CIFE Center for Integrated Facility Engineering •Stanford University

CIFE Seed Proposal Summary Page
2004-2005 Projects

Proposal Title:

Case Studies on the Implementation and Benefits of 3D and 4D CAD

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Proposal Number (Assigned by CIFE):

Total Funds Requested: $36,029

First Submission? Yes **If extension, project URL:**

Abstract:

The evaluation and justification of 3D and 4D CAD as well as the utilization and management of 3D and 4D models constitute an important problem in promoting 3D and 4D models at all levels of the industry, including owners, contractor, designers, consultants, and trade contractors. However, we lack a panorama of actual uses of 3D and 4D models on a variety of completed projects, including the reported benefits from the uses of these models, and the documented implications of the benefits on overall project performance. Hence, we cannot learn sufficiently from all the past experience and pass it on to implement 3D and 4D modeling on future projects. Furthermore, we lack well-established metrics that would allow us to articulate the level of utilization of 3D and 4D CAD and the corresponding benefits 3D and 4D models make over existing processes. For this reason, we cannot measure and track the benefits captured by a certain level of utilization of 3D and 4D models. These barriers often frustrate the investment decisions and implementation determination. This proposed research aims to compile a portfolio of 3D and 4D uses on 20-30 construction projects completed in the last five years; to illustrate qualitatively how the actual use of 3D and 4D models leads to desired benefits and how these realized benefits impact the overall project performance; to develop potential metrics to measure the level of utilization for 3D and 4D models and the benefits captured by the use of 3D and 4D models; and to explore the feasibility of quantifying the level of 3D and 4D utilization and the corresponding benefits related to overall project performance.

Motivating Business Problem:

One of the major barriers towards effective adoption and use of IT in the construction industry is the uncertain payoff of IT. Until firms feel that the benefits of IT are clear, relatively few firms will embrace advancements in IT, such as 3D and 4D modeling.

In several classes in the Stanford Construction Engineering and Management Program, industry guest speakers have discussed why some firms embrace 3D and 4D CAD and others do not. Two main explanations emerged: a visionary leader and the threat of intense competition. Therefore, the companies embracing the new technologies buy into the state-of-art of 3D and 4D CAD based on their strategic vision rather than a systematic and formalized analysis of the its value proposition. We are missing an explicit understanding of how 3D and 4D CAD contributes to the improvement of the overall project performance. Other speakers, e.g., Wendy Li from Webcor in the CEE 243 class, pointed out that the novel technology brightens up Webcor's image and offers an advantage to the company in getting work.

In addition to marketing benefits, 4D models have other potential benefits. They enable a diverse team of project participants to understand and comment on the project scope and corresponding schedules in a proactive and timely manner. They enable the exploration and improvement of the project executing strategy; facilitate improvements in constructability with corresponding gains in on-site productivity and make possible the rapid identification and resolution of time-space conflicts (Fischer and Kunz 2004).

Using 3D and 4D CAD as a marketing tool to gain competitive edge will not be sustainable in the long run. In the long term companies will need to figure out how to deploy such visual models effectively and efficiently across their projects (Fischer and Kunz 2004). What we are missing today is a straightforward implementation roadmap regarding how to appropriately utilize 3D and 4D models on projects to realize their desired benefits.

The evaluation and justification of 3D and 4D CAD as well as the utilization and management of 3D and 4D models constitute an important problem in promoting 3D and 4D CAD at all levels of the industry, including owners, contractor, designers, consultants, and trade contractors. First of all, we lack a panorama of actual uses of 3D and 4D models on a variety of completed projects, the reported benefits from the uses of models, and the documented impact of these benefits on overall project performance. Hence, we cannot learn from all the past experience and pass it on to implement 3D and 4D modeling on future projects. Secondly, we lack well-established metrics that would allow us to articulate the level of utilization of 3D and 4D CAD and the corresponding benefits 3D and 4D models make over existing processes. For this reason, we cannot measure and track the benefits captured by a certain level of utilization of 3D and 4D models. These barriers often frustrate the investment decisions and the determination of appropriate implementations, but they also provide the motivation for the research efforts proposed here.

