CASE STUDIES OF BIM ADOPTION FOR PRECAST CONCRETE DESIGN BY MID-SIZED STRUCTURAL ENGINEERING FIRMS

SUBMITTED: September 2007
REVISED: January 2008
PUBLISHED: June 2008
EDITORS: T. Olofsson, G. Lee, C. Eastman

Israel Kaner, Graduate student
Faculty of Civil and Environmental Engineering, Technion, Israel Institute of Technology, Israel
email: israelkaner@gmail.com

Rafael Sacks, Assoc. Prof.
Faculty of Civil and Environmental Engineering, Technion, Israel Institute of Technology, Israel
email: cvsacks@technion.ac.il

Wayne Kassian, P. Eng
Kassian Dyck & Associates, Consulting Engineers, Canada
email: wkassian@kdassociates.com

Tomas Quitt, P.E.C.E.
Star Engineers, Israel
email: office@stareng.co.il

SUMMARY*: BIM is a complex technology. Although its potential benefits are clear, its integration in structural engineering firms requires leadership and persistence as well as careful planning. Sophisticated three-dimensional parametric modelling software for precast concrete structures has been commercially available since 2005. Early adopters have gained sufficient experience with precast concrete buildings to allow analysis and comparison of their adoption strategies. Four detailed case-studies, observed at two mid-sized engineering firms in the last two years, have been recorded and analysed. They shed light on the obstacles that had to be overcome, the achievements and disappointments, and the changes in workflow and personnel that the firms have experienced. The results reveal clear improvement in engineering design quality, in terms of error-free drawings, and steadily increasing improvement in labour productivity. The firms' clients have also begun to exploit the rich information available with BIM, but not to the extent expected. Progress in adopting BIM is slow but certain. The conclusions may help the managers of structural engineering firms who are planning their own adoption process to avoid some of the pitfalls of replacing 2D CAD practices with BIM.*

KEYWORDS*: Building information modelling (BIM), 3D parametric modelling, Productivity, Precast concrete, Structural engineering.*

1. INTRODUCTION

Extensive research and development in academia and industry has led to the emergence of powerful and practical building information modelling tools for structural analysis, design and detailing. They are gradually being adopted in structural engineering design firms. However, software tools alone are insufficient for successful BIM adoption. Deep changes in terms of work practices, human resources, skills, relationships with clients and contractual arrangements are required for success. Indeed, best results can only be achieved when change extends beyond the borders of any individual organization adopting the technology (Eastman et al. 2008).

The experiences of early adopters of BIM tools in structural engineering practice provide the opportunity to research what practices work, how adoption can be pursued, and what the impacts are. Detailed information was collected from two medium-sized structural engineering firms, one each in Canada and Israel, describing their BIM adoption process over a two year period. Both perform a significant portion of their work for precast concrete fabricators.

Four case study buildings (two from each firm) were recorded and studied. Each firm provided one architecturally unique project, where BIM enabled design and detail of precast elements with complex geometries in short times, and one fairly standard project. The data obtained enabled analysis of productivity gains and of the learning curves experienced. The results were compared with other cases reported in the research literature (Sacks and Barak 2007). The lessons learned by each firm are compared and discussed against the backdrop of these milestone projects. The decision-making process before starting the implementations, the needs of the industry and of the companies, management considerations, the problems encountered, how adoption was planned and executed, changes in personnel and the re-education of engineers trained in a '2D world', the benefits of formal vs. informal in-house training, the barriers to effective model exchange, the relationships with clients and precast fabrication plants, and the next steps for implementation of viewers in support of building erection, are all discussed.

2. BACKGROUND

2.1 Building Information Modelling

Building Information Modelling (BIM) can be defined as “a computable representation of the physical and functional characteristics of a facility and its related project/lifecycle information using open industry standards to inform decision making for realizing better value” (NBIMS 2007). BIM enables data to be organized and used/reused during the facility lifecycle to document transactions, identify data requirements specific to disciplines and inform business decisions to improve value.

