars to several hundred million dollars.
- The thirty-two projects include public and private projects in residential, commercial, institutional, industrial, and transportation sectors.
- The delivery methods of the thirty-two projects include design-bid-build, design/build, and CM/GC.

From the study of the thirty-two case projects, we developed a framework that consists of 4 main categories, 14 factors, and 74 measures to capture, describe and organize the characteristics of a 3D/4D modeling implementation in terms of:

- modeling uses (i.e., why 3D/4D models were used);
- timing of model uses (i.e., when 3D/4D models were created and used);
- stakeholder involvement (i.e., who was involved in the 3D/4D modeling implementation);
- modeled data (i.e. what was modeled and the level of detail of the 3D/4D models);
- software (i.e., with which software tools 3D/4D models were created or analyzed);
- workflow (how was the 3D/4D modeling implementation carried out);
- effort/costs (how much effort/cost was needed to implement 3D/4D modeling); and
- benefits (what were the benefits of the 3D/4D modeling implementation).

To assess the descriptive power of this framework to document implementations of 3D/4D modeling, we used three criteria to evaluate how well the framework documents these implementations.

- We made the framework as “objective” as possible so that the documentation of a 3D/4D modeling implementation relies as little as possible on personal judgment and as much as possible on implementation facts.

- We checked that the framework is "consistent" to ensure that the measures in this framework are replicable and applicable across a wide spectrum of projects with variations in project type, size, delivery method, time period of design and construction, and project location.
- We ensured that the documentation of 3D/4D modeling implementations is "sufficient" to compare implementations with each other and learn from them.

To demonstrate how the framework supports comparisons of 3D/4D modeling experiences across projects, we developed five crosswalks to discern the similarities and differences among implementations of 3D/4D modeling on the 32 case projects. The five crosswalks show:

- nine 3D model uses, seven 4D model uses and their related benefits to building design as well as project processes and organization (p.25 and p.29);
- seven time periods of 3D/4D model uses and the timing of their related benefits to building design as well as project process and organization (p.43);
- eleven situations of key stakeholder involvement and their corresponding impacts (p.52);
- three situations of the timing of developing levels of detail in 3D/4D models and their corresponding impacts (p.59, p.59 and p.64); and
- six steps in a typical workflow of 4D modeling and three issues that lead to inefficiencies in each step of the workflow (p.67).

From analyzing the five crosswalks, we substantiate and refine the common beliefs about 3D/4D modeling implementations (p.71). In addition, we found out the following patterns for 3D/4D modeling implementations on the thirty-two case projects.

- The uses of 3D/4D models vary according to the business drivers of the project stakeholders, project challenges, and project phases when 3D/4D models are created. The four primary uses of 3D models are 1) interaction with non-professionals, 2) construction planning, 3) drawing production, and 4) design coordination. Moreover, companies are starting to integrate 3D/4D models for more data-driven tasks such as analysis of design options, supply chain management, cost estimating and change order management, facility management, and establishment of owner requirements.

- The use of 3D/4D models early in the design phase not only results in immediate benefits (which relate to the ongoing project process and organization) but also late benefits (which accrue during the downstream processes and relate to the performance of a finished building product). However, the use of 3D/4D models in the preconstruction and construction phases mostly leads to immediate benefits.
- The benefits to every individual stakeholder and to the whole project team are maximized when all the key stakeholders are involved in creating and using 3D/4D models.
- Creating 3D/4D models just-in-time and at the appropriate level of detail that matches a particular model use is instrumental in maximizing benefits. The appropriate level of detail depends not only on model uses but also information available at a particular stage of a project.
- In a typical workflow of 4D modeling, steps 1, 2, and 3 (i.e., collecting data, modifying the original schedule, and creating or modifying 3D models) involve no technical issues with regard to 4D modeling software; step 4 (i.e., linking 3D model and schedule) involves only software technical issues; steps 5 and 6 (i.e., reviewing 4D models and updating 4D models) involve software technical issues as well as issues pertinent to data exchange and organizational alignment.

Although we collected the financial data for as many projects as possible, we were not able to determine a pattern between the project cost and the cost (work-hours) of creating 3D/4D models. The main reason is that this kind of information is often confidential and not accessible.

Some of our findings resonate with guidelines in the AGC *Contractors' Guide to BIM,* such as guidelines on “one model or composite model”, “the BIM Process basics in a typical project scenario”, “partial BIM uses”, “the project delivery method”, “getting over the wall”. The concrete case data in this report and in-depth analysis from synthesizing these cases also reinforce the insights of the AGC expert panel on how to get started with a BIM-based process. This report illustrates the common ground shared between the AGC's BIM guidelines (p.74). The difference of this report to the AGC's BIM guidelines lies in that AGC's guidelines were generated from the experience, beliefs and visions of an expert panel, whereas the implementation patterns in this report emerged from our empirical studies on 32 projects.

In the next phase, we will extend this research to:

1. developing a better way of quantifying the value of benefits and differentiating the value of benefits to different stakeholders;
2. validating how helpful the framework is for generating 3D/4D modeling guidelines and managing 3D/4D modeling implementations;
3. investigating the benefits and uses of 3D/4D models in different contexts of companies or countries;
4. conducting a large-size survey to verify the implementation patterns emerging from this study and generalize to a broader range of cases for 3D/4D modeling implementations;
5. extending the 3D model uses emerging from the 32 case studies: 1) to other important model uses such as 3D laser scanning for as-built documentation and CNC usage (e.g., metal cutting by MEP subs); and 2) to new areas of model uses such as 4D workflow optimization;
6. studying inter-organizational implementation of 3D/4D modeling and to address lessons learned from facilitating exchange and interoperability of information and standardizing the work methods for 3D/4D modeling implementations.

This report will help a reader gain in-depth understanding of implementation and impact of 3D/4D modeling.

- What drives the use of 3D/4D models by different project stakeholders, in different project phases, and for different project sizes, complexity, or contractual relationships?

- How will model uses impact on building design as well as project processes and organization?
- How will the timing of 3D/4D modeling affect the timing of benefits?
- How will different situations of stakeholder involvement have impacts on the benefits accrued to them?
- How will the timing of developing levels of details in 3D/4D models correlate to the benefits reaped on a project?
- What leads to inefficiency in a typical workflow of 3D/4D modeling?

With the framework, practitioners will be able to:

- document, compare, and learn from their own projects;
- design the implementation in terms of the level of detail in 3D/4D models (i.e., modeling product), the stakeholders to be involved in building and using 3D/4D models (modeling organization), and the timing to start 3D/4D modeling (modeling process) and customize the modeling product, organization, and process to different model uses.

With the framework, researchers will be able to:

- conduct a large-size case survey with a structured form and well-defined measures;
- investigate the relationships between the controllable factors and the values of creating different kinds of 3D/4D models.

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1. Introduction

Teicholz (2004) suggests that the introduction of 3D object-based CAD is one of the most important new approaches to construction productivity improvement to allow improved design, team collaboration, construction bidding, planning and execution, and real owner value at all stages of a project's life cycle. Despite this vision, few project teams avail themselves of the continued and widespread use of ***3D/4D modeling***[1] to the extent possible and economical. One challenge of crossing the "chasm" (Moore 1999) from "early adopters" (a few visionaries) to "early majority" (most pragmatists) lies in the lack of concrete and formal understanding of ***implementations*** and ***impacts*** of 3D/4D modeling on projects.

Many researchers and practitioners have reported on the use of 3D/4D modeling on single projects (e.g., Collier and Fischer 1995; Griffis et al. 1995; Fischer et al. 1998; Koo and Fischer 2000; Coble et al. 2000; Riley 2000; Schwegler et al. 2000; Bergsten and Knutsson 2001; Whyte 2001; Rischmoller et al. 2001; Messner and Lynch 2002; Roe 2002; de Vries and Broekmaat 2003; Kam et al. 2003; Hastings et al. 2003; O'Brien 2003; Staub et al. 2003; Haymaker et al. 2004; McQuary 2004; Webb and Haupt 2004; Sersy 2004; Cunz and Knutson 2005; Bedrick and Davis 2005; Eberhard 2005; Gonzales 2005; Hagan and Graves 2005; Hamblen 2005; Holm et al. 2005; Joch 2005; Jongeling et al. 2005; Khanzode et al. 2005; Koerckel 2005; Sampaio et al. 2005; Sawyer 2005; Majumdar and Fischer 2006). These papers and presentations inform AEC professionals about the benefits realized and obstacles encountered on individual projects. However, ad-hoc experiences from one project cannot be generalized (Yin 1994) and hence are not sufficient for AEC professionals to formalize guidelines on 3D/4D modeling and apply them to other projects.

Analyzing these references, we found a number of general beliefs (Table 1) about what has been learned from implementations and impacts of 3D/4D modeling. These beliefs

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[1] The definitions of the terms formatted in bold and italic are in Appendix A. The definitions of the acronyms are listed in Appendix B.

are tacit knowledge (Polanyi 1966) and hence might be valid or could be wrong (Cross and Woozley 1980) when AEC professionals apply them from one situation to another.

The case examples and our own experience suggest that today the implementation of 3D/4D modeling is based on anecdotes from past projects and general beliefs. Using only anecdotes and general beliefs to guide the implementation of 3D/4D modeling does not lead AEC professionals to a grounded understanding of important ***implementation factors*** and ***measures***. To overcome the limitation of single-case demonstrations and general beliefs, we need to establish a structured and formal way to describe 3D/4D modeling practices on a project and to allow the comparison of the similarities and differences across projects. The goals of our research were: 1) to provide a framework so that AEC professionals can document 3D/4D modeling experiences and compare them across projects; 2) to provide researchers with a framework which provides the opportunity of cross-case pattern analysis that is useful for generating theory (Eisenhardt 1989).

Table 1: General beliefs (GB) about implementations and impacts of 3D/4D modeling

• **Model Uses**	
GB1	A 3D model is useful for a wide range of purposes, such as cost estimating, construction planning, analysis, automated fabrication and project control applications, but for now 3D/4D modeling is primarily used as a visualization and marketing tool (Bazjanac 2004).
GB2	The uses and benefits of three-dimensional design in residential and commercial buildings have not been shown (Griffis and Sturts 2003).
GB3	Lack of design-build or other collaborative contractual models should not be viewed as a reason to avoid 3D/4D modeling practices (Gonzales 2006).
GB4	3D/4D models are more applicable for the uses on certain projects which involve challenging characteristics such as a complex design, fast-paced project delivery, tight budget, high-tech facilities, etc. (Koivu et al. 2003).
GB5	There are many 3D/4D models developed for many different uses (Bedrick 2005).

• **Timing of 3D/4D Modeling**	
GB6	There is a time lag between a 3D/4D modeling effort and reaping the corresponding benefits (Fischer 2004).
GB7	It is essential to capitalize on project opportunities early to make 3D/4D models have a lasting and positive effect on the facility over its total life span (Kam 2002).
GB8	Designers benefit directly from building detailed 3D models. A design in 3D costs less than a design in 2D for an architect (Carpenter 2006).
• **Key Stakeholders involved in 3D/4D Modeling and Review Process**	
GB9	The more stakeholders involved in implementing 3D/4D modeling; the more benefits accrue to them as a whole and to each stakeholder individually (Fischer 2004).
• **Level of Detail in 3D/4D Models**	
GB10	Creating 3D and 4D models at the appropriate level of detail is instrumental in reaping their benefits (Fischer 2004).
• **Effort Required for the Workflow of 3D/4D Modeling**	
GB11	The limitations of 3D/4D modeling software tools and issues stemming from data exchange and organizational alignment are the main stumbling blocks to an efficient modeling process (Bazjanac 2004).

To develop such a framework, we studied and documented the implementation of 3D/4D modeling on thirty-two case projects. This paper presents:

- A framework to document the implementation of 3D/4D modeling on the thirty-two case projects.
- ***Crosswalks*** which compare 3D/4D modeling across projects and demonstrate the implementation ***patterns***.
- The outcomes from the juxtaposition of general beliefs against the implementation patterns shown in the crosswalks.

2. Framework to Document Implementations and Impacts of 3D/4D Modeling

We started this study by learning about implementations of 3D/4D modeling on 15 projects (projects 1-15 in Table 4). While it was fascinating to learn about these cases, it was difficult to compare implementations of 3D/4D modeling and discern implementation patterns and general insights because a common vocabulary and structure to describe the implementations did not exist. As a starting point for a formal and structured framework, we used a list of questions originally developed by the ***Virtual Builders Roundtable***. The framework is based on two assumptions. First, the implementation of 3D/4D modeling is shaped by its context, i.e., project characteristics and company background. Second, the implementation of 3D/4D modeling affects the design of the product (building), the project organization, and the processes carried out on a project. In turn, this impact on product, organization, and process design affects the overall project performance. In the following sections, we present how the whole framework is structured and describe three criteria to assess how well the framework can document 3D/4D modeling implementations.

In the framework (Table 2), the vertical structure as presented by the header row represents the evolving process of planning, executing, and evaluating 3D/4D modeling, and the horizontal structure as presented by the column header represents the increasing level of detail in documentation when 3D/4D modeling is implemented. The framework has four main ***categories***. Each category is described with several ***factors***. Each factor is described with one or several ***measures***.

The four main categories relate to the main tasks that AEC professionals need to carry out when implementing 3D/4D modeling. First, the motivation and incentive of using 3D/4D models on a project is often triggered by situations, challenges, requirements, and constraints on a project or within a company. Therefore, implementing 3D/4D modeling is subject to the project-specific or company-specific context (Category A). Second, when planning and implementing 3D/4D modeling (Category B), practitioners need to consider a range of specific implementation factors. Third, after the implementation of 3D/4D modeling, AEC professionals have to evaluate and assess the perceived and quantifiable impacts (categories C and D) during the project run-time and upon its completion.

To document these major tasks in detail, it is necessary to formalize and structure factors within each of the four categories, i.e., context, implementation, perceived impacts, and quantifiable impacts. We organize the context category into two factors: project and organization context. The implementation category characterizes the implementation of 3D/4D modeling with seven factors, i.e., why (modeling uses), when (timing of model uses), who (stakeholder involvement), what (modeled data), with which tools (3D/4D modeling software), how (workflow), and for how much (effort/costs) a 3D/4D modeling implementation was done. The perceived impact category uses three factors, i.e., the impacts of 3D/4D modeling on the ***Product*** (i.e., facilities), ***Organization*** of the design-construction-operation team, and Work ***Processes***, to describe the professionals' perception of implementing 3D/4D modeling on a project. The quantifiable impact category has two factors: performance during the project run-time and final performance upon project completion.

It is also necessary to identify measures that provide concrete measurements of the factors. In Table 3, the 1st and 2nd columns specify all the 74 measures in the framework. In summary, the framework consists of 4 main categories, 14 factors, and 74 measures.

Table 2: Framework of the implementation and impacts of 3D/4D modeling

Categories	Factors			Measures (See Table 3)
Context	**A1**		Project Characteristics and Challenges	**A1.1 – A1.7**
	A2		Company Context of Project Participants	**A2.1 – A2.3**
Implementation	**B1**		Model Uses	**B1.1 – B1.2**
	B2		Timing of Model Use	**B2.1 – B2.2**
	B3		Stakeholder Involvement	**B3.1 – B3.9**
	B4	**B4(a)**	Data: Modeled Scope	**B4(a).1**
		B4(b)	Data: Model Structure	**B4(b).1 – B4(b).2**
		B4(c)	Data: Level of Detail	**B4(c).1 – B4(c).5**
		B4(d)	Data: Data Exchange	**B4(d).1 – B4(d).3**
	B5	**B5(a)**	Tools: Software Functionality	**B5(a).1 – B5(a).4**
		B5(b)	Tools: Software Interoperability	**B5(b).1**
	B6		Workflow	**B6.1 – B6.5**
	B7		Effort and Cost	**B7.1 – B7.2**
Perceived Impacts	**C1**		Perceived Impacts on Product	**C1.1 – C1.2**
	C2		Perceived Impacts on Organization	**C2.1 – C2.2**
	C3		Perceived Impacts on Process	**C3.1 – C3.2**
Quantifiable Impacts on Project Performance	**D1**		Performance during Project Run-time	**D1.1 – D1.16**
	D2		Final Performance upon Project Completion	**D2.1 – D2.6**

Table 3: Measures in the framework

Notes: Qual – Qualitative; Quan – Quantitative; Obj – Objective; Subj – Subjective; Con – Consistent; Suffi – Sufficient							
Column Number							
#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**
ID	**Measures**	**Qual**	**Quan**	**Obj**	**Subj**	**Con**	**Suffi**
A1.1	Type of project	x		x		100%	
A1.2	Contract type	x		x		100%	
A1.3	Contract value vs. value of scope modeled		x	x		62.50%	
A1.4	Project location	x		x		100%	
A1.5	Project start and completion	x		x		100%	
A1.6	Project size		x	x		68.75%	
A1.7	Site constraints	x		x		59.38%	
A2.1	Vision into 3D/4D implementation within the project participant's companies	x			x	28.13%	*
A2.2	R&D activities within the project participant's company	x		x		28.13%	*
A2.3	Current 3D/4D practices within the project participant's company	x		x		100%	*
B1.1	Model use	x		x		100%	
B1.2	Types of model uses	x		x		100%	
B2.1	Project phase(s) when the 3D/4D model was built	x		x		100%	
B2.2	Project phase(s) when the 3D/4D model was used	x		x		100%	
B3.1	Stakeholder organization(s) initiating 3D/4D modeling effort	x		x		100%	
B3.2	Stakeholder organization(s) paying for the 3D/4D model	x		x		93.75%	
B3.3	Stakeholder organization(s) building/using the 3D/4D model	x		x		100%	
B3.4	Number of individuals building/using the 3D/4D model		x	x		84.38%	
B3.5	Stakeholder organization(s) reviewing the 3D/4D model	x		x		71.88%	
B3.6	Number of individuals reviewing the 3D/4D model		x	x		53.13%	
B3.7	Stakeholder organization(s) owning the 3D/4D model	x		x		31.25%	*
B3.8	Stakeholder organization(s) controlling 3D/4D modeling	x		x		31.25%	*
B3.9	Stakeholder organization(s) influencing on 3D/4D modeling	x		x		31.25%	*
B4(a).1	Modeled scope of project	x		x		96.88%	

ID	Measures	Qual	Quan	Obj	Subj	Con	Suffi
B4(b).1	Data structure in the 3D/4D model (layers, hierarchy)	x		x		96.88%	
B4(b).2	Number of layers or hierarchical levels in the 3D/4D model		x	x		53.13%	
B4(c).1	Levels of detail in the 3D/4D model		x	x		93.75%	
B4(c).2	Number of 3D CAD objects in the 3D model vs. number of 3D CAD objects in the 4D model		x	x		46.88%	
B4(c).3	Number of activities in the 4D model		x	x		71.43%	
B4(c).4	Number of links between 3D CAD objects and activities		x	x		71.43%	
B4(c).5	Number of design (or schedule) alternatives modeled		x	x		62.50%	
B4(d).1	Information flow among project participants	x		x		90.91%	*
B4(d).2	Model deliverables for each participating organization	x		x		63.64%	*
B4(d).3	Challenges in the data exchange process	x			x	81.82%	*
B5(a).1	3D/4D modeling software used	x		x		100%	
B5(a).2	Rating of software functions to satisfy the modeling requirements on a numerical scale from 1-5		x		x	100%	
B5(a).3	Useful 3D/4D software functionality	x			x	90.63%	
B5(a).4	Missing 3D/4D software functionality	x			x	90.63%	
B5(b).1	Challenges in software interoperability	x		x		81.82%	*
B6.1	Workflow of the 3D/4D modeling process	x		x		75%	
B6.2	Number of iterations of the 3D/4D model		x	x		65.63%	
B6.3	Reasons for iterations of the 3D/4D model	x			x	81.25%	
B6.4	The best aspects of the 3D/4D modeling process	x			x	93.75%	
B6.5	Needed improvements in the 3D/4D modeling process	x			x	84.38%	
B7.1	Time (man-hours) to build the 3D/4D model		x	x		56.25%	
B7.2	Costs of building the 3D/4D model		x	x		37.50%	
C1.1	Rating of the impact of the 3D/4D model on building design on a numerical scale from 1-5		x		x	100%	
C1.2	Explanation of the impact on product	x			x	100%	
C2.1	Rating of the impact of the 3D/4D model on project organization on a numerical scale from 1-5		x		x	100%	
C2.2	Explanation of the impact on project organization	x			x	100%	

ID	Measures	Qual	Quan	Obj	Subj	Con	Suffi
C3.1	Rating of the impact of the 3D/4D model on project processes on a numerical scale from 1-5		x		x	100%	
C3.2	Explanation of the impact on processes	x			x	100%	
D1.1	Reduced number of deficiency correction notices (rework)		x	x		6.25%	
D1.2	Increased number of design alternatives		x	x		62.5%	
D1.3	Enhanced capacity of producing permit drawings, working drawings, detail drawings (numbers of drawings created from 3D models vs. total numbers of drawings produced)		x	x		6.25%	*
D1.4	Reduced design effort		x	x		12.50%	
D1.5	Change in the distribution of design effort	x		x		9.37%	*
D1.6	Increased accuracy of cost estimates (e.g., 95% of cost items estimated within +/- 2% of variation of final cost)		x	x		12.50%	
D1.7	Reduced cost estimating effort		x	x		12.50%	
D1.8	Closeness of bid result		x	x		6.25%	
D1.9	Reduced turnaround of permitting		x	x		12.5%	
D1.10	Reduced turnaround of shop-drawing review		x	x		3.13%	
D1.11	Reduced engineering lead time of material procurement		x	x		6.25%	
D1.12	Reduced number of field RFIs		x	x		6.25%	
D1.13	Reduced number (or reduced cost growth) of change orders		x	x		3.13%	
D1.14	Reduced turnaround of change order processing		x	x		6.25%	*
D1.15	Reduced response latency (reduced time to clarify a problem)		x	x		12.50%	
D1.16	Increased number of stakeholders engaged		x	x		3.13%	
D2.1	3D/4D models help define the project scope better	x		x		3.13%	
D2.2	3D/4D models help improve client satisfaction	x		x		3.13%	
D2.3	3D/4D models help reduce a project's first costs		x	x		0%	
D2.4	3D/4D models help reduce a project's life-cycle costs		x	x		3.13%	
D2.5	3D/4D models help reduce the time of project execution		x	x		12.50%	
D2.6	3D/4D models help improve safety performance (lost workday cases)		x	x		0%	

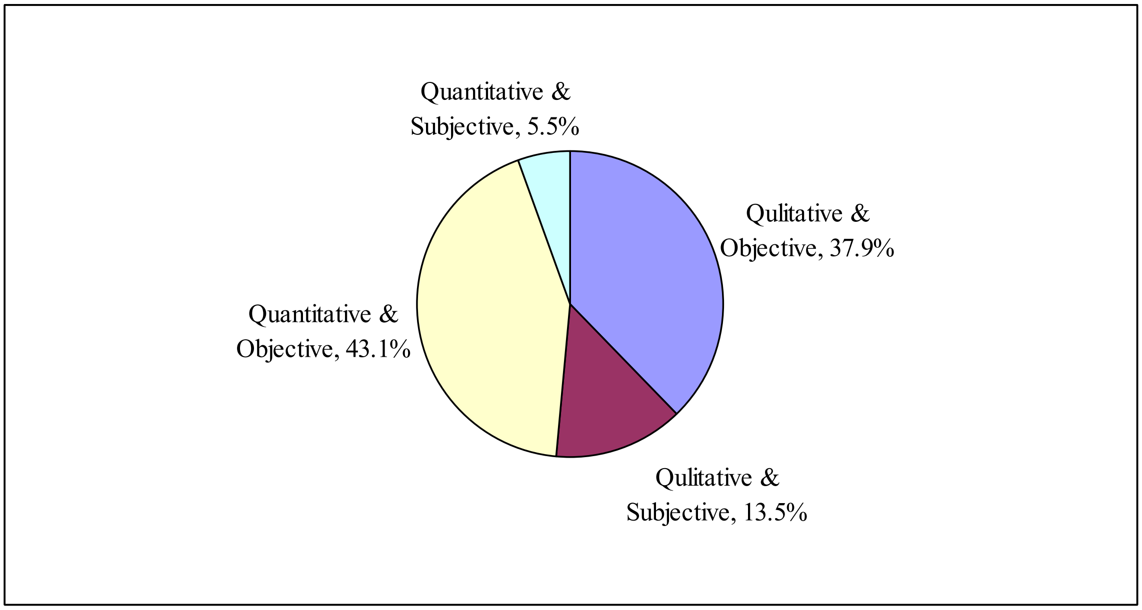
In addition to organizing the framework in a hierarchical structure from categories to factors and further into measures, we evaluated the descriptive power of the framework by assessing how well the framework documents 3D/4D modeling objectively (marked by "x" in the 5th column of Table 3), consistently (noted by the percentage in the 7th column of Table 3) and sufficiently (marked by "*" in the 8th column of Table 3).