Research Objectives

The specific objectives of this research are:

- To compile a portfolio of 3D and 4D applications on 20-30 construction projects completed in last five years.
- To illustrate qualitatively how the actual use of 3D and 4D models lead to benefits and how these realized benefits impacted the overall project performance.
- To develop potential metrics to measure the level of utilization for 3D and 4D models and the benefits captured by the use of 3D and 4D models.
- To explore the feasibility of quantifying the level of 3D and 4D utilization and the corresponding improvements in overall project performance.

The first two objectives aim to learn from all the past experience and provide an explicit, initial 3D and 4D implementation roadmap for facility managers and AEC service providers (designers, general contractors, subcontractors) who plan to use 3D and 4D models to assist in visualizing, planning, analyzing, and communicating a design and construction schedule based on past experience. The last two objectives will provide insights into the feasibility of quantifying the 3D and 4D value proposition so that clients and senior managers can be convinced to invest aggressively in emerging construction information technology (CIT).

Relationship to CIFE Goals

CIFE research, since its inception in 1988, has focused on developing theories and models for Construction Information and Technology (CIT) in support of integration. In addition to research on CIT and methods for Virtual Design and Construction (VDC), there is also a need to understand the business aspect of transforming business and engineering processes to consistently reap the benefits of VDC and improve overall project performance.

This proposed research is consistent with the latter part of the CIFE research focus. The quantification of the VDC value proposition is one of the most important steps that should be taken to accelerate the diffusion of CIT in the AEC industry. The value proposition of the CIT application cannot be captured until we have an in-depth understanding of how varied uses of CIT lead to different benefits and the resulting improvement of the overall project performance. This proposed research, taking 3D and 4D modeling technology as an informative example, is expected to qualitatively validate the value of using CIT innovation to increase the effectiveness of project processes in the AEC industry, and to explore the feasibility of establishing a statistical relationship between the quantitative assessment of CIT utilization and expected project performance. This proposed research belongs to the thrust area - "Value of Innovative Design-Construction Processes".

Theoretical and Practical Points of Departure

This research builds upon several prior research efforts. Firstly, the Construction Industry Institute (CII) conducted a research in the use of three-dimensional computer models on the industrial process and commercial power sector of the AEC industry spanning from 1993 to 1995 (Griffis et al., 1995). This study used a survey questionnaire on 93 projects to identify the most common usage of 3D models, the perceived benefits by users, greatest perceived impediments to the use of 3D in construction, and a statistical analysis of the difference between the use of 2D CAD and 3D CAD.

The CII study enlightens the proposed research in terms of understanding the benefits of 3D models. However, 4D models extend the use of 3D models by combining them with construction (and other) activities to display the progression of construction over time. The proposed research will address the more versatile applications of 3D and 4D models. Rather than a simple extension of the CII study from the benefits of 3D models to those of 3D and 4D models, the proposed research will study how the actual use of 3D and 4D models lead to benefits and how these realized benefits impacted the overall project performance. In addition, the suggested survey method which was administered to a large number of 3D practitioners in the CII study is not suitable for the proposed research. Since 4D CAD is still an emerging innovation which has been or is currently implemented on only dozens of construction projects, we will study specific cases to generate a foundation for the proposed research.

Members of the 4D research group at CIFE have supported construction project teams in applying 4D models on their projects. They use the insights gained from applying the 4D models in real world settings to formulate research questions, help formalize specific knowledge, and test research prototypes. In their experience, 4D models offer benefits on simple and complex projects, on new construction and on retrofit project, and at the detailed nuts and bots level as well as for overall project planning.

CIFE technical report #118 (Koo and Fischer 1998) documented a feasibility study of 4D CAD for the McWhinney project. CIFE working paper #64 (Haymaker and Fischer 2001) reported challenges and benefits of 4D modeling on the Walt Disney Concert Hall Project. CIFE technical report #122 (Staub-French and Fischer 2001) detailed a case study of using 3D and 4D models on the Sequus Pharmacuticals for the electronic design, cost and schedule integration. CIFE technical report #143 (Fischer and Kam 2002) illustrated the PM4D approach and processes on the Helsinki University of Technology Auditorium-600 (HUT-600) project. These reports discuss the application of 3D and 4D modeling and the corresponding benefits on one particular project. Results from a single-case study are not considered generalizable, but are transferable (Yin 1994). More research effort is needed to line up additional cases to determine similarities and differences in the process of implementing 3D and 4D CAD as well as understand their relationship with the varied benefits that can be captured and the overall project performance that can be achieved.