Earlier research (Sacks and Barak 2007) revealed that the main issues that concern structural engineering firms when considering adoption of BIM are:

- Improvements in engineering design productivity and production detailing productivity, which should lead to direct cost reduction within engineering firms.
- Increased value of the engineering service provided to building owners and construction contractors, which lead to cost reductions for those participants but have only indirect impact on the profitability of engineering firms. Examples are error reduction, shortened lead times and enhanced information flows to support logistics.

The main obstacles that have been identified are:

- The lack of adequate interoperability between BIM software tools (Eastman 1999; Gallaher et al. 2004).
- The need to develop new workflows and standards that would be suited to, and better exploit, BIM tools (NBIMS 2007).
- A shortage of personnel skilled both in BIM and in structural engineering.
- The relatively high initial investment needed for training, setup of templates and custom component libraries and for software purchase (Sacks et al. 2007).

2.2 Precast concrete construction

Precast concrete is a construction method in which concrete is cast in reusable moulds and cured in a controlled environment, then transported to the construction site and lifted and fixed in the structure. The two main types of use are for structural elements (such as beams, columns and slabs, which may or may not be prestressed) and architectural facades. In the US the total annual turnover of the precast industry reported in 2002 was about 7.97 billion dollars (Census 2005). Structural precast accounts for approximately 42% of the total.

There are five main actors that participate in the precast construction process: owner, architect, structural engineer, precast fabricator and erection crews. In most countries the precast fabricator is responsible for detailed engineering design of its product. Although some maintain engineering staff in house, most of the fabricators procure the service from independent engineering design firms. Both of the firms discussed in this paper functioned in this way.

BIM research and development for the architecture, engineering and construction industry in general focuses on provision of parametric 3D modelling software and on achieving interoperability between various applications. In the specific context of the precast industry the main efforts have been those of the Precast Concrete Software Consortium (a consortium formed in 2001 in North America to ensure that BIM software would be custom-tailored for the precast concrete industry) (Eastman et al. 2003; PCSC 2003) and the Industry Alliance for Interoperability (IAI 2007). As a result of the PCSC research and the efforts of software developers, two commercial BIM applications have been available for precast concrete engineering since the end of 2005. All of the case studies researched here were executed using one of these, *Tekla Structures* (versions 12 and 13).

A precast concrete extension to the IAI’s Industry Foundation Class (IFC) schema, called PCC-IFC, was developed by 2003 (Karstila et al. 2002), but practical interoperability for precast remains an elusive goal (Kiviniemi 2006). A range of technical difficulties encountered in information exchanges between architects and precast engineers for the narrow domain of architectural façade panels has been highlighted in recent research (NIBS 2007).

The directly measurable benefits of BIM for the precast concrete industry are expected to be significantly reduced engineering costs and costs of rework due to errors (Sacks et al. 2005a). Additional, and potentially more significant, benefits are enhanced cost estimating accuracy, drastic reduction in engineering lead time, improved customer service and support for automation in production. Naturally, since BIM represents a paradigm shift from the use of 2D computer aided drafting, the transition is likely to involve personnel issues. It is also likely to present the opportunity for rethinking and possibly reengineering existing workflows and information flows in both engineering and in production. Companies should therefore carefully prepare strategies and working plans for the adoption phase and should implement monitoring procedures to enable benchmarking process. In economic terms, the net direct benefit to precast fabricators should be in the range of 2.3-4.2 percent of the total project cost (Sacks et al. 2005a).

3. CASE STUDY COMPANIES

The two companies studied are medium sized structural engineering firms. However, they are located in quite different parts of the world and had different introductions to BIM. The first was a pioneer who participated in defining the desired functionality of precast BIM software; the second was an early adopter, but only became familiar with BIM once commercial software was available. Interestingly, their motivations for adopting BIM were strikingly similar.

Kassian Dyck & Associates (‘KD&A’) is a privately owned mid-sized structural engineering firm in Calgary, Canada. The firm provides structural engineering design and drawing services for steel, concrete, precast, masonry and wood structures. Assignments range from multi-family residential projects to large commercial and institutional buildings. The industrial group has completed many projects such as conveyor structures, storage tanks, oil and gas drilling equipment, an offshore service platform, and steel support towers. The firm has extensive experience in precast concrete including parking garages, precast buildings, architectural cladding, stadiums and bridges. Approximately 50% of the firm’s workload has been design and detailing of precast concrete structures for manufacturers across North America.

