Evaluation of Economic Impact of Three-Dimensional Modeling in Precast Concrete Engineering

Rafael Sacks[1]

Abstract: Sophisticated three-dimensional parametric modeling software for design and detailing of precast/prestressed concrete construction is currently under development. The technology holds the potential to reduce costs, shorten lead times, and avoid errors in production and erection. To date, however, no rational assessment has been made of the costs and benefits of adoption. No standard methodology exists for the assessment of the benefits of information technology in the construction industry. This paper establishes a qualitative checklist of the expected costs and benefits for precast construction, proposes hypotheses for estimating them, and presents data to support initial assessment of the magnitude of the short-term factors. It also establishes a bench mark of engineering costs for North American precast companies. The bench mark is intended for ongoing assessment of the planned integration of the technology in the member companies of the North American Precast Concrete Software Consortium.

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Introduction

"The application of computer aided design in architecture lagged considerably behind applications in engineering. Hostility to the idea among architects, and ignorance of the potentials of computer-technology, perhaps contributed to this; but the fundamental reason undoubtedly was economic." (Mitchell 1977).

Intuitive assessments of the economic viability of computerization of the engineering and production processes in construction are insufficient motivators for realistic development and adoption of information technology (IT). Achieving full return on investments in IT in construction requires simultaneous development not only of appropriate software, but also of new business and engineering processes. Attempting the former alone, as in the integration of computer-aided drafting (CAD) in most of the construction industry to date, does not yield the benefits that might be expected from fully computer-integrated construction. For example, a survey of North American precast concrete contractors found that almost 100% of precast design is performed using CAD (PCI 2001). However, electronic drafting has not resulted in significant change in the process workflows in precast construction (Sacks et al. 2004b). computer aided design is used to generate paper drawings, which remain the sole medium of communication of design to the production and erection stages of the process. computer aided design drawings are not machine readable, so that information transfers for process activities such as structural analysis, bills of material, coordination between building systems, quality control, rebar fabrication, and piece production, are still done by people. For many of these activities, the labor cost of data re-entry negates the economic viability of localized automation. For all, it introduces an element of human error. In practice, little of the design and production automation potential inherent in IT is exploited. There has been minimal impact on design and fabrication workflows and the business process; CAD has replaced physical drawing boards with electronic ones.

Research in the field of computer integrated construction has indicated, however, that significant economic benefits can be achieved if existing work processes are adapted to fully exploit the capabilities inherent in computer modeling of buildings (Teicholz and Fischer 1994; Navon et al. 1995; Pastor et al. 2001). This may include changes to the culture, behavior, and structure of the organization (Love and Irani 2001). In addition, anecdotal evidence that attributes increased efficiencies in the design and detailing of structural steel, and reduced error rates in its fabrication, to three-dimensional (3D) parametric modeling, is increasingly available (Tekla 2002).

The North American Precast Concrete Software Consortium was formed in response to these influences, and initiated a research and development program to integrate sophisticated 3D parametric modeling software and a building product model (Eastman 1999) in the operations of its member companies. Completion of the first stage of the program (Eastman et al. 2001) has already spawned two independent efforts to develop advanced design and engineering software platforms for precast concrete. To date however, no rational assessment has been made of the expected economic impact. Numerous researchers have concluded that the absence of clearly defined and quantified benefits have contributed to impeding investment in IT in construction companies (Mitropoulos and Tatum 1999; Andresen et al. 2000; Marsh and Flanagan 2000; Love and Irani 2001). This situation is exacerbated if the software required for an industry subsector is

[1]Senior Lecturer, Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel. E-mail: cvsacks@technion.ac.il

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not directly available commercially, thus requiring investment in research and development (R&D). Research and Development is typically under funded in construction companies (Andresen et al. 2000). In fact, the average total investment in R&D reported by precast concrete companies for 2001 amounted to only 0.03% of net sales (Brummet and Olsen 2002); the maximum for any individual company was 0.2%.

The present stage of the research reported here focuses on the short-term benefits. It aims to:

1. list the potential areas of benefit of the adoption of 3D parametric modeling and data integration in the precast concrete industry;
2. propose hypotheses for the impacts of each benefit and methods for their assessment;
3. establish current performance bench mark data, to enable both initial estimation of the potential benefits, and future measurement of them as the information technologies are integrated in the industry; and
4. estimate the expected benefits, in terms of their impact on the engineering and production process, for architectural and structural precast producer companies.

The results may aid the managers of precast concrete companies to better understand the value of the technology and encourage them to finance industry-wide R&D efforts. At a later stage, as adoption of the information technologies in the precast industry progresses, it may be possible to draw conclusions concerning the validity of the hypotheses for use in predicting the value of introducing 3D modeling into other sectors of the construction industry.

The following section reviews economic impact assessment in construction IT research. Next, the scope, methods and measures of the study are defined. The assumed costs and benefits of 3D parametric modeling design and drafting automation, and data integration in the precast concrete industry are cataloged. For each, the first three aims listed above are addressed together: appropriate methods and suitable measures for assessing the economic impact are set out, and a performance bench mark is established. bench mark data were collected from five precast companies. Finally, a model for assessing the impact at the process level is proposed and its use is demonstrated.

Economic Assessment of Information Technology in Construction

In any commercial, industrial or business sector, investments in new technology must be justified in economic terms. The impacts of investments in IT are often difficult to assess, primarily because the more significant benefits are indirect. Information technology not only automates specific information intensive activities, it also acts as an enabler for more fundamental process change and automation in many business and production environments (Remenyi et al. 1995; Johnson and Clayton 1998; Remenyi 1999). Similarly, the costs of implementing an IT infrastructure are not limited to direct costs; organizational, human resource and other costs are significant and may exceed the direct costs (Love and Irani 2001).

In the case of the construction industry, IT impact assessment is complicated further by the vertical fragmentation common in the industry. Construction projects are collaborative efforts involving numerous distinct companies in ad-hoc groupings that typically do not persist beyond the life of a single project. The impacts of IT cross company boundaries: significant benefits of IT adoption by design firms for example, accrue during construction, benefiting contracting firms and building owners (Eastman et al. 2002). Assessing the value of information integration is particularly difficult in this context. An additional factor influencing the approach of construction companies to evaluation of IT is the cost of making the evaluation itself via-à-vis the perceived validity of the results.

Nevertheless, a number of strategies have been proposed for economic assessment of IT impacts in construction. Traditional methods for analyzing investment opportunities calculate measures such as return on investment, internal rate of return, and net present value. These provide crisp numbers for comparison of alternative investments. They can also be used within calculation frameworks that evaluate the risk associated with an investment, such as the controlled interval and memory method (Cooper and Chapman 1987).