Methods:

The following research steps are necessary to accomplish the objectives of this study.

1. *Collect Data from multiple-case studies in a retrospective way to identify the characteristics of 3D and 4D utilization, the benefits reaped by 3D and 4D applications, and the overall project performance improved by 3D and 4D benefits.*

In this proposed research, we attempt to ask how the actual use of 3D and 4D models lead to particular benefits and how these realized benefits impacted the overall project performance. Case studies are an appropriate research method because case studies can answer "how" questions that are being asked about a contemporary set of events, over which the researcher has little or no control (Yin 1994).

The multiple case studies will provide a bird's eye view of the current practice of 3D and 4D CAD applications, and capture the cost and value of implementing 3D and 4D models during the overall project process. The implementation of 4D CAD in the AEC industry is currently at its introductory stage. Most companies consider using 4D modeling first on some pilot projects, i.e., specific engineering problems on a construction project, to test if the technology is useful before investing in a full-scale implementation. Thus, very few projects have been completed with 4D models from scratch. Most projects used 3D and 4D modeling to address problems over the courses of one or two specific project phases. Multiple-case studies allow the investigation of the value of implementing 3D and 4D modeling in the context of the overall project planning, design, construction and operation processes.

The proposed work builds on a list of questions designed by the Virtual Builders Roundtable for interviews with professionals who have worked on projects that have employed 3D and 4D models (Appendix A). We have briefly tested the applicability of this list of questions to determine the level of implementation and benefits of 3D and 4D models to several recent projects where CIFE researchers have helped with 4D model implementation or documentation (Appendices B and C).

The first part of the list of questions (Appendix A) was designed to collect general information about a case project, such as its size, type, construction time, contracting methods, etc. The second part of the list was designed to collect specific data regarding the characteristics of implementing 3D and 4D models, such as the purpose of 3D and 4D models, project phases when 3D and 4D models were built, technical particulars of 3D and 4D models (e.g., level of detail, number of components, number of layers, number of activities, number of links, etc.), stakeholders involved in 3D and 4D modeling, software functionality used, etc. The third part of the list helps identify the realized benefits of 3D and 4D models as perceived by stakeholders. The fourth part of the list is to recognize the impact of 3D and 4D benefits on project schedule performance, cost performance, safety performance, scope performance, change order and rework performance, and organizational decision-making performance.

Subtask 1: Complete the pilot data collection for twelve case projects on which 3D and 4D models were built or documented by CIFE researchers. (Data collection for subtask 1 is about 50% complete, a summary is provided in Appendix B.)

This pilot study involves twelve construction projects completed in the last 5 years on which CIFE researchers and students participated in the process of 3D and 4D modeling and documentation (Appendix B). We selected these projects to test the list of questions and because we could easily interview the student modelers.

Two sources of evidence, available documentation and interviews were the basis for data collection for the pilot study. CIFE working papers and technical reports that document the use of 4D modeling on four of the twelve case projects were reviewed to understand the project background and the 3D and 4D implementation process. A one-hour focused face-to-face or telephone interview was conducted by Ju Gao with the CIFE student modelers for each of the twelve case projects. The interviewer followed the structured questions in the designed list of questions (Appendix A). The interviews were open-ended and assumed a conversational manner. Open-ended questions allowed inquiry about specific examples. As a final check of consistency and validity, interviewees were also given the opportunity to review the question-and-answer table to make corrections. More data will be collected with other stakeholders involved in these projects with regard to their evaluation of 3D and 4D benefits and the impacts on the overall project performance.

The pilot study ensured that the questions in the designed list of questions are clearly stated and on target. They also indicated that most of the data needed are available either in a qualitative or quantitative way.

Subtask 2: Collect data from 10-20 more case projects on which 3D and 4D models were built by industry professionals. The projects will be selected by contacts through CIFE members. Each contact should include the names of two or three representative stakeholders who were involved in the process of 3D and 4D modeling. These representatives will be interviewed and data will be collected as in the pilot study.

