AN ANALYTICAL MODEL TO EVALUATE AND COMPARE 3D MODELING PRODUCTIVITY ON CONSTRUCTION PROJECTS

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ABSTRACT

Project managers have applied 3D CAD technology on a number of pilot construction projects to visualize construction sequences and schedules. Construction engineers who worked on these pilot projects generally agree that 3D CAD technology offer benefits in supporting construction management tasks. However, the construction industry has not adopted the technology on a large scale within the last decade. Some practitioners and most researchers mainly attribute this to the immaturity of the commercially available 3D and 4D software.

The Center for Integrated Facility Engineering (CIFE) at Stanford University has collected empirical 3D implementation data on a number of construction projects since 1997. We developed a method that enables researchers to evaluate and compare the modeling productivity on construction projects using the collected data as input. To test this method we analyzed the 3D modeling productivity on a selected number of the pilot projects. A first chronological comparison of the analysis results shows that there have been improvements in the productivity of building the 3D models necessary to support decision making. Contrary to the technological focus of much of the research work and the belief among some practitioners this suggests that technology is no longer the main impeding factor towards a wide spread use of technology.

Within this paper we first briefly introduce the observed pilot projects and the data sets CIFE researchers collected on them. We then explain the method we developed to evaluate and compare the 3D modeling productivity on these construction projects. We finally discuss the initial findings showing trends that the productivity of building 3D models is improving. In particular we show how these findings contradict with the beliefs that technology is still the main impeding factor towards a large scale implementation of 3D models on construction projects.

KEY WORDS

Decision Making, Construction, 3D Modeling, Data Analysis.

INTRODUCTION

Various construction companies have supported project management with 3D and 4D CAD on a number of projects in the last couple of years. Researchers and practitioners alike agree on the large potential 3D CAD technology offers on these projects. For example, Webb et. al

(2004) argue, that by managing and tracking design and construction changes effectively using 4D CAD, a fair portion of the costs of construction waste can be reduced and eliminated. According to Barrett (2000) 3D model technology has the potential to provide an improved relationship between construction designers and constructors. Coles and Reinschmidt (1994) reported that creating a 4D model assisted in the construction planning process. Fischer (2001) argued that project managers can use 3D model technology to present ideas to the client and in this way improve collaborative working. Koo and Fischer (2000) showed that project managers can use 3D models to assess whether a construction schedule can be executed. Vaugn (1996) provides evidence for the usefulness of 3D models to evaluate different construction schedule alternatives. Generally, the use of 4D CAD simulations allows considerable savings to be made on construction projects by identifying problems prior to construction and avoiding re-work during the project (Heesom and Mahdjoubi, 2004).

Though practitioners realize the benefits of using 3D models for construction planning, construction teams still do not use the technology on most construction projects. Webb et al. identify missing 3D model performance measures as one factor that impedes a large-scale implementation throughout the construction industry. Research about the measurement of 3D model implementation efficiency is still very immature. The available documentation of pilot implementation projects (Collier and Fischer, 1995; Haymaker and Fischer, 2001; Kam and Fischer, 2002; Webb et. al, 2004) analyzes the efficiency of applying 3D models using anecdotal evidence. Whisker et al. (2003) and Koo and Fischer (2000) assessed the efficiency of 3D model supported planning by comparing the scheduling efficiency of student groups that are supported with 3D models with the scheduling efficiency of student groups that use traditional construction planning tools. Songer et al. (2001) contribute the hesitation of most construction teams to implement the technology on their projects to the high investment costs in the technology that are necessary. Webb et al. (2004) contributes this high investment costs to the amount of time needed to produce a 3D model.

Within this paper we introduce a method that we used to measure and compare the 3D modeling productivity on construction projects. To test the method, we present the empirical data collected from case studies on six pilot projects that used 3D models to support construction management from 1997 to 2005. We also show the results of an initial data analysis with respect to these six case studies. Although the results of the analysis are not statistically sound due to the small number of projects that we collected data from, they show first evidence of an exponential improvement in 3D modeling productivity over time. To give the reader a better understanding of the data results, we will first briefly describe the pilot projects and the data sets we collected in the next section. Then we introduce the method we used to measure and compare the 3D modeling productivity and discuss the initial results,

PILOT PROJECTS OBSERVED BY CIFE RESEARCHERS

We presents six pilot projects cases on which CIFE researchers collected data using personal interviews with project managers, researchers and students that worked or observed these projects. Table 1 shows a list of questions we asked.

