QUANTITATIVE ASSESSMENT OF THE IMPACT OF 3D MODELLING OF BUILDING STRUCTURES ON ENGINEERING PRODUCTIVITY

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ABSTRACT

Parametric three-dimensional modelling of buildings is assumed to offer numerous advantages over computer-aided drafting for structural engineers. Assessment of the extent and nature of the potential benefits is a difficult task because 3D modelling has yet to be adopted in practice. Research based on benchmarking existing practice at the level of distinct engineering activities for complete projects, coupled with full-scale modelling experiments, has been pursued in an effort to estimate the degree of productivity gain and to identify local process impacts and changes for precast and cast-in-place reinforced concrete structures. The experimental results completed to date show that a structural engineering practice should be able to significantly increase its productivity. The degree of benefit that can be achieved is primarily dependent on the proportion of drawing production activity to the firm's overall activity, because the greatest increase in productivity is achieved in this area, ranging from 21% to 61% for cast-in-place reinforced concrete structures.

KEY WORDS

3D Modelling, Productivity, Engineering Design, Drafting, Building Structures

INTRODUCTION

Parametric three-dimensional (3D) modelling has the potential to replace the age-old paradigm of 2D drawings as the main medium of design, communication and information storage for construction in civil engineering. Its advantages include inherent maintenance of data integrity, provision of machine-intelligible building information, embedding of design intent using parametric relationships, support for automated detailing, and automatic production of drawings and bills of material (Sacks et al. 2004). 3D modelling has been recognized to be economically advantageous in structural steel fabrication for some years, is currently being adopted in precast concrete construction, and capabilities for cast-in-place reinforced concrete are being developed, as can be seen in Figure 1. Interestingly, the first

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adopters and promoters (and therefore the first beneficiaries) of 3D modelling in the architecture, engineering and construction industry have been those closest to the construction phase (fabricators, contractors, etc.), rather than those who generate building information. This appears to be an anomaly, because generating drawings consumes the major part of the resources of design practices, while it is a minor part of a construction organization's expenses. Some of the explanations for this are that design practices cannot concentrate the capital required to integrate sophisticated and expensive software; that construction companies can leverage the benefits in error reduction and logistics improvements that result, while designers are not party to those savings; and lastly, that the economic benefit for design practices has yet to be proven explicitly (Eastman et al. 2002).

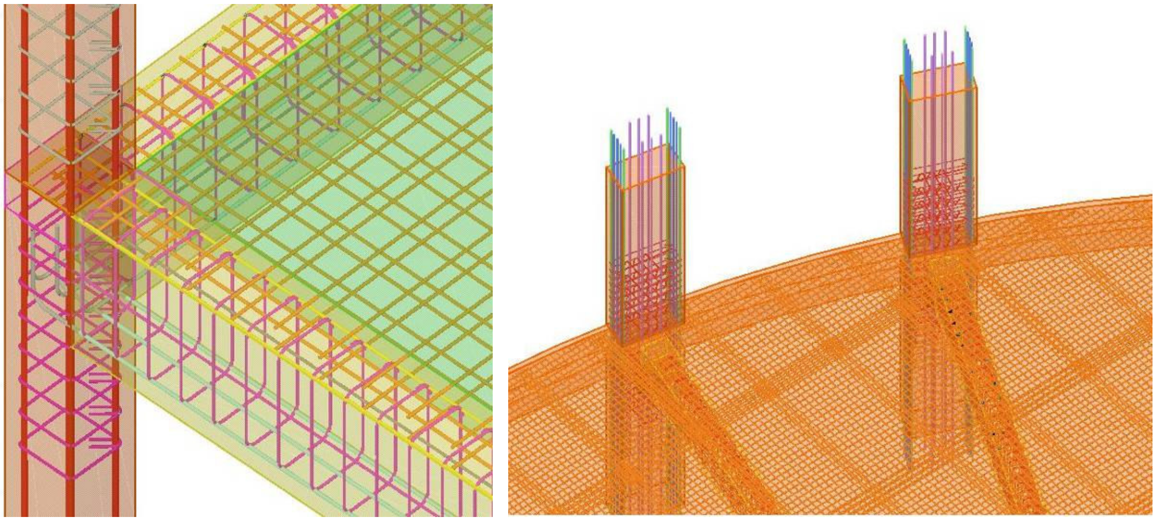

Figure 1. 3D parametric models of cast-in-place reinforced concrete elements.