2. *Analyze Data from multiple-case studies to illustrate qualitatively how the use of 3D and 4D models lead to benefits and how these realized benefits impacted the overall project performance.*

The multiple-case studies involve multiple variables of analysis, i.e., the actual use of 3D and 4D models, perceived benefits, and the overall project performance. Each variable is manifested by several dimensions or characteristics. For example, actual use of 3D and 4D models can be described by characteristics such as the scope of 3D and 4D utilization, the point of time to initiate the use of 3D and 4D models, the duration of 3D and 4D models used on project, the level of detail in the 3D and 4D models, the number of stakeholders involved in providing input to and in reviewing the 3D and 4D models, and an evaluation regarding software functionality and the quality of the modeling process. Perceived benefits can be manifested either as their impact on product, process and organization or as visualization, planning, analysis, and communication tools. Overall project performance can be depicted by the schedule, cost, safety, scope, rework, change order, or decision-making performance. A framework of analysis is shown as Figure 1. By a comparative analysis across multiple case projects of the variables and their dimensions or characteristics, we can gain insights and qualitatively illustrate how the use of 3D and 4D models leads to benefits and how these benefits impact project performance. In addition, project-specific data such as project type, site conditions, and contract type will also be investigated to see if they have any impact on the utilization of 3D and 4D models.

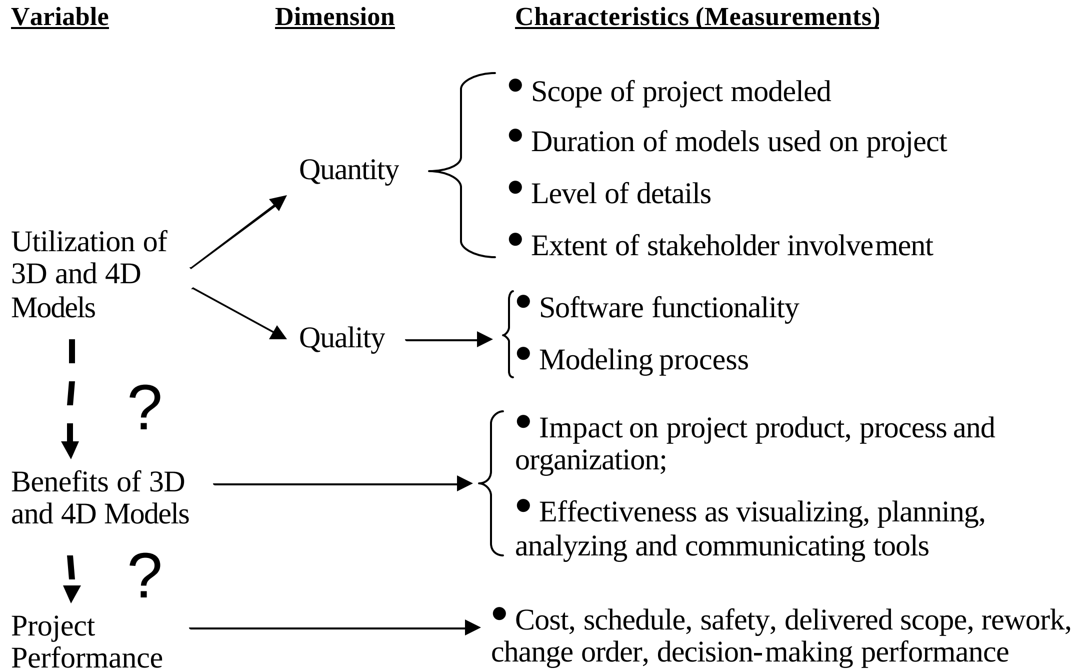

Figure 1: Framework of Analysis

From parts of the data collected from the pilot multiple case studies, one example of analysis results is shown in Appendix C. Appendix C links the major phases of projects when 3D and 4D models were used to the major benefits reaped by using 3D and 4D models and to specific case examples. For example, 3D and 4D models on case project P4 were adopted from the conceptual planning to the construction phase, and seven benefits were realized from the use of 3D and 4D models. On the other hand, three benefits were captured from using 3D and 4D models during the early construction phase only on case project P12.

3. Develop potential metrics to measure the utilization of 3D and 4D models and the benefits captured by the use of 3D and 4D models.