Irani and Love (2001) suggest that they are of limited value for IT investments because they are unable to evaluate the broader human and organizational implications of the technology. A method proposed by Andresen et al. (2000) attempts to address this issue; it involves a three-tiered framework, yielding comparisons of expected versus measured values for: (1) efficiency benefits, in terms of currency, (2) effectiveness benefits, in terms of weighted scores, and (3) performance benefits, in qualitative linguistic terms. However, the input for the method is based on the subjective opinion of the assessor. The scope of effort required for each assessment is also likely to render it impractical for use by individual small to medium enterprises, although it could potentially be used for industry-wide assessment.

Discrete event simulation can also be used to provide effective assessment of the results of process changes in construction (Tommelein 1998). Back and Moreau (2000) employed the method to evaluate the impact of electronic communication of drawing files in a construction project, and were able to compare the resulting durations of a full design cycle with the durations of the same process using physical delivery. Another approach is to assess the impact of IT in general terms on early adopters in an industry sector using statistical data, and then extrapolate from that experience to other companies (Chapman 2001; Thomas et al. 2001). This method requires large samples of industry-wide global project performance indicators, as well as data for companies who have already adopted the technologies. The samples must also be sufficiently large to be statistically significant, in terms of filtering out the impact of influences other than IT on the project processes.

In their own right, no one of the methods described above provides a directly applicable, practical and reliable method for justification of 3D parametric modeling, automation of design and detailing, and information integration in precast construction. No single method can be applied universally because precast construction is in fact a complex process composed of multiple activities with different responses to automation and different measures of their responses. Effective assessment requires that IT enabled process improvements be assessed in two stages and corresponding levels of detail:

- the potential reduction in cost and duration must be estimated at the microlevel of individual activities, and
- the results must be assessed collectively in the framework of a complete process or major process phase.

This is the approach adopted in this work.

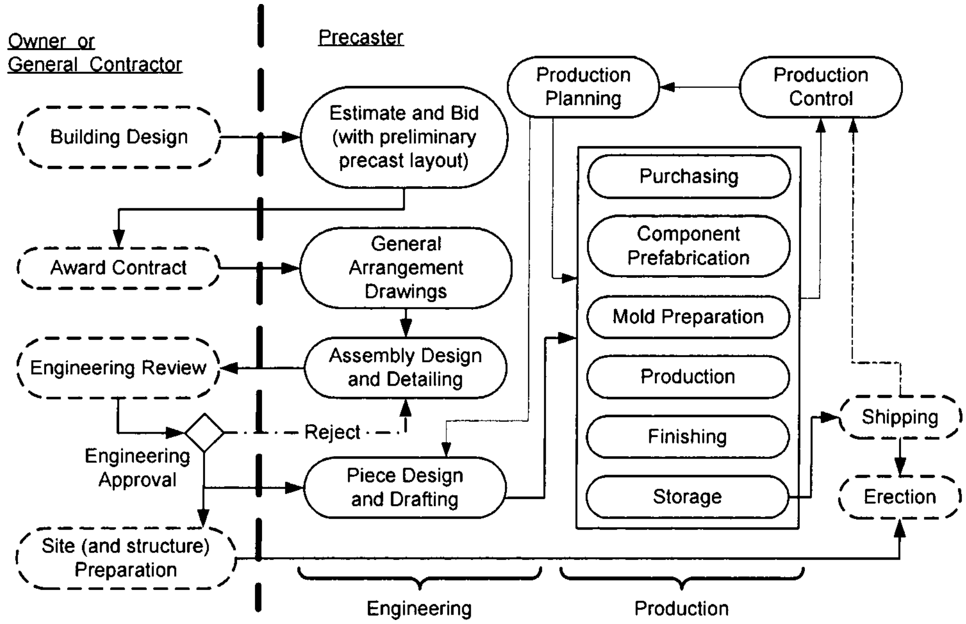

Fig. 1. Generic process of precast concrete engineering and production

Scope, Measures, and Methods

IT adoption and investment decisions must ultimately be taken at the level of the individual company. Thus the industry-wide benefits commonly cited in construction IT research cannot be expected to drive company management decisions unless the payoff to their organization is plainly apparent. We therefore restrict the scope of the following discussion to the organizational boundaries of precast concrete producers. Such companies are not homogeneous in their makeup—some outsource engineering and detailing activities, others do all in-house, and some mix the two; some employ their own erection teams, while others do not. Nevertheless, from the point of view of the majority of precast concrete producers, once a project is contracted, it can be broadly divided into four (possibly overlapping) stages: engineering, production, storage, and erection. This study focuses on the engineering and production activities. The activities selected for inclusion are shown with full boundaries in Fig. 1 (those out of scope are dashed). The scope of IT innovation considered has two stages: (1) replacement of two–dimensional (2D) drafting with 3D parametric modeling for engineering design, analysis and production of precast concrete buildings; and (2) integration of the information flows within a company based on a precast building product model.

An additional problem in evaluating IT is that adoption is not instantaneous. Customization, training, testing, and implementing the necessary organizational and human resource changes typically develops over a number of years. During this time, other influences, including normal business cycle fluctuations and procedural and technical changes initiated by management, impact the process being measured. The IT impact must be isolated from these influences. This can be achieved in part by selecting appropriate measures. For example, the influence of wage increases was excluded by measuring hours worked instead of recording costs in assessing productivity.

Similarly, production rates and net durations for individual activities are not useful measures when considering complex work processes. Rather, the throughput of the whole process, in terms of product quantity, quality and duration must ideally be measured (Hopp and Spearman 1996). Global measures such as company profitability are problematic in that they cover broad influences, and unit price is rejected due to its inclusion of profit, which varies from project to project. Costs per unit of precast product ($\$/\mathrm{m}^2$ or $\$/\mathrm{m}^3$) and unit production cycle time (days/unit) are more effective measures (when comparing pre-and post-IT integration values, fixed wage, and material costs can be assumed for converting production hours and material quantities to costs).

Finally, construction projects vary in terms of their type, complexity, scale, location, and contract type, all of which influence the engineering and production of their precast concrete pieces. Where possible, data has been aggregated according to classifications of type, size and level of complexity, as defined in Table 1 (complexity is measured as the total number of pieces/number of piece marks. This an imperfect measure: projects with groups of marks with high degrees of similarity between them may in fact be less complex than projects where each mark is significantly different, despite having a smaller piece/mark ratio. It is used nevertheless for architectural projects, as any other measure requires subjective assessment).