Since its inception in 1994, the firm has completed over 2,000 projects in North America. In addition, its staff has participated in several international projects (in South America, Taiwan, China, Qatar, Kazakhstan and the North Sea).

Star Engineers Ltd. (‘Star’) is a consulting structural engineering firm founded in 1980. It is a privately owned, with a staff that numbered 22 engineers and drafters at the time of this study, with a labour capacity of some 65,000 hours per annum. The firm offers a wide range of services in the field structural design and offers construction expertise for industrial plants, public buildings, university campus buildings, shopping centres, residential neighbourhoods, libraries etc. It also offers a specialized service in precast concrete design; precast projects represent approximately 35% of the firm’s annual turnover. The firm makes extensive use of computerized analysis and design tools, as well as computer-aided drafting.

3.1 Motivations for implementing BIM

As the engineer of record on numerous building projects, KD&A’s partners observed that beginning in the late 1990’s, steel fabricators were increasingly submitting steel shop drawings created with parametric 3D steel detailing software. At the time, the precast industry did not have this capability. The firm realized that there would be benefits in preparing precast shop drawings using the same concept: the idea of “pre-building” a precast project in the virtual world of BIM software, and ensuring all geometry, details, and connections within the model are correctly placed and coordinated would be extremely useful to reduce the likelihood of errors. KD&A was a founder member of the PCSC. The firm has successfully used the resulting BIM tools since their delivery as commercial software in 2005.

During fabrication or erection of precast elements, geometry or connection errors on drawings can be costly to repair, so traditionally much time is spent on checking and vetting drawings. Technologists preparing traditional precast CAD drawings must use the 2D drawings and visualize the structure in 3D, and coordinate between numerous drawings to ensure nothing is overlooked. KD&A realized that as a first step, BIM could be used to review potential conflicts or project complications within the model, so they could be easily discovered and resolved prior to issuing drawings for construction. The use of the BIM software also inherently reduced the possibility of misaligned connections, incorrect architectural features, and geometry conflicts, so that shop drawings could be created without the need for detailed checking or cross coordination between drawings.

As a consultant, their long-term goal was to use BIM technology to enhance productivity and quality in producing designs and drawings. This is important because labour is their major resource; drawing and checking presently consume some 83% of the labour input in typical projects (traditionally, precast CAD projects for the firm range in magnitude from 1,000 to 8,000 total labour hours. The breakdown of hours is typically: general and project management 7%; erection layouts 25%; engineering 10%; shop drawings 38%; and checking 20%).

Reducing the likelihood and frequency of drawing errors was a short-term goal. Management realized that even if there was no immediate reduction in man-hours by moving to BIM from CAD drafting, the benefits of reducing design and drawing errors was a key advantage.

In addition, the firm realized the benefits of BIM in providing a database of information that is useful for owner and contractors. Since the firm utilizes computer design and analysis software, they realized the future benefit of having BIM software that could harmonize with analysis software and streamline the engineering process.

Star's objectives in adopting BIM were identical to those of KD&A in terms of productivity and error reduction, but there were also two important differences. Although Star did not cite use of the project information database by owners as a potential benefit, they identified a different but very important tactical benefit – the ability to absorb design changes initiated by owners or contractors. During several years preceding the adoption of BIM, Star engineers had provided precast design and engineering services for several major precast fabricators under outsourcing agreements. Problems related to design and drafting errors that led to problems of mismatched pieces and connections in the field, low productivity in preparing shop drawings (especially where design changes were frequent), and long cycle times for design reviews led the firm's principle engineers to consider BIM as a means to improve their precast design service. Their perception of the potential was heightened when their firm participated in a BIM productivity study conducted at the Technion – Israel Institute of Technology by providing a complex building for ghosting . The firm established three main objectives:

- To increase their capability *to absorb design changes* with a minimum of rework in preparing and reconciling different drawings;
- To harness the capabilities of 3D visualization of the project in order to check for and *avoid design errors*. This was particularly necessary for viewing complex and congested arrangements of embeds, reinforcing and prestressed strands;
- To *improve productivity*, by producing schedules and shop drawings for precast structures in as automated a fashion as could be achieved.
- To *visualize* the structure, specifically to show the owner the spatial precast elements in three dimensions.