This paper reports on the first phase of a research effort to examine the economic impact of this shift specifically for the case of engineering design practices. The goal of this phase was to explore potential productivity gains, including consideration of new work processes; the second phase will develop the economic model. Its scope covers structural design and production detailing for two construction methods – cast-in-place reinforced concrete and precast concrete. At present, 3D schematic modelling of structures for structural *analysis* is common, but structural design is still mostly communicated using drawings.

Measuring productivity gains due to new technologies in structural engineering services is not straightforward. No two construction projects are quite alike, either in their physical composition or in the progression of their design and detailing, which makes comparison between projects, built with and without 3D modelling, difficult. Secondly, 3D modelling is not yet a mature technology for design of building structures, making measurement of complete cases of 'future use' impossible. Lastly, the process of engineering design and detailing is itself likely to be different for 3D modelling than it is for 2D CAD. Productivity for each activity from one set cannot simply be compared with that of equivalent parallel activities from another set. The paper describes the approach developed to overcome these challenges and presents case study data and experimental results.

MEASURING ENGINEERING PRODUCTIVITY

A number of factors make it difficult to measure the productivity of engineering design and drafting activity in structural engineering. Economic productivity is commonly defined as the ratio of the quantity and quality of units produced to the quantity and quality of inputs (for multi-factor productivity), or the quantity and quality of outputs to the labour per unit of time (for labour productivity). The inputs into an engineering activity are relatively straightforward to measure – they are the raw material (preceding architectural or conceptual design) and the working hours that the design team spends producing the output. The outputs, however, are more elusive. What are the units produced by engineering activities? How can we measure their quantity, let alone their quality? What degree of detail is appropriate?

INPUTS AND OUTPUTS, QUANTITY AND QUALITY

One approach to defining units of measurement, adopted by Thomas et al. (1999) for the fifth and final phase of architectural design (construction documentation), is to assume that the product of architectural and/or engineering activity is simply the tangible set of contract documents produced, i.e. the set of drawings, specifications and bills of quantity produced. The total output of all documents (of different kinds and for different projects) is measured and aggregated over a fixed period of time (monthly, for example). Measuring the gross inputs of an entire design office over such a fixed period of time is straightforward; the data describing inputs (worker hours) collected in this way is accurate and easily obtained. The approach is limited, however because it ignores factors such as the complexity and size of the project designed and so can only be used within narrow contexts. It also ignores the quality aspect. A possibly better approach, adopted in CII engineering productivity research projects (Walsh et al. 2004), is to measure output in terms of the built product, using units such as floor area, concrete volume or component counts, and apply factors for project complexity and other influences.

An important observation is that engineering design provides a service, not a tangible product. The drawings and documents themselves are a means to communicate information needed to expedite the construction process, but they are not the information itself and they do not have any intrinsic value to the end user of a building. Measurement of productivity in other service industries, such as banking, insurance, and medical care includes consideration of both quantity and quality, in inputs as well as in outputs (Vuorinen et al. 1998), although there are no standardized methods. Service industry products are often bundled together (Sherwood 1994); measuring construction project outcomes, such as budget, schedule and quality conformance (as opposed to products) has been proposed, but it is highly susceptible to 'noise', in that many factors other than engineering service quality influence the outcomes.

While it is difficult to assess the intrinsic quality of design documents, it is clear that wide variation in their value is possible (Chang et al. 2001). Sets of design documents prepared by different design offices may contain differing levels of information detail, the number of design errors inherent in the documents will vary, different contractual environments require varying types of construction documents, and the eventual costs of construction depend on the quality of the information itself. Even seemingly unrelated factors, such as the timeliness of provision of the documents, affect their value to the project owner. Retrospective evaluations of design quality have been incorporated in a number of research efforts (Chang et al. 2001; Duffy 1998; Fayek and Sun 2001; Sacks et al. 2003). Measures include parameters such as delays and cost overruns in fabrication and construction due to design deficiencies, costs incurred due to constructability problems, and others.

A simple approach would be to measure the quantity and quality of engineering design output together as the total remuneration that a client is willing to pay for that service, which is an economically valid and accurate assessment of its value. However, in the absence of clear and understandable prospective measures of quality, it is axiomatic that the price paid for engineering design will reduce to meet the minimum possible cost of producing that design (plus some margin of profit) with no value ascribed to, and no money paid for, quality.