Table 1: The case study protocol – questions

Project Data			
1	Type of project (e.g., retail, office, mixed use, etc.)		
2	Contract type		
3	Contract value		
4	Estimated budget for modeled project scope		
Characteristics of 3D Modeling			
1	What was the purpose of the 3D model? (Provide a brief statement about the main reason to build the model(s))		
2	Number of objects in the 3D model		
3	Duration to build the 3D model (man-hours)		

Table 2 depicts project characteristics of the six cases. The budget of the six projects ranges from less than five million dollars to more than a hundred million dollars. The project types were either commercial, industrial, institutional or transportation. Projects were delivered with several contractual arrangements (design-bid-build, CM/GC, etc.).

Table 2: Characteristics of project cases

Case	**Year**	**Type of Project**				**Type of Contract**		**Project Size**		
		Commercial	Industrial	Institutional	Transportation	Design -bid-build	CM/ GC	Small (<= $ 5m)	Medium ($ 5-100 m)	Large (>=$ 100m)
C1	1997	√				√		√		
C2	2001	√				√			√	
C3	2002		√				√			√
C4	2003			√			√			√
C5	2004		√			√			√	
C6	2005				√		√			√

Table 3 summarizes the main application areas of the 3D models on the six case projects. Although the use of 3D models was specific in each case project, on five of the six projects project managers linked the 3D model to construction schedules to 4D models. In this way project managers could detect schedule interferences, review master schedules and support constructability review and site operations analysis.

Table 3: Uses of 3D models on the case projects

Case	Uses of 3D Models
C1	The project managers linked the 3D model with the project schedule to create a 4D model. This 4D model aided the project managers and superintendents in checking the integrity of the master schedule and construction sequencing, as well as detecting potential time-space conflicts and site accessibility problems.
C2	The project managers linked the 3D model with the project schedule to create a 4D model. Project managers needed this 4D model to accelerate the project. The project suffered a two-month delay due to unforeseen site conditions (hazardous materials found during excavation). The risk was that the project would miss the turnover. Thus, the project required tight scheduling of concrete placement and steel erection. The general contractor also used the 4D model to plan difficult logistical challenges, such as lifting concrete five floors inside tight quarters.
C3	The construction manager used 3D modeling to ensure ideal routing of telecommunication lines. To minimize the possibility of data corruption due to telecommunication line installation, the owner's telecommunication group demanded that all cable tray routing meet very strict criteria for avoiding clashes with or too close proximity to other building services. The 4D model was needed to analyze schedule and sequencing assumptions for validity and efficiency so that coordination problems could be found before MEP contractors installed the telecommunication lines in the field.
C4	The general contractor proposed the concrete roof alternative and compared it with the planned steel roof in 3D models to see which was more economical and less prone to constructability issues.
C5	Project managers of the general contractor linked the 3D model with the project schedule to create a 4D model. The general contractor used the 4D model to visually communicate the roof construction sequence to subs. The general contractor especially used the 4D model to communicate the installation sequence to sub-contractors (i.e., ironworkers, painters, interior ceiling installation, and crane operator).
C6	Project managers used the 3D models for constructability design review and construction sequencing and coordination. Project managers also used the 4D model to track the work progress. In particular, project managers reviewed interface areas with shared structural components between different contractors.

Table 4 documents quantitative data collected from the case studies. The scope of the 3D modeling effort is characterized by the contract value of the modeled scope. The size of the 3D models is measured by the number of 3D objects each 3D model consisted of. The effort to build the 3D models is quantified by the man-hours 3D modelers spent during the development of the 3D model.

Table 4: Quantitative case project data

Case	C1	C2	C3	C4	C5	C6
Year	1997	2001	2002	2003	2004	2005
Scope of the 3Dmodel						
Estimated budget for modeled scope (U.S. $ million)	2	72	128	250	20	750
Size of the 3D model						
Number of 3D components in the 3D model	24360	13000	18700	3052	21605	44711
The effort of building the 3D model						
Duration to build the 3D model (man-hours)	276	350	500	120	60	2000

DATA ANALYSIS TECHNIQUE

Based on our experience of researching more than 30 3D modeling implementation projects since 1995 we identified three different factors that influence the 3D modeling productivity on construction projects:

1. The skill of the 3D modelers,
2. The 3D modeling capabilities of the used CAD applications and
3. The complexity of the 3D model.

We started to analyze the 3D modeling productivity on the above described projects by dividing the number of objects within each of the 3D models by the time the 3D modelers on the projects needed to create the entire 3D model. In this way we obtain the average number of 3D objects that 3D modelers were able to produce per hour on the projects.