The descriptive power of the framework can be evaluated by three criteria:

- We made the framework as "objective" as possible so that the documentation of a 3D/4D modeling implementation relies as little as possible on personal judgment and as much as possible on implementation facts.
- We checked that the framework is "consistent" to ensure that the measures are replicable and applicable across a variety of projects.
- We ensured that the documentation of 3D/4D modeling implementations is as "sufficient" as needed to compare implementations with one other and learn from them.

It is important to depict the objectivity of the measures in the framework through examination of their data types and the interactions between them (Wang et al. 1993). The 3rd – 6th columns in Table 3 show that the data types for these measures can be "qualitative" or "quantitative", "objective" (based on implementation facts and numbers), or "subjective" (based on personal perceptions). The distribution of the measures with respect to their data types is shown in Figure 1. In summary, 81% of the measures are objective and 19% subjective; and 51% of the measures are qualitative and 49% quantitative.

Figure 1: Different data types for measures and their distribution in the framework



- “Qualitative and Objective”: These measures specify facts, e.g., types of model uses, project phases, stakeholders involved, software used, etc.
- “Qualitative and Subjective”: These measures are perceptions such as opinions about useful or missing 3D/4D software functionality, needed improvements in the 3D/4D modeling tools, process, education, etc., as well as the impacts of 3D/4D modeling on the design of product, organization, and process.
- “Quantitative and Objective”: These measures are numerical representations of facts, e.g., contract value, project size, number of people building, using, and reviewing 3D/4D models, number of 3D CAD objects in 3D/4D models, amount of time and cost to build 3D/4D models, reduced number of field RFI, change orders and rework, etc. Most measures in this group focus on the hard evidence in terms of how much effort was put into 3D/4D modeling and how significantly the 3D/4D models contributed to the improvement of project performance.
- “Quantitative and Subjective”: These measures capture perceptions numerically, e.g., ratings of the impacts of 3D/4D modeling on the design of product, organization and process.

The framework has a high percentage (81 %) of objective measures. The high percentage of objective measures in the framework implies that the documentation of 3D/4D modeling is less prone to bias. Although subjective measures are not a significant part of the framework, they provide insights not obtainable by objective measures. Therefore, this framework emphasizes the need for both objective and subjective data to support or complement each other in describing implementations and impacts of 3D/4D modeling.

In addition to checking the objectivity of the measures, we checked the descriptive power of the framework against the other two criteria: “consistent” and “sufficient”.

“Consistent”: To be applied across a variety of projects, measures in a framework need to be consistent, i.e., they are applicable from one case to another. “Consistent” assesses the replication of each measure across all the cases (the 7th column of Table 3), which is calculated as a percentage ratio of the number of cases that exhibited the information for each measure to the total number of cases we studied. If one particular measure is replicated in more cases, we can have more confidence that this measure is consistent.

When new measure(s) (i.e., measures not observed on previous cases and not originally covered in the framework) emerge from a particular case, we added them to the framework and tested the replicability of them in the subsequent case studies.

We stratify the 74 measures in the framework into three groups according to their replication (Figure 2).

- Level 1 (high level of replication – measures replicated in more than 75% of the case projects): 56% of the 74 measures were observed in more than 75% of the case projects. These measures focus mostly on describing the project context to implement 3D/4D modeling and specifying the implementation factors (such as model uses, timing, stakeholder involvement, level of detail, workflow, etc.) and their impacts on product, organization and process.
- Level 2 (medium level of replication - measures replicated in 25% - 75% of the case projects): 20% of the 74 measures were observed in 25% - 75% of the case projects. These measures (such as contract value, modeling cost, and so on) did

not reach the high level of replication in our case studies because they were often confidential and not accessible.

- Level 3 (low level of replication - measures replicated in fewer than 25% of the case projects): 24% of the 74 measures were observed in fewer than 25% of the case projects. Most measures at this level fall into the category "quantifiable project performance." During the study of the thirty-two cases, we only found a handful of companies that had quantified the performance improvements attributable to 3D/4D models. Although these measures tend to have a low level of replication, we retain them in the framework because they highlight the opportunity to document them in more cases.

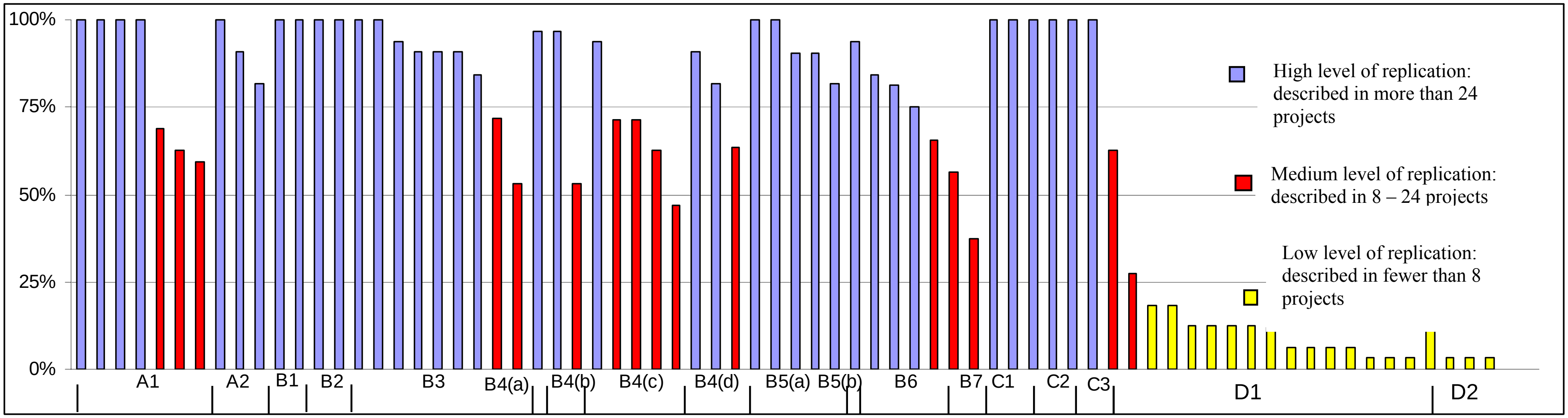
Since the framework has a high percentage of measures that have a medium or high level of replication (20% + 56% = 76%), we can have confidence that the framework is consistent.

"Sufficient": To capture the characteristics of 3D/4D modeling implementations as much as needed to compare implementations with one other and learn from them, a framework needs to be sufficiently developed to include complementary aspects of 3D/4D modeling among different cases. "Sufficient" assesses the degree of saturation of the framework, which is intended to incorporate new insights, i.e., new measures (marked by "*" in the last column of Table 3), as they emerged from documenting more cases.

The fewer new measures we add to the framework as we carry out more case studies, the more confidence we can have that the framework is sufficiently developed. After the study of 3D/4D modeling on 21 cases, the framework had 61 measures. Afterwards, we studied 11 more projects and found 13 new measures. These newly added measures expand the view of 3D/4D modeling at the level of a project to that at the level of a firm so as to exhibit such characteristics as company context, inter-organizational collaboration, data exchange, software interoperability, etc. Thus, the degree of saturation of the framework after completion of the 32 cases was 82.4% [= 61/ (61 + 13)]. Afterwards, I applied this framework to eight more case studies (not covered by this report). The eight case studies "saturate" factors and measures in this framework and I could not find new factors and measures. That is to say, the saturation of the framework after the completion of the 40 cases was 100%.

In summary, this framework is of value because it provides a common ground for comparing 3D/4D modeling practices across projects. A grounded understanding from the comparison of 3D/4D modeling implementations should help guide AEC professional to better implement 3D/4D modeling and achieve more significant improvements in project performance. By applying the framework to the thirty-two cases, we conclude that the framework is able to describe 3D/4D modeling implementations objectively, consistently, and sufficiently because it is comprised of a high percentage (81%) of objective measures, a high percentage (76%) of measures at a high/medium level of replication, and exhibits a high degree of saturation (100%).

Figure 2: Three levels (high, medium, and low) of replication of the measures in the framework



Factors		
A1		Project Characteristics and Challenges
A2		Company Context of Project Participants
B1		Model Uses
B2		Timing of Model Use
B3		Stakeholder Involvement
B4	**B4(a)**	Data: Modeled Scope
	B4(b)	Data: Model Structure
	B4(c)	Data: Level of Detail
	B4(d)	Data: Data Exchange
B5	**B5(a)**	Tools: Software Functionality
	B5(b)	Tools: Software Interoperability

Factors	
B6	Workflow
B7	Effort and Cost
C1	Perceived Impacts on Product
C2	Perceived Impacts on Organization
C3	Perceived Impacts on Process
D1	Performance during the Project Run-time
D2	Final Performance upon Project Completion

3. Overview of Case Projects and the Approach of Data Collection and Analysis

Table 4 gives an overview of the thirty-two case projects. Sixteen of the first twenty-one construction projects involved researchers, students and visitors at the Center for Integrated Facility Engineering (CIFE) at Stanford University in the process of 3D and 4D modeling. On the last eleven projects, 3D/4D modeling was carried out by AEC organizations in Finland. The case studies on the eleven Finish projects were part of the research collaboration between the Virtual Building Environments (VBE) II project sponsored by the Technology Agency of Finland (Tekes) and the Global VDC Studies in the U.S., Finland, and China sponsored by CIFE. Table 4 also depicts that the thirty-two case projects range in size from a few million dollars to several hundred million dollars, include public and private projects in a range of construction sectors (residential, commercial, institutional, industrial, and transportation), and were delivered with several contractual arrangements (design-bid-build, design/build, and CM/GC.).

We used a list of questions as the data collection protocol. Two sources of evidence, available documents and interviews, provided the empirical data for the case studies.

- *Primary data from interviews:* For each case study, I met with one (17 out of 32 cases) or a few interviewees (15 out of 32 cases) who were introduced by the contacts within CIFE and its member companies. The interviewees were licensed professionals (architects and engineers), project managers, CAD directors, research & development managers, and independent consultants. In each case study, we focused the interview discussion on specific project experiences where the implementation and impacts of 3D/4D modeling occurred. These interviews assumed an open-ended and conversational manner, which allowed inquiry about specific facts and solicitation of interviewees' opinions.
- *Secondary data from available documents:* Whenever possible, we requested screen shots of 3D/4D models, workflow diagrams, company brochures, etc., which helped us become more familiar with the implementations of 3D/4D models on the case projects.

Table 4: An overview of the thirty-two case projects and their project contexts

Case #	**Case Projects**	**Type of Project**					**Delivery Method**			**Project Size**		
		CF	ISF	IDF	TF	RF	DBB	DB	CM/GC	S	M	L
1	McWhinney Office Building, Colorado (1997-1998) (Koo and Fischer 2000)	√					√			√		
2	Sequus Pharmaceuticals Pilot Plant, Menlo Park (1997- 1999) (Staub et al. 2003)			√				√			√	
3	Experience Music Project, Seattle (1998 - 2000) (Fischer et al. 1998)		√						√			√
4	Paradise Pier, Disney California Adventure, Los Angeles (1998 - 1999) (Schwegler et al. 2000)	√					√					√
5	Helsinki University of Technology Auditorium-600 (HUT-600), Helsinki (2000 - 2002) (Kam et al. 2003)		√						√	√		
6	Baystreet Retail Complex, Emeryville (2000 - 2002)	√					√					√
7	Genentech FRCII, South San Francisco (2001 - 2003)			√					√			√
8	Walt Disney Concert Hall, Los Angeles (1999 - 2003) (Haymaker et al. 2004)		√						√			√
9	Hong Kong Disneyland, Hong Kong (2001 - 2005)	√					√					√
10	Pioneer Courthouse Seismic Upgrade and Rehabilitation Project, Portland (2003 - 2005)		√				√				√	
11	MIT Ray and Maria Stata Center, Boston (2000 - 2004) (Hastings et al. 2003)		√						√			√
12	Banner Health Good Samaritan Hospital, Phoenix (2002 - 2004)	√							√			√
13	California Academy of Science Project, San Francisco (2003 - 2006)		√						√			√
14	Terminal 5 of Heathrow Airport, London (2003 - 2007) (Koerckel 2005)				√		√					√
15	Residential Building, Stockholm (2002 - 2003) (Jongeling et al. 2005)					√	√			√		
16	Pilestredet Park Urban Ecology Project, Oslo (1997-2005) (Gao et al. 2005)					√	√				√	

Case #	Case Projects	Type of Project					Delivery Method			Project Size		
		CF	ISF	IDF	TF	RF	DBB	DB	CM/GC	S	M	L
17	Regional Office Building, Washington DC (2004-2007)		√				√					√
18	Jackson Courthouse, Jackson, Mississippi (2004-2007) (Majumdar and Fischer 2006)		√				√				√	
19	Samsung LSI Fab Facility, Kiheung, Korea (2004-2005)			√			√					√
20	Camino Medical Campus, Mountain View (2004-2007) (Khanzode et al. 2005)	√							√			√
21	Fulton Street Transit Center, New York (2002-2009)				√				√			√
22	A Town-planning Project, Finland (2004 - 2005)					√	√				√	
23	Mamselli Low-rise Housing, Finland (2004 – 2005)					√		√		√		
24	Headquarter Building for NCC-Finland, Finland (2003 – 2004)	√						√			√	
25	Tali Apartment Building Project, Finland (2005 – 2006)					√		√		√		
26	Office Building Project in Oulu, Finland (2003 – 2004)					√		√			√	
27	Semi-detached Houses in Kerava (2003 – 2004)					√		√		√		
28	Koskelantie 22-24 Residential Renovation Project, Finland (2004 – 2005)					√	√			√		
29	Vantaan Silkinkulma Apartment, Finland (2003 – 2004)					√		√		√		
30	Vantann Ankkahovi Apartment, Finland (2004 – 2005)					√		√		√		
31	Pfizer, Scandinavian Headquarter Building, Finland (2001 – 2003)	√					√				√	
32	Aurora 2 University Building in Joensuu, Finland (2004 – 2006)		√				√				√	

LEGEND	
CF	Commercial Facilities (e.g., office and retail complexes, theme parks)
ISF	Institutional Facilities (e.g., university facilities, theaters, museums, public administration facilities)
IDF	Industrial Facilities (e.g., pharmaceutical, biotech, semi-conduct)
TF	Transportation Facilities (e.g., airport terminals, subway transit centers)
RF	Residential Facilities (e.g., apartment buildings, houses)
DBB	Design-Bid-Build

LEGEND	
DB	Design-Build
CM/GC	Construction Managers / General Contractors (CM at Risk)
S	Small (=< $ 5 million)
M	Medium ($ 5 – 100 million)
L	Large (>= $ 100 million)

Table 5: An example of the process of discovering new measures and factors

Case No.	**Aggregation level 1**	**Aggregation level 2**	**Aggregation level 3**
	Narratives	**Measures**	**Factors**
23	*“The 3D models modeled three design and two life-cycle alternatives (architectural features, two air-conditioning system alternatives: mixed cooling vs. displaced cooling system). 3D models enabled the team to develop multiple alternatives early in the project and provided additional valuable life-cycle parameters to the decision-makers during early project phases.”*	Enable development of multiple design alternatives early on	Perceived impact on process
25	*“The 3D model gave a clear view of how pieces go together. The initial design required stick built by the Architect, but in order to save time and costs in the fabrication process, the fabricator suggested using prefabricated panels. 3D model facilitated the demonstration that the use of prefabricated panels in stead of stick built would be more cost-effective. The initial design plan was changed from stick built to panelized based on joint study of the 3D model.”*		
26	*“Along with the 3D modeling process, the on-site co-created detailing crossed contractual barriers and sped up the shop drawing approval process. The 3D modeling minimized the number of review sessions. The cycle time of design review was reduced from 5-6 weeks to 2-3 weeks.”*	Expedite design coordination, shop drawing approval process, and production of construction documents	
21	*“3D models allowed the generation of elevations and plans in a single time-cutting step as well as all the modifications to one model.”*		
23	*“The architects reported about 50% time savings in the design documentation phase as a result of object-oriented libraries and catalogues, parametric properties, knowledge reuse, and various automation tools.”*		

The data analysis consisted of three activities.

- *Transcribing and checking interview data:* I transcribed every interview conversation from notes and tape recording and then wrote case narratives. I also checked with interviewees by asking them to proofread the case narratives or clarifying something that I had not understood well during the interviews. In addition, I triangulated with extant documentations (the 1^{st} column of Table 4) to make sure that the data present in the case narratives is correct and accurate.

- *Replicating existing factors and measures:* Based on the case narratives, I entered project data (actual implementation information) into the framework spreadsheet so as to replicate existing factors and measures.

Discovering new factors and measures: The grounded theory method (Corbin and Strauss 1998) provides explicit procedures to conceptualize new factors and measures as they emerge from case studies. I carried out data coding by assembling or sub-clustering words or break sentences into segments (Strauss and Corbin 1998). Table illustrates an example of the coding process. I compared case narratives, combined identical or similar statements (aggregation level 1) to form new measures (aggregation level 2), and then linked the new measures to an existing factor or pooled the closely-related measures to form a new factor (aggregation level 3).

After a review of the 32 cases and their project contexts, in the next section, we discuss the findings emerging from our data analysis, including the crosswalks that illustrate the implementation patterns for 3D/4D modeling, the likely causal relationships between implementations and impacts, and the validation of general beliefs**.**

4. Findings from Analyzing Crosswalks and Validating General Beliefs

We developed five crosswalks to illustrate the implementation patterns and analyze the relationships between implementations and impacts of 3D/4D modeling:

- ***Crosswalk 1:*** nine 3D model uses, seven 4D model uses and their related impacts on building design as well as project processes and organization;
- ***Crosswalk 2:*** seven time periods of model uses vs. their timing of impacts;
- ***Crosswalk 3:*** eleven situations of key stakeholder involvement and the corresponding impacts;
- ***Crosswalk 4:*** three situations with respect to the timing of developing levels of detail in 3D/4D models and the corresponding impacts;
- ***Crosswalk 5:*** six steps in a typical workflow of 4D modeling and three issues that lead to inefficiencies in each step of the workflow.

From analyzing the five crosswalks about 3D/4D modeling implementations, we noticed five implementation patterns for 3D/4D modeling:

1. The uses of 3D/4D models vary according to the business drivers of project stakeholders, different project challenges and the project phases when 3D/4D models are created. The four primary uses of 3D models are 1) interaction with non-professionals, 2) construction planning, 3) drawing production, and 4) design coordination and clash detection. Companies are starting to integrate 3D/4D models for more data-driven tasks such as analysis of design options, supply chain management, cost estimating and change order management, facility management, and establishment of owner requirements.
2. The use of 3D models early in the design phase results not only in immediate benefits (which relate to improved project process and organization) but also late benefits (which accrue during the downstream processes and are a result of the improved project process and performance of the finished building product). In contrast, the use of 4D models in the preconstruction and construction phases mostly leads to immediate benefits.

3. The benefits to every individual stakeholder and to the whole project team are maximized when all the key stakeholders are involved in creating and using 3D/4D models.
4. Creating 3D/4D models at the appropriate level of detail is instrumental in maximizing the benefits. The appropriate level of detail depends not only on the model use but also the information available at a particular stage of a project.
5. In a typical workflow of 4D modeling, steps 1, 2, and 3 (i.e., collecting data, modifying the original schedule, and creating or modifying 3D models) involve no technical issues with regard to 4D modeling software; step 4 (i.e., linking 3D model and schedule) involves only technical software issues; steps 5 and 6 (i.e., reviewing 4D models and updating 4D models) involve technical software issues and other issues pertinent to data exchange and organizational alignment.

We were not able to find a pattern between the project cost and the cost (man-hours) of creating 3D/4D models. The main reason is that this kind of information is often confidential and was not accessible to us on enough projects to draw corresponding conclusions.

We juxtaposed the implementation patterns emerging from the crosswalks with original general beliefs (Table 1) so as to cross-check their validity.

4.1 Findings from Crosswalk 1 vs. General Beliefs about Model Uses

In this report, we define and account for the impacts of 3D/4D modeling as 1) the benefits accruing to project stakeholders and 2) the efforts or costs required to develop and use the models as well as to overcome obstacles. Model uses refer to the purposes of developing 3D/4D model. From the study of the thirty-two cases, we summarized and categorized the use of 3D models into 9 types and the use of 4D models into 7 types. We found that 3D modeling was used for:

- establishing the owner's requirements
- interacting with non-professional stakeholders
- analyzing design options

- checking multi-disciplinary system clashes and constructability issues
- producing construction documents
- supporting cost estimating
- managing supply chains
- planning for construction execution
- managing facility operations.

We also noticed that 4D modeling was used for:

- strategic project planning
- developing contractor's proposals
- comparing proposals from GC or subs by the owner
- permitting
- master scheduling
- constructability review (A 4D model improves constructability planning because it helps expose constructability problems related to access, temporary support, availability of work space, and completion of prerequisite work, especially time-space conflicts between concurrent activities (Staub and Fischer 1998).)
- analysis of site operations.

Crosswalk 1 relates model uses (referring to Table 6 for 3D model uses and Table 7 for 4D model uses) with their corresponding impacts on building design, project processes and organization as well as their related benefits to project stakeholders.