4. CASE STUDY PROJECTS

To illustrate the progress achieved by these firms along the learning curve of BIM adoption, two case study projects are presented for each, in chronological order. Each company began with a project in which it was responsible for only a part of the structure, and then progressed to a total precast structure. The first two projects were designed by KD&A: the Blackfoot Museum project required design of precast façade panels with complex piece geometries, and the Eagle Ridge project is a large scale residential apartment project with multiple total precast structure buildings. The second two projects were designed by STAR: the Modi'in commercial centre involved design of precast concrete beams with complex curved geometry that carried hollow-core slabs in an otherwise cast-in-place concrete parking structure, and the Shelter project was a total precast single story building.

4.1 Blackfoot Crossing (KD&A)

Blackfoot Crossing Historical Park in Alberta Canada is a cultural and educational museum/tourist attraction of the native Blackfoot people. The architecture of the heritage museum building was complex as the entire structure was designed and detailed to represent the traditional Blackfoot culture, including themes of eagle feathers, buffalo, tepees, and other Blackfoot motifs. During construction, a decision was made to change the site laid granite cladding on the west side of the structure to architectural precast concrete panels. The concrete walls and steel framing were already in place.

The geometry was complex. The building's walls were stepped and curved both horizontally and vertically, as can be seen in Fig. 2. The new architectural facade was to be cast as numerous flat panels, but the pieces had to follow the existing curved structure. Precast pieces included wall panels notched around existing windows, spandrel panels, column covers, and base cladding panels. It was critical that the panels' geometry should be aligned with the openings, doors and windows in the existing cast-in-place concrete and steel walls. All of the pieces had diagonal intersecting reveal patterns. As a result, KD&A elected to make its first exclusive use of BIM for architectural facades on this project, primarily to ensure proper and accurate geometry.

4.1.1 Modelling workflow

A digital survey was undertaken on site, and the existing building geometry and all openings were provided in a 3D CAD file. The CAD file and the architectural CAD floor plans were imported into the BIM software (Fig. 1), and the precast panel geometry was developed to match the 3D survey (Fig. 2). During development of the precast model, it was discovered that additional as-built survey information was required to provide geometry in complex areas, so additional digital survey information was requested and this was provided by the contractor and imported into the model to complete the modelling. All of the erection layout drawings (see example in Fig. 3) and the individual precast panel drawings (see Fig. 4) were created using the BIM software.

As this was the firm's first use of the BIM software for architectural panels, the drawings were exported to CAD for final touch-up and for adding the manufacturer's standard lift hook details. Steel connection hardware drawings were issued as CAD drawings using the precast manufacturer's standard hardware drawings.

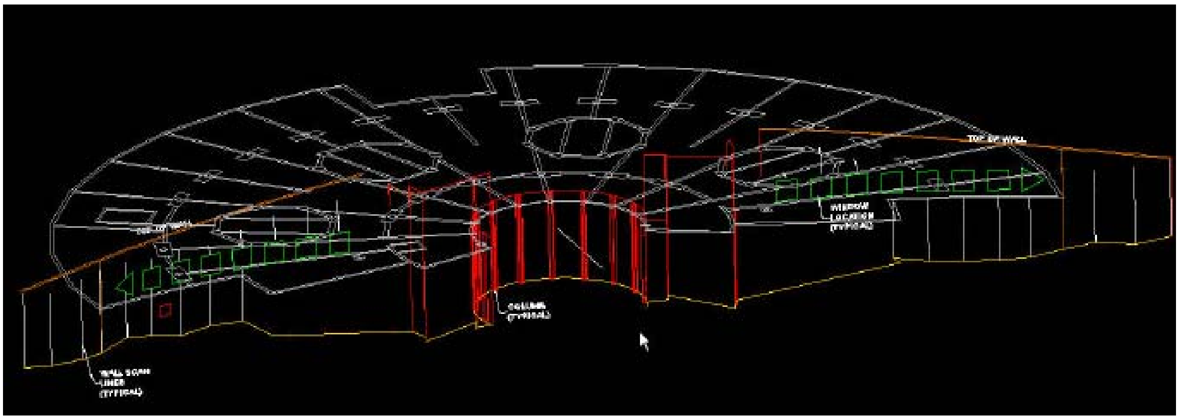


Fig. 1 Blackfoot Crossing - 3D digitial survey model imported into BIM software as reference geometry.