Table 1. Precast Project Classifications

Project type	Small	Medium	Large
Architectural			
Facade area (m^2)	$\leqslant 1{,}000$	1,001–10,000	$>10{,}000$
Piece count	$\leqslant 100$	101–750	>750
Complexity (piece/mark/ratio)	Low: $\geqslant 2$	—	High: <2
Structural			
Floor area (m^2)	$\leqslant 7{,}500$	7,501–30,000	$>30{,}000$
Piece count	$\leqslant 250$	251–1,000	$>1{,}000$

Table 2. Current Net Hours Worked (Architectural Projects-Hours per $1,000\ m^2$ of Facade)

	Project size and complexity				
	Large		Medium		Small
Activity	Low	High	Low	High	Low
Job coordination	7.7	12.3	10.2	5.5	52.4
Engineering	50.2	67.1	80.5	58.9	190.7
Erection drafting	113.5	103.2	153.0	128.8	468.3
Erection checking	16.8	10.0	11.3	2.7	37.0
Production Drafting	137.5	127.3	60.5	155.9	341.2
Production Checking	46.0	65.1	88.9	76.1	125.9
Total engineering	74.8	89.4	102.0	67.1	280.1
Total drafting	297.1	295.7	302.4	360.7	935.5
Total	371.9	385.0	404.4	427.9	1215.6

Table 3. Current Net Hours Worked (Structural Projects-Hours per $1,000\ m^2$ of Floor)

	Project size		
Activity	Large	Medium	Small
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

Engineering Stage Bench Mark

Although precast buildings can be conceptualized as complete building system assemblies, they are composed of discrete concrete pieces and the connections between them. The pieces and connections, in turn, can be decomposed into their component parts (rebar, prestress strand, embeds, etc.). Design, engineering analysis, and fabrication detailing are performed separately at each level (assembly, piece and connection, component) ("Engineering" in Fig. 1). Timesheet data describing current practice were collected from precast companies for each level, for both engineering design and drafting tasks. The net cost component of the engineering and drafting activities in existing practice (i.e., with 2D CAD) was assessed on the basis of hours worked per $1,000\ m^2$ of façade for 12 architectural projects considered to be typical by the representatives of the companies who provided the data. The results, sorted according to project size and complexity, are listed in Table 2. Similarly, the hours worked per $1,000\ m^2$ of floor area for 14 typical structural projects are listed in Table 3.

However, we are concerned not only with net hours worked but with reduction in the gross duration of the engineering process. The timesheets were analyzed further to extract a bench mark for typical architectural precast and structural precast processes through time. A project involving design of an office building façade (Project A) and a large hospital parking garage project (Project S) serve to illustrate this in the following discussion. The timesheets for the engineering phase, which recorded the activities performed by the project coordinator, engineer and drafters assigned to the project, are illustrated in Gantt chart form in Fig. 2. The full black line within each activity bar shows the actual net hours expended on each activity. As can be seen, the engineering phase in Project A was 125 working days and 188 days in Project S; however the work was not continuous, nor were the teams assigned exclusively to each project.

These example processes are not optimal even under current conditions. Comparison with suboptimal instances is likely to lead to overoptimistic evaluations. Therefore, in order to consider the impact of new IT, an optimal minimum baseline bench mark must first be established for the existing process. This is governed by internal constraints (application of resources) and external constraints (duration of submittal review). To set the baseline duration, the following assumptions were made:

1. the overall project schedule objective of the owner and /or the general contractor is "as soon as possible,"
2. exclusive and continuous assignment of the project team to the project; and
3. a reasonable minimum value is set for the submittal review duration. Analysis of the durations over 52 projects in a sample set provided yielded a median actual duration of 26 calendar days. The 5th percentile value—approximately 4 days—is adopted. The precast company representatives considered this to be the minimum reasonable practical duration.

Fig. 3 shows the results. The baseline duration of the engineering phase is 80 working days for Project A and 122 days for Project S.

Engineering Stage Benefits

The impact of parametric 3D modeling on precast engineering cannot be estimated directly in terms of the categories of labor input listed in Table 2, because the process itself is changed. The fundamental difference is that buildings are modeled rather than drawn (Sacks et al. 2003). Erection drafting of numerous sheets—elevations, floor plans, sections, etc.—is replaced with 3D modeling supported by automated layout routines. Drawings are still produced, but they are no longer information repositories that must be individually drawn and maintained, but reports that are generated almost entirely automatically by the system. three-dimensional modeling with embedded parametric behavior means that the relationships between specific types of building parts can be predefined generically (e.g., doors can only exist within walls, beams must rest on structural supports, stairs must connect floors). Application and maintenance of those relationships between occurrences of the parts is automatic. In this way, parametric modeling systems provide the functionality needed to efficiently assemble and edit the models. They rely both on definition of the topological and other constraints between parts, and on making the parametric parts available in libraries classified according to part types. Thus effective 3D parametric modeling