Table 6: Crosswalk 1 (Part I) - linking the use of 3D models to the corresponding impacts on product, process, and organization and the related benefits to project stakeholders

3D Model Uses	**Impacts on Product, Process, Organization** • *Impact on product*: the effects that 3D/4D modeling has on the design of the physical elements within a facility • *Impact on organization*: the effects that 3D/4D modeling has on the timing of engaging project stakeholders, on the number of stakeholders engaged, and on work responsibilities and contractual relationships between stakeholder organizations • *Impact on process*: the effects that 3D/4D modeling has on the execution and sequencing of tasks in the design-construction-operation process		**Benefits to Whom** Beneficial results that accrue to project stakeholders
1 – Establishment of owner requirements	Product	Improve the quality of building design (by satisfying owner requirements better)	Owner (or Developer)
		Case Example: 32	
		Improve the quality of building design (by establishing realistic energy, cost, and environmental targets earlier)	Owner (or Developer) Designer
		Case Example: 32	
2 – Interaction with non-professionals (e.g., for client briefing, schematic design review, development permitting, marketing, etc.)	Product	Improve the quality of building design (by reviewing how the design meets functional requirements, e.g., space program, sightlines, lighting, acoustics, etc.)	Owner (or Developer) End user
		Case Examples: 5, 18, 21, 31, 32	
	Process	Facilitate the process for owners and end users to inspect and evaluate aesthetic and functional characteristics of the building design	Owner End user Designer
		Case Examples: 5, 18, 31, 32	
		Accelerate the turnaround of permit approvals (by planning commissions and city councils) so as to facilitate an early start of developers' marketing efforts	Developer Authorities
		Case Example: 25	
		Facilitate the process for homebuyers to compare various alternatives and make an decision to buy	Developer End user
		Case Examples: 25, 26, 27, 29, 30	
		Facilitate the process for non-professionals to understand design intent and stay up-to-date with project development	Owner (or Developer) End user Designer Authority General public
		Case Examples: 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	
	Org.	Engage more non-professionals in providing more input and hence having more influence on building design	
		Case Examples: 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	

3D Model Uses	**Impacts on Product, Process, Organization**		**Benefits To Whom**
3 – Analysis of building design options	Product	Improve the quality of building design (by exploring more design options)	Owner (or Developer) Designer End user
		Case Examples: 5, 8, 11, 14, 22, 23, 28, 29, 30, 31, 32	
	Process	Facilitate the exploration of options (by updating parameters in 3D CAD objects and changing the look and behavior of an facility more correctly, quickly, and completely)	
		Case Examples: 5, 8, 11, 14, 22, 23, 28, 29, 30, 31, 32	
		Accelerate decision-making (by fast analysis of options)	
		Case Examples: 5, 8, 11, 14, 22, 23, 28, 29, 30, 31, 32	
	Org.	Engage more professional disciplines in design review so as to provide more input to building design at the right time	
		Case Examples: 4, 5, 6, 7, 8, 11, 14, 22, 23, 28, 29, 30, 31, 32	
4 – Design checking (system coordination and/or constructability review)	Product	Improve the quality of design (by reviewing constructability according to the GC's or subcontractors' know-how)	Owner (or Developer) GC, Subs
		Case Examples: 2, 5, 7, 21, 25, 26, 28, 29, 30, 32	
		Improve the quality of building design (by coordinating architectural, structural, and MEP system design)	Owner (or Developer) Designer
		Case Examples: 2, 7, 20, 23, 24, 25, 28, 29, 30, 31, 32	
	Process	Accelerate the turnaround of design coordination (by combining other consultants' 3D-information with the architect's model and checking for interference between separate systems)	Owner (or Developer) Designer
		Case Examples: 2, 7, 20, 23, 24, 25, 28, 29, 30, 31, 32	
		Facilitate the iterative design process between multiple disciplines (by keeping every discipline working on up-to-date information)	Owner (or Developer) Designer GC and subs
		Case Examples: 2, 5, 7, 20, 23, 24, 25, 26, 28, 29, 30, 31, 32	
	Org.	Engage downstream designers, the GC and subs early and frequently in the schematic design and design development phases	
		Case Examples: 2, 5, 7, 20, 23, 24, 25, 26, 28, 29, 30, 31, 32	
5 – Production of construction documents	Product	Improve the completeness and consistency of construction documents (by reducing design errors in drawings)	Owner Designer Builder
		Case Examples: 2, 3, 5, 8, 11, 14, 22, 23, 24, 25, 28, 29, 30, 31, 32	
	Process	Facilitate the automatic and fast production of construction documents (by extracting information directly from 3D models for plans, sections and elevations, architectural and construction details, window/door/finish schedules, etc.)	Designer
		Case Examples: 2, 3, 5, 8, 11, 14, 22, 23, 24, 25, 28, 29, 30, 31, 32	
		Facilitate change management (by automatically updating drawings when changes are made in a 3D model)	Designer
		Case Examples: 2, 3, 5, 8, 11, 14, 22, 23, 24, 25, 28, 29, 30, 31, 32	
		Facilitate procurement and fabrication (by directly extracting dimensions and component placement information from 3D models for fabricators or suppliers)	Fabricator Supplier
		Case Examples: 3, 8, 11, 14, 24, 28, 29, 30, 32	
		Facilitate work on site and assembly (by cutting members to precise dimensions for adequate fit)	Fabricator Supplier GC and subs
		Case Examples: 3, 8, 11, 14, 24, 28, 29, 30, 32	

5– (Continued.)	**Impacts on Product, Process, Organization**		**Benefits To Whom**
	Org.	Engage fewer or no draftsmen in drawing production (by allowing little or no division between design development and construction documentation)	Designer
		Case Example: 22	
		Engage more designers' efforts in the early design phase	Designer
		Case Examples: 3, 8, 11, 22	
6 – Quantity takeoff, cost estimating and change order management	Product	Improve the accuracy of cost estimation (by obtaining actual and verifiable quantities from a 3D model)	Owner (or Developer) GC
		Case Examples: 2, 5, 7, 25, 26, 27, 28, 29, 30, 32	
	Process	Accelerate the determination of the project budget	Owner (or Developer) Designer GC
		Case Examples: 5, 32	
		Accelerate estimating and cost feedback to design	
		Case Examples: 2, 5, 7, 25, 26, 27, 28, 29, 30, 32	
		Facilitate the management of owner-initiated change orders (by quickly showing the cost impact of these change orders and improving the accuracy of Bills of Quantities)	Owner (or Developer) GC
		Case Examples: 26, 27	
	Process	Release foremen from repetitive work in terms of re-calculating and verifying the quantities from estimators	GC
		Case Examples: 26, 27	
		Reduce chances for the owner to overpay contingency for unforeseen change orders and allowance for materials or equipment not yet selected (by accurately defining the scope of work in subcontract bid packages)	Owner
		Case Examples: 28, 29, 30	
	Org.	Engage more estimators' effort in their company's R&D activities (by using man-hours saved from cost estimating)	GC
		Case Examples: 26, 27	
7– Supply chain management	Process	Facilitate the generation of building product specifications early in the design phase (by integrating standard building product libraries to the design in 3D models)	Owner (or Developer) Fabricators (or suppliers)
		Case Examples: 5, 28, 29, 30, 32	
		Incorporate more off-site fabrication and assembly in building design and hence reduce field labor costs (by integrating standard building product libraries in 3D models)	
		Case Examples: 3, 8, 11, 14, 28, 29, 30	
		Shorten engineering lead-time (by synchronizing schedule and scope information between engineers, fabricators, and contractors)	Designer Fabricator GC and subs
		Case Examples: 3, 8, 11, 14, 24, 32	
		Accelerate manufacturing turn-around (e.g., by transferring 3D CAD data to computer-numerically-controlled (CNC) fabrication)	
		Case Examples: 2, 3, 8, 11, 14, 24, 28, 29, 30, 32	
		Facilitate the process for fabricators and subcontractors to visualize and understand the intricacy of framing and connection details in a 3D structural model	Fabricators Subs
		Case Examples: 24, 32	
		Reduce the amount of material stored on site (by producing smaller batches of shop drawings and placing procurement orders more frequently)	GC and subs
		Case Example: 14	

3D Model Uses	**Impacts on Product, Process, Organization**		**Benefits To Whom**
8 – Construction planning/4D modeling	*Case Examples: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19, 20, 21, 24, 32*		See Table 7
	See Table 7		
9 – Facility management	Product	Improve the control of building life cycle costs, the operation of technical systems, and the working conditions for facility maintenance and management personnel (by enabling a 3D–model-based FM system)	Owner Facility Manager
		Case Examples: 5, 31, 32	
	Process	Facilitate the space-planning for facility managers in the early stage of a project (by color-coding user units and departments)	Facility Manager
		Case Example: 32	
		Facilitate the re-use of as-built 3D data in the operations and maintenance phase (by updating the information from the design phase and developing as-built 3D data during construction)	
		Case Examples: 31, 32	
		Facilitate the performance reporting for facility managers to steer the building operation (conformance to targets) with the help of clearly documented performance metrics	
		Case Example: 31	

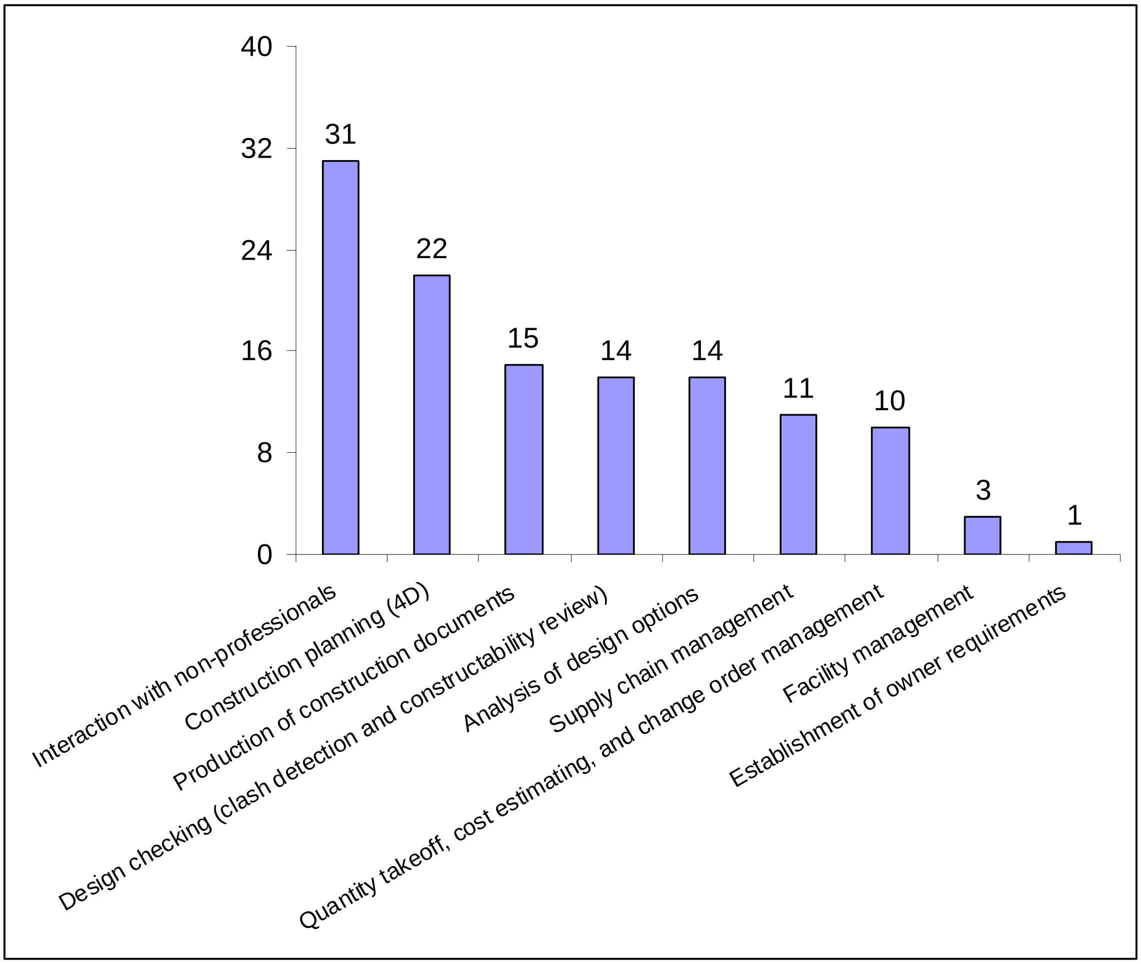
Table 7: Crosswalk 1 (Part II) - linking the use of 4D models to the corresponding impacts on product, process, and organization and the benefits to project stakeholders

4D Model uses	Impacts on Product, Process, Organization		Benefits To Whom
Strategic project planning	Product	Improve the quality of design (by enabling designers to better understand construction challenges)	Owner/ GC
		Case Examples: 4, 16	
	Process	Expedite work packaging and phased handover	Owner/ GC
		Case Examples: 4, 9	
		Support the evaluation and analysis of multiple construction and facility operation strategies during master planning	
		Case Examples: 4, 9, 13, 17	
	Org.	Engage more project participants in strategic project planning	
		Case Examples: 4, 16	
		Engage project participants early to visualize project scope and gain insights on project goals	
		Case Examples: 4, 13, 16, 17, 20, 21	
Contractor's proposal	Org.	Win contract by showing the contractor's capability to execute the work	CM/GC
		Case Examples: 11, 12	
		Pursue subsequent work with the same client	
		Case Example: 12	
Owner's bidding and GC's subcontracting	Process	Make construction bids closer in range	Owner/GC
		Case Examples: 4, 11	
		Brief bidders about the owner's or GC's intentions	
		Case Examples: 4, 11, 12	
		Facilitate communication of the construction sequencing required by engineers' specifications to potential contractors	
		Case Example: 10	
Permit approval	Process	Expedite construction permitting	CM/GC
		Case Examples: 8, 11	
Master scheduling and construction sequencing	Process	Improve the reliability and executability of the contractor's master schedule	CM/GC Subs Fabricator/ Supplier FM (Facility Manager)
		Case Examples: 1, 3, 4, 6, 7, 8, 9, 11, 19, 20, 21, 24, 32	
		Streamline concurrent facility operations and construction	
		Case Examples: 12, 17	
		Facilitate communication of project status to stakeholders	
		Case Examples: 1, 3, 4, 6, 7, 8, 9, 11, 12, 17, 19, 20, 21, 24, 32	
Constructability review	Process	Enable early detection of potential site logistics and accessibility constraints	CM/GC Subs
		Case Examples: 1, 3, 4, 5, 6, 8, 10, 11, 12, 13, 14, 16, 19, 20, 21	
	Org.	Externalize and share project issues among more project stakeholders so as to solve discovered problems more collaboratively	
		Case Examples: 1, 3, 4, 5, 6, 8, 10, 11, 12, 13, 14, 16, 19, 20, 21	
Operations planning/analysis	Process	Enable early identification of work scope and interferences between trades	CM/GC Subs
		Case Examples: 2, 3, 7, 8, 11, 14, 15, 19, 20, 21	
	Org.	Engage subs early to coordinate their work	
		Case Examples: 2, 3, 7, 8, 11, 14, 15, 19, 20, 21	

We now compare implementation patterns emerging from Crosswalk 1 to general beliefs about model use (GB 1, 2, 3, 4, and 5).

GB1: A 3D model is useful for a wide range of purposes, such as cost estimating, construction planning, analysis, automated fabrication, and project control applications; but for now 3D/4D models are primarily used as a visualization and marketing tool.

Figure 3: Frequency of each model use: ranked by the number of projects (of the total thirty-two cases) exhibiting that model use

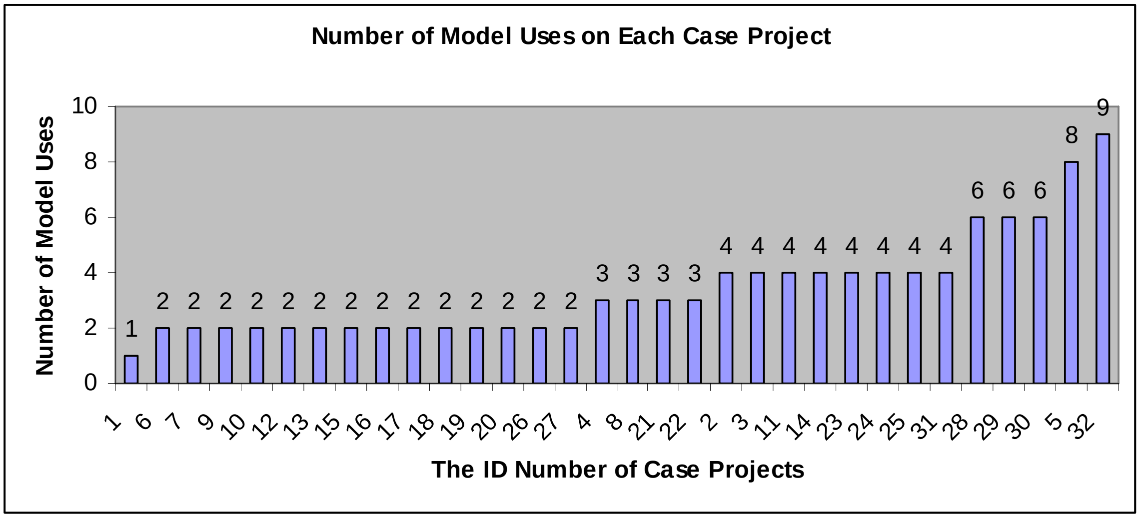


The data from the case examples substantiate the first part of this belief. However, we have to modify the second part according to the evidence from the cases. We define the frequency of one particular model use as the number of projects of the total thirty-two cases which exhibited that model use. As shown in Figure 3, we found that the use of a

3D model to interact with non-professionals (e.g., owners, end users, planning commissions, city councils and the general public) is the most frequent use. In addition, about half of the case projects implemented 3D modeling for construction planning, drawing production, and design checking. These observations indicate that interaction with non-professionals, construction planning, drawing production, and design checking are the four primary uses of 3D models. A handful of projects used 3D models for analysis of design options, supply chain management, cost estimating and change order management, facility management, and establishment of owner requirements. This implies that companies are starting to leverage 3D/4D models for more data-driven tasks.

We saw some interesting combinations of model uses. That is to say, when a project has one model use, it often has another model use. Regarding the number of model uses on each case project, Figure 4 shows that 26 out of the 32 projects implemented two to four model uses.

Figure 4: Number of model uses on each case project

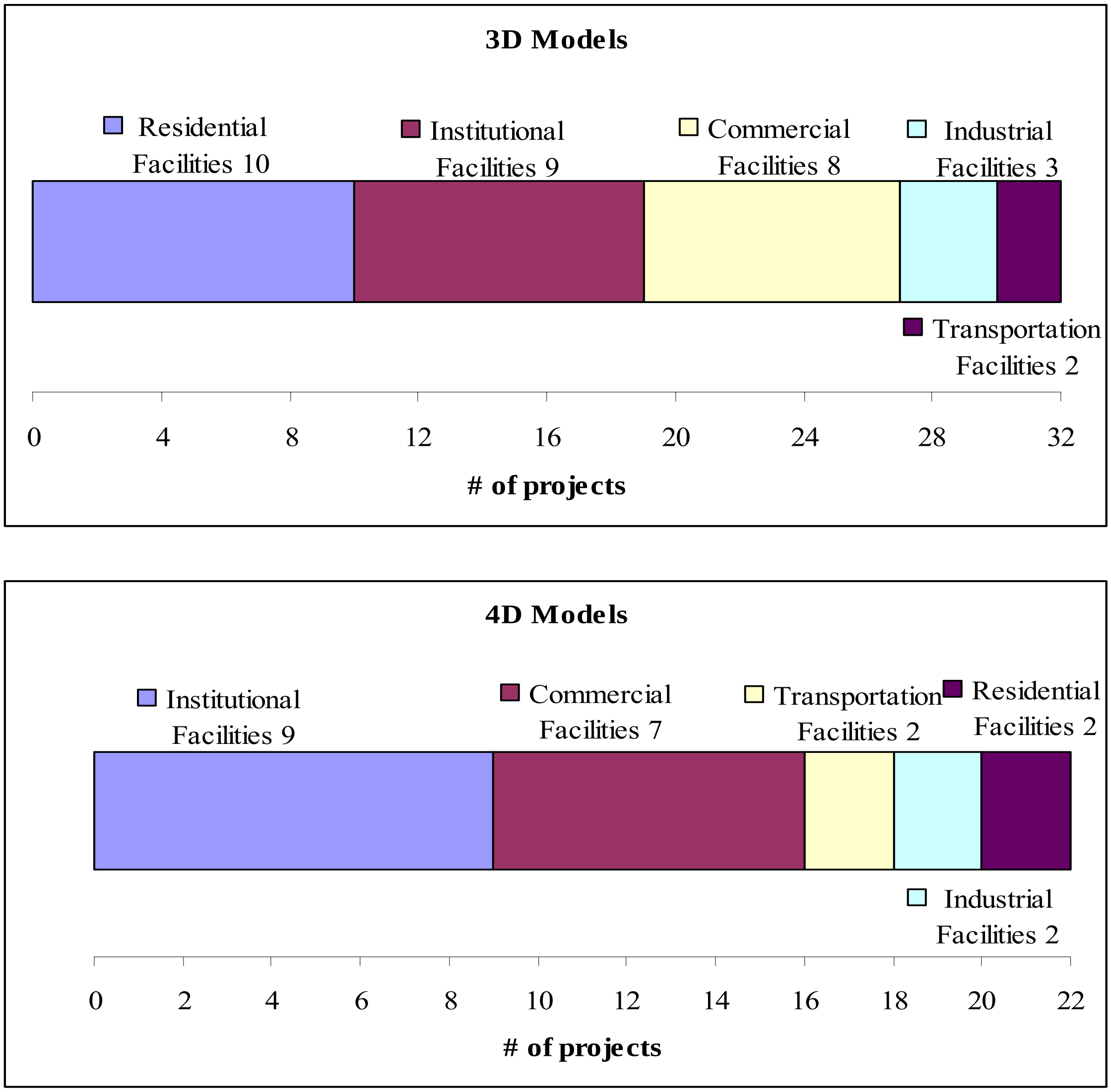


Therefore, we refine the last part of GB1 as follows. In practice, the primary use of 3D models is not only focused on interaction with non-professionals but also on construction planning, design checking and drawing production.

GB2: The use and benefits of three-dimensional design in residential and commercial buildings have not been shown.

Based on the data shown in Figure 5, we refine GB2 as follows: it is common to use 3D models on residential projects (10 out of the 32 3D modeling cases) and institutional projects (9 out of the 32 3D modeling cases) and to use 4D models on commercial projects (7 out of the 22 4D modeling cases) and institutional projects (9 out of the 22 4D modeling cases). Both 3D and 4D models lend themselves well to commercial, institutional and transportation facilities.

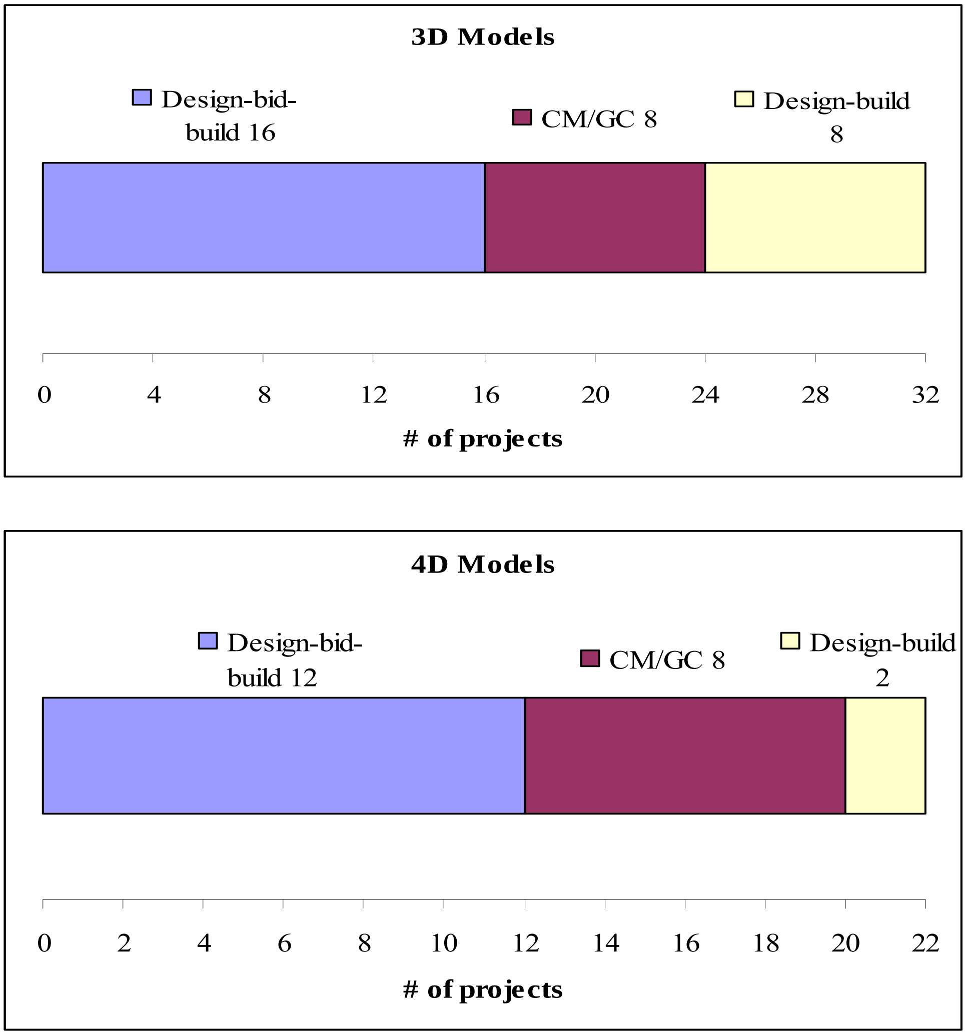
Figure 5: Using 3D/4D Models on various types of building projects



GB3: Lack of design-build or other collaborative contractual models should not be viewed as a reason to avoid 3D/4D modeling practices.

Based on the data shown in Figure 6, we agree with GB3: 3D/4D models apply to projects with all types of delivery methods. It is common to use 3D/4D models on design-bid-build projects (16 out of the 32 3D modeling cases and 12 out of the 22 4D modeling cases) and CM/GC projects (8 out of the 32 3D modeling cases and 8 out of the 22 4D modeling cases). 3D/4D models also lend themselves to design-build projects. Therefore, lack of design-build or other collaborative contractual models should not be viewed as a reason to avoid 3D/4D modeling practices.