STRATEGIES AND DEGREE OF DETAIL

There are five levels at which engineering productivity could be assessed, in increasing order of degree of resolution:

1. A country's national accounts, using census data such as the economic census performed every five years in the US (Census 2004). Unfortunately, significant doubts have been raised concerning the validity of such calculations, given the wide discrepancies identified results for construction productivity obtained using US economic census data vis-à-vis results based on work study measurements (Rojas and Aramvareekul 2003).
2. In design offices over fixed periods, using methods of the kind employed Thomas et al. (1999), in which the outputs were measured by counting the various construction documents produced, and then applying conversion factors and rules of credit to compute the output in terms of 'equivalent architectural detail drawings'.
3. Complete projects, using the hours spent by specific design teams on specific projects as input. Output measures are straightforward, but depend on the type of construction project considered. The influence of degree of repetition of designed pieces can be accounted for using correction factors on the results, as done by (Walsh et al. 2004), or by further classification of projects (Sacks 2004). However, the method is restrictive in that it can only be used to make comparisons between like projects.

Most investigations reported in the literature use one of these first three methods. All three are independent of the design process and of any possible changes in the process itself. But by the same token, they cannot provide any information regarding the impact of 3D modelling on specific engineering activities, nor can they reveal process changes. Thus they cannot provide any insight into the ways in which 3D modelling can best be exploited. The latter two are also subject to the influence of variations in the number of design changes occurring, which can be very significant when the sample sizes are relatively small. Research has shown that the frequency of design changes varies widely over different projects (Manavazhi and Xunzhi 2001).

4. Engineering activities within complete projects, where the inputs of specific engineering activities are measured. 3D modelling experiments do not have to cover entire project

processes – experimental results for selected process stages can be combined with benchmark results for unaffected activities to provide measures of expected 3D modelling productivity for complete projects. This method was selected because it is the only method that can provide data at the level of detail required. The implementation methods are described in detail in the next section.

5. Engineering activities on specific building assemblies, where the inputs for the activities are further broken down in terms of specific building assemblies.

BENCHMARKING 2D DRAFTING

With these considerations in mind, two pragmatic experimental methods were designed for use at the level of activity types. Both require a benchmark database of structural engineering design projects in which hours spent are recorded for both engineering and drafting staff for each of the main activities performed. This section briefly describes the 2D drafting benchmarking effort. The following section reports on three sets of 3D modelling experiments in more detail.

Data describing the hours invested in the various engineering analysis, design, detailing and drafting activities were collected from precast company engineering departments and consulting engineering offices. The population for this survey numbered 52 precast projects (US and Canada) and 14 cast-in-place projects from design offices in three countries. Using process models for each engineering office as a mechanism for detailing and comparing activities, the hours for each activity were collected from staff timesheets.

A number of factors must be isolated before meaningful comparisons can be made between productivity data collected for different projects from different companies. Project type and size, construction method, the number of different versions produced, and a 'repeat factor' are used to determine categories of projects; a separate benchmark value is established for each. Details of the procedures can be found in (Sacks and Barak 2006). Table 1 shows results for structural precast projects grouped according to activity types (Sacks et al. 2005), and Table 2 shows the summary results for cast-in-place building structures.

3D MODELLING OF SELECTED ACTIVITIES FOR BENCHMARK PROJECTS

PRECAST MODELLING

Full-scale 3D modelling experiments for five medium-sized precast concrete building structures, for the modelling, erection drawings and piece detailing activities were previously completed and reported (Sacks et al. 2005). The first two of these activities are comparable to the 2D drawings process activity 'erection drafting'; for this sample, an average of 5.5 hours/1,000 m^2 was required, as compared with 52.1 hours/1,000 m^2 (from Table 1).

FULL-SCALE CAST-IN-PLACE BUILDING MODELLING

Modelling experiments were performed for cast-in-place structures in a laboratory setting. In these experiments, full sets of production drawings (both architecture and structural engineering) of three cast-in-place reinforced concrete building structures that had recently been built were obtained from engineering practices and reproduced using 3D parametric software. The offices also provided detailed records of the hours expended on each project. The focus of this experiment was on specific activities within the overall process, performed for complete buildings, as described in the methodology section above.