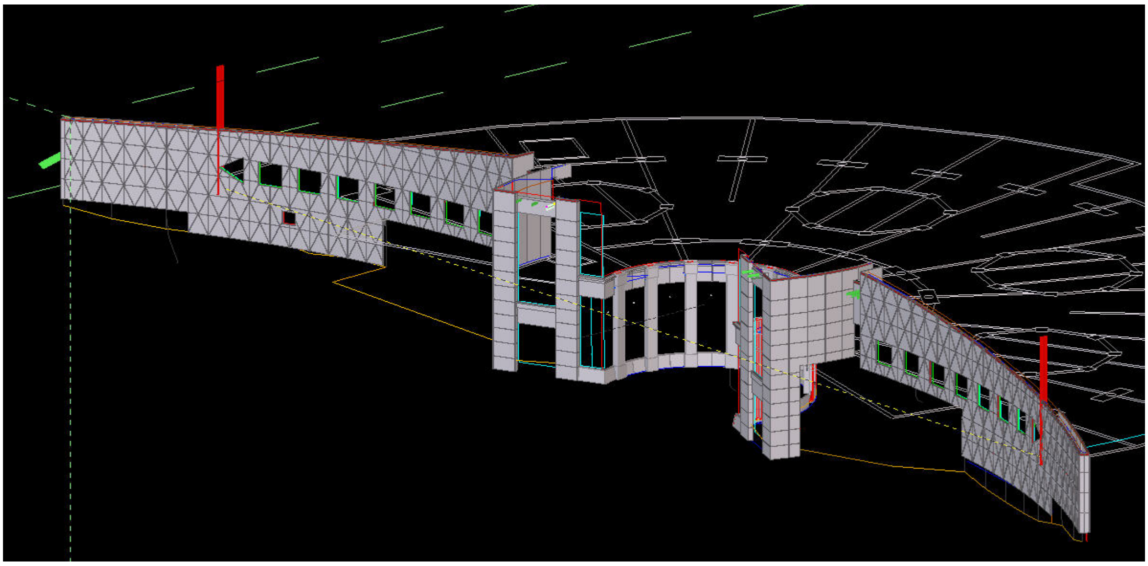


Fig. 2 - Blackfoot Crossing architectural precast model.