Figure 6: Using 3D/4D models on projects with various delivery methods



GB4: 3D/4D models are more applicable for use on certain projects which involve characteristics such as a complex design, fast-paced project delivery, tight budget, high-tech facilities, etc.

The data from the thirty-two cases and Crosswalk 1 are in agreement with GB4 in that project characteristics have impacts on 3D/4D model uses. We also found that the use of 3D/4D models depends not only on the challenging characteristics of facilities but also the business drivers of stakeholders and the different project phases when 3D/4D models are created and used. There are two threads running through the following explanation. The numbered list shows how the uses of 3D/4D models vary according to the business drivers of different stakeholders. The bulleted list shows, for a particular stakeholder, how the uses of 3D/4D models vary according to different project characteristics or different project phases.

1. When **developers** drive the use of a 3D model on residential projects, the following four bullets demonstrate their viewpoints of the purposes and benefits of implementing 3D modeling in light of the characteristics of residential projects (e.g., cases 25, 27, 28, 29, and 30).

    - *Permitting:* Real estate developers are very sensitive to “time to revenue”. Homes and apartments must meet the standards of local building codes. Therefore, from 3D models, developers can produce documents that define a project’s scope of work well. In addition, they can use the visualization power of 3D models to persuade city and county planning authorities and accelerate the turnaround of the building permit approval.
    - *Marketing:* After the approval of the building permits, developers also use 3D architectural models as marketing and sales aids. In one way, sales-focused 3D images and brochures are produced to show homebuyers in graphical form what the various alternatives look like. In another way, by accessing project websites, customers are able to compare different finishing materials and alternative layouts and their effect on prices.

- *Pricing and procurement:* In the schematic design phase, 3D models provide a way to obtain cost estimates, bill of quantities, specifications, and schedules from the architect's component-based 3D model in just a few hours. This estimate prepared early in the project's life is compared to the developer's cost target to ensure that architects size the project and select materials within the budget of the developer. In the design development phase, architects can design with manufacturers' product libraries so that more off-site prefabrication and assembly are possible and these building products are presented in a schedule with precise styles and specifications for procurement and manufacturing. During the pre-construction and bidding phases, general contractors also send material lists to subcontractors and acquire subcontractors' pricing. They are less likely to overpay or underpay subcontractors because they can take off quantities accurately from the 3D model.
- *Change management:* If the design of residential projects has to be modified because of buyer-initiated change orders, 3D modeling facilitates changes of the suite mix, layout, etc. In addition, builders can use 3D models to precisely estimate the cost effects of change orders and promptly provide information to construction sites, e.g., what material has been changed and what is the quantity of this material.

2. When **owners** drive the use of 3D models on non-residential buildings such as educational facilities, office buildings, and government projects (cases 5, 18, 30, and 31), they usually have business drivers as follows.

   - In the conceptual planning phase, owners want to improve the quality of design to meet functional requirements or energy, cost, and environmental targets.
   - In the schematic design phase, owners expect to improve project scope definition and study better solutions to arranging or rearranging spaces for the end users as well as opportunities to change building functions in the future.
   - In the operations and maintenance phase, owners intend to pass data from 3D design models to the FM database so that the data can be reused to achieve better building performance and life-cycle costs.

When owners (or CM-agents) drive the use of 4D models for strategic project planning in the design phase (e.g., cases 4, 9, 16, and 21), the projects typically have multiple prime contractors. Owners have to facilitate a fast-paced project delivery, to manage the complexity of the interfaces between different bid packages, and to coordinate the commitment to common schedule objectives required of all contracted parties. In this aspect, 4D models help the owner or CM: 1) to plan the project milestones; 2) to develop the overall site management strategies; 3) to determine the contract packages (by visualizing the break-up of project scope into contractual "chunks", and seeing the progression of these contractual "chunks" over time); and 4) to manage the scope and sequence of bid packages (so as to close the gaps as work is handed off from one party to the next). More easily visualizing the project scope in 4D models also enables all project stakeholders to get rapid insights into the project goals, an overall view of the challenges in the broader context of the project, and an easy understanding of how their work interacts.

When owners drive the use of 4D models on renovation and modernization projects (cases 10 and 17), they usually leverage 4D models as a visualization and coordination tool in response to the challenges in the preservation of historic buildings or the issues stemming from concurrent building renovation and tenant relocation.

3. When **architects** drive the use of 3D models on residential projects, the following two bullets demonstrate their viewpoints of the purposes and benefits of implementing 3D modeling in light of the characteristics of residential projects (e.g., cases 22, 23, 28, 29, and 30).

    - *Design Simulation:* The residential sector is a highly competitive marketplace that asks for high-quality building products to satisfy consumers' needs. Designing residential projects in 3D enables the precise representation of the area, size, and layout and facilitates a fuller exploration of design options.
    - *Drawing production*: A relatively large number of housing and apartment buildings involve identical or similar building parts or even entire buildings that

have similar designs. The deployment of 3D modeling eliminates unnecessary repetitive work. Therefore, one internal motivation of using 3D models in architectural firms is to make the design process more efficient. One of the guest speakers on the CIFE 2006 summer program commented that in his practice a design in 3D costs 50% of a design in 2D for an architect (Carpenter 2006).

When architects, detailers, or fabricators drive the use of 3D models for design analysis and supply chain management on commercial, institutional, or transportation projects (e.g., cases 3, 8, 11, 14, and 24), these types of projects usually have demanding architectural and structural characteristics as follows.

- *Geometric complexity, unusual shape, long span structures or complex details (e.g., steel frame connections, reinforcement assembly details, etc.):* 3D models offer easy visualization of the complexity and act as excellent tools to ensure precise engineering and detailing and secure the proper functioning of a structure.
- *A large number of steel or pre-cast concrete members:* This characteristic requires that the information (e.g., drawings or schedule information) flows more smoothly between project team members to improve the efficiency of designing, detailing, procuring, and expediting the erection of a steel or pre-cast concrete structure. In response to this demand, 3D models facilitate the computer numerically controlled (CNC) fabrication process and ensure that fabricated panels will line up precisely on site and no or dramatically fewer field-fittings will be required. By giving exact dimensions for manufacturing, 3D models also create bills of materials (BOM) that are valuable in procuring the materials needed in construction. Engineering lead-time is shortened 1) by streamlining information flows between engineering, fabrication, and erection, and 2) by reducing batch sizes of shop drawings from 3D models and making more frequent but smaller orders (Koerckel 2005).

4. When **construction managers or general contractors** drive the use of 3D models for MEP design coordination and clash detection in the design development phase, the projects are usually pharmaceutical, biotech, or healthcare facilities with

challenges as follows (e.g., cases 2, 7, and 20). These technical projects involve complex MEP systems (usually under the design/build delivery system) that need spatial and installation coordination (Korman et al. 2003). Therefore, 3D models are used to detect clashes of the MEP systems so that the work carried out later by different subcontractors does not interfere with each other.

When construction managers or general contractors drive the use of 3D models for cost estimating, the projects are often delivered by a CM/GC approach (e.g., Case 13) where the GC is selected early in the schematic design process. With 3D-model based cost estimating, the GC can provide more prompt and frequent cost feedback to the architect, which facilitates value engineering or the design for cost effectiveness.

When construction managers or general contractors drive the use of 4D models for constructability review and trade coordination in the preconstruction or the early construction phase, the projects are usually geometrically complex or have site constraints that limit space for contractors to stage materials and execute their work (e.g., cases 3, 6, 8, 11, 12, 14, 16, and 21). These features require significant planning and coordination of logistics to ensure that construction operations run smoothly. With 4D models, general contractors and subcontractors can identify congested areas and access issues, manage lay-down areas, staging areas and temporary structures, check workflow and accessibility, optimize crane locations and material delivery, and review safety conditions.

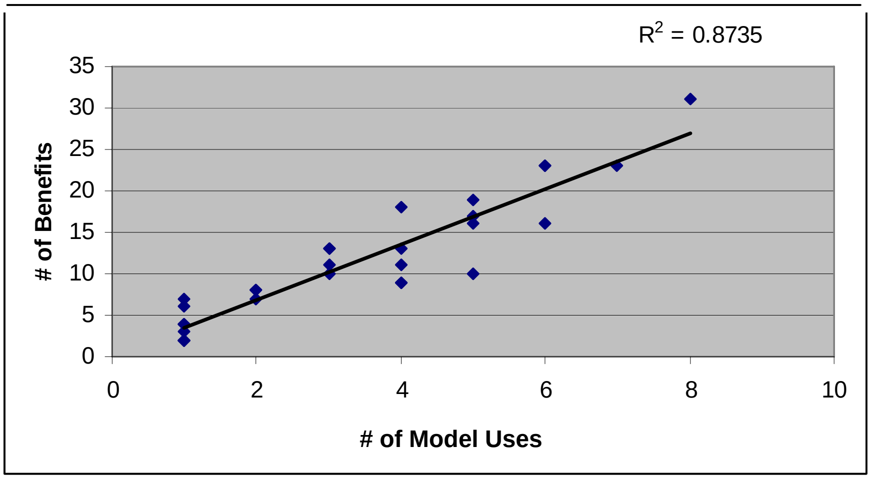
When construction managers or general contractors drive the use of 4D models for validating master schedules and construction sequencing in the preconstruction or early construction phase, the projects often have tight schedules and must-meet deadlines that require fast-track construction or acceleration to allow prompt project delivery (e.g., cases 1, 4, 6, 8, 11, and 19). In some cases, the projects also have schedule constraints on construction activities to disturb building operations as little as possible (e.g., case 21). When desired, 4D models enable a much more detailed and thorough analysis of a construction schedule by more people in a shorter period of time than traditional methods.

GB5: There are many 3D/4D models developed for many different uses.

The findings based on Crosswalk 1 support this point. Crosswalk 1 (Table 6 and Table 7) demonstrates that there are many 3D/4D models developed for many different uses in the design and construction phases of a building, before and during the creation of the real world structure. Each model use plays a part in supporting project team members to accomplish a particular professional task they are expected to do.

To investigate the correlation between the model uses and impacts on the thirty-two case projects, we charted the scatter plot shown in Figure 7. Each single data point represents the documented situation on a particular case, i.e., how many uses of 3D/4D models were realized on a particular project and how many benefits were obtained (as accounted from the data sources (case examples) in Table 6 and Table 7). These individual points were then connected by a trend line. Because the R^2 (correlation constant) value is 0.8735, we can say with a high degree of certainty that this line describes the trend in the data. That is to say, the higher the number of uses of the 3D/4D models on a project, the higher the number of benefits.

Figure 7: The trend line correlates the number of model uses to the number of benefits for the thirty-two cases (each case is represented by a dot).



4.2 Findings from Crosswalk 2 vs. General Beliefs about Timing of 3D/4D Modeling

Timing of 3D/4D modeling includes the time at which project participants create the models and the length of time that these models are used. Timing of impacts is the time at which the impacts are reaped and the length of time during which they are in effect. A few projects (cases 3, 8, 11, 24, 25, 28, 29, 30, and 32) implemented 3D and 4D modeling from the very beginning of the project to the completion of design and construction (Table 8). Most case projects used 3D and 4D models to address project challenges over the course of one or two specific project phases.

Crosswalk 2 (Table 9) links the major phases of a project when 3D and 4D models are used (as shown in the light-grey boxes) to the timing of the impacts on the product, organization, and processes (as shown in the dark-grey boxes). The length of the light-grey box indicates the timing of a particular model use. Below each light-grey box, several dark-grey boxes stretch over one or a few project phases, representing the timing of impacts. The horizontal axis in Crosswalk 2 depicts the phases in the design and construction processes that are most common to building construction projects: Schematic Design (basic appearance and plans), Design Development (defining systems), Construction Documents (details of assembly and construction technology), Preconstruction (purchasing and award of contracts for construction as well as final fabrication shop drawings), Construction (manufacture and installation of components or labor-intensive field construction and installation), and Operations and Maintenance. Crosswalk 2 enables AEC professionals to look at each phase and determining whether and how 3D/4D modeling improves the existing processes, and what investments to make for future phases. We compared insights from Crosswalk 2 to the general beliefs about timing of 3D/4D modeling (GB 6, 7, and 8).

Table 8: The thirty-two case projects - timing of 3D/4D model use and timing of impacts

░ **Timing of 3D/4D Model Use**

▓ **Timing of Impacts**

Case #	**Case Projects**	**Schematic Design**	**Design Development**	**Construction Documents**	**Pre-construction**	**Construction**	**Operations & Maintenance**
1	McWhinney Office Building					░ ▓	
2	Sequus Pharmaceuticals Pilot Plant		░	░ ▓	░ ▓	░ ▓	
3	Experience Music Project	░	░	░ ▓	░ ▓	░ ▓	
4	Paradise Pier, Disney California Adventure	░	░	░ ▓	░ ▓	░ ▓	
5	HUT-600	░ ▓	░ ▓	▓		▓	▓
6	Baystreet Retail Complex					░ ▓	
7	Genentech FRCII				░	░ ▓	
8	Walt Disney Concert Hall	░	░	░ ▓	░ ▓	░ ▓	
9	Hong Kong Disneyland	░			▓		
10	Pioneer Courthouse				░ ▓		
11	MIT Ray and Maria Stata Center	░	░ ▓	░ ▓	░ ▓	░ ▓	
12	Banner Health Good Samaritan Hospital				░ ▓	░ ▓	
13	California Academy of Science Project		░ ▓	░ ▓	░ ▓	░ ▓	
14	Terminal 5 of London's Heathrow Airport			░ ▓	░ ▓	░ ▓	
15	Residential Building in Sweden					░ ▓	
16	Pilestredet Park Urban Ecology Project	░ ▓			▓	▓	
17	Regional Office Building *	░ ▓					
18	Jackson Courthouse *	░ ▓					

░ **Timing of 3D/4D Model Use**

▒ **Timing of Benefit**

	Case Projects	**Schematic Design**	**Design Development**	**Construction Documents**	**Pre-construction**	**Construction**	**Operations & Maintenance**
19	Samsung LSI Fab Facility					░ ▒	
20	Camino Medical Campus		░ ▒	░ ▒	░ ▒	░ ▒	
21	Fulton Street Transit Center			░ ▒	░ ▒	░ ▒	
22	A Town-planning Project in Finland	░ ▒	░ ▒	░ ▒			
23	Mamselli Low-rise Housing Project	░ ▒	░ ▒	░ ▒		▒	
24	Headquarter Building for NCC-Finland	░ ▒	░ ▒	░ ▒	░ ▒	░ ▒	
25	Tali Apartment Building Project *	░ ▒	░ ▒	░ ▒	░ ▒	░ ▒	
26	Office Building Project in Oulu				░ ▒	░ ▒	
27	Semi-detached Houses in Kerava				░ ▒	░ ▒	
28	Koskelantie 22-24 Residential Renovation	░ ▒	░ ▒	░ ▒	░ ▒	░ ▒	▒
29	Vantaan Silkinkulma Apartment Building	░ ▒	░ ▒	░ ▒	░ ▒	░ ▒	▒
30	Vantann Ankkahovi Apartment Building	░ ▒	░ ▒	░ ▒	░ ▒	░ ▒	▒
31	Pfizer, Scandinavian Headquarter Building	░ ▒	░ ▒	░ ▒	░ ▒		░ ▒
32	Aurora 2 University Building in Joensuu *	░ ▒	░ ▒	░ ▒	░ ▒	░ ▒	

Note (*):

- At the time of writing this report, cases 17 and 18 were still under design development; therefore the impacts of 3D/4D modeling during the downstream phases have not been documented yet.
- At the time of writing this report, cases 25 and 32 were still under construction; therefore the impacts of 3D/4D modeling during the operations and maintenance have not been documented yet.

Table 9: Crosswalk 2 – linking 3D/4D model uses with the impacts on product, organization, and process along the project timeline

<table>
<tr><th colspan="3">Engineering and Design Phase</th><th rowspan="2">Pre-construction Phase</th><th rowspan="2">Construction Phase</th><th rowspan="2">Operations and Maintenance Phase</th></tr>
<tr><th>Schematic Design</th><th>Design Development</th><th>Construction Documents</th></tr>
</table>

Legend: ░ **Timing of Model Use** ▒ **Timing of Impact on Product, Organization, and Process**

<table>
<tr><td>░ <i>Establishment of Owner Requirements</i></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">▒ Process: (owner) Reliable design based on realistic energy cost, and environmental targets</td><td></td><td></td><td></td><td>▒ Product: Better quality building and better achievement of the owner objectives</td></tr>
</table>

<table>
<tr><td colspan="2">░ <i>Interaction with Non-professionals</i></td><td></td><td></td><td></td><td></td></tr>
<tr><td>▒ Process: (owners and end users) Easy evaluation of design forms vs. functions</td><td></td><td></td><td></td><td></td><td>▒ Product: Better quality of building, design forms better complying with functions, and more end user satisfaction</td></tr>
<tr><td></td><td></td><td></td><td colspan="2">▒ Process: (homebuyers) Easy comparison of alternatives and making the decision to buy</td><td></td></tr>
<tr><td>▒ Process: (authorities) Fast permitting</td><td colspan="3">▒ Process: (developer) Quick start of developer’s marketing</td><td></td><td></td></tr>
<tr><td colspan="5">▒ Process: (owners, end users, planning commissions, city councils, and the general public) Better understanding of design intent and project status</td><td></td></tr>
<tr><td colspan="5">▒ Org.: (owners, end users, planning commissions, city councils, and the general public) More and earlier involvement in terms of providing more input and hence having more influence on a project</td><td></td></tr>
</table>

<table>
<tr><td colspan="2">░ <i>Analysis of Design Options</i></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">▒ Product: Improved quality of building design in terms of meeting aesthetic and technical functions</td><td></td><td></td><td></td><td>▒ Product: Better life-cycle performance and more end user satisfaction</td></tr>
<tr><td colspan="2">▒ Process: Easy exploration of design options</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">▒ Process: Fast analysis and timely decision-making</td><td></td><td></td><td></td><td></td></tr>
</table>

<table>
<tr><th colspan="3">Engineering and Design Phase</th><th rowspan="2">Pre-construction Phase</th><th rowspan="2">Construction Phase</th><th rowspan="2">Operations and Maintenance Phase</th></tr>
<tr><th>Schematic Design</th><th>Design Development</th><th>Construction Documents</th></tr>
</table>

Legend: ░ **Timing of Model Use** ▒ **Timing of Impact on Product, Organization, and Process**

<table>
<tr><td></td><td colspan="2">***Design Checking (System Coordination and Constructability Review)***</td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">**Product:** Better design solution and well-coordinated drawings</td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">**Process:** Easy clash detection, fast design coordination, and better coordination and communication between multiple disciplines</td><td></td><td rowspan="2">**Process:** Reduced field requests for information (RFI), change orders (C.O.), and rework because the facility design has been coordinated within and across multiple disciplines</td><td></td></tr>
<tr><td></td><td colspan="2">**Org.:** Early and frequent involvement of downstream designers, GC, and subs</td><td></td><td></td></tr>
</table>

<table>
<tr><td></td><td colspan="2">***Production of Construction Documents***</td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">**Product:** Better quality of construction documents</td><td>**Process:** Accurate schedule/BOQ for procurement</td><td>**Process:** Prefab pieces more likely to fit together in the field</td><td></td></tr>
<tr><td></td><td colspan="2">**Process:** Easy and quick drawing production</td><td></td><td>**Process:** Easy and quick change management</td><td></td></tr>
<tr><td></td><td colspan="2">**Org.:** No draftsmen</td><td></td><td></td><td></td></tr>
<tr><td colspan="3">**Org.:** Longer involvement of architects in the entire design process</td><td></td><td></td><td></td></tr>
</table>

<table>
<tr><td colspan="4">***Quantity Takeoff and Cost Estimating***</td><td></td><td></td></tr>
<tr><td>**Process:** Prompt determination of project budget</td><td colspan="2">**Process:** Fast cost feedback to design</td><td>**Process:** Fast process for construction estimate</td><td></td><td></td></tr>
<tr><td colspan="4">**Product:** More accurate cost estimation</td><td>**Process:** Better management of change orders</td><td></td></tr>
<tr><td></td><td></td><td></td><td>**Org.:** Better prices for subcontract bid packages</td><td>**Org.:** Foremen released from repetitive work of re-calculating quantities</td><td></td></tr>
</table>

Engineering and Design Phase			Pre-construction Phase	Construction Phase
Schematic Design	Design Development	Construction Documents		

Legends: ░ **Timing of Model Use** ▒ **Timing of Impact on Product, Organization, Process**

Supply Chain Management				
Process: Early specification of building products in design				**Process:** Reduced construction time with more off-site prefabrication and assembly
		Process: Reduced engineering lead-time by streamlining schedule information flows between engineering, fabrication, and erection		
		Process: Reduced batch sizes of drawings and frequent and small orders of materials	**Process:** Quicker manufacturing turnaround and reduced response time for RFIs	**Process:** Reduced amount of material stored on site
			Process: Easy process for fabricators and subcontractors to understand the intricacy of the structural frame and connection details in a 3D structural model	**Process:** Smooth field construction and reduced field RFIs and rework

Construction Planning / 4D Modeling				
Process: Better communication and coordination in the process of strategic project planning **Org.:** More project stakeholders involved early in providing input to strategic project planning				**Process:** Work packaging and phasing less prone to interference **Process:** Better communication of construction status to project stakeholders **Process:** Well-coordinated renovation and facility operation
		Process: Winning the construction contract by showing the contractor's capability **Process:** Better understanding of the engineer's specification or owner's intention by the contractors		
		Process: Bids closer in range		
		Process: Fast construction permitting		
		Process: Improved reliability and executability of master schedules		**Process:** Timely meeting of project milestones
		Process: Better communication and coordination in constructability review		**Process:** Reduced field C.O.s and rework and improved site safety
		Process: Better communication and coordination of site operations		
				Process: Smooth field construction, subcontractors' work less prone to interference

Engineering and Design Phase			Pre-construction Phase	Construction Phase	Operations and Maintenance Phase
Schematic Design	Design Development	Construction Documents			

Legend: ░ **Timing of Model Use** ▒ **Timing of Impact on Product, Organization, and Process**

					Facility Management
					Product: Better response to end users' space needs
					Product: Well-performed operation of technical systems and better working conditions
					Process: Seamless transfer and reuse of as-built information, and building performance reporting to facility manager

GB6: There is a time lag between implementing 3D/4D modeling and reaping the corresponding benefits.

The data from the case examples partly confirm the above belief. However, we have to adjust GB6 to make it more appropriate to the situations observed in the cases. Crosswalk 2 (Table 9) shows that, among all the benefits attainable from one particular 3D model use, some benefits come along immediately with that use of 3D models while other benefits occur later. The immediate benefits often affect the effectiveness and efficiency of the current design process as well as the communication and coordination within the project organization; while the late benefits mostly have an impact on the downstream construction and O&M process as well as the quality and performance of the building. For example, the use of 3D models for design checking (as manifested in cases 2, 3, 7, 8, 11, 14, 20, 21, 23, 24, 25, 29, 30, 31, and 32) facilitates a more efficient and reliable design process by easy clash detection (benefit to the design process) and allows earlier and more frequent feedback from other designers and contractors (benefit to the organization). These are immediate benefits reaped along with the use of 3D models for design checking. The benefits occurring after the design checking include a reduction in field RFIs, change orders, and rework in the construction phase (benefits to the construction process) and a completed building product that has well-coordinated systems (benefits for the product). In Crosswalk 2 (Table 9), some immediate and late benefit "boxes" are shown in the same row. This means that the late benefits are the ripple effects of the immediate benefits that have been realized early on. For instance, 3D visualization in the schematic design phase can assist designers in space-planning. This immediate benefit subsequently leads to a finished building product that better responds to end users' space needs in the O&M phase.

Crosswalk 2 (Table 9) also shows that most benefits of 4D modeling on the thirty-two case projects took effect immediately (cases 1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 19, 20, 21, 24, and 32). These immediate benefits manifest themselves in engaging more project stakeholders to identify more problems (such as schedule slippage, site logistics and accessibility problems, and trade stacking) and solve them more collaboratively.

However, when 4D models are used in the design phase for the purpose of strategic project planning (cases 4, 9, 16, and 17) and constructability review (cases 4, 5, 20, and 21), the lag between the timing of the 4D modeling efforts and the actual realization of the benefits, such as on-time completion, fewer RFIs, and change orders, can be significant.