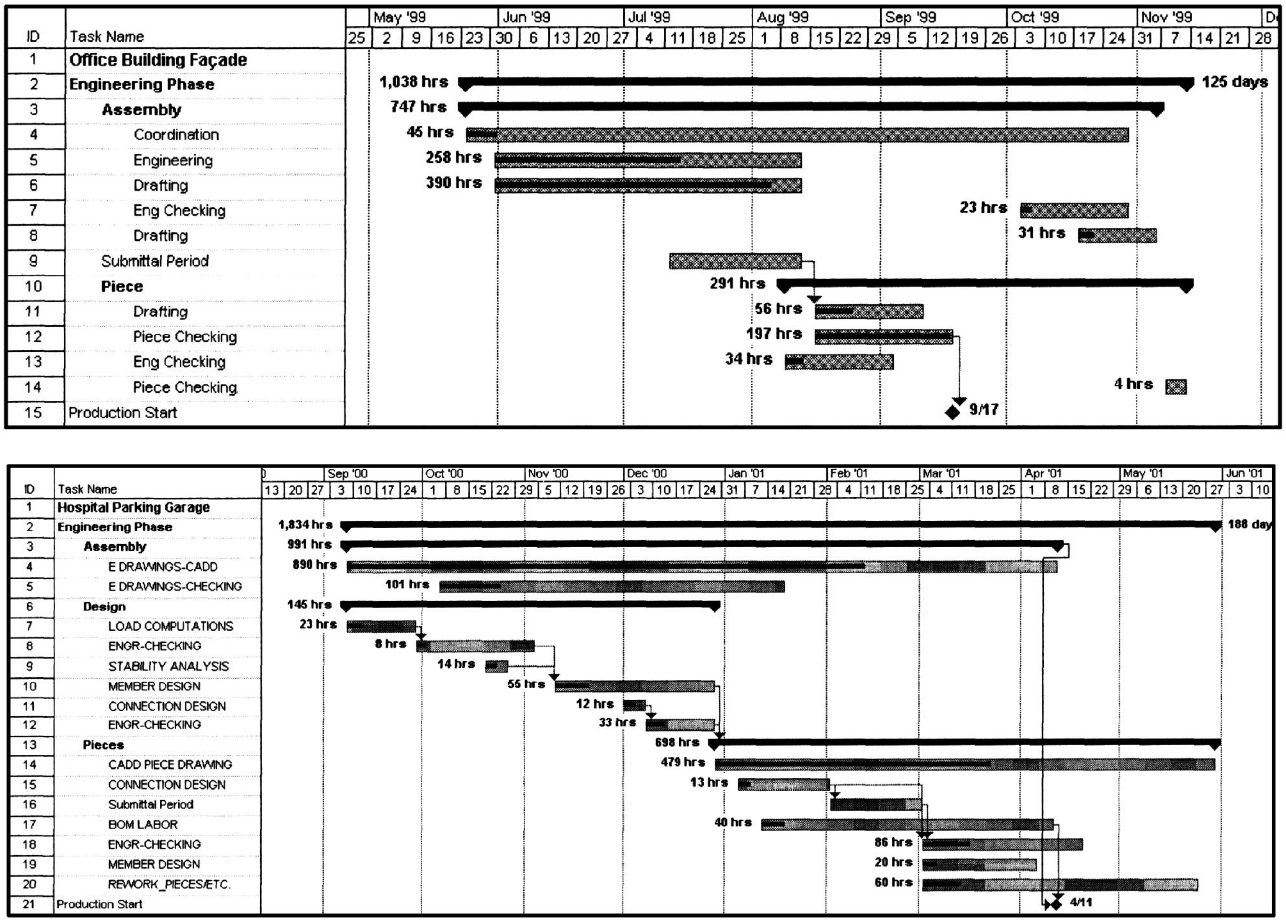

Fig. 2. Actual engineering phase durations for Projects A and S

software aids designers in the tasks for which their skills are required and automates as far as possible the more prescriptive (though not necessarily less complex) tasks.

Engineering design is facilitated, both at the assembly and the part level, in that existing analysis and design tools can be linked into the applications in such a way that their input is extracted automatically from the 3D model—repeat data entry is no longer required. The parametric modeling software enables modelers to apply connections between pieces in a top-down fashion, such that the gross geometry of each piece is automatically adapted to fit in relation to all the other pieces with which it makes contact (Sacks et al. 2004a). Production drawings and bills of material are produced automatically. In theory, production drafting and checking could be eliminated, however a limited amount of "cleaning up" and annotation of the drawings generated is assumed to continue to be necessary.

The resulting process for Project A cited in the bench mark data above (Fig. 3) is shown in Fig. 4.

No precast project has yet been fully detailed in production conditions using 3D parametric systems such as those under development at present. Specific assumptions must therefore be made concerning the reasonable durations of each activity in the process. The assessments that follow were based on the extensive experience in the structural steel industry using 3D parametric modeling (Xsteel and SDS/2 applications); on bench mark tests (Sacks et al. 2004a) conducted using the Xengineer application (the basis for one of the precast platforms under development); and on experience gained modeling a real building during piloting of prototype software at a precast plant. The following assessments are made:

1. *Modeling the assembly* (Task 20 in Fig. 4) involves laying out vertical and horizontal grid control planes, placing column, floor, and façade assembly objects (which automatically subdivide into individual pieces such as double tee floor elements or façade panels according to user-defined parameters), and finally laying out any pieces that are not members of repetitive arrays. For a standard precast parking garage, this can be completed within a day. For the hospital façade project, assuming the need to generate a limited number of nonstandard panel cross sections, 4–5 days are allocated.
   Additional time (1–2 days) may be required if the support structure—structural steel, cast-in-place concrete or precast—is not available in model form. Producing the initial set of drawings for review by the owner's representatives [Task 21 in Fig. 4(a)] requires selection of predefined templates or definition of the drawing views and their arrangement on sheets. The pieces are numbered automatically and the drawings are generated. A duration of 3–5 days is a conservative estimate that includes management, plotting, communication, and other corollary tasks.
2. *Coordination* with other building trades and designers [Task 24 in Fig. 4(a)], is assumed to occupy the engineer as before (Task 7 in Fig. 3), despite the expectation that the model should enable rapid checking and testing of the impact of other building systems on the precast pieces.
3. *Assembly structural analysis and design* is facilitated by di-