The utilization of 3D and 4D models and the corresponding benefits will be measured by developing metrics for each characteristic of the two variables. Some characteristics can be measured by objective measurements. Some characteristics are more likely to be measured by subjective evaluation, such as the rating of the variation in stakeholders' attitudes.

4. Discuss the feasibility of quantifying the level of 3D and 4D utilization and the corresponding benefits related to the improvement of the overall project performance.

Based on the results of the multiple case studies, we will discuss the feasibility of quantifying the level of utilization and project performance. We will also organize a workshop during the CIFE summer program to review the research results, including the application of the list of questions and the qualitative benefits found through the case studies, with industry professionals. In addition, the following questions will be discussed: (1) Is it practical to quantify and establish and cause-effect relationship between 3D/4D utilization, benefits, and impact on project performance? (2) What would be needed for quantifying the level of 3D and 4D utilization and the corresponding benefits related to the improvement of the overall project performance?

Industry Involvement:

CIFE is in a unique position in that it sponsors research and receives input and guidance from its member companies, which include the industry leaders in the VDC technologies. This proposed research project focuses on the use of 3D and 4D computer models in construction applications. The member companies that have experience with the use of 3D and 4D computer models on construction projects will be contacted and invited to participate in this proposed research. Their input is critical to the success of this research.

Research Schedule and Risks:

For each quarter of the project we plan to perform one set of research tasks. Table 1 summarizes the proposed research tasks and deliverables for this proposed research.

	Research Tasks	**Deliverables**
Quarter 1 (to be completed before the requested funding starts)	• Complete data collection for the pilot study • Select 10-20 more case projects	• Data spreadsheets • Initial analysis of the pilot study
Quarter 2	• Collect data on the selected case projects	• Data spreadsheets
Quarter 3	• Analyze data from the multiple case studies • Develop metrics for the utilization of 3D and 4D models and the realized benefits	• Analysis of the multiple case studies (Working Paper) • Documentation of metrics
Quarter 4	• Discuss the feasibility of these metrics and quantitative methods at the CIFE summer program • Submit Technical Report	• Documentation of discussion • CIFE Technical Report

Table 1. List of proposed tasks and deliverables. Funding for quarters 2, 3, and 4 is requested in this proposal. Funding for quarter 1 is provided through an award from the Dean of the School of Engineering during Academic Year 03/04.

We foresee the following potential risks with respect to the research tasks:

- *Defining metrics that will yield significant results*: To minimize the risk of using metrics that are not valuable to industry or not usually documented on projects, we will solicit feedback and review these metrics with professionals in CIFE member firms.
- *Feasibly conducting multiple case studies with a good rate of response and little bias*: Positive response from the industry and good data, both quantitatively and qualitatively, allow conclusive results to be drawn from the analysis. The challenge is to engage participation in this retrospective study, either because it is hard to recall data from the memory, or because it is cumbersome to dig up the data in piles of project documents. To minimize this risk we will use snowball sampling (i.e., case projects are selected by contacts we know and interviewees will then be introduced by the contacts who know

these interviewees) and we will use multiple sources of information (e.g., evaluations from different stakeholders) as much as possible.

Next Steps:

If the proposed research can validate that a quantitative study appears feasible, the next step will be to collect quantitative data on the level of 3D and 4D utilization, the overall benefits reaped by using 3D and 4D models, and the corresponding improvements in project performance. Statistical analysis can then be conducted to investigate statistical relationships between the above variables.

Furthermore, this proposed research is limited to one domain-specific application of CIT, i.e., 3D and 4D modeling. Further research will need to be broader to explore the potential value proposition of a "big idea", i.e., the VDC method which is in a much richer context of integrating the Product (i.e., facilities), Work Processes and Organization of the design - construction - operation team in order to support explicit business objectives.

Funding for such possible extensions will be sought from a group of industry sponsors and the National Science Foundation.

References:

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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.* Construction Industry Institute. Research Report 106-11, September 1995.

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Staub-French, S. and Fischer, M. 2001. *Industrial Case Study of Electronic Design, Cost, and Schedule Integration.* CIFE Technical Report #122, January 2001.