Table 1. Activity level benchmark data for structural precast projects

Project Size	Large	Medium	Small
Floor area (m^2)	≤ 7,500	7,501 - 30,000	> 30,000
Piece Count	≤ 250	251 – 1,000	> 1,000
Engineering Activity (hours/1,000m^2).			
Job Coordination	1.6	4.3	13.7
Engineering	11.7	11.0	24.4
Erection Drafting	25.5	52.1	171.5
Erection Checking	0.2	2.9	11.4
Production Drafting	36.1	49.6	94.6
Preparation of Bills of Material	1.2	5.3	19.5
Production Checking	1.0	11.2	25.3
Total Engineering	13.5	18.2	49.5
Total Drafting	63.8	118.3	311.0
Total	77.3	136.5	360.5

Table 2. Adjusted activity level benchmark data for cast-in-place structures.

	Min	**Weighted Average**	**Max**	**Min**	**Weighted Average**	**Max**
	hours/1,000m^2			hours/m^3		
Commercial						
Engineering	37	221	394	0.18	0.91	1.43
Drafting	118	238	350	0.56	0.97	1.27
Total	155	459	745	0.73	1.88	2.70
Public/educational						
Engineering	284	385	417	0.66	0.72	1.59
Drafting	345	424	795	0.61	0.79	2.65
Total	629	809	1212	1.26	1.52	4.24
Residential						
Engineering	37	65	115	0.05	0.09	0.33
Drafting	120	157	182	0.16	0.22	0.42
Total	157	221	297	0.21	0.30	0.75

The modellers (three final year structural engineering students) modelled each building, as shown in Figure 2, to a level of detail that included all of the concrete and reinforcing information required to produce a complete set of production drawings. For each project, a representative subset of the drawings themselves was also generated. The total number of hours recorded for each of these buildings is listed in Table 3, together with the hours recorded for each project by the engineering offices that provided them.

This experiment addressed the difficulty posed by the fact that the research is predictive – there is not yet any significant population of design offices using 3D modelling from which a benchmark of 3D practice might be collected. However, it is flawed in that it is based on data for 2D drawing collected from real engineering design projects, while the 3D modelling data was recorded in experimental conditions. The main factor that should be isolated is the influence of design changes on the inputs applied in the real projects. The hours recorded for design changes in the original projects were therefore excluded from the benchmark data. The productivity enhancements predicted by the process model comparisons for design changes could therefore not be measured in this experiment.

An additional drawback is that the skill level of the engineering staff that performed the real work may be different to that of the modellers who perform the experiment. The second experiment, described below, was designed to evaluate the impact of these factors.

Table 3. Experimental data for three reinforced concrete structure building projects.

	Project A	**Project B**	**Project C**
Experimental Scope	One of the four buildings, 4,927 m3 concrete, 57 drawings.	Complete building, without pedestrian bridge and external elevator shaft, 88 drawings.	13,000 m2; 9,750 m3 concrete; 870 tons rebar; 13 story apartment building, pad footings, flat slabs.
Modelling	131	191	140
Reinforcement detailing	444	440	333
Drawing production	89	181	126
Total 3D	**664**	**875**	**599**
Comparative 2D Hours	1,704	1,950	760
Reduction	**61%**	**55%**	**21%**

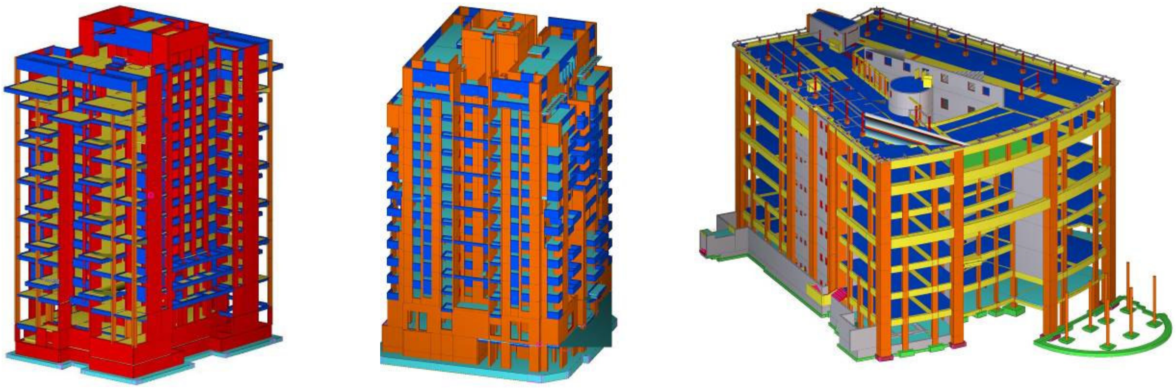
Project A Project B Project C

Figure 2. Isometric views of projects A, B and C.