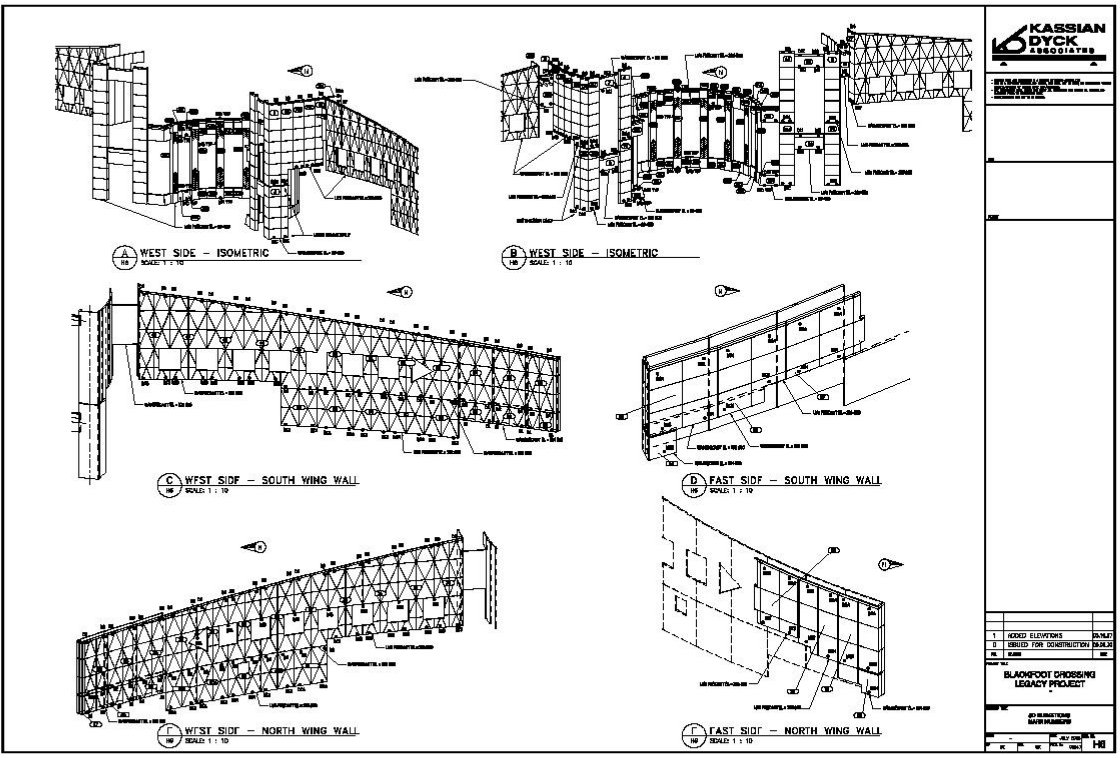


Fig. 3 - Blackfoot Crossing – sample general arrangement drawing.

4.1.2 Modelling difficulties and successes

The entire project was modelled and designed by a single engineer, who had training and was familiar with the software features and capabilities, but had not used it for a real project. The total labour hours recorded (Table 1) were about the same as the estimate of the input that would have been required to complete the project using traditional CAD procedures. However, there were no drawing errors that led to construction problems on site, and all pieces built in accordance with the shop drawings fit the complex curved geometry of the structure. All of the reveals and architectural features lined up between adjacent pieces.

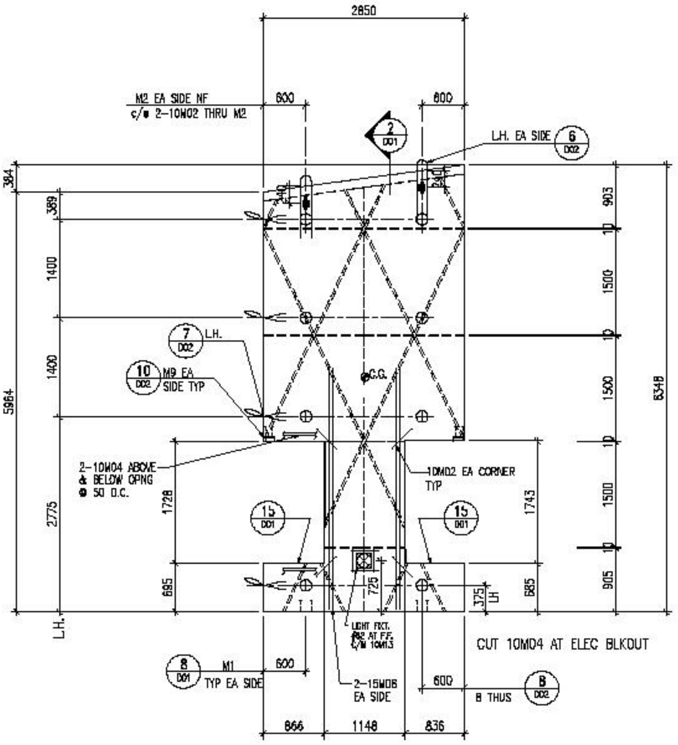


Fig. 4 - Blackfoot Crossing – typical piece fabrication shop drawing.

Fig. 5 – Blackfoot Crossing – completed piece in the precast yard.

Table 1. Project and Productivity Project Data

Project	Blackfoot Crossing (KD&A)	Eagle Ridge (KD&A)	Modi'in (Star)	
			Level -3.50	Level 0.00
Project Type	Architectural Precast Facade	Total Precast Structure	Prestressed Concrete Girders	
Concrete quantity (m^3)	71.6	3,700	82	49
Number of general arrangement drawings	21	25	42	36
Number of shop drawings	63	522	30	33
BIM working hours	489*	2,854**	124	95

Estimated CAD working hours		502*	3,583***	171	181
Productivity (hours/m^3)	BIM	6.8	0.8	1.51	1.94
	CAD	7.0	1.0	2.09	3.68
	Reduction (%)	2.6%	20.3%	27.8%	47.4%
Productivity (hours/drawing)	BIM	7.8	5.5	4.12	3.17
	CAD	8.0	6.9	5.70	6.02
	Reduction (%)	2.6%	20.3%	27.7%	47.3%

* Excluding 145 hours of engineering and project management.