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

Appendix A: Case Study Protocol – Question and Answer Table

Project Data			
1	Project Owner		
2	Architect		
3	Builder		
4	Type of project (e.g., retail, office, mixed use, etc.)		
5	Contract scope (e.g., shell, interior build-out, tenant improvements, etc.)		
6	Contract type		
7	Contract value		
8	Project location		
	Project size		
9	Number of units		
10	Project Square Feet (Meters)		
11	Site Area		
12	Offsite are available for construction (for parking, laydown, etc.)		
Characteristics of Utilizing 3D and 4D Models			
13	What aspects of the project were analyzed (constructability, safety, sequence, material flow, crane position site logistics, etc.)		
14	What was the purpose of the model? (Provide a brief statement about the main reason to build the model(s))		
	3D Model		
15	Number of objects in 3D model		
16	Organization of the 3D model (i.e., layers, hierarchy, etc.)		
17	Number of layers or levels in hierarchy in 3D model		
18	3D Modeling Software used		
19	Organization(s) building the 3D model (e.g., Architect, Builder, Independent Modeler)		
20	Number of people building the 3D model		
21	Duration to build the 3D model (hours)		
22	Cost to create 3D model		
23	Project phase(s) when 3D model was built (e.g., schematic design, design development, construction documentation, construction, etc.)		
24	Who initiated the 3D modeling effort?		
25	Who paid for the 3D model?		
26	Was there an explicit budget line item for the 3D modeling effort?		
	Schedule		
27	Number of activities in project schedule		
28	Scheduling software used		
29	Levels of activities in schedule		
	4D Model		
30	Number of 3D components (objects) in 4D model		
31	Number of activities in 4D model		
32	Number of links between activities and 3D components		
33	Number of design and schedule alternatives modeled		
34	Number of iterations of 4D model		
35	Levels of detail in 4D model		

36	Translation software/format used to prepare 3D model for input to 4D model		
37	4D Modeling Software used		
38	Organization(s) building the 4D model (e.g., Architect, Builder, Independent Modeler)		
39	Number of people building the 4D model		
40	Duration to build the 4D model (hours)		
41	Cost to create 4D model		
42	Project phase(s) when 4D model was built (e.g., schematic design, design development, construction documentation, construction, etc.)		
43	Who initiated the 4D modeling effort?		
44	Who paid for the 4D model?		
45	Was there an explicit budget line item for the 4D modeling effort?		
	Use of 3D and 4D Models		
46	Number of people reviewing the 3D model		
47	Number of people reviewing the 4D model		
	How were the 3D/4D models shown? Check all options that apply below:		
48	Computer screen		
49	Projector		
50	Over the web		
51	Printouts		
52	Videos, movies		
53	Other (explain)		
54	Types of queries (for models linked to databases)?		
55	Describe process (workflow) used to update the 4D model		
	Evaluation of Software Functionality and Modeling Process		
	Was 3D and 4D software functionality successful in satisfying modeling requirement? (Rate on a scale of 1 to 5, 1 being a negative impact, 3 being no impact, 5 being a positive impact)		
56	Most useful 3D software functionality		
57	Missing 3D software functionality		
58	Most useful 4D software functionality		
59	Missing 4D software functionality		
60	Was the modeling effort successful?		
61	What were the best aspects of the 3D/4D model and related efforts?		
62	What aspects of the 3D/4D model and related processes need to be improved?		
63	Would you do the modeling again the same way? What would you do to improve the modeling process and impact?		
Benefits of 3D and 4D Models (Rate on a scale of 1 to 5, 1 being a negative impact, 3 being no impact, 5 being a positive impact)			
1	Rating of impact on product (design)		
2	Explanation of impact on product, i.e., how did the 3D and 4D models affect the design of the facility		
3	Rating of impact on process (schedule)		
4	Explanation of impact on process		
5	Rating of impact on project organization		
6	Explanation of impact on project organization		
7	Rating of effectiveness of 3D and 4D models as a visualizing tool		
8	Rating of effectiveness of 3D and 4D models as a planning tool		
9	Rating of effectiveness of 3D and 4D models as a analyzing tool		