Therefore, we refine GB6 as follows: The use of 3D/4D models early in the design phase results not only in immediate benefits (which relate to the ongoing project process and organization) but also late benefits (which accrue during the downstream processes and relate to the performance of a finished building product). However, the use of 3D/4D models in the preconstruction and construction phases mostly leads to immediate benefits. In other words, there are immediate and later benefits from implementations of 3D/4D modeling.

GB7: It is essential to capitalize on project opportunities early on to make 3D/4D models have a lasting and positive effect on the facility over its total life span.

One finding based on Crosswalk 2 is in agreement with GB7. The last column in Crosswalk 2 (Table 9) identifies benefits (in the O&M phase) which have lasting and positive effects on the facility. For example, the improvement of overall project performance in case 5 was demonstrated by a 10%-15% savings in first cost and a 5%-25% potential savings in the life-cycle cost. These lasting impacts (demonstrated by cases 5, 18, and 32) are brought about by using 3D models in the early planning and design phase. For example, 3D/4D models facilitate evaluation of product (building) design forms vs. functions and help set and manage towards aggressive but realistic targets for energy, cost, and environmental performance. In addition, 3D/4D models support space-planning by color-coding different user units and departments, involve end-users early in a project's decision-making process, and assist designers in exploring alternatives of building shape and space layout via simulation and analysis. Crosswalk 2 also shows that these 3D model uses are initiated from the start of schematic design throughout design development.

GB8: Designers benefit directly from building detailed 3D models. A design in 3D costs less than a design in 2D for an architect.

Designers often argue that if owners do not pay for 3D modeling it is cumbersome for them to build 3D models. However, the findings of Crosswalk 2 (Table 9) show that designers benefit directly from building detailed 3D models. Designers not only gain the benefit of design cost reduction but also the improvement of design quality and process.

In these cases (cases 3, 5, 8, 11, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, and 32), designers utilized 3D models for the architectural, structural, HVAC, or electrical systems to support client briefing or produce the construction documents. Moreover, a few cases (cases 5, 11, 22, 23, 28, 29, 30, 31, and 32) witnessed the use of 3D models for design analysis or design checking with respect to systems coordination. Crosswalk 2 (Table 9) demonstrates that these uses of 3D models lead not only to late benefits to the downstream processes but also to immediate benefits that occur in the design phase and of interest for designers themselves.

The benefits that occur in the design phase and are of interest for designers are:

- 3D modeling improves the quality of design by reducing errors and inconsistencies. When working with 3D models (as shown in cases 31 and 32), designers can test their design virtually, trust the results from the analysis, and provide clients with a design that is more reliable and economical.
- 3D modeling leads to a reduction in the number of late design changes that are caused by design errors, incorrect understanding of the design by the owner, or inadequate assessment of existing site conditions. The later a change occurs in the design process, the more expensive it becomes for the designer (and the project team as a whole) because of the number of subsequent drawing changes, and the riskier it becomes because the design changes may not be coordinated among all of the various engineers, consultants, and contractors. With 3D models (as shown in cases 5, 11, 31, and 32), designers produce better building information up front (like visual and

financial effects of changing glazing, lighting, or other energy conservation strategies), make better design decisions, and hence avoid many late design changes.

- 3D modeling might not reduce design effort (man-hours) in total but it changes the distribution of design effort between design development and construction documents. As demonstrated by interviewees' experiences in cases 5, 11, 22, 23, 28, 29, 30, and 31, designers attempt to maximize client satisfaction and hence gain repeat business by shifting design hours saved from the productivity improvement in drawing production to developing better quality design.

4.3 Findings from Crosswalk 3 vs. General Beliefs about Key Stakeholder Involvement

Key stakeholders on a project include the owner/developer and AEC service providers, i.e., the designers, general contractors, and subcontractors. Key stakeholders involved in the 3D and 4D modeling process play two primary roles, i.e., they lead (i.e., coordinate the whole process of 3D/4D modeling) or they are involved (i.e., participate partially in the process of building, reviewing, or using 3D/4D models). Crosswalk 3 (Table 10) links the situations in which key stakeholders take on different roles to the number of benefits that accrue to them individually. Findings from Crosswalk 3 (Table 10) are then compared to the general beliefs about key stakeholder involvement (GB9).

GB9: The more stakeholders are involved in implementing 3D/4D modeling; the more benefits will accrue to them as a whole and to each stakeholder individually.

Often individual stakeholders evaluate the benefits of 3D and 4D modeling purely from their "stakeholder" perspectives (i.e., with a "WIIFM" ("what's in it for me") attitude). Although the viewpoint of each individual stakeholder is important because each of them makes the decision whether or not to implement 3D/4D modeling, it is also important to reflect the impacts on the whole project team as well. Based on Crosswalk 3 (Table 10), we drew "spider" diagrams (Figure 8, Figure 9, and Figure 10) to reveal not only the benefits of 3D/4D modeling to each individual stakeholder but also the "scope of impacts" (i.e., number of benefits) of 3D/4D modeling for the key project stakeholders as a whole. In these charts, the four axes stand for the owner, designer, general contractor, and subcontractors respectively. The number of benefits to each stakeholder (as shown in Table 10) is measured along the axis and highlighted by the axis marker. The 3D/4D model's "scope of impacts" for the key project stakeholders as a whole is the area enclosed by the lines that join the markers. In Figure 8, Figure 9, and Figure 10, the biggest area is bounded by the blue lines. This pattern illustrates that, no matter who is leading, the benefits (i.e., 3D/4D model's scope of influence) are maximized for the project team as a whole when all the key stakeholders are involved. For example, on case 20, one of the MEP subs commented that the more other trades participate in the model the more accurate the model becomes. Therefore, the MEP subs can fabricate more items.

Table 10: Crosswalk 3 – linking key stakeholders' roles in the 3D and 4D modeling process to the benefits to them as individual stakeholders

Situations **• Leading** **• Involved** (applicable cases listed in parentheses)	**Average # of Benefits per Case (for Owner)**	**Average # of Benefits per Case (for Designer)**	**Average # of Benefits per Case (for GC)**	**Average # of Benefits per Case (for Subs)**
Owner Leading				
Situation 1: Owner leading and GC involved (4) (26) (27)	6	1	8	5
Owner leading and designer involved (18)*	2	1	0	0
Situation 2: ***Owner leading and designer, GC, and subs involved*** (24) (25) (28) (29) (23) (32)	**9**	**12**	**10**	**10**
Situation 3: Only owner leading and involved (9) (10) (16) (17)	3	0	0	0
GC Leading				
Situation 4: ***GC leading and owner, designer, and subs involved*** (2) (20) (21)	**4**	**3**	**7**	**8**
Situation 5: GC leading and owner and subs involved (7)*	3	2	4	6
Situation 6: GC leading and owner involved (12)*	2	0	7	3
Situation 7: GC leading and only subs involved (19)*	0	0	6	6
Situation 8: Only GC leading and involved (1) (6) (13)	1	0	3	3
Designer Leading				
Situation 9: ***Designer leading and owner, GC, and subs involved*** (3) (8) (11) (14)	**2**	**7**	**9**	**11**
Situation 10: Designer leading and GC and owner involved (5) (31)	5	11	3	2
Situation 11: Designer leading and owner involved (22) (23)	3	10	2	2

Note (*): More cases are needed, but this case supports GB9.

Figure 8: The number of benefits of 3D/4D modeling to the key project stakeholders in the “owner leading” situations

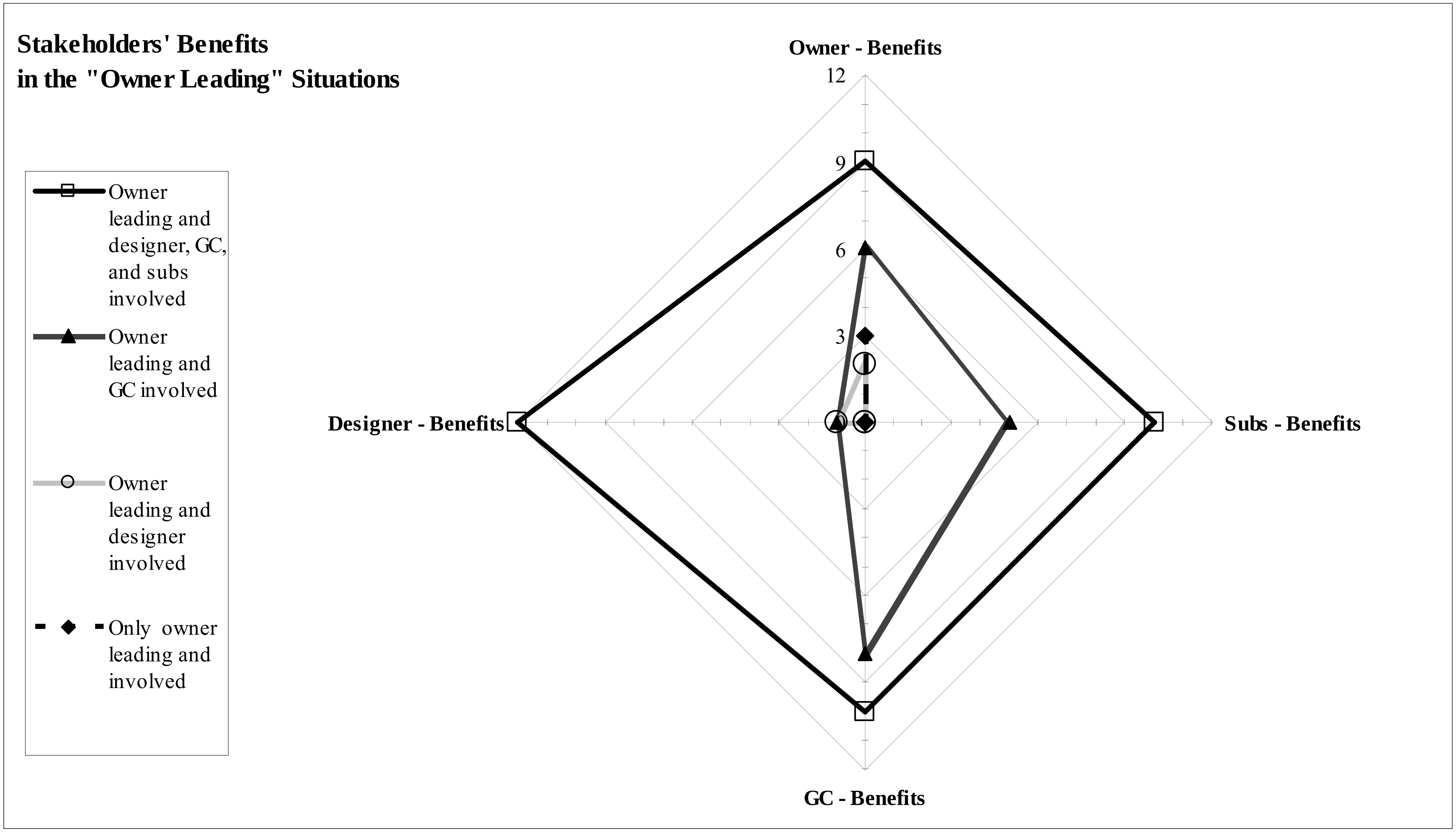


Figure 9: The number of benefits of 3D/4D modeling to the key project stakeholders in the “GC leading” situations

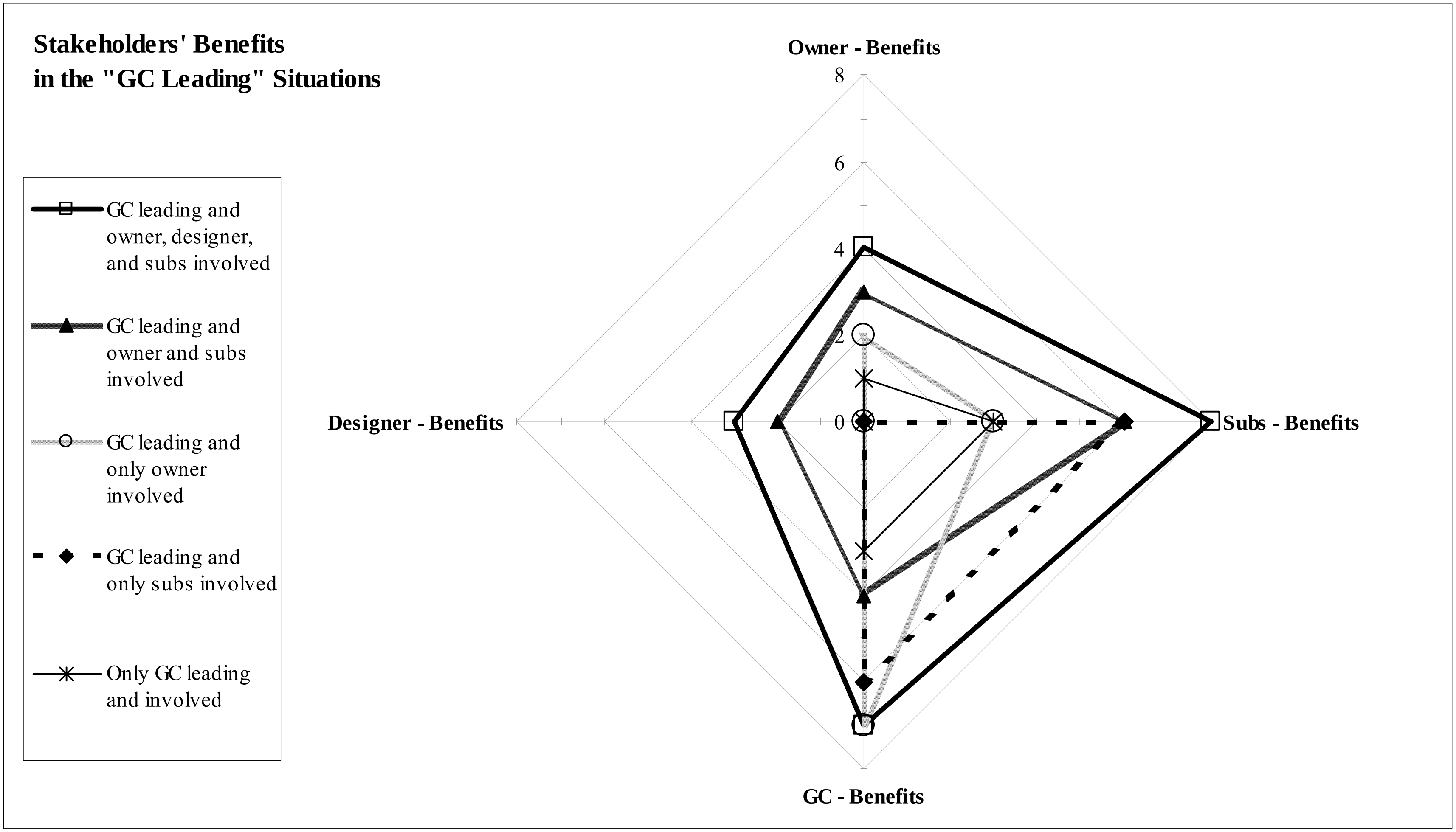
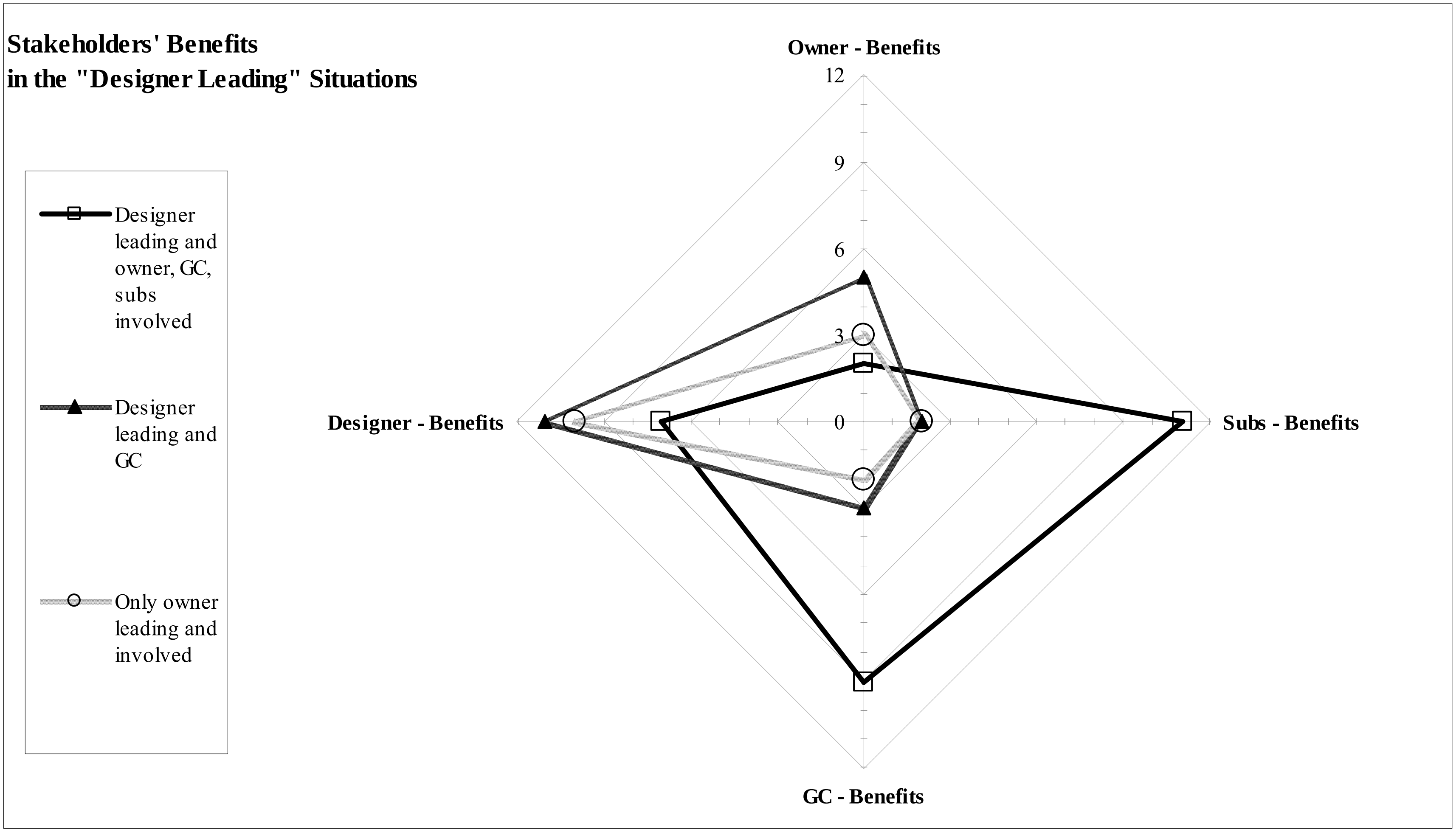


Figure 10: The number of benefits of 3D/4D modeling to the key project stakeholders in the “designer leading” situations



In spite of the common pattern mentioned above, we found that Figure 10 is inconsistent with the pattern in Figure 8 and Figure 9. The blue trapezoid in Figure 8 and Figure 9 not only has the biggest area but also encircles the rest of the polygons. However, the blue trapezoid in Figure 10 overlaps the rest of the polygons even though it has the biggest area. The pattern in Figure 8 and Figure 9 illustrates that the benefits to every individual stakeholder as well as to the whole team are maximized simultaneously when all the key stakeholders are involved. On the other hand, the pattern in Figure 10 illustrates that when the designer leads and all the key stakeholders are involved, the benefits to the whole team are maximized while the designer and owner do not reap the most benefits. Since we are dealing with just a few cases under this circumstance, we studied these relevant cases in more detail to interpret this potential inconsistency.

We found that this irregularity in terms of the benefits to individual stakeholders when the designer leads (Figure 10) is attributed to two reasons. First, other stakeholders such as general contractors and subcontractors gained more benefits than designers and owners when the use of 3D models was process-focused. For example, in cases 3, 8, 11, and 14, the 3D models created by the design team directly yielded the geometric data that was needed by contractors and fabricators to detail and manufacture eccentrically shaped metal skins or complicated reinforcement. The single data set in the 3D models facilitated the processes of detailing and prefabrication. 3D models also facilitated the construction process when fabricated members were lined up precisely on site without field-fittings. Second, for cases 3, 8, and 11, more benefits would be documented on the side of the designer if we had been able to directly talk to the designer rather than interpreting the designer's benefits from interviewing other stakeholders and reviewing secondary data from available documents.

The trapezoid in green represents cases 5 and 31, where the owner and designers attained more benefits. In cases 5 and 31, the 3D models aided in lighting simulation, comfort analysis, simulation of energy performance, air flow analysis, and environmental and life cycle assessment. The 3D models provided additional valuable life-cycle parameters to the owner during early project phases by enabling the design team to develop multiple design alternatives for comfort (indoor air and lighting), energy-efficiency (heating, cooling and electricity), cost (investment, maintenance and life cycle cost), and environmental impacts (LCA) early in the project. Through defining performance and cost targets and comparing design alternatives, the resulting quality of the building both in terms of energy performance and life cycle costs is better (Hänninen and Laine 2004). Therefore, individual stakeholders, such as the owner and designer, gained more benefits than the GC and subs when the use of 3D models was product-focused.

Therefore, we refine GB9 as follows:

- No matter who is leading, the scenario where all the key stakeholders are involved offers most benefits for the whole project team. This is a win-win opportunity that all stakeholders can take advantage of.
- When the owner or GC is leading, the benefits to each individual stakeholder are maximized when all the key stakeholders are involved.
- When the designer is leading, the benefits to the owner and designer are maximized if the use of 3D model is product-focused. The benefits to the GC and subs are maximized if the use of the 3D model is process-focused. More cases are needed to confirm this pattern.

4.4 Findings from Crosswalk 4 vs. General Beliefs about Level of Detail in 3D/4D Models

AEC professionals have to decide the level of detail of the 3D/4D models. There are two common issues in developing the appropriate level of detail: 1) how to define the "level of detail"; 2) how to determine whether the level of detail is appropriate. We developed a matrix to define the level of detail in the 3D/4D models. By examining the level of detail of the 3D/4D models on the 32 case projects and assembling them in the matrix, we gained the following insights.

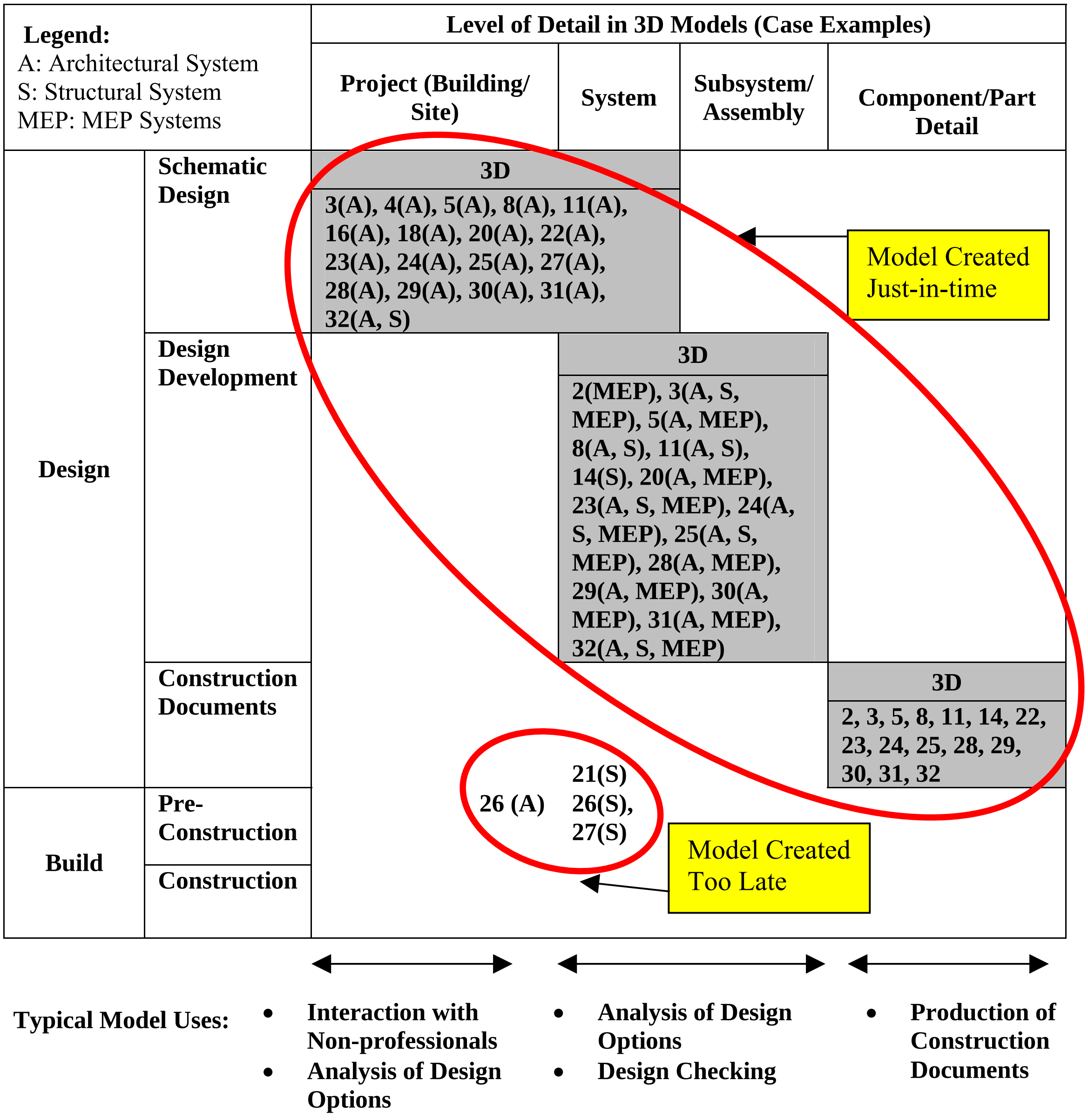
- Two factors, i.e., model use and information available at a particular project stage, are important to determine the appropriate level of detail of the 3D/4D models.