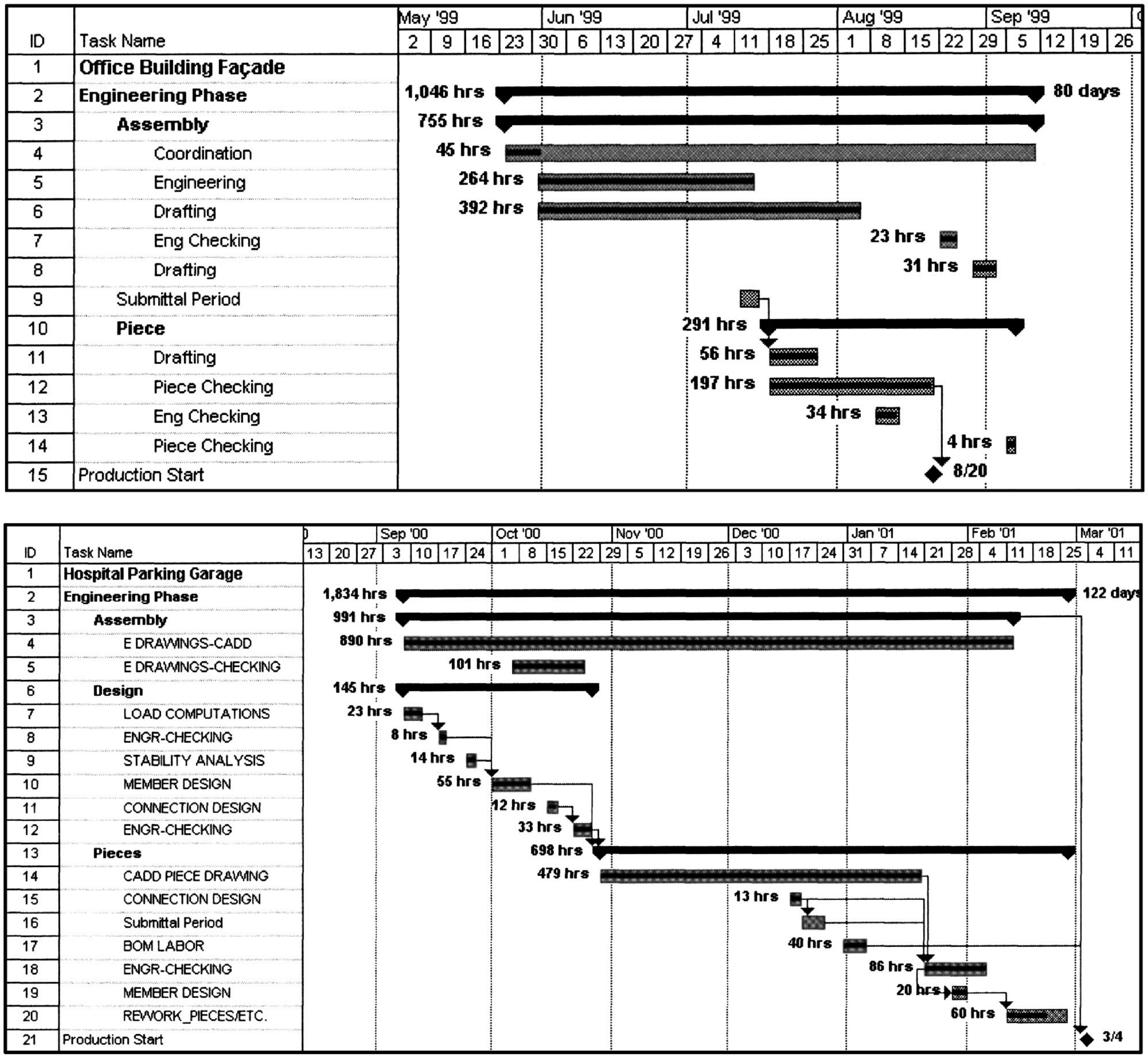

Fig. 3. Minimum duration bench marks for Projects A and S

rect data exchange between the modeling and analysis software. This has been shown to be effective practice in structural steel using the CIS/2 data model (AISC 2002). A 20% improvement in productivity is assumed for Task 23 [Fig. 4(a)]. In Task 25, modeling assembly detail, connection and joint details are applied and sized in a highly automated fashion. This leverages the capabilities of the systems to store parametric connection libraries and to select and apply them using design rules that can be based on the analysis results (reactions) stored in the model. Nevertheless, the task requires thorough attention to detail and an engineering level check that any automated routines have produced desirable results in all situations. Five to 6 full days are allocated.

4. *Precast piece design*. In the existing process, precast member design software is commonly used. The only improvement considered is the removal of the need for repeat data entry. Prototypical operation of a commercial piece design application directly from 3D parametric modeling software has already been demonstrated to enable direct data transfer. Nevertheless, due to the brief duration of the activity in the architectural bench mark case (8 h), no reduction was assumed.
5. *Piece production drawings* (shop tickets) and *bills of material* are produced automatically by the system. The 6 days allocated for this task are required for review and "cleaning up" of drawings for overlaid dimensions, unclear notes, etc. It is expected that this period will gradually become shorter as companies learn to customize the automated drawing production routines to match their drafting practices.
6. As in the existing process, three days are allocated for checking of piece-mark production drawings. This reflects time spent checking engineering logic and design intent. This conservatively ignores the fact that there is no need to check drawing integrity (compatibility between assembly drawings and piece drawings is a major source of error in the existing process—it is eliminated with high confidence where geometrical and topological integrity is maintained automatically through the parametric behaviors embedded in the assembly and its parts, and where a single model drives the generation of both sets of drawings).

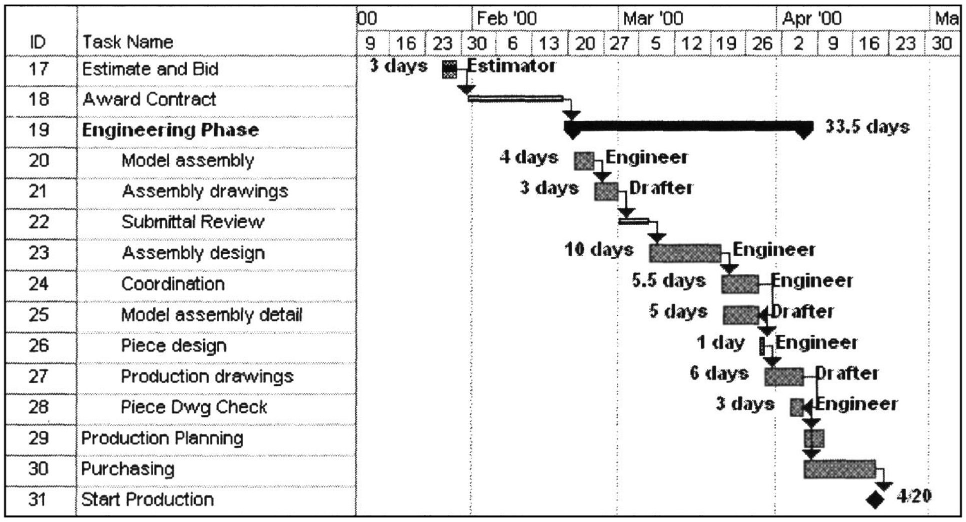

Fig. 4. Reengineered engineering stage process

In as far as all of the above are predictions of future practice, precise values for productivity rates cannot be determined, and the estimates should be viewed with caution. Nevertheless, the estimates are the basis for the economic assessment; they have been checked by precast companies' drafting managers and senior engineers who have trained on the new prototype software. Given the re-engineered process, as described up to this point, the various specific benefits can now be enumerated, assessed and evaluated.

Reduction of Design and Drafting Errors

An earlier study (Sacks et al. 2003) revealed that the sources of error in precast construction that can be traced to the engineering stage are:

1. errors in engineering design calculations and errors of judgment;
2. errors that introduce inconsistencies between assembly drawings and piece production drawings (i.e., "shop tickets"), which include drafting errors and piece detailing errors;
3. errors resulting from lack of coordination between different building systems; and
4. errors due to inadequate management of design and detailing changes.

All of these errors result in high costs of quality control, rework and rejection of complete precast pieces. Data were therefore collected from four precast companies that maintain detailed records of errors, their sources, and their consequences. The data cover a total of 37,529 pieces produced, within which there were 2,087 repairs and 54 remakes as a result of engineering and drafting errors alone. The first five columns of Table 4 summarize the error data collected.