10	Rating of effectiveness of 3D and 4D models as a communication tool		
Impact of 3D and 4D Benefits on Project Performance			
	Evaluation of Cost Performance		
1	Did building the 3D/4D models affect the profitability of the overall project (company specific)?		
2	Did building the 3D/4D model reduce or increase design cost? Give change in cost.		
3	Did building the 3D/4D models increase the accuracy of cost estimates?		
	Evaluation of Schedule Performance		
4	Did building the 3D/4D model reduce or increase design time? Give change in work hours and calendar time.		
5	Did building the 3D/4D model reduce the time of construction? Give change in days or weeks.		
6	Did building the 3D/4D models increase the accuracy of the project schedule?		
7	Did building the 3D/4D models increase the ability to predict and plan future tasks?		
	Evaluation of Safety Performance		
8	Did building the 3D/4D models impact safety, AFR (Accident Frequency Ratio)? (lost day cases = days away from work + restricted days)		
	Evaluation of Scope Performance		
9	Did building the 3D/4D mo dels improve customer satisfaction?		
10	Did building the 3D/4D models help to well define the project scope?		
	Evaluation of Rework Performance		
11	Did building the 3D/4D models reduce the number of defects, rework? Give percent or cost reduction if available.		
	Evaluation of Change Performance		
12	Did building the 3D/4D models improve change order performance? Give percent or cost reduction if available.		
	Evaluation of Organization Decision-Making Performance		
13	Did building the 3D/4D models improve decision-making promptness? (% of decision made within ? Days)		
14	Did building the 3D/4D models improve communication efficiency? (% of RFI responded within ? Days)		
15	Did building the 3D/4D models improve meeting effectiveness? (% of participation in meetings)		
16	Did building the 3D/4D models improve coordination effectiveness? (number of coordination meeting, time spent on meetings)		

Appendix B: Brief summary of case study projects and 3D and 4D applications

Project ID	Time Period	Project and Location	3D and 4D Models
P1	98	McWhinney Office Building, Colorado	(Pre-construction Phase) 4D model identified the lack of detail in master schedule, checked omission of activities in the schedule, validated original sequencing strategy, determined best sequence of installation for MEP and floor frame, detected a possible accessibility problem in the lobby area. By analyzing the 4D model of the first building, problems detected and recommendations to improve could be offered for the two remaining buildings. Two weeks were saved in project schedule. (*Document: CIFE TR #118; Interviewee: Bonsong Koo*)
P2	98	Experience Music Project, Seattle	(Construction Phase) 4D model validated original sequencing strategy, determine best sequence of installation for concrete and structural steel, tower crane location and hoisting analysis, identified invalid assumption for tower crane location, re-sequenced some concrete operations to lessen trade stacking, helped immensely in visualizing project schedule and sequencing of operations for subcontractors and specialty suppliers. 4D model united project team in schedule analysis and aided overall communication and understanding of the project complexities. *(Interviewee: Ragip Akbas)*
P3	98-99	Paradise Pier, Disney California Adventure, LA	(Pre-bidding Phase) A 4D model including staging and lay down areas was part of bid documents to verify the aggressive but realistic timeline. The winning bid came in slightly under the owner, WDI's budget and proposed a schedule that was two months shorter. (Schwegler et al., 2000)
P4	99	Sequus Pharmaceuticals, Menlo Park, CA	(Conceptual Design through Construction Phase) 3D models were leveraged to support design coordination, visualization using 3D walk-thru, constructability analysis, and automated quantity takeoff. 4D model helped identify access issues for equipment installation, identified what areas needed to remain clear to ensure that equipment could be installed as planned, and coordinated MEP construction with equipment installation. 3D and 4D models resulted in increased field productivity, less rework, 60% fewer requests for information, and fewer change orders compared to a traditional 2D paper-based process. (*Document: CIFE TR #122; Interviewee: Sheryl Staub-French*)
P5	00-02	Walt Disney Concert Hall, LA	(Through-out Schematic Design, Detailed Design Phase, Construction Planning and early phases of Construction) 3D model was used extensively for dimensional control and fabrication in the construction process. 4D models helped with schedule creation and schedule analysis and communication of schedule and construction methods to subs, owner and other stakeholders. 4D Steel, Concrete, and Exterior Enclosure model examined the overall sequencing for the major