- The evolving level of detail in the 3D/4D models along the typical project timeline accommodates different model uses.
- The categorization of the timing of developing the level of detail in the 3D/4D models as "just-in-time", "too early", and "too late" enables AEC professionals to identify the situations when models are created too early or too late and thus to analyze the corresponding reasons and the subsequent ramifications.
- Creating 3D/4D models just-in-time and at the appropriate level of detail that matches the model use is instrumental in maximizing the benefits. Table 10 (p.52) shows the correlation between the timing of developing the level of detail in the 3D/4D models and the corresponding benefits. Table 10 also demonstrates that some cases in which 3D/4D models were created at the right timing and at the right level of detail gained more benefits than other cases in which the level of detail of the 3D/4D models was developed "too early" or "too late".

GB10: Creating 3D and 4D models at the appropriate level of detail is instrumental in reaping their benefits.

To determine the appropriateness with respect to the level of detail in the 3D/4D models, we first developed a method to define the "level of detail". As shown in the 2nd row of Figure 11, the 3D model can reflect various levels of detail, including the project (building/site), system, sub-system, component, and part. As shown in the 2nd and 3rd header rows of Figure 12, the level of detail in the 4D model is determined by the data hierarchy in the 3D model as well as the level of detail in the work breakdown structure of a project schedule. The level of detail in a schedule can be identified by a bimonthly or monthly schedule (corresponding to the work at the building, site, or system level), by a weekly schedule (corresponding to the work at the subsystem level), by a day-to-day operational schedule (corresponding to the work at the component level), and by an hourly operational schedule (corresponding to the work on the part level).

Figure 11: Crosswalk 4 (Part I) – linking the level of detail in 3D models with the timing of 3D modeling



Legend: A: Architectural System S: Structural System MEP: MEP Systems		**Level of Detail in 3D Models (Case Examples)**			
		Project (Building/ Site)	**System**	**Subsystem/ Assembly**	**Component/Part Detail**
Design	**Schematic Design**	**3D** **3(A), 4(A), 5(A), 8(A), 11(A), 16(A), 18(A), 20(A), 22(A), 23(A), 24(A), 25(A), 27(A), 28(A), 29(A), 30(A), 31(A), 32(A, S)**			
	Design Development		**3D** **2(MEP), 3(A, S, MEP), 5(A, MEP), 8(A, S), 11(A, S), 14(S), 20(A, MEP), 23(A, S, MEP), 24(A, S, MEP), 25(A, S, MEP), 28(A, MEP), 29(A, MEP), 30(A, MEP), 31(A, MEP), 32(A, S, MEP)**		
	Construction Documents				**3D** **2, 3, 5, 8, 11, 14, 22, 23, 24, 25, 28, 29, 30, 31, 32**
Build	**Pre-Construction**	**26 (A)**	**21(S)** **26(S),** **27(S)**		
	Construction				

Model Created Just-in-time

Model Created Too Late

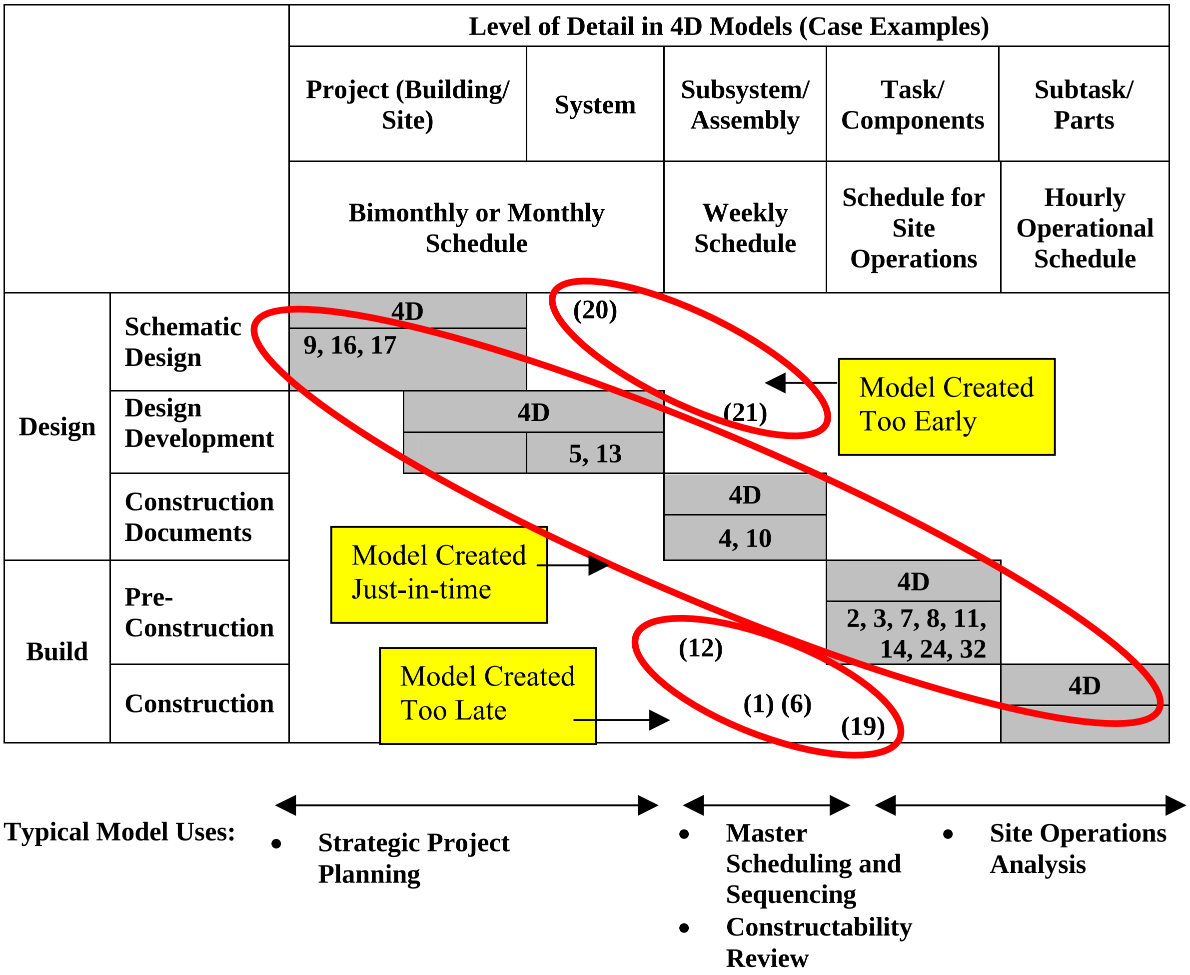
Typical Model Uses:

- **Interaction with Non-professionals**
- **Analysis of Design Options**

- **Analysis of Design Options**
- **Design Checking**

- **Production of Construction Documents**

Figure 12: Crosswalk 4 (Part II) – linking the level of detail in 4D models with the timing of 4D modeling and the model uses.



As shown in Figure 11 and Figure 12, each column in the matrix corresponds to a certain level of detail in the 3D/4D model. Each row represents a phase during the design and construction process. The text under the double-arrowed lines in the bottom of these figures exemplifies model uses that the levels of detail need to serve. Each cell in the table maps the level of detail to the information available in a project phase and needed for a particular model use. Thus, the appropriateness of the level of detail is twofold: 1) the level of detail in 3D/4D models should accommodate the model use; 2) the level of detail in 3D/4D models is subject to the information available at different design and construction stages.

Figure 11 maps the evolving level of detail in a 3D model along the typical project timeline to accommodate a particular model use.

- *Level of detail of architectural system:* Cases 3, 4, 5, 8, 11, 16, 18, 20, 22, 23, 24, 25, 27, 28, 29, 30, 31, and 32 demonstrate that the 3D model of the architectural system evolved throughout the phases of schematic design and design development. In the early schematic design phase, the architectural 3D model was a dimensionally accurate summary of the fundamental form and geometry of a building or site. These models were used to communicate the essential forms of a building to nonprofessionals, e.g., clients, end users, authorities, or communities. In the late schematic design phase (50% SD) and the design development phase, the basic building form was enriched with details about the actual sizes, styles, material types, and finishes of the architectural subsystems including walls, floors, roof, windows, and doors.
- *Level of detail of structural system:* Cases 3, 8, 11, 14, 20, 23, 24, and 25 demonstrate that the 3D modeling of the structural system was often started in the design development phase. Before creating the structural 3D model, structural engineers often used the architect's model as input for strength calculations of the preliminary framing plan, evaluated the appropriateness of the architectural design, and compared different options for the framing plan in the schematic design phase. Case 32 is an exception of the above pattern. On this project, the structural engineers started 3D modeling for a number of alternative structural systems and material combinations early in the schematic design phase. For example, they modeled three alternatives for foundation beams, i.e., steel, pre-cast concrete (selected), and cast-in-place concrete. These options were then evaluated to meet the criteria with regard to the architectural appearance, material costs based on the BOM, and the contractor's specialization and expertise. Cases 3, 8, 11, 14, 20, 23, 24, and 25 also demonstrate that the level of detail in the structural 3D model evolved throughout the design development phase. In the early design development phase, the structural 3D model had rough framing information of the superstructure (and/or foundation). In the late design development phase, the structural 3D model included more detail about the geometry, dimensions,

member properties, connection types, and materials of the structural subsystems, e.g., beams, columns, plates, bolts, etc.

- *Level of detail of the MEP systems:* Cases 2, 3, 5, 20, 23, 24, 25, 28, 29, 30, 31, and 32 demonstrate that building system designers started the 3D modeling of the MEP system in the design development phase. Before creating the MEP 3D model, building system designers used the architect's model as the basis to set up the preliminary sizing of the heating, cooling, and ventilation systems (cases 2, 3, 5, 20, 23, 24, 25, 28, 29, 30, 31, and 32) and supported the optimization of the building shape from the viewpoint of energy performance (cases 5, 23, 24, 25, 28, 29, 30, 31, and 32) in the schematic design phase. When the system specifications were in place and the best system solution was chosen, they started to model the HVAC and electrical systems in the design development phase. Late in design development, the MEP 3D models were combined with the 3D architectural and/or structural model to check for interferences between these models (cases 5, 20, 23, 24, 25, 28, 29, 30, 31, and 32).

Likewise, Figure 12 maps the level of detail that a 4D model entails at a particular project stage to serve a particular 4D model use.

- *Level of detail in the early design phase:* Cases 9, 16, and 17 show that 4D models built in the early design phase and used for strategic project planning do not have to be detailed models that accurately mirror real structures. From a process perspective, 4D models reflect the scheduling detail to the extent that each activity in the schedule lasts approximately 3-4 weeks. From a product perspective, 4D models incorporate blocks of the site and buildings or entail rough information of the major architectural features (e.g., exterior shell and interior floors).
- *Level of detail in the 50%-100% construction documents phase:* Cases 4 and 10 show that a 4D model built around the 50%-100% construction documents phase reflects the detail of the master schedule in which most activities last no longer than 10 days. It also includes more product detail at the subsystem level, such as exterior walls, staircases, interior partitions, roofing, and glazing in the architectural system, slabs, frames, trusses, lobby walls, and elevator shafts in the structural system, and HVAC,

electrical, plumbing in the MEP systems. In addition, if a 4D model at this level of detail is used for constructability review that includes accessibility and logistics (e.g., lay-down, staging areas and temporary structures, crane locations, etc.), 3D modeling has to represent the shape and configuration of the building components in a fairly accurate manner. However, if the purpose of the 4D model is to validate construction sequencing at the master-schedule level, 4D models do not depend on highly accurate 3D models representing building components.

- *Level of detail in the early construction phase:* Cases 2, 3, 7, 8, 11, 14, 24, and 32 show that a 4D model built in the early construction phases and used for analysis of trade operations reaches the level of detail at which the day-to-day operations of the various subcontractors and their workflows are represented. In such detailed 4D models, 3D objects often represent the activity zones within certain subsystems that are prone to time-space conflicts, e.g., the equipment platform, the tight work face of the metal-panel skin, the complex ceiling, etc. Contractors often isolate these risky parts of construction and study them in 4D models to plan the details of site operations.

In addition to defining the "level of detail", identifying the two factors related to the "appropriateness" of the level of detail, and illustrating the evolving pattern of the level of detail in relation to the two factors, Figure 11 and Figure 12 also categorize the timing of developing the level of detail in the 3D/4D models as "just-in-time", "too early", and "too late". If a case example fell into the grey box that depicts the ideal timing of producing a certain level of detail, the 3D/4D model on that project was created just-in-time with the appropriate level of detail. If a case example fell into an upper-right blank area, the 3D/4D model on that project was built too early due to the lack of available level of detail. If a case example fell into a lower-left blank area, the 3D/4D model on that project was generated too late despite the earlier availability of the required level of detail.

This categorization enables AEC professionals to identify the situations when models are created too early or too late and thus analyze the corresponding reasons and the subsequent ramifications. 4D models were sometimes created too late because designers only delivered 2D construction documents or they were too liability-focused to share 3D models and hence the GC had to make extra and duplicated efforts to build 3D models. When a 4D model was built too late, there were two side-effects (as shown in cases 1, 6, 12, and 19). In some cases, the GC narrowed the modeled scope and focused on the scope of work that was most expensive or that appeared most risky. But such a small-scale 4D model was of limited use and could not be used to coordinate all the work in the field. A scope of work that was not modeled might cause significant problems during construction. In other cases, the GC modeled the complete scope of work but disregarded detail and accuracy to some degree so that the full-scale 4D model was simplified. In consequence, further benefits and cost savings, from using the 4D model to analyze day-to-day operation alternatives, could not be realized.

Table 11 links the timing of developing the level of detail of the 3D/4D models to the average number of benefits reaped on each case project. It demonstrates that creating 3D/4D models just-in-time and at the appropriate level of detail that matches a particular model use is instrumental in maximizing benefits.

Table 11: Crosswalk 4 (Part III) – linking the timing of developing the level of detail in 3D/4D models with their corresponding benefits.

Scenario	**Timing and Level of Detail**	**Average # of Benefits per Case**
1	The 3D model was created just in time and at the appropriate level of detail to serve a particular model use. *Case Examples: 2, 3, 4, 5, 8, 11, 14, 16, 18, 20, 22, 23, 24, 25, 28, 29, 30, 31, 32* The 4D model was created just in time and at the appropriate level of detail to serve a particular model use. *Case Examples: 2, 3, 4, 5, 7, 8, 9, 10, 11, 13, 14, 16, 17*	5
2	The 4D model was created too early to serve a particular model use because the necessary information for the higher level of detail in the 4D model was not yet available. *Case Examples: 20, 21*	2
3	The 3D model was created too late to serve a particular model use, even though the necessary information for the higher level of detail in the 3D model would have been available earlier. *Case Examples: 21, 26, 27* The 4D model was created too late to serve a particular model use, even though the necessary information for the higher level of detail in the 4D model would have been available earlier. *Case Examples: 1, 6, 12, 19*	2

4.5 Findings from Crosswalk 5 vs. General Beliefs about Effort Put into the Workflow of 4D Modeling

Benefits need to be weighed against the time investment (effort) in the workflow of building, reviewing, and updating 3D/4D models. Although the modeling effort varied in different project organizations, almost all the cases that we studied followed the same workflow of 4D modeling, as shown in the 1st column of Crosswalk 5 (Table 12).

- *Step 1:* 4D modelers collect needed information, e.g., 2D CAD drawings, master schedules in P3 or Microsoft Project.
- *Step 2:* 4D modelers modify the original schedule to reflect the needed level of detail in the 4D model, for example, breaking down a single activity in the original schedule into separate activities.
- *Step 3:* 4D modelers create a 3D model from scratch or modify the 3D design model into a 3D construction model to visualize the planned construction sequence more fully. They often add temporary structures, staging areas, cranes, etc., for visualization. Moreover, large 3D CAD objects that are built by several activities are split up and small 3D CAD objects are grouped to represent construction work packages.
- *Step 4:* 4D modelers link the 3D CAD objects to the corresponding activities.
- *Step 5:* Project participants review construction alternatives, detect possible problems and discuss solutions in a 4D modeling environment, e.g., on a computer screen, with a projector, by printouts, over an online collaboration system, or in an immersive virtual reality environment, etc.
- *Step 6:* 4D modelers update the 3D model and/or the schedule to incorporate resolutions to the detected issues and add design and schedule information to the 3D and 4D models as the project evolves.

In addition to specifying the typical workflow of 4D modeling, Crosswalk 5 (Table 12) also lists a number of reasons for inefficiencies in each step of this workflow. Findings from Crosswalk 5 are compared to the general belief about effort put into the workflow of 3D/4D modeling (GB12).

GB 12: The limitations of 3D/4D modeling software tools and issues of data exchange and the organizational alignment are the main stumbling blocks to an efficient modeling process.

Findings from Crosswalk 5 (Table 12) support the above claim. Crosswalk 5 links the issues concerned with three particular implementation factors, i.e., modeled data, software tools, and stakeholders' involvement and roles in the project organization, to inefficiencies in each step of the workflow. Several interesting observations emerged:

- Steps 1, 2, and 3 (i.e., collecting data, modifying the original schedule, and creating or modifying 3D models) involve no technical issues with regards to 4D modeling software.
- Step 4 (i.e., linking 3D model and schedule) involves only technical software issues.
- Steps 5 and 6 (i.e., reviewing 4D models and updating 4D models) involve technical software issues and other issues pertinent to data exchange and organizational challenges.

The missing software functionality as shown in the 3rd column of Crosswalk 5 reduces the productivity of the modeling process and adds to the demand on time and resources since project teams have to use workarounds to overcome these technical challenges.

Data exchange difficulty is another stumbling block to an efficient workflow as shown in the 4th column of Crosswalk 5 (Table 12). For example, the modeled data may not be at the needed level of detail at a point in time because the design cannot be finalized yet, or the source of the modeled data (e.g., schedule) is available but not consistent with the intended scope of modeling and level of detail, or the modeled data from the upstream stage does not fit the modeling input required by the downstream stages. In addition, issues of organizational alignment as shown in the last column of Crosswalk 5 (Table 12) also result in delays and more cost. Crosswalk 5 supports GB 12. To carry out 4D modeling in an efficient way, the limitations of 3D/4D modeling software tools and issues stemming from data exchange and organizational alignment need to be resolved.

Table 12: Crosswalk 5 – causes of inefficiency in each step of the workflow of 4D modeling

Workflow of 4D Modeling	4D Modeling Software Tool Issues	Data Input and Exchange Issues	Organizational Alignment Issues
1. Collecting data (schedules, drawings, specs, or other text documents)	None found in the 4D modeling cases	• The input of schedule information is not available in the design phase so that the construction sequences can be analyzed.	• It is hard for a 4D modeler to collect data from estimators, schedulers, project managers, project engineers and site managers on a large-size project where project participants have difficulties to really understand the work that has to be done and project participants don't have time to communicate with one another. • The construction schedule cannot be finalized because of design changes.
2. Modifying the original schedule	None found in the 4D modeling cases	• The original schedule is not consistent with the intended scope of modeling. • The modeling process itself exposes discrepancies of existing sources of information and missing information.	• Schedulers do not tailor their schedules to 4D modeling needs.
3. Creating or modifying 3D models	None found in the 4D modeling cases	• The 3D exchange "view" of the model has to be modified because development of specific data is not the designer's job or because the data cannot be meaningfully defined in the early phase of project development. For example, the GC has to reconfigure the architect's 3D model for construction planning, i.e., adding extra 3D elements (or components) to represent construction activities and temporary structures (e.g., cranes, lay-down, staging areas, scaffolding, etc.), and organizing 3D components into "constructible" groups to facilitate 4D linking. • Since the layering organization in a 3D model is usually different from the organization of the schedule, the 4D modeler needs to reorganize the geometric information for the 4D model to fit the schedule organization (Fischer et al. 1998).	• The design cannot be finalized because of changes. • The GC has to create a 3D model from scratch because the architect is not required to deliver the design in 3D and only 2D CAD data is available. • The GC has to build a 3D model from scratch because the architect or engineer would not share 3D models. • Some modelers are not experienced enough to handle issues involved in 4D modeling, such as re-organizing 3D components into "constructible" groups. • The GC has to wait until the architect has a complete 3D model ready for sharing. • Subs cannot start MEP design in 3D until the final footprint is determined by the end of schematic design.

Workflow of 4D Modeling	4D Modeling Software Tool Issues	Data Input and Exchange Issues	Organizational Alignmen Issues
4. <u>Linking 3D model and schedule</u> • Import 3D model to 4D software • Create links between activities and 3D components	• 4D software does not support a naming convention that incorporates both the names of 3D components and activities. • 4D software does not support automated linking of 3D components and activities. • 4D software does not support a hierarchical view of the schedule at multiple levels of detail.	None found in the 4D modeling cases	None found in the 4D modeling cases
5. <u>Reviewing 4D models</u> • Focus on parts of the 4D model for specific analysis of a schedule • Show 3D/4D models on the computer screen, with a projector, through printouts, over an online collaboration system, or in a CAVE, etc. • Review the 4D model to detect possible problems and discuss solutions	• 4D software does not support a distributed work environment. • Current hardware or software is not able to display of large 4D models.	• The 4D model does not facilitate an analysis of alternatives because it cannot convey all the information (e.g., changes in crew composition, distances between parallel workflows, amount of equipment, crews, available work spaces, etc.) that is required to evaluate important aspects of trade operations.	• Subs fail to inform the GC in advance of field issues they want to resolve with 3D/4D models. Hence, the GC is not able to prepare and present 3D/4D models in a way that is really targeted at the subs' needs.
6. <u>Update & revise 4D models as the project evolves</u>	• 4D software cannot synchronize the updates of the 3D model and the schedule automatically. • 4D software cannot automatically update links between 3D CAD objects and activities; rearranging the links manually is simple but time-consuming.	• It is difficult to make the right schedule along with a lot of design changes. Schedule changes are difficult to manage due to the large number of activities and the large number of dependencies between them. • Modelers have to incorporate the design changes into the 4D models.	• Design decisions are not finalized at one stage before moving on to the next stage.

5. Conclusions

5.1 A Summary of Findings

Anecdotal evidence in single cases and general beliefs about what has been learned from implementations and impacts of 3D/4D modeling are not sufficient for AEC professionals to formalize implementation guidelines and apply them across projects. Through case studies on 32 construction projects that used 3D and 4D modeling in the late 1990s and early 2000s, we developed a framework to objectively, consistently, and sufficiently document 3D/4D modeling experiences. This framework consists of 4 main categories, 14 factors, and 74 measures. We conclude that the descriptive power of the framework is good for the following reasons:

- This framework is credible because 81% of the 74 measures are objective.
- This framework is consistent because 56% of the 74 measures are replicated in more than 24 cases.
- This framework is sufficient to cover the key facts of implementing 3D/4D modeling because only 17.6% of the 74 measures were newly added to the framework as we carried out studies on eleven additional cases.