Parametric 3D modeling systems maintain geometric and topological integrity between the design data of individual pieces and that of the assemblies in which they fit. They also enable automation of repetitive detailing tasks. By automating these aspects, the element of human error is reduced. The potential contribution to error reduction has been estimated based on detailed case studies of errors in precast construction (Sacks et al. 2003b). Classifying the results under the error source groupings, as in Table 4, allows calculation of an initial estimate of the potential benefit in terms of total cost: the estimate is 0.40%–0.46% of total project cost.

Shortened Lead-Time and Increased Responsiveness to Clients

Currently, lead time from contract award until production can begin averages 3–4 months (Sacks et al. 2004b). The projects analyzed in Figs. 2–4 above show that lead time in the architectural façade project can be reduced from the baseline minimum of 80 to 34 working days, and from 122 to 48 days for the structural project. Lead time can be reduced further if more than one engineer and/or drafter is assigned to the project. Parametric 3D mod-

Table 4. Cost of Errors as a Percentage of Total Project Cost

	Error correction project phase					
Error source	Engineering	Production	Erection	Total	Estimated error reduction level[a]	Potential benefit
Assembly Design	0.01%	0.16%	0.02%	0.19%	70–80%	0.13–0.15%
Drafting	0.01%	0.06%	0.05%	0.12%	90–100%	0.11–0.12%
Piece Detailing	0.00%	0.08%	0.00%	0.08%	80–90%	0.06–0.07%
Coordination	0.00%	—	0.18%	0.18%	55–65%	0.10–0.12%
Total	0.02%	0.30%	0.25%	0.57%	—	0.40–0.46%

[a]Sacks et al. (2003)

Table 5. Cumulative Hours Worked for Baseline and Information Technology (IT) Enabled Processes

	Architectural (hours per 1,000 m^2 façade)					Structural (hours per 1,000 m^2floor		
	Large		Medium		Small			
Project size and complexity	Low	High	Low	High	Low	Large	Medium	Small
Bench mark process								
Total engineering	74.8	89.4	102.0	67.1	280.1	13.5	18.2	49.5
Total drafting	297.1	295.7	302.4	360.7	935.5	63.8	118.3	311
Total	371.9	385.0	404.4	427.9	1,215.6	77.3	136.5	360.5
IT enabled processes (upper estimate)								
Total engineering	36.6	43.8	50.0	32.9	137.3	7.8	10.6	28.7
Total drafting	47.5	47.3	48.4	57.7	149.7	10.2	18.9	49.8
Total	84.2	91.1	98.4	90.6	286.9	18.0	29.5	78.5
Proportion of total project cost	6.5%	5.5%	6.7%	4.8%	9.22%	3.6%	6.6%	8.5%
Potential savings (% of total project cost)								
Upper estimate	4.8%	4.0%	4.8%	3.7%	6.7%	2.6%	5.0%	6.4%
Lower estimate	4.5%	3.8%	4.5%	3.5%	6.3%	2.5%	4.8%	6.1%

eling systems that employ an object-based data storage system allow multiple users to work simultaneously on the same model. Assigning two engineers and two drafters to appropriate activities in the project of Fig. 4 could conceivably reduce the lead time by a further 12 days, to just 20 working days.

Making changes to a completed building design using CAD is time consuming and complex because of the need to manually maintain consistency between numerous drawings. The fact that changes are automatically propagated through a parametric model, together with automated production of drawings and other documentation, make incorporation of design changes feasible and less error prone than in current practice.

Reduction of Direct Engineering Design and Drafting Costs

The major element of productivity gain is in the direct labor costs of producing drawings. Once a designer completes detailing a 3D model, the software can produce all of the production drawings automatically. This includes building assembly and erection drawings, piece drawings, and component drawings (required for rebar, plates, special models and other separately fabricated items). A second benefit derives from the fact that in current CAD practice, separate data entry is required for quantity takeoff for estimating, structural analysis, preparation of bills of material, and other data processing tasks. A 3D model composed of meaningful building objects—as opposed to CAD drawings that cannot be interpreted by software—enables full automation of most of these tasks.

Table 5 shows the cumulative labor hours for engineering and drafting personnel for the baseline (Fig. 3) and IT enabled processes (Fig. 4) set out above. As the figures imply, parametric modeling requires relatively more input from competent designers than from less-qualified drafting personnel than is the case in conventional CAD. This is particularly true in the first phase of assembly layout design and modeling (Eastman et al. 2001), because architectural and engineering design decisions must be made concurrently with input of the parametric model.

In Table 6, the relative reductions from Table 5 are applied to the bench mark data reported in Table 2. In order to express benefits as a percentage of overall project cost, they are divided by the relative portion of total engineering and drafting cost as a part of the total project cost for each category. This portion has a weighted average of 6.09% (with a range between 4.8 and 9.22% for architectural projects and between 2.6 and 12.8% for structural projects) for the data set collected, which is compatible with the average of 5.59% (with a range between 4.95 and 7.82%) reported for companies of similar size in an industry wide survey for 2001 (Brummet and Olsen 2002). Also, the relative cost ratio of engineering versus drafting personnel must be applied (a value of 1.67 was assumed). The results show potential savings ranging from 2.6 to 6.7% of total project cost. The relative impact on smaller and simpler projects is greater than that on larger and more complex projects.

No estimate was made for possible reduction in engineering overhead costs associated with the reduction in engineering hours. Over the long term, it is expected that engineering overheads will shrink slightly less than in direct proportion to the decline in total hours invested in engineering and drafting (i.e., on the order of 66–71%). In the short term however, no significant reduction in fixed costs is to be expected. Some companies include overheads in their representative engineering costs, while others separate them as part of a general overhead account. In any event, data defining the proportion of overheads attributable to engineering activities alone was not available.

Table 6. Productivity Benefits of Information Technology (IT) Enabled Process

Personnel hours	Baseline process	IT enabled process	Reduction
Architectural			
Engineering	366	180–196	49–54%
Drafting	680	112–136	16–20%
Total	1,046	292–332	28–32%
Structural			
Engineering	574.5	313–373	54–65%
Drafting	1,259.5	204–224	16–18%
Total	1,834.0	517–597	28–33%

Long-Term Benefits

Beyond the short-term benefits, the availability of information-rich 3D models is expected to result in additional economic benefits throughout the process—in sales, engineering, production, and erection. These are outlined below.

Enhanced Accuracy of Cost Estimating

Parametric 3D modeling systems lend themselves to rapid generation of building models. It is possible to generate highly detailed bills of material within hours. Quantity takeoff data can then be manipulated in a cost estimating system to produce a bid. More accurate cost estimates may enable lower risk contingencies in bidding.