A comparison of the time needed to create each 3D model object across the projects does show any trends in the 3D modeling productivity as the complexity of the 3D models of the pilot projects varies significantly (Table 5,
Figure **1**). Therefore, we need to find a way to normalize the time needed to create one 3D model object based on the complexity of the various models.

Table 5: 3D modeling productivity on the case projects

Case	C1	C2	C3	C4	C5	C6
Year	1997	2001	2002	2003	2004	2005
Number of 3D components in the 3D model	24360	13000	18700	3052	21605	44711
Duration to build the 3D model (man-hours)	276	350	500	120	60	2000
3D model productivity	88.26	37.14	37.4	25.43	360.08	22.36

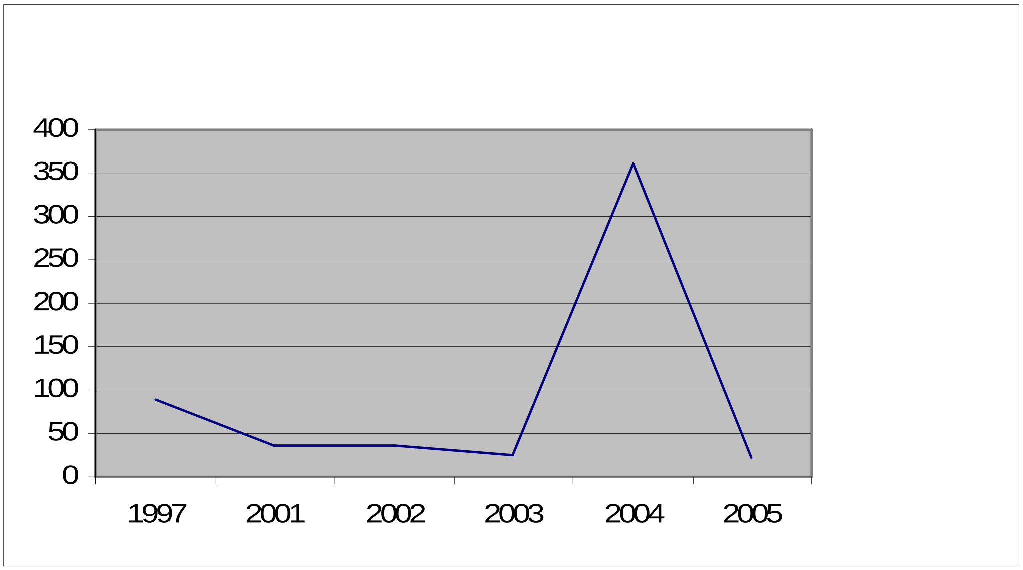

Figure 1: 3D modeling productivity, produced 3D objects per working hour

Within the literature project complexity is defined as 'consisting of many varied interrelated parts' (Baccarini, 1996). More interrelations between design components result in more interrelations in 3D model objects. Therefore, we argue that 3D modeling is more complicated on complex projects. Project complexity affects project objectives like time and cost (CIOB, 1991; Bennet and Fine, 1980; Rowlinson, 1988). Usually the estimated budget of construction projects accounts for both of these two factors. Time related factors that drive the estimate are for example labor cost, home office and field office overhead, and equipment ownership and operating costs. Accordingly, we used the estimated project budget as a third factor within our data analysis to normalize the 3D modeling productivity over the varying complexity of the 3D models of the pilot projects. The final formula we used to compare the 3D modeling productivity on the pilot projects is:

$$P = \frac{T}{O} \cdot B$$

Equation 1

with

P – 3D modeling productivity
T – Time in hours to model the 3D model
O – Number of objects in 3D model
B – Estimated project budget

DISCUSSION OF THE INITIAL DATA ANALYSIS

Table 6 and

Figure 2 show the application of Equation 1 for the data from the six case projects. The analysis results show a nearly linear increase of 3D modeling productivity from 1997 to 2004. The curve represented in

Figure 2 also suggests an exponential increase of the 3D modeling productivity for the entire data analysis period from 1997 to 2005 due to a sudden increase of 3D modeling productivity from 2004 to 2005. This productivity trend provides first evidence of the overall improvement of the skills of the 3D modelers that created 3D civil engineering models. Furthermore, this trend provides evidence that the use of 3D modeling CAD applications has also become more efficient.