To demonstrate the potential use of the framework, we also devised five crosswalks that compare the similarities and differences between implementing 3D/4D modeling across projects. The findings from analyzing the five crosswalks have substantiated and refined common beliefs about 3D/4D modeling implementations. Five key insights into the patterns for 3D/4D modeling implementations emerge from the five crosswalks as follows:

- The uses of 3D/4D models vary according to the business drivers of the project stakeholders, different project challenges, and project phases when 3D/4D models are created. The four primary uses of 3D models are 1) interaction with non-professionals, 2) construction planning, 3) drawing production, and 4) design coordination. Moreover, companies are starting to integrate 3D/4D models for more data-driven tasks such as analysis of design options, supply chain management, cost estimating and change order management, facility management, and establishment of owner requirements.

- The use of 3D/4D models early in the design phase results in not only immediate benefits (which relate to the ongoing project process and organization) but also late benefits (which accrue during the downstream processes and relate to the performance of a finished building product). However, the use of 3D/4D models in the preconstruction and construction phases mostly leads to immediate benefits.
- The benefits to every individual stakeholder and to the whole project team are maximized when all the key stakeholders are involved in creating and using 3D/4D models.
- Creating 3D/4D models just-in-time and at the appropriate level of detail that matches a particular model use is instrumental in maximizing benefits. The appropriate level of detail depends not only on model uses but also information available at a particular stage of a project.
- In a typical workflow of 4D modeling, steps 1, 2, and 3 (i.e., collecting data, modifying the original schedule, and creating or modifying 3D models) involve no technical issues with regard to 4D modeling software; step 4 (i.e., linking 3D model and schedule) involves only technical software issues; steps 5 and 6 (i.e., reviewing 4D models and updating 4D models) involve technical software issues and other issues pertinent to data exchange and organizational alignment.

Table 13 summarizes the outcomes of using crosswalks to validate the general beliefs listed in Table 1 (p.2).

Table 13: Outcomes of using crosswalks to validate the general beliefs about implementation and impact of 3D/4D modeling

Beliefs	**Validation**	**Patterns Demonstrated by the 32 Case Projects**
(Legend: √ agreement; ≠ contradiction; Δ refinement)		
• 3D/4D Model Use (Crosswalk 1)		
GB1	Δ	3D models are useful for a whole range of purposes, such as cost estimating, construction planning, and many other analyses, automated fabrication, and project control applications. In practice, the primary uses of 3D models are not only focused on marketing but also have been extended to construction planning, design checking, and drawing production.
GB2	Δ	It is common to use 3D models rather than 4D models on residential projects; both 3D and 4D models lend themselves well to commercial, institutional, and transportation facilities.
GB3	√	It is common to use 3D/4D models on design-bid-build and construction management projects; 3D/4D models also lend themselves to design-build projects. Lack of design-build or other collaborative contractual relationships should not be viewed as a reason to avoid 3D/4D modeling practices.
GB4	Δ	To reap the benefits of 3D/4D modeling, project stakeholders have to realize what they can do with the models. The uses of 3D/4D models vary according to distinct business drivers of project stakeholders, different characteristics of facilities, and the project phases when 3D/4D models are created.
GB5	Δ	3D/4D models are developed for many different uses. The more purposes 3D/4D models are used for, the more benefits they offer.

Beliefs	Validation	Patterns Demonstrated by the 32 Case Projects
(Legend: √ agreement; ≠ contradiction; Δ refinement)		
• **Timing of the Use of 3D/4D Models (Crosswalk 2)**		
GB6	Δ	The use of 3D/4D models early in the design phase results in not only immediate benefits (which relate to the ongoing project process and organization) but also late benefits (which accrue during the downstream processes and relate to the performance of a finished building product). However, 3D/4D models in the preconstruction and construction phases mostly leads to immediate benefits.
GB7	√	It is essential to capitalize on project opportunities early on to make 3D/4D models have a lasting and positive effect on the facility over the project design and construction phases.
• **Timing of the Use of 3D/4D Models (Crosswalk 2)**		
GB8	Δ	The use of 3D models leads not only to late benefits to the downstream processes but also to immediate benefits that occur in the design phase and to the interest of designers themselves. These immediate benefits include: 1) improved quality of design by reducing design errors and inconsistencies; 2) a reduction in the number of late design changes caused by design errors, owner misunderstanding or inadequate assessment of existing site conditions; 3) a change in the distribution of design efforts in different phases of design.
• **Key Stakeholder involvement in 3D/4D Modeling Process (Crosswalk 3)**		
GB9	Δ	The more stakeholders are involved in 3D/4D modeling, the more benefits accrue to them individually and to the whole project team.
• **Level of Detail in 3D/4D Models (Crosswalk 4)**		
GB10	Δ	Creating 3D/4D models just in time and at the appropriate level of detail that matches a particular model use is instrumental in maximizing benefits.
• **Effort Put into the Workflow of 4D Modeling (Crosswalk 5)**		
GB11	√	The limitations of 3D/4D modeling software tools and issues pertinent to data exchange and organizational alignment are the main stumbling blocks to an efficient modeling process.

5.2 Relevance to the AGC Contractor's Guide to BIM

The Associated General Contractors of America (AGC) published the AGC *Contractors' Guide to BIM* based on several contractors' experiences and general beliefs about BIM implementation. The objective of the guide is essentially to educate contractors about BIM, including its benefits, tools and applications. This document provides useful guidelines on how to get started: implementing BIM from a 2D conversion versus a 3D design; the basic software tools that support BIM and the related collaboration; the BIM process and how it is to be conducted; clarification of the fundamental responsibilities of each team member relative to the BIM process; and finally, the main areas of risk management that contractors should begin to think about (AGC 2007).

All the 3D models in the 32 case projects are qualified as BIM models since these models cover 3D object-oriented building components with information such as geometry, spatial relationships, quantities, or properties, etc. Some of our findings in this report resonate with guidelines in AGC *Contractors' Guide to BIM.* Table 14 illustrates the common ground shared between the BIM guidelines by AGC and the implementation patterns emerging from our 32 case studies. The concrete case data in this report and in-depth analysis from synthesizing these cases also reinforce the insights of the AGC expert panel on how to get started with a BIM-based process.

Table 14: Relevance of this report to the AGC *Contractors' Guide to BIM*

Guidelines in AGC *Contractors' Guide to BIM*	**Findings in This Report**
"One of the earliest lessons learned is that there is rarely one model. … It is not unusual, particularly while the 2D conversion continue to be the norm, for multiple models to be made available on the same project." (AGC 2007, p.5)	We saw some interesting combinations of model uses. That is to say, when a project has one model use, it often has another model use. Regarding the number of model uses on each case project, Figure 4 (p.31) shows that 26 out of the 32 projects implemented two to four model uses.
"Contractors are making use of intelligent models for portions of the project scope to assist them with many of their traditional activities." (AGC 2007, p.6)	In some cases, the GC narrowed the modeled scope and focused on the scope of work that was most expensive or that appeared most risky. Regarding the number of modeled building systems, Table 15 (p.83) shows that 24 out of the 32 projects modeled only specific trades and portions of their whole project scopes.
"The BIM process in a typical project scenario are outlined, answering the "what, when, where, and how" of BIM in a "Model Based" process. Contractors should have an appreciation and understanding of "why" BIM is worthwhile and address the "who" (the responsibility of each of the team members)." (AGC 2007, p.10)	The framework characterizes the implementation of 3D/4D modeling with seven factors, i.e., why (modeling uses), when (timing of model uses), who (stakeholder involvement), what (modeled data), with which tools (3D/4D modeling software), how (workflow), and for how much (effort/costs) a 3D/4D modeling implementation was done (p.5).

Guidelines in AGC *Contractors' Guide to BIM*	**Findings in This Report**
"Some of the more common "early" uses that most contractors experience in their experience in their experiment with BIM: • *Visualization* • *Scope Clarification* • *Partial Trade Coordination* • *Collision Detection /Avoidance* • *Design Validation* • *Construction Sequencing/Phasing Plans/Logistics* • *Marketing Presentations* • *Options Analysis* • *Walk-through and Fly-through* • *Virtual Mock-ups* • *Sightline Studies"* *(AGC 2007, p.13)*	We found that the primary uses of 3D/4D models are (p.30): • *Visualization and Marketing Presentations:* 31 out of the 32 projects used 3D/4D models to interact with non-professionals (e.g., owners, end users, planning commissions, city councils and the general public). • *Partial Trade Coordination, Construction Sequencing, Phasing Plans, and Logistics:* 22 out of the 32 projects used 3D/4D models for construction planning which entails activities such as trade coordination, construction sequencing, project phasing, and site logistics. • *Collision Detection/Avoidance and Design Validation:* 14 out of the 32 projects used 3D/4D models for design checking, i.e., clash detection and constructability review.
"Getting the maximum benefits from the technology and BIM is directly correlated to the ability to Maximize collaboration on a project." (AGC 2007, p.17)	No matter who is leading, the scenario where all the key stakeholders are involved offers most benefits for the whole project team. This is a win-win opportunity that all stakeholders can take advantage of (p.52).

Guidelines in **AGC *Contractors' Guide to BIM***	**Findings** **in This Report**
"To fully use BIM, it must be on project delivered with some kind of collaborative approach such as CM at-Risk or Design-Build. However, experience has shown that there are still benefits to the contractor on traditional Design-Bid-Build projects." (AGC 2007, p.17)	3D/4D models apply to projects with all types of delivery methods. It is common to use 3D/4D models on design-bid-build and construction management projects; 3D/4D models also lend themselves to design-build projects. Figure 6 (p. 33) shows that the distribution of CM at-Risk, Design-Build, and Design-Bid-Build projects in the 32 projects that implemented 3D models is 25%:25%:50%. The distribution of CM at-Risk, Design-Build, and Design-Bid-Build projects in the 32 projects that implemented 4D models is 36%:9%:55%.
"There are many barriers keeping contractors from using the latest technology and BIM. The barriers include fears, initial investment costs, the time to learn how to use the software, and perhaps for many the biggest barrier: the lack of support from senior leadership of the company."(AGC 2007, p.18)	To carry out 4D modeling in an efficient way, the limitations of 3D/4D modeling software tools and issues stemming from data exchange and the organizational alignment need to be resolved. Table 12 (p.67) shows that among the six steps of 4D modeling workflow, three steps (steps 4, 5, and 6) involve software issues and five steps (steps 1, 2, 3, 5, and 6) face organizational challenges.

5.3 Practical and Scientific Contributions

Practitioners can use the framework to document, compare, and learn from their own cases. This framework contributes to the development of an empirical knowledge base for 3D/4D implementation. Based on the knowledge base, practitioners can guide and prioritize their own implementation efforts rather than jump starting it without action plans. For example, practitioners document their 3D/4D implementation projects using the eight measures as shown in Table 15, i.e., model uses, number of model uses, modeled systems, number of modeled systems, involved stakeholders, number of involved stakeholders, project phases, and number of project phases. After documenting a sufficient number of 3D/4D implementation projects, they can identify the range of possible model uses and figure out the implementation plan of 3D/4D modeling. That is to say, practitioners can design the implementation in terms of the level of detail in 3D/4D models (i.e., modeling product), the stakeholders to be involved in building and using 3D/4D models (modeling organization), and the timing to start 3D/4D modeling (modeling process) and customize the modeling product, organization, and process to different model uses.

Project participants generally come to the table with some contingency funding to cover the unknowns of what they perceive to be their responsibilities (CURT 2006). Practitioners can use the performance measures in this framework to document how 3D/4D models support risk management, e.g., unspent contingency for scope changes. With the documentation, practitioners will discern the risk reduction opportunities of 3D/4D models and become better informed on how much contingency is really allocated for a particular risk. Ultimately for owners, better contingency management may result in project savings or increased quality (CURT 2006).

Researchers can use the framework to conduct a large-size case survey which allows statistical analysis of implementation patterns across cases (Larsson 1993). This framework provides a structured form and well-defined measures for documenting a large number of cases. Researchers can apply the framework as a coding scheme to case studies and systematically convert those qualitative case measures into quantifiable variables. In doing so, researchers will be able to statistically analyze their cases with coded data and cross-validate or extend the findings from our case studies.

In addition, the five crosswalks categorize nine 3D model uses, seven 4D model uses, eleven situations of key stakeholder involvement, and three situations of the timing of developing levels of detail in 3D/4D models. The classification of a particular implementation factor (e.g., the model use, stakeholder involvement, and the level of detail) provides the opportunity for cross-case analysis and generalization of the patterns pertinent to that particular implementation factor. For example, researchers can pool relevant cases of the four primary uses (Figure 3) of 3D models (i.e., interaction with non-professionals, construction planning, drawing production, and design checking) into data sets that are sufficiently large for statistical analysis of the implementation patterns pertinent to these model uses. This will assess the magnitude of the relationship between the effort and the value of creating different kinds of 3D models more precisely than the assessment we could make in this report.

5.4 Next Steps

We suggest the following steps for further studies:

1. Developing a better way of quantifying the value of benefits and differentiating the value of benefits to different stakeholders.

   In this report, we simply counted the number of benefits as a way of quantification. In a future study, we plan to capture the value of benefits and differentiate the value of benefits to different stakeholders.

2. Validating how helpful the framework is for generating 3D/4D modeling guidelines and managing 3D/4D modeling implementations.

   In this report, we demonstrated the use of the framework by comparing 3D/4D modeling experiences across projects. A further step is to validate how helpful the framework is for generating 3D/4D modeling guidelines and managing 3D/4D modeling implementations. For example, we selected eight measures from the framework and documented these measures for the 32 case projects (Table 15). Based on the documented case data, we generated some general guidelines for planning the implementation of 3D/4D modeling for design checking and MEP coordination.

   - Guideline for building 3D models: The modeled scope includes architectural, structural, and MEP systems.

- Guideline for the organizations that implement 3D modeling: The architect, structural engineer, MEP designers (or MEP subcontractors), and GC are the key players in 3D modeling and design coordination.
- Guideline for the process of creating and using 3D models: Designers start to build their disciplinary models in the design development phase. Disciplinary models are combined for design coordination in the construction documents phase and for constructability review in the pre-construction phase.

3. Investigating the benefits and uses of 3D/4D models in different contexts of companies or countries.

   This report focused on describing and comparing the implementations and impacts of 3D/4D modeling at the project level. This project-based approach did not consider the organizational and social contexts of the implementation of 3D/4D modeling at the company level as well as at the country level. In a next step, we will further develop the framework and crosswalks to document and benchmark:

   - how the implementation approach of 3D/4D modeling in one company differs from implementations in other firms with respect to issues such as their 3D/4D software platform choices, data standardization, research and development activities, external strategic alliance, and internal organizational alignment;
   - how the implementation of 3D/4D modeling is different in one national or regional context from another, given the influences of institutional factors, e.g., market structure, organizational forms, work practices, national and professional culture, technology support, and government support/policy, etc.

   Therefore, we need to carry out further case studies to support the specific understanding with regard to the benefits and uses of 3D/4D models in different contexts of companies or countries.

4. Conducting a large-size survey using probability sampling (instead of convenience sampling) to verify the framework and generalize the implementation patterns

emerging from the 32 cases to more recent projects of 3D/4D modeling implementations.

The 32 cases focused on projects involving researchers, students and visitors at the Center for Integrated Facility Engineering (CIFE) at Stanford University to support the 3D/4D modeling effort and projects where AEC organizations in Finland carried out the 3D/4D modeling efforts. These case projects were selected because they offered good access to people and data. This data collection of convenience cases satisfies four basic criteria from an analytical point of view (Ferber 1977).

- The 32 case projects implemented 3D/4D modeling to support project team members to accomplish professional tasks. Hence we can firmly establish the relevance of these cases to the topic under study, i.e., the experiences of using 3D/4D models by industry professionals on real life projects.
- The sample size (32 cases) is adequate to generalize the implementation patterns for analytical purposes. Implementation patterns generalized from the results of the 32 cases are justifiable because this generalization is based on the accumulation of case studies.
- We attempted to cover a wide range of projects with different project types, sizes, delivery methods, time periods of design and construction, and project locations to explore the generality of 3D/4D model uses and the applicability of a framework to document 3D/4D modeling implementations on a broad range of projects. Therefore, the 32 cases are representative of 3D/4D modeling implementations in practice.
- Ferber (1977) argues that another justifiable use of a convenience case is to illustrate the application of some new method or technique. Since 3D/4D modeling is still an emerging innovation which has been or is currently implemented on a small percentage of construction projects, a convenience case can convey a much better feeling of realism.

In the future, we suggest a large-size survey using probability sampling (instead of convenience sampling) to verify the framework and generalize the implementation patterns.

5. Extending the 3D model uses emerging from the 32 case studies.

   Based on the 32 projects, we categorized nine 3D model uses. This is by no means an exhaustive list of all the 3D model uses in practice but it gives an indication of primary model uses taking place. We suggest that future research extends the 3D model uses emerging from the 32 case studies: 1) to other important model uses such as 3D-laser scanning for accurate as-built documentation and CNC usage (e.g., metal cutting) by MEP subs; and 2) to new areas of model uses such as 4D workflow optimization.

6. Studying inter-organizational implementation of 3D/4D modeling and addressing lessons learned from facilitating exchange and interoperability of information and standardizing the work methods for 3D/4D modeling implementations.

   In this study, we have not found plenty of experiences related to inter-organizational implementation of 3D/4D modeling. This is more a problem of implementing data-exchange integration standard in software (e.g., the Industry Foundation Classes (IFC)) and developing standardized work methods for clear definitions of objects (e.g., IFD library) and clear definitions of process protocols and exchange requirements (e.g., the Information Delivery Manual (IDM)).

   - Researchers and software companies need to develop a better way to exchange 3D model data electronically between software applications. Researchers have already invested a vast amount of work in developing 3D model standards or 3D model exchange interfaces for the building sector by developing IFC.
   - Different 3D models used for the different software applications by the various stakeholders require different levels of detail. Standardized work

methods are needed to switch between different levels of detail and views among construction practitioners from different stakeholder organizations.

Therefore we suggest further case studies to focus on inter-organizational implementation of 3D/4D modeling and to address lessons learned from implementing interoperability and standardizing the work methods for 3D/4D modeling implementations.

Table 15: An example of using eight measures in the framework to document the 32 cases so as to develop some general guidelines

Legend	**Modeled Systems**	**A**: Architectural System; **S**: Structural System; **MEP**: MEP System
	Stakeholder Groups	**OW**: owner; **AR**: Architect; **SE**: Structural Engineer; **D(MEP)**: MEP Designer; **GC**: General Contractor; **Sub**: Subcontractor
	Project Phases	**SD**: Schematic Design; **DD**: Design Development; **CD**: Construction Documents; **PC**: Pre-construction; **CON**: Constructions
	Model Uses	**Own. Req't.**: Establishment of owner requirements; **Non-prof. Int.**: Interaction with non-professionals; **Dgn. Anal.**: Design analysis; **Dgn. Coor.**: Design coordination; **CD. Prod.**: Production of Construction Documents; **Est. & BOQ**: Cost estimation and bill of quantity; **Sup. Mgnt.**: Supply chain management; **Constr. Pln.**: Construction planning; **Fac. Mgnt.**: Facility management

Case #	**3D/4D Models**	**Model Uses**	**# of Model Uses**	**Level of Detail (Modeling Product)**		**Stakeholder Involvement (Modeling Organization)**		**Timing of 3D/4D Modeling (Modeling Process)**	
				Modeled Systems	**# of Modeled Systems**	**Involved Stakeholder Groups**	**# of Key Stakeholder Groups**	**Project Phases**	**# of Project Phases**
1	4D	Constr. Pln.	1	A+S+MEP	3	GC	1	CON	1
2	3D and 4D	Non-prof. Int. + Dgn. Coor. + CD. Prod. + Constr. Pln.	4	A+S+MEP	3	AR+GC+Sub(MEP)	3	SD+DD+CD+PC	4
3	3D and 4D	Non-prof. Int. + CD. Prod. + Sup. Mgnt. + Constr. Pln.	4	A+S	2	AR+GC+Sub(Steel)	3	SD+DD+CD+PC	4
4	3D and 4D	Non-prof. Int. + Constr. Pln.	2	A+S	2	OW	1	DD+CD	2
5	3D and 4D	Non-prof. Int. + Dgn. Anal. + Dgn. Coor. + CD. Prod. + Est. & BOQ + Constr. Pln.	6	A+MEP	2	AR+D(MEP)+GC	3	SD+DD+CD	3
6	4D	Non-prof. Int. + Constr. Pln.	2	S	1	GC	1	CON	1
7	4D	Non-prof. Int. + Constr. Pln	2	A+S+MEP	3	GC	1	PC+CON	2

Legend	**Modeled Systems**	**A**: Architectural System; **S**: Structural System; **MEP**: MEP System
	Stakeholder Groups	**OW**: owner; **AR**: Architect; **SE**: Structural Engineer; **D(MEP)**: MEP Designer; **GC**: General Contractor; **Sub**: Subcontractor
	Project Phases	**SD**: Schematic Design; **DD**: Design Development; **CD**: Construction Documents; **PC**: Pre-construction; **CON**: Constructions
	Model Uses	**Own. Req't.**: Establishment of owner requirements; **Non-prof. Int.**: Interaction with non-professionals; **Dgn. Anal.**: Design analysis; **Dgn. Coor.**: Design coordination; **CD. Prod.**: Production of Construction Documents; **Est. & BOQ**: Cost estimation and bill of quantity; **Sup. Mgnt.**: Supply chain management; **Constr. Pln.**: Construction planning; **Fac. Mgnt.**: Facility management

Case #	**3D/4D Models**	**Model Uses**	**# of Model Uses**	**Level of Detail (Modeling Product)**		**Stakeholder Involvement (Modeling Organization)**		**Timing of 3D/4D Models (Modeling Process)**	
				Modeled Systems	**# of Modeled Systems**	**Involved Stakeholder Groups**	**# of Key Stakeholder Groups**	**Project Phases**	**# of Project Phases**
8	3D and 4D	Non-prof. Int. + Dgn. Anal. + CD. Prod. + Sup. Mgnt. + Constr. Pln.	5	A+S	2	AR+GC+Sub(Steel)	3	SD+DD+CD+PC+CON	5
9	4D	Non-prof. Int. + Constr. Pln.	2	A	1	OW	1	SD	1
10	4D	Non-prof. Int. + Constr. Pln.	2	S	1	OW	1	CD	1
11	3D and 4D	Non-prof. Int. + Dgn. Anal. + CD. Prod. + Sup. Mgnt. + Constr. Pln.	5	A+S	2	AR+GC+Sub(Steel)	3	SD+DD+CD+PC+CON	5
12	4D	Non-prof. Int. + Constr. Pln.	2	A+S	2	GC	1	PC	1
13	4D	Non-prof. Int. + Constr. Pln.	2	S	1	GC	1	SD	1
14	3D and 4D	Non-prof. Int. + Dgn. Anal. + CD. Prod. + Sup. Mgnt. + Constr. Pln.	5	S	1	SE+Sub(Rebar)	2	DD+CD+PC	3

Legend	**Modeled Systems**	**A**: Architectural System; **S**: Structural System; **MEP**: MEP System
	Stakeholder Groups	**OW**: owner; **AR**: Architect; **SE**: Structural Engineer; **D(MEP)**: MEP Designer; **GC**: General Contractor; **Sub**: Subcontractor
	Project Phases	**SD**: Schematic Design; **DD**: Design Development; **CD**: Construction Documents; **PC**: Pre-construction; **CON**: Constructions
	Model Uses	**Own. Req't.**: Establishment of owner requirements; **Non-prof. Int.**: Interaction with non-professinals; **Dgn. Anal.**: Design analysis; **Dgn. Coor.**: Design coordination; **CD. Prod.**: Production of Construction Documents; **Est. & BOQ**: Cost estimation and bill of quantity; **Sup. Mgnt.**: Supply chain management; **Constr. Pln.**: Construction planning; **Fac. Mgnt.**: Facility management