			structural and enclosure activities. 4D Element 2 model examined major MEP within Element 2. 4D Interior Hall model examined all the activities affecting this highly congested and complex space: structural steel, concrete, plaster, wood finishes, mechanical, electrical, and scaffolding. 4D Detail Hall Ceiling model examined the ceiling installation. 3D and 4D models facilitate constructability review and sub coordination. (*Document: CIFE WP #64; Interviewee: John Haymaker*)
P6	01-02	Helsinki University of Technology Lecture Hall, Finland	(Conceptual Planning through Construction Document Phase) 3D minimized data re-entry, improved accuracy of timelines and quality of design data. 3D HVAC-CAD benefited the project team with interference detection. Based on architectural 3D models of the schematic design alternatives, the mechanical engineers conducted in-depth studies for thermal conditions, energy simulation, interior temperature profiles, air displacement stratification, and life-cycle costs. 4D model was utilized to review spatial designs in virtual walk-through, and comprehend construction sequences in 4D animations. (*Document: CIFE TR #143; Interviewee: Calvin Kam*)
P7	02-03	Hong Kong Disneyland, HK China	(Conceptual Planning and Schematic Design) 4D models helped coordinate accessibility and space conflict issues during the handover of preliminary site work to construction mobilization between different participants. (*Interviewee: SK Lyu*)
P8	01	Genentech Offices and Laboratories for Biotech Research, SF, CA	(Pre-construction and Early Construction Phase) 4D models analyzed schedule and sequencing assumptions for validity and efficiency, facilitated communication with subcontractors and owner. One 4D model examined overall construction sequence; the other 4D model examined steel erection, pre-cast wall, and window installation sequence. (*Interviewee: Calvin Kam*)
P9	00-02	Baystreet, Emeryville, CA	(Pre-construction and Early Construction Phase) 4D models examined sequences of foundation, concrete, steel structure, etc. to find cost-effective ways to accelerate the project. (*Interviewee: Calvin Kam*)
P10	03	GSA Courthouse, Portland, Oregon	(Construction Document Phase) 4D model helped coordinate/comprehend the base-isolation sequence as specified by the structural engineers. (*Interviewee: Calvin Kam*)
P11	03	California Academy of Science	(Schematic Design Phase) 4D models showed how roof could be built in terms of materials, constructability, pros and cons of two roof systems. (*Interviewee: Calvin Kam*)
P12	03	HMH Hospital	(Pre-construction Phase) 4D models examined flow of construction; two alternatives were compared and schedule was optimized. (*Interviewee: Arto Kiviniemi*)

Appendix C: Summary of benefits of using 3D and 4D models as identified in the pilot multiple-case studies (P1, P2,…P12 - Project ID)

	Visualization Tool	**Planning & Analysis Tool**	**Communication Tool**
Conceptual Planning and Schematic Design	• Owner can be shown around the virtual premises earlier and will better understand the definition of project scope, which results in less rebuilding due to owner initiated change orders. Case Examples: (P4, P5, P6, P7)	• Designer can conduct a study on feasibility of different materials for structural systems with the assistance of 3D and 4D models. Case Example: (P11)	• It brings in early involvement of construction, operation and maintenance personnel. Case Examples: (P4, P5) • It is easy to explain to architect, structural and service engineers when the designs and drawings are needed, which result in efficient procurement with complete designs and drawings. Case Examples: (P6, P7)
Detailed Design and Pre-construction	• Bottlenecks (e.g., accessibility, etc.) are easier to notice in advance, which result in less rework. Case Examples: (P1, P4, P5, P9, P10)	• It allows full investigation of feasibility of design and sequencing strategy in schedule, constructability and operationability. Case Examples: (P1, P2, P4, P5, P6, P8, P9, P10, P12)	• It helps contractor explain the aggressive but realistic timeline to the owner during the bidding process. Case Example: (P3)
Construction	• It helps visualize project schedule and sequencing of operations for subcontractors and specialty suppliers. Case Examples: (P2, P4, P5, P12)	• It facilitates trade workflow and access points. Case Examples: (P2, P4, P5, P12) • It allows effective analysis of appropriate crane size, location and capacity. Case Examples: (P2, P5)	• Misunderstanding between GC and subs will be cleared up. Case Examples: (P2, P4, P5, P8, P12)