Integration with Enterprise Resource Planning Systems

This aspect extends to many of the information dependent production management tasks, such as automatic generation of part and material lists, on-line procurement, production and erection scheduling, and production control. Most precast companies have some form of enterprise resource management system in place. Data describing a company's projects, such as bills of material from drawings, schedules, etc., must be extracted from design drawings and keyed into the Enterprise Resource Planning systems. At present, this must be done manually. The single model and object-oriented nature of the 3D model database facilitate direct data exchange. The advantages are reduced work effort, elimination of human error, increased frequency of data input, and the possibility of transferring schedule, production, quality, and other information back to the 3D design model for enhanced information visualization.

Production Automation

The labor cost of personnel needed to key design data into computer numerically controlled machines has been a key barrier to extensive use of such equipment. In many plants, CNC machines such as rebar benders have been installed, but cannot achieve their full potential. Other examples of CNC machinery that is currently available are welding machines, milling and/or laser cutting machines for production of styrofoam mold parts, laser projection systems for layout activities, wire mesh bending machines, cranes, and other piece-handling equipment, and robotic arms and applicators for sand blasting and acid etching. All of these can be driven by data extracted directly from a 3D computer model.

Costs

The costs of IT adoption in construction are both direct and indirect. The direct costs include software, hardware, installation and configuration, overheads, employee training, maintenance, and financing. The indirect costs include management resources and time, employee time, salary changes and staff turnover, productivity losses, business process re-engineering, and organizational restructuring (Love and Irani 2001). The costs, like the benefits, must be expressed as a percentage of cost of sales for the organization. One-time investments must be amortized over their expected lifetime using a rate of interest that reflects the alternative opportunity cost of capital for the company.

Table 7. Direct Costs Per Workstation with Three-Dimensional Parametric Modeling Software

	Initial investment	Annual expense (following 4 years)	5 year annual equivalent (at 20% annual interest)
Software	\$15,000–\$20,000	—	\$5,016–\$6,688
Hardware	\$3,500–\$5,000	—	\$1,170–\$1,672
Installation	\$1,600–\$2,400	—	\$535–\$803
Training	\$3,000–\$5,000	\$1,000–\$2,000	\$1,669–\$3,003
Maintenance	—	\$2,000–3,000	\$2,000–\$3,000
Salary growth	—	\$1,000–\$5,000	\$1,000–\$5,000
Total	\$23,100–\$32,400		\$11,390–\$20,165

Direct Costs

Table 7 lists the range of direct annual costs expected for a single workstation, with one-time investments amortized over 5 years. Assuming the productivity rates calculated in Table 6, and a typical working year of 1,920 h, the direct costs can be expressed per $1{,}000\ m^2$ built. However, as fixed costs, their application to any specific project cost is subject to the rate of utilization within the company for any given year. They are therefore calculated only in context, as in the example presented below.

Most precast companies currently employ specialized engineering software, CAD drafting tools, and standard personal computing hardware for their engineering operations; others outsource this activity to external design consultants. In either case, the cost of the "do nothing" alternative should be deducted from the direct costs calculated above. Table 8 reflects the current cost per workstation running CAD software or engineering software, assuming similar license costs for each. If the number of workstations were to remain constant, the result would be a net direct cost of between \$6,651 and \$9,057. However, the productivity gain in staff hours should be reflected in a corresponding reduction in the number of workstations, with a correction for any increase in capacity. This can be done at a company level, as described in the next section.

Indirect Costs

Management Resources and Time

Management resources and time are consumed in evaluating the new technology, making the decision to adopt, and then implementing the change. Employees (one representative of each work-

Table 8. Direct Costs Per Workstation with Computer-Aided Drafting or Engineering Software

	Initial investment	Annual expense (following 4 years)	5 year annual equivalent (at 20% annual interest)
Software	\$2,000–\$3,000	—	\$669–\$1,003
Hardware	\$1,200–\$2,000	—	\$401–\$669
Installation	\$500–\$800	—	\$167–\$268
Training	\$1,500–\$2,500	\$750–\$1,500	\$1,001–\$1,834
Maintenance	—	\$1,250–\$2,000	\$1,250–\$2,000
Total	\$5,200–\$8,300	\$2,000–\$3,500	\$3,488–\$5,774

ing group affected by the change, in this case engineers and drafters) are likely to participate in support of this activity.

Personnel and Salary Changes

Drafters who are experienced CAD users are required to learn new computer-aided building modeling tools. Experience in the structural steel industry has shown that an experienced CAD detailer or engineer can be trained on a 3D parametric system within one week, and can become fully productive within a few months. For lack of any other indicator, we therefore assume that salaries of engineering personnel will increase marginally (note that the impact of this figure is relatively small compared to the significant change in productivity, and therefore accuracy in its prediction is not given high priority). Overall, the productivity gains lead to reductions in total staff—those who master the new software are more likely to be retained.

Productivity Loss

This cost expresses the learning curve experienced by users as their skills in using the new IT grow. As an approximation, full productivity can be assumed to be achieved within one year from initial training, with a linear rate of change. A different factor with similar impact is the **rate of uptake of the technology**. The fact that construction is project based enables management to adopt a risk averse strategy, in which adoption is delayed for part of the staff, in parallel with full adoption by others. This must also be factored into any specific company level analysis.

Business Process Reengineering and Organizational Restructuring

Business process reengineering and organizational restructuring are not considered in the short term. In general, the organizational structure within precast companies' engineering departments is shallow: the reduction in levels that commonly occurs with IT adoption in other organizations (Hochstrasser 1992), is therefore not expected to occur. The only significant cost in this regard is that one or more individuals within an engineering department will be required to maintain the computerized parametric 3D catalogs of standard cross sections, connection types, finishes, etc. needed for operation of the system.

Example of Evaluation of Short-Term Cost/Benefit

The method adopted to evaluate the benefit and/or cost impact of the new information technology comprises three stages. First, enumerate and evaluate the benefits for typical full project processes; second, enumerate the costs for typical companies, and evaluate wherever possible; and last, apply the results of the first two stages to a model of adoption in a specific company. This section presents the third stage.