** 498 hrs engineering and project management, 2,854 hrs modelling and drawing production.

*** 1,080 hrs erection layouts, 1,640 hrs shop drawings, 863 hrs checking.

4.2 Eagle Ridge (KD&A)

The Eagle Ridge project is a residential complex consisting of 22 buildings. All of the building structures are 22.2m x 90 m in plan with either 4 or 6 stories. They have cast-in-place footings and underground parking basements. The buildings are total precast structures, consisting of load bearing walls, columns, beams, hollow-core floors and roofs, exterior insulated sandwich panels, precast stairs and landings, precast elevator shafts, and cantilevered balcony slabs. The exterior walls had a brick pattern finish. Fig. 6 shows a general view of the structural model of the first phase, a cluster of four buildings (three 6 storey buildings and one 4 storey building). All of the buildings have the same overall footprint, but differences occur at the basement and ground floors due to different underground parking conditions.

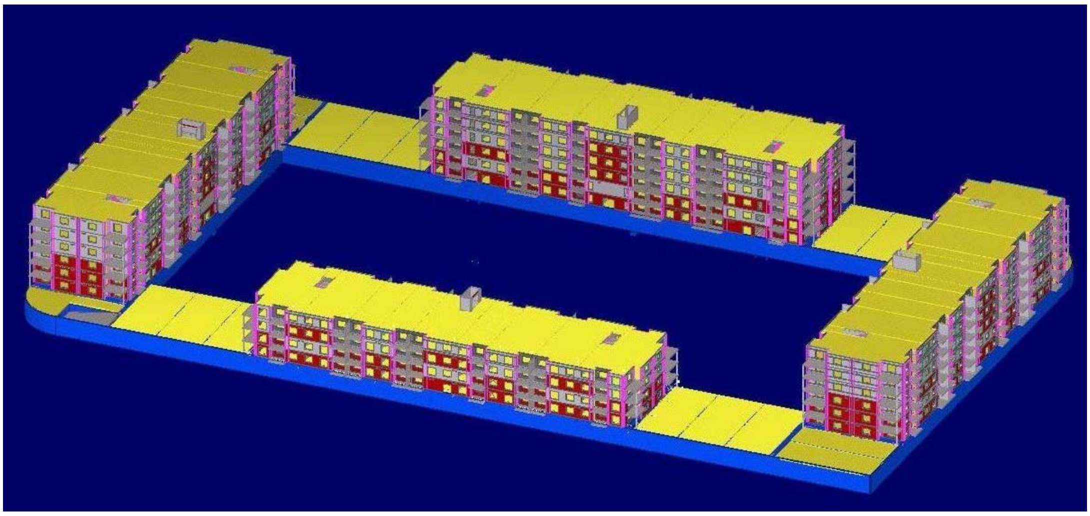


Fig. 6. The model of the first phase of Eagle Ridge project.

The owner's schedule demanded that the precast design and detailing had to be performed in a relatively very short time, in order to get precast pieces into fabrication quickly. When KD&A was approached to undertake the project, it assessed that lack of staff due to prior commitments to other projects would make it impossible to meet the project milestones using traditional CAD drafting. After reviewing the complexity of the project and assessing the anticipated productivity benefits of using the BIM model, a decision was made to accept the project and utilize the BIM approach, based on the assumption that it could be done with less labour and in shorter duration than with CAD. At the time of writing, three buildings have been erected and the fourth is under construction.

4.2.1 Modelling workflow

Modelling and design started simultaneously, before the architect's drawings were completed. In the initial design development stage (first four to six weeks), the model was used extensively in meetings with the precast manufacturer, owner, and architect to review project details and complexities. In preparation for each meeting, snapshots were made of model views, requests for information were annotated directly onto them, and they were distributed to the design team (an example is shown in Fig. 7). As a result of issues discovered during modelling, the architectural drawings were updated and revised to suit decisions made from viewing the BIM model.