STUDENT CAPSTONE PROJECTS

In this set of experiments, a select group of final year structural engineering students at the Technion-IIT used both 2D drafting and 3D modelling in parallel to complete their final year design projects. The projects include structural design, analysis and production drafting of buildings. Students pursue individual projects and are mentored weekly by practicing structural engineers. Two of the three students had no prior experience in computer-aided drafting – they were trained to use software of both types (2D: AutoCAD 2000i, 3D: Tekla Structures 11.1) within the framework of the experiment, and progressed along the learning curves of each to comparable degrees.

The significance of this experiment is not in its scale but in the degree of control it allowed, in three respects in particular:

- The students produced identical sets of drawings in both systems.
- The level of proficiency of use achieved in using each system was similar.
- The experimental setting enabled precise recording of the hours invested.

The results of this experiment are recorded in Table 4. This experiment is considered to be conservative because only a small subset of the full drawing set that would be required in a real engineering project was produced for each building. Although accurate extrapolation of the results to a full drawing set is not possible, it is likely that the measured productivity gain would be significantly greater than that indicated by the results, because 3D modelling has an initial overhead for model preparation which is absent in 2D drafting.

Table 4. Student project experiment results.

	Project D	**Project E**	**Project F**
Project Description	Commercial (office tower)12 story circular plan office tower; two story basement and 10 identical office floors	Residential (apartment block)14 stories; 13 residential floors and one basement parking garage floor	Commercial (parking garage)10 story parking garage with two story basement
Floor area (m^2)	18,000	8,400	7,780
Total 2D drafting hours	112	168	101
Total 3D modelling hours	67.5	95	89
Reduction	40%	43%	12%

DISCUSSION

PRODUCTIVITY

Each set of experiments measured the potential for enhanced productivity that can be achieved in only two of the engineering activity types covered in the process model, i.e. drawing production and quantity take-off. Table 5 shows the results for drawing production alone (based on the case study data, drawing production consumes approximately 60% of the total hours spent in structural engineering).

The full-scale experiment results are considered more reliable than the student projects for two reasons: the full scale experiments were executed over a cumulative 2,138 hours, while the student projects represent a total of 252 hours; and the level of detail in the student project drawings was very low, thus reducing the leveraged benefit of the hours that must be invested in modelling before drawings are produced.

The proportion of detailed shop drawings, and their level of detail, is much larger in precast concrete than in cast-in-place, which suggests that the productivity gain for cast-in-place should be lower than that for precast, as the figures indicate.

Table 5 Productivity gains for drawing production.

	Min Productivity Gain	**Max Productivity Gain**
Full-scale building model experiments	21%	61%
Student capstone projects	12%	43%
Precast concrete design	82%	84%

LEARNING CURVE

Two distinct phenomena delay achievement of peak productivity after initial adoption of a 3D BIM system. The first is the individual learning curve experienced as the user gains proficiency in using the particular software system; the second is the degree of integration and setup completed by the company as a whole. Most design offices have local formats for drawings and schedules, and have libraries of commonly used connections, details, etc., which can be automated. Only once these are fully integrated in the new software system can the individual users derive benefit from them.

In the full-scale experiments, we assume that the skill levels achieved by the students in the BIM lab in using 3D BIM software are comparatively lower than the skill levels of engineering and drafting staff in using the 2D CAD tools in the design offices from which case study buildings were drawn. Similarly, the depth of integration of the 2D CAD tools in the design office workflows is assumed to be deeper than that achieved in the laboratory. The effect on the productivity results is to render them conservative, since increased skill and integration would increase the measured productivity gains.

CONCLUSIONS

The experimental results show that a structural engineering practice should be able to increase their productivity significantly. The degree of benefit that can be achieved is primarily dependent on the proportion of drawing production activity to the firm's overall activity, because the greatest increase in productivity is achieved in this area, ranging from 21% to 61% for cast-in-place reinforced concrete structures.

As a result, the size and composition of design firms is likely to change as 3D BIM is introduced. Because 3D models are useful at the early stages of design and analysis, it is likely that the skill set of a modeller would include conceptual engineering skills as well as the ability to produce design documents. Engineers may assume a greater share of the overall workload, or a new professional role – the structural modeller – may emerge.

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