Table 6: Normalized 3D modeling productivity

Case	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Year	1997	2001	2002	2003	2004	2005
Number of 3D components in the 3D model	24360	13000	18700	3052	21605	44711
Duration to build the 3D model (man-hours)	276	350	500	120	60	2000
3D model productivity	88.26	37.14	37.4	25.43	360.08	22.36
Estimated modeled scope (U.S. $ million)	2	72	128	250	20	750
Normalized 3D model productivity (Equation 1)	176.52	2674.28	4787.2	6358.33	7201.67	16766.63

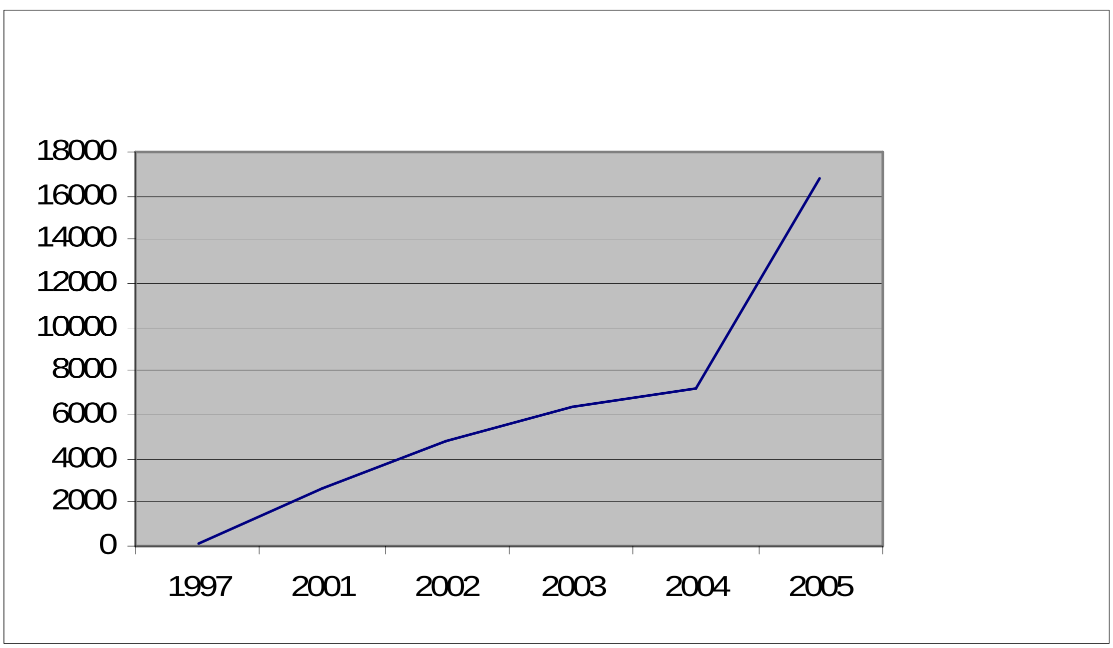

Figure 2: 3D modeling productivity, produced 3D model objects per hour times estimated project budget in one million dollars

However, due to the limited number of pilot projects we suggest that readers need to carefully reflect upon the outcomes of our initial data analysis. For example, the sudden productivity increase between 2004 and 2005 might be largely explained by unique project characteristics of case C6. Further research needs to reinforce our initial findings. Researchers need to apply the analysis technique we introduce in this paper on a large number of projects to offer statistically sound results for the improvement of the 3D modeling productivity. Researchers also need to analyze data from future projects to validate the exponential increase in 3D modeling productivity that the curve of our initial data analysis suggests.

CONCLUSION

To be able to analytically compare the 3D modeling productivity on six pilot projects from 1997 to 2005 we used three factors:

1. Duration to build the 3D model,
2. The number of objects in the 3D model and
3. The overall project budget.

Our initial findings of the data analysis show a linear increase in 3D modeling productivity till 2004. Furthermore, the data suggests an exponential increase in productivity within the future. Due to the limited number of six pilot projects the analysis results within this paper are not statistically sound and therefore can only provide first evidence for a linear or even exponential productivity increase.

Nevertheless, the data shows a general increase in 3D modeling productivity in the last couple of years. This contradicts to the general opinion of most researchers that the acceptance of 3D models within the construction industry has not improved in the last year due to the fact that the development of 3D models is too expensive (Songer, et. al, 2001; Webb, et. al, 2004). Thus, we believe that research needs to identify non-technical factors that influence the implementation of 3D models on projects to increase the overall use of 3D models in the construction industry.

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