Case #	**3D/4D Models**	**Model Uses**	**# of Model Uses**	**Level of Detail (Modeling Product)**		**Stakeholder Involvement (Modeling Organization)**		**Timing of 3D/4D Models (Modeling Process)**	
				Modeled Systems	**# of Modeled Systems**	**Involved Stakeholder Groups**	**# of Key Stakeholder Groups**	**Project Phases**	**# of Project Phases**
15	4D	Non-prof. Int. + Constr. Pln	2	A+S	2	Sub(Concrete)	1	CON	1
16	4D	Non-prof. Int. + Constr. Pln	2	A	1	OW	1	SD	1
17	4D	Non-prof. Int. + Constr. Pln	2	A	1	OW	1	SD	1
18	3D	Non-prof. Int. + Constr. Pln	2	A	1	OW	1	SD	1
19	4D	Non-prof. Int. + Constr. Pln	2	S	1	GC	1	CON	1
20	3D and 4D	Non-prof. Int. + Dgn. Coor. + CD. Prod. + Sup. Mgnt. + Constr. Pln	5	A+S+MEP	3	AR+SE+GC+Sub(MEP)	4	DD+CD+PC+CON	4
21	3D and 4D	Non-Prof. Int. + Dgn. Coor. + Constr. Pln	3	S+MEP	1	GC	1	CD+PC	2
22	3D	Non-Prof. Int. + Dgn. Anal. + CD. Prod.	3	A	1	AR	1	SD+DD+CD	3

Legend	**Modeled Systems**	**A**: Architectural System; **S**: Structural System; **MEP**: MEP System
	Stakeholder Groups	**OW**: owner; **AR**: Architect; **SE**: Structural Engineer; **D(MEP)**: MEP Designer; **GC**: General Contractor; **Sub**: Subcontractor
	Project Phases	**SD**: Schematic Design; **DD**: Design Development; **CD**: Construction Documents; **PC**: Pre-construction; **CON**: Constructions
	Model Uses	**Own. Req't.**: Establishment of owner requirements; **Non-prof. Int.**: Interaction with non-professinals; **Dgn. Anal.**: Design analysis; **Dgn. Coor.**: Design coordination; **CD. Prod.**: Production of Construction Documents; **Est. & BOQ**: Cost estimation and bill of quantity; **Sup. Mgnt.**: Supply chain management; **Constr. Pln.**: Construction planning; **Fac. Mgnt.**: Facility management

Case #	**3D/4D Models**	**Model Uses**	**# of Model Uses**	**Level of Detail (Modeling Product)**		**Stakeholder Involvement (Modeling Organization)**		**Timing of 3D/4D Models (Modeling Process)**	
				Modeled Systems	**# of Modeled Systems**	**Involved Stakeholder Groups**	**# of Key Stakeholder Groups**	**Project Phases**	**# of Project Phases**
23	3D	Non-Prof. Int. + Dgn. Anal. + Dgn. Coor. + CD. Prod.	4	A+S+MEP	3	AR+SE+D(MEP)	3	SD+DD+CD	3
24	3D and 4D	Non-Prof. Int. + Dgn. Coor. + CD. Prod. + Sup. Mgnt. + Constr. Pln	5	A+S+MEP	3	AR+SE+D(MEP)+GC	4	SD+DD+CD+PC+CON	5
25	3D and 4D	Non-Prof. Int. + Dgn. Coor. + CD. Prod. + Est. & BOQ	4	A+S+MEP	3	AR+SE+D(MEP)+GC	4	SD+DD+CD+PC	4
26	3D	Non-Prof. Int. + Est. & BOQ	2	A+S	2	AR+SE+D(MEP)+GC	4	PC+CON	2
27	3D	Non-Prof. Int. + Est. & BOQ	2	A+S	2	GC	1	SD+PC+CON	3
28	3D	Non-Prof. Int. + Dgn. Anal. + Dgn. Coor. + CD. Prod. + Est. & BOQ + Sup. Mgnt.	6	A+MEP	2	AR+SE+D(MEP)+GC	4	SD+DD+CD+PC	4

Legend	**Modeled Systems**	**A**: Architectural System; **S**: Structural System; **MEP**: MEP System
	Stakeholder Groups	**OW**: owner; **AR**: Architect; **SE**: Structural Engineer; **D(MEP)**: MEP Designer; **GC**: General Contractor; **Sub**: Subcontractor
	Project Phases	**SD**: Schematic Design; **DD**: Design Development; **CD**: Construction Documents; **PC**: Pre-construction; **CON**: Constructions
	Model Uses	**Own. Req't.**: Establishment of owner requirements; **Non-prof. Int.**: Interaction with non-professinals; **Dgn. Anal.**: Design analysis; **Dgn. Coor.**: Design coordination; **CD. Prod.**: Production of Construction Documents; **Est. & BOQ**: Cost estimation and bill of quantity; **Sup. Mgnt.**: Supply chain management; **Constr. Pln.**: Construction planning; **Fac. Mgnt.**: Facility management

Case #	**3D/4D Models**	**Model Uses**	**# of Model Uses**	**Level of Detail (Modeling Product)**		**Stakeholder Involvement (Modeling Organization)**		**Timing of 3D/4D Models (Modeling Process)**	
				Modeled Systems	**# of Modeled Systems**	**Involved Stakeholder Groups**	**# of Key Stakeholder Groups**	**Project Phases**	**# of Project Phases**
29	3D	Non-Prof. Int. + Dgn. Anal. + Dgn. Coor. + CD. Prod. + Est. & BOQ + Sup. Mgnt.	6	A+MEP	2	AR+SE+D(MEP)+GC	4	SD+DD+CD+PC	4
30	3D	Non-Prof. Int. + Dgn. Anal. + Dgn. Coor. + CD. Prod. + Est. & BOQ + Sup. Mgnt.	6	A+MEP	2	AR+SE+D(MEP)+GC	4	SD+DD+CD+PC	4
31	3D	Non-Prof. Int. + Dgn. Anal. + Dgn. Coor. + CD. Prod. + Fac. Mgnt.	5	A+MEP	2	AR+SE+D(MEP)+GC	4	SD+DD+CD	3
32	3D and 4D	Non-Prof. Int. + Own. Req't. + Dgn. Anal. + Dgn. Coor. + CD. Prod. + Est. & BOQ + Sup. Mgnt. + Constr. Pln. + Fac. Mgnt.	9	A+S+MEP	3	AR+SE+D(MEP)+GC	4	SD+DD+CD+PC+CON	5

References

Bazjanac, V. (2002). “Early Lessons from Deployment of IFC Compatible Software.” *Lawrence Berkeley National Laboratory Paper LBNL-51548*. 2002.

Bazjanac, V. (2004). “VBE Technical Issues (LBNL).” *Presentation to VBE Meeting at CIFE,* Center for Integrated Facility Engineering, Stanford, CA, June 14, 2004.

Bedrick, J. and Davis, G. (2005). “VDC from the Executive Office (Webcor Builders).” *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 22, 2005.

Bedrick, J., Rinella, T., Bevins, R., and Hecht, L. (2005). “Interoperability Challenges for BIM Implementers.” *Presentation to Building Connections 2005, the 2nd Congress on Digital Collaboration in the Building Industry,* AIA, Washington D.C., Nov 10, 2005.

Bergsten, S. and Knutsson, M. (2001). “4D CAD-An Efficient Tool to Improve Production Method for Integration of Apartments in Existing Buildings.” *Proceedings of the CIB-W78 International Conference IT in Construction in Africa 2001: Implementing the next generation technologies*, CSIR, Division of Building and Construction Technology, Pretoria, South Africa, also available at http://buildnet.csir.co.za/constructitafrica/au, pp. 3-1 to 3-10

Carpenter, R. (2006). “Users Perspective on How to Introduce 3D Modeling Broadly (Onyx Architects).” *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 19, 2006.

Coble, R.J., Theisen, D., and Blatter, R.L. (2000). “Application of Four-Dimensional Computer-Aided Design (4D CAD) in the Construction Workplace.” *Proceedings of the Congress*, Orlando, FL, Feb 20-22, 2000, Walsh, Kenneth D. (Ed.) ASCE. pp. 984-989.

Collier, E. and Fischer, M. (1995). “Four-Dimensional Modeling in Design and Construction.” *Technical Report Nr. 101*, Center for Integrated Facility Engineering (CIFE), Stanford.

Cross, R. and Woozley, A. (1980). *Plato's Republic: A Philosophical Commentary*, The Macmillan Press, 1980.

Cunz, D. and Knutson, G. (2005). "VDC for Construction Coordination (M.A. Mortenson Co.)." *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 21, 2005.

CURT WP 1003 (2006). "Optimizing the Construction Process: An Implementation Strategy." *CURT WP 1003.* The Construction Users Roundtable, June 2006.

Danso-Amoako, M.O., Issa, R.R.A., and O'Brien, W. (2003). "Framework for a Point-N-Click Interface System for 3D CAD Construction Visualization and Documentation." *Towards a Vision for Information Technology in Civil Engineering: 4th Joint International Symposium on Information Technology in Civil Engineering*. Flood, Ian (Ed.), November 15–16, 2003, Nashville, Tennessee, USA. pp. 1-9.

de Vries, B. and Broekmaat, M. (2003). "Implementation Scenarios for 4D CAD in Practice." In Maas, G. and van Gassel, F. (Eds.): *Proceedings of the 20th International Symposium on Automation and Robotics in Construction*. 2003. Eindhoven, NL: Eindhoven University of Technology. pp. 393-398.

Eberhard, D. (2005). "Case Examples (Parsons Brinckerhoff)." *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 20, 2005.

Eisenhardt, K.M. (1989). Building Theories from Case Study Research. *Academy of Management Review*, Vol. 14, pp. 532-550.

Ferber, R. (1977). Research by Convenience. *The Journal of Consumer Research*, Vol. 4, No. 1. (Jun., 1977), pp. 57-58.

Fischer, M., Aalami, F., and Akbas, R. (1998). "Formalizing Product Model Transformations: Case Examples and Applications." Artificial Intelligence in Structural Engineering: Information Technology for Design, Collaboration, Maintenance, and Monitoring. *Lecture Notes in Artificial Intelligence 1454*, Smith, Ian (Ed.), Springer, July 1998, pp. 113-132.

Fischer, M., Haymaker, J., and Liston, K. (2003). "Benefits of 3D and 4D Models for Facility Managers and AEC Service Providers." *4D CAD and Visualization in Construction - Developments and Applications*, Issa, R.R.A., Flood, I., and O'Brien, W. (eds), Balkema, pp. 1-32.

Fischer, M. (2004). "VBE Metrics." *Presentation to VBE Meeting at CIFE,* Center for Integrated Facility Engineering, Stanford, CA, June 14, 2004.

Gao, J., Tollefsen, T., Fischer, M., and Haugen, T. (2005). "Experiences with 3D and 4D CAD on Building Construction Projects: Benefits for Project Success and Controllable Implementation Factors." *22nd CIB-W78 Conference on Information Technology in Construction, CIB Publication 305*, Raimar J. Scherer, Peter Katranuschkov, Sven-Eric Schapke (eds), Institute for Construction Informatics, Technical University Dresden, Germany, July 19-21, pp. 225-234.

Gonzales, J. (2005). "VDC for Facility Operations Planning (Intel)." *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 21, 2005.

Gonzales, D. (2005). "Comments & Discussion on the Recommendations for Lean Virtual Design & Construction (RQ Construction)." *Presentation to Lean Design Forum*, Lean Construction Institute, Chicago, IL, June 1, 2006.

Griffis, F.H., Hogan, D., and Li, W. (1995). "An Analysis of the Impacts of Using Three Dimensional Computer Models in the Management of Construction." *CII Research Report 106-11*, Construction Industry Institute. September 1995.

Griffis, F.H. and Sturts, C.S. (2003). "Fully Integrated and Automated Project Process (FIAPP) for the Project Manager and Executive." *4D CAD and Visualization in Construction: Developments and Applications*, Issa, R., Flood, I., and O'Brien, W. (Eds). A. A. Balkema, Lisse, The Netherlands, pp. 55-73.

Hagan, S. and Graves, T. (2005). "VDC for Facility Owner (GSA)." *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 22, 2005.

Hamblen, M. (2005). "Project at World Trade Center Site Puts Advanced Design Tools to Test." *Computerworld*, 39(10), pp. 7-7.

Hastings, J., Kibiloski, J., Fischer, M., Haymaker, J., and Liston K. (2003). "Four-Dimensional Modeling to Support Construction Planning of the Stata Center Project." *Leadership and Management in Engineering,* 3(2), ASCE. pp. 86-90.

Haymaker, J., Fischer, M., Kunz, J., and Suter, B. (2004). "Engineering Test Cases to Motivate the Formalization of an AEC Project Model as a Directed Acyclic Graph of Views and Dependencies." *ITCon (Electronic Journal of Information Technology in Construction)* Vol. 9, pp. 419-441, http://www.itcon.org/2004/30.

Hänninen, R. and Laine, T. (2004). "Product Models and Life Cycle Data Management." *Xth International Conference on Computing in Civil and Building Engineering*. Bauhaus University, Weimar, June 02-04, 2004.

Holm, C., Addeman, F., Tyson, W., and Ford, B. (2005). "Case Study: Disney's Expedition Everest (Walt Disney Imagineering)." *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 20, 2005.

Joch, A (2005) "Virtual Reality and Digital Modeling Go On Trial for a Federal Courtroom design." *Architectural Record,* 193(1), pp. 184-184.

Jongeling, R., Kim, J., Mourgues, C., Fischer, M., and Olofsson, T (2005). "Quantitative Analyses using 4D Models – An Explorative Study." *1st International Conference on Construction and Engineering Management (ICCEM 2005)*, C. Park (ed.), KICEM Korea Institute of Construction Engineering and Management, Oct. 16-19, Seoul, Korea, pp. 830-835.

Kam, C., Fischer, M., Hanninen, R., Lehto, S., and Laitinen, J. (2002). "Capitalizing on Early Project Opportunities to Improve Facility Life-Cycle Performance." *Proceedings of International Symposium on Automation and Robotics in Construction, 19th (ISARC).* National Institute of Standards and Technology, Gaithersburg, Maryland. September 23-25, 2002, pp. 73-78.

Kam C., Fischer M., Hänninen R., Karjalainen A., and Laitinen J. (2003). "The product model and Fourth Dimension project." *ITcon (Electronic Journal of Information Technology in Construction), Special Issue IFC - Product models for the AEC arena*, Vol. 8, pp. 137-166.

Khanzode, A., Fischer, M., and Reed, D. (2005). "Case Study of the Implementation of the Lean Project Delivery System (LPDS) using Virtual Building Technologies on a large Healthcare Project." *Proceedings 13th Annual Conference of the International Group for Lean Construction (IGLC-13)*, Sydney, July 19-21, pp. 153-160.

Koerckel, A. (2005). "VDC for Site Operations (Strategic Project Solutions)." *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 21, 2005.

Koivu, T., Laine, T., Iivonen, V. and Gonzales, D. (2003). "Options for the Finnish FM/AEC Software Packages for Market Entry in the U.S." *VTT Research Note 2211*, VTT Technical Research Centre of Finland, Espoo, Finland. 2003.

Koo, B. and Fischer, M. (2000). "Feasibility Study of 4D CAD in Commercial Construction." *Journal of Construction Engineering and Management*, ASCE, 126 (5), pp. 251-260.

Korman, T.M., Fischer, M., and Tatum, C.B. (2003). "Knowledge and reasoning for MEP coordination." *Journal of Construction Engineering and Management*, ASCE, 129(6), pp. 627–634.

Kunz, J. and Fischer, M. (2005). "Virtual Design and Construction: Themes, Case Studies and Implementation Suggestions." *The Center for Integrated Facility Engineering (CIFE) Working Paper #097*, Stanford University, June 2005.

Larsson, R. (1993). "Case survey methodology: Quantitative analysis of patterns across case studies." *Academy of Management Journal*, Vol. 36, pp. 1515–1546.

Majumdar, T. and Fischer, M. (2006) "Virtual Reality Mock-up Model." *Proc. Joint International Conference on Computing and Decision Making in Civil and Building Engineering*. Hugues Rivard (Canada), Hani Melhem (USA), Edmond Miresco (Canada) ed. 14-16 June, 2006. Montreal, Canada. pp. 2902-2911.

McQuary, J. (2004). "Case Example (Fluor)." *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 24, 2004.

Messner, J. I., and Lynch, T. (2002). "A Construction Simulation Model for Production Planning at the Pentagon Renovation Project." *International Workshop on Information Technology in Civil Engineering 2002*. Anthony D. Songer, John C. Miles - Editors, November 2–3, 2002, Washington, D.C., USA. pp. 145-153.

Moore, G. A. (1999). *Crossing the Chasm – marketing and selling high-tech products to mainstream customers*. Harper Business. New York.

NISTIR 6763 (2001). *Benefits and Costs of Research: A Case Study of Construction Systems Integration and Automation Technologies in Commercial Buildings.* National Institute of Standards and Technology. December 2001.

O'Brien, W. (2003). "4D CAD and Dynamic Resource Planning for Specialist Contractors: Case Study and Issues." *4D CAD and Visualization in Construction: Developments and Applications*, Issa, R., Flood, I., and O'Brien, W. (Eds). A. A. Balkema, Lisse, The Netherlands, pp. 101-124.

Polanyi, M. (1966). *The Tacit Dimension*, Routledge and Kegan Paul, London, UK, 1966.

Riley, D. (2000). "The Role of 4D modeling in Trade Sequencing and Production Planning." *Proc. of Construction Congress VI*, ASCE, pp. 1029-1034.

Rischmoller, L., Fischer, M., Fox, R., and Alarcon, L. F. (2001). "4D Planning and Scheduling (4D-PS): Grounding Construction IT Research in Industry Practice." *Proceedings of the CIB-W78 International Conference IT in Construction in Africa 2001: Implementing the next generation technologies*, CSIR, Division of Building and Construction Technology, Pretoria, South Africa, also available at http://buildnet.csir.co.za/constructitafrica/au, pp. 34-1 to 34-11.

Roe, Andrew (2002). "Building Digitally Provides Schedule, Cost Efficiencies." *Engineering News Record*, 248(7), pp. 29.

Sampaio, A.Z., Henriques, P.G., Ferreira P.S., and Luizi R.P. (2005). "Vizualizing Construction Processes by Means of Virtual 3D Models: Two Study Cases." *Proceedings (469) Applied Simulation and Modelling*. Hamza, M. H. (Ed.) Benalmádena, Spain. June 2005. pp. 469-020.

Sawyer, T. (2005). "Maturing Visualization Tools Make Ideas Look Real." *ENR: Engineering News-Record,* 255(2), pp. 28-33.

Schwegler, B.R., Fischer, M., O'Connell, J.M., Hanninen R., and Laitinen J. (2001). "Near- Medium- and Long-Term Benefits of Information Technology in Construction." *CIFE Working Paper #65*, July, 2001.

Schwegler, B., Fischer, M., and Liston, K. (2000). “New Information Technology Tools Enable Productivity Improvements.” *North American Steel Construction Conferenc*e, American Institute of Steel Construction (AISC), Las Vegas, Feb. 23-26, pp. 11-1 to 11-20.

El-Sersy, A. (2004). “Objectives & Experiences Implementing BIM (CCC).” *Presentation to CIFE Summer Program*, Center for Integrated Facility Engineering, Stanford, CA, June 23, 2004.

Staub, S., Fischer, M., Kunz, J., and Paulson, B. (2003). “An Ontology for Relating Features with Activities to Calculate Costs.” *Journal of Computing in Civil Engineering*, 17(4), pp. 243-254.

Staub, S. and Fischer, M. (1998). “Constructibility Reasoning based on a 4D Facility Model.” *Structural Engineering World Wide*, T191-1 (CD ROM Proceedings), Elsevier Science Ltd.

Teicholz, P. (2004). “Labor Productivity Declines in the Construction Industry: Causes and Remedies.” *AECbytes Viewpoint #4*: http://www.aecbytes.com/viewpoint/issue_4.html.

Wang, R.Y., Kon, H.B., and Madnick, S.E. (1993). “Data Quality Requirements Analysis and Modeling.” *Proceedings of the Ninth International Conference on Data Engineering*. April 19-23, 1993, Vienna, Austria. pp. 670-677.

Webb, R.M. and Haupt, T.C. (2004). “The Potential of 4D CAD as A Tool for Construction Management.” *Journal of Construction Research*, 5(1), pp. 43-60.

Whyte, J. (2001) “Business Drivers for the Use of Virtual Reality in the Construction Sector.” *Conference on Applied Virtual Reality in Engineering & Construction Applications of Virtual Reality: Current Initiatives and Future Challenges*. 4th-5th October 2001, Chalmers University of Technology Goteborg, Sweden. pp. 99-105.

Yin, R.K. (1994). *Case Study Research Design and Method.* 2nd Edition, Sage Publication Inc., CA.

Appendix A: Glossary (in an alphabetical order)

Term	Definition
3D Modeling	3D modeling creates a representation of the form of a building design in 3D form, including 3D geometry modeling, 3D object modeling, and 3D parametric modeling.
4D Modeling	4D modeling combines a 3D model with project activities to display the progression of a project over time.
Benefit of 3D/4D Modeling	The benefits of 3D/4D modeling refer to the advantageous results that project stakeholders attain from using 3D/4D models on their projects.
Case Study	Case study is a strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence (Yin 1994).
Categories	Categories are concepts that stand for a given phenomenon. They depict the matters that are important to the phenomena being studied. In this report, categories are related to the main tasks AEC professionals need to carry out when implementing 3D/4D modeling.
Crosswalk	A crosswalk is a form of cross-tabulation that qualitatively shows the correlation between two factors (NISTIR 2001).
Factors	Factors specify a category further by denoting information such as when, where, why, and how a phenomenon is likely to occur. For example, one factor of implementing 3D/4D modeling is “model use” which explains “why” 3D/4D modeling was used.
Impact of 3D/4D Modeling	The impact of 3D/4D modeling is the effect 3D/4D modeling has on building product design and project processes and organization. It includes the benefits accruing to project stakeholders and the efforts/costs required to overcome obstacles.

Term	Definition
Impact of 3D/4D Modeling on Process	The impact of 3D/4D modeling on the tasks and their execution in the design and construction processes (Kunz and Fischer 2005), e.g., making the execution easier, faster, or earlier.
Impact of 3D/4D Modeling on Product	The impact of 3D/4D modeling on the design of physical elements within a building or plant (Kunz and Fischer 2005), e.g., better design quality in terms of meeting design functions.
Impact of 3D/4D Modeling on Organization	The impact of 3D/4D modeling on the work responsibility and role relationships between organizational groups that design, construct and operate a project (Kunz and Fischer 2005).
Implementation Factors	Implementation factors are the main aspects that shape and affect the implementation of 3D/4D modeling.
Implementation of 3D/4D Modeling	Implementation of 3D/4D modeling is the practical application of 3D/4D modeling tools for helping AEC professionals with their tasks on a project.
Measures	Measures capture a factor in terms of its characteristics. For example, we measure (qualify) "model uses" by specifying "types of model uses." Types of model uses can be classified according to the tasks 3D/4D modeling facilitates. In these case studies, we classified nine types of model uses.
Patterns	Patterns are formed when classifications of characteristics align themselves along a continuum or range. For example, we show the pattern of "model use" by aligning nine types of model uses along the project timeline and by ranking them according to their frequency of occurrence on the 32 case projects.
Virtual Builders Roundtable (VBR)	The VBR is a group of designers, engineers, fabricators, and builders active in the development of virtual building processes and technologies to share knowledge among the members and to reduce the risks, costs, and time associated with today's construction environment. The mission of the group is to. http://www.virtualbuilders.org/index.html

Appendix B: List of Acronyms and Abbreviations

2D	2-dimensional
3D	3-dimensional
4D	4-dimensional, i.e., 3-dimensional + time
AEC	Architecture, Engineering, and Construction
BIM	Building Information Model
CAD	Computer-Aided Design
CD	Construction Document
CFD	Computational Fluid Dynamics
CM	Construction Manager or Construction Management (delivery method)
DD	Design Development
DWG	AutoCAD Drawing File
GC	General Contractor
HVAC	Heating, Ventilating, and Air-conditioning systems
IFC	Industry Foundation Classes
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MEP	Mechanical, Electrical, and Plumbing
SD	Schematic Design
Sub	Subcontractor