The benefits accrue from engineering productivity gains, error reduction and increased capacity utilization. All are dependent on the rate of technology adoption and any corresponding forecasted growth in volume. The first two are multiplied by the planned annual rate of adoption of the new technology over the years considered; the third is multiplied by the forecast cost of sales divided by current cost of sales (the cost of sales is used instead of turnover to exclude the impact of any change in profitability). The annual benefit B_k can be calculated as follows:

$$B_k = a_k \sum_i \sum_j CF_{ijk}(p_{ij} + e_{ij}) + \left(\frac{\sum_i \sum_j CF_{ijk} - C_P}{C_C - C_P} \right) p_0 \quad (1)$$

where a_k=level of adoption in any given year k, ranging from 0 to 1; i=one of (architectural, structural); j=one of (small, medium, large); k=number of years after initial investment in IT; CF_{ijk}=target annual cost of sales for projects of type i and size j in year k attributable to IT adoption; p_{ij}=engineering productivity gain for projects of type i and size j (from Table 6); e_{ij}=error reduction gain for projects of type i and size j (from Table 4); C_P=present cost of annual sales for all projects; C_C=cost of sales assuming full utilization of production and erection resources; and p_0=maximum potential overhead gain (4.2%). The costs are the direct costs of new parametric 3D modeling workstations (less the cost of CAD workstations that are removed) and the indirect costs associated with organizational change. The number of new parametric modeling workstations in any given year is given by the adoption level for that year multiplied by the existing number of workstations and any increase in overall volume, and corrected for the associated productivity gain. The current costs of the existing workstations replaced by the new technology are deducted, but with a one year delay. The annual costs C_k can be estimated as

$$C_k = n \left(\frac{\sum_i \sum_j CF_{ijk}}{C_P} \right) (a_k \overline{P} C_{3D} - a_{k-1} C_{CAD}) + CI_k \quad (2)$$

with

$$\overline{P} = \frac{\sum_i \sum_j CF_{ijk} P_i}{\sum_i \sum_j CF_{ijk}} \quad (3)$$

where P_i=relative productivity of parametric modeling workstation to standard CAD workstation (Table 5); C_{3D}=predicted annual cost of 3D parametric modeling workstations (Table 7); C_{CAD}=current direct annual cost of CAD/engineering workstations (Table 8); n=number of existing engineering and drafting workstations; and CI_k=annual indirect costs.

The model enables evaluation of a company IT adoption plan. The rate of uptake must be set, and the production volume must be forecast for the different project types. The following simplified numeric example illustrates the calculation and indicates the kind of results that can be expected:

Given a precast company with an annual cost of sales of $30,000,000, and which specializes in one project type (say medium sized architectural projects), what is the cash flow change that can be expected during and immediately after adoption of 3D parametric modeling? The company operates 20 existing CAD workstations. The IT adoption plan calls for an adoption rate of 20% per year over 5 years and for one employee to be dedicated to the adoption over the full period at half time. The calculation can be simplified to

$$B_k = a_k CF_k (p + e) + \left(\frac{CF_k - C_P}{C_C - C_P} \right) p_0 \quad (4)$$

and

Table 9. Information Technology Adoption Cash Flow Example (All Figures are Thousands of Dollars)

Year	1	2	3	4	5	6
Upper benefit estimate	$286	$571	$857	$1,142	$1,428	$1,428
Lower cost estimate	$38	$37	$35	$34	$33	$19
Cash flow	$248	$535	$821	$1,108	$1,395	$1,409
Lower benefit estiamte	$264	$528	$792	$1,056	$1,320	$1,320
Upper cost estimate	$48	$47	$46	$46	$22	
Cash Flow	$216	$481	$745	$1,010	$1,274	$1,298

$$C_k = n\left(\frac{CF_k}{C_P}\right)(a_k PC_{3D} - a_{k-1}C_{CAD}) + CI_k \tag{5}$$

where CF_k=target annual cost of sales for projects in year k attributable to IT adoption; p=engineering productivity gain for projects (from Table 6); and e=error reduction gain for projects (from Table 4).

Conservatively assuming no change in production volume over this period (i.e., $CF_k = C_P$), the resulting cash flow of the IT adoption for such a company is shown in Table 9. Note that costs reduce at the end of the period because the total number of workstations is reduced. The eventual annual savings are estimated at 4.3–4.7% of total costs.

Conclusions

Enumeration and evaluation of all of the potential benefits of the adoption of parametric 3D modeling for building design, detailing and construction is difficult, because the impact on business processes is expected to be as significant as the improvements in engineering efficiency. The availability of a parametric model enables both direct process improvements (e.g., automated detailing) and indirect improvements that involve fundamental changes to the business process (e.g., high-accuracy estimating before contract closure, automated production, etc.). Productivity gains within activities that are automated directly can be estimated; benefits across a supply chain are more difficult to assess. It is difficult to predict the indirect costs of any construction IT innovation (e.g., loss of productivity during transition). The rate of integration of new technology is also difficult to predict, and the overall time period for assessment of the investment is unclear.

For these reasons, this study has focused on short-term benefits. At the engineering stage, these include direct productivity gains and indirect productivity gains based on resolution of problems inherent in the existing CAD based design process. Similarly, in the production stage, productivity improvements resulting from automated information transfer and limited production automation are considered, together with reduction in design-related errors. Potential benefits resulting from more fundamental process changes (such as reordering of the design process, or adoption of lean production procedures), which are made possible by integrated information sharing with materials, production and erection management information systems, etc., were not considered.

Nevertheless, a number of conclusions can be drawn. The primary short-term benefit of 3D parametric modeling is a reduction in the cost of drafting, estimated in the region of 80–84%. Engineering costs are reduced in the range of 35–51%. As expected, the proportional impact is greater for smaller and more complex projects, which are design intensive, than for large projects. The reduction in overall project costs ranges from 2.5 to 6.7%. Elimination of design related errors contributes approximately 0.5% of overall project cost. Thus a company executing a diverse range of projects can expect savings in the region of 5% of total erected cost.

The direct costs are negligible in proportion to the predicted savings, as can be seen from Table 9. This is due to the fact that the major proportion of engineering costs in any company is in salaries and not in hardware or software. The relatively large jump in seat price from traditional CAD and engineering software to parametric 3D modeling software (from annual costs of $3,400–$5,800 to the range of $15,400–$20,100 in annual costs) does not change this situation, and should not be a factor in the decision to adopt or reject the new technology.

The risk associated with the inability to estimate indirect costs can be managed by maintaining existing engineering systems during initial adoption of the new systems. This is reflected in the model by assuming a 1 year lag between introduction of new and decommissioning of old systems.

The first contribution of this work is in qualitative enumeration of the expected benefits and costs of the adoption of 3D modeling in precast concrete construction. In the short term, the model developed can enable any company to gain an understanding of the benefits of 3D parametric modeling for its operations. As such, its significance may be in enabling precast companies to take the steps necessary with increased confidence. The long-term contribution is expected to be in that it provides bench marks of engineering and drafting productivity and of error levels, against which the actual impact on the industry can be measured.

Monitoring the results in precast companies as the software is incorporated in their operations, and evaluating them against the bench marks, should provide results of value with regard to measurement of IT adoption in other sectors of the construction industry. The impact on the business, engineering, production and erection processes are likely to be of particular interest.

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