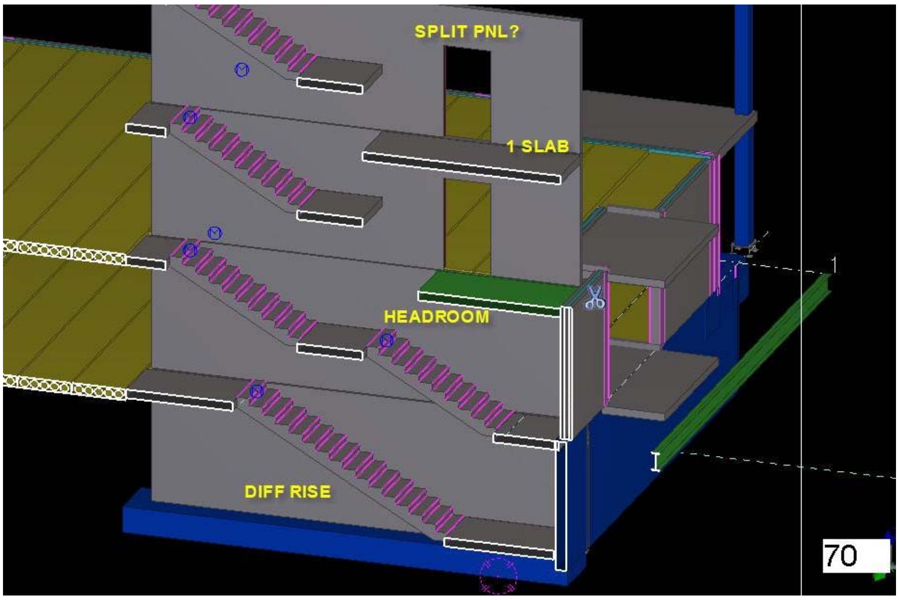
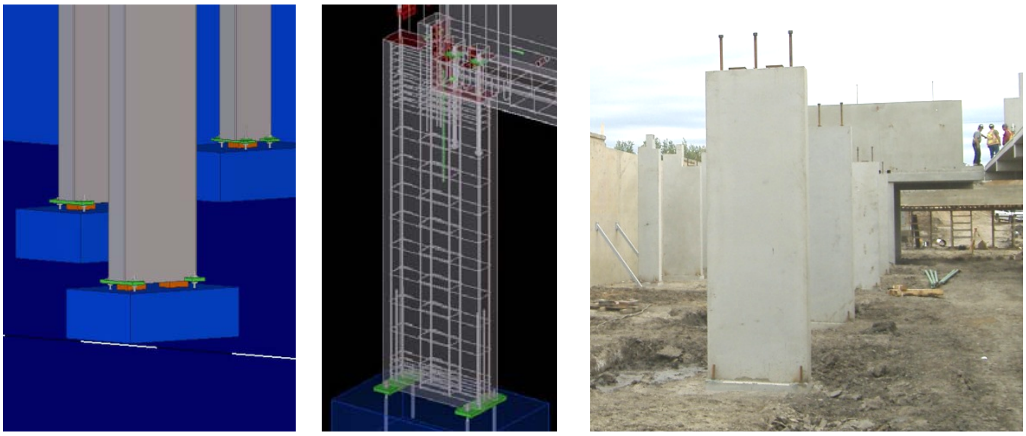


Fig. 7. Eagle Ridge model snapshot marked up with requests for information.

The engineering calculations were undertaken by an intermediate level engineer, with some additional engineering provided by a senior engineer. Design software was used for much of the analysis and design. On a typical CAD precast project of this magnitude, a team of at least three drafting technologists would have been used to create all of the drawings and to check them. The project was modelled and issued on schedule with just two modelling personnel: an engineer who was familiar with BIM and a junior technologist who was new to the software. This was the firm's first experience using BIM for a complete precast structure.

All erection layout drawings and all piece cast unit drawings were created and edited within the BIM software, and issued as PDF files to the precaster. Fig. 8 shows a typical sequence. Once the model was complete, the shop drawings were created automatically from the software. From five minutes to two hours (depending on the complexity of each piece, ranging from simple hollow-core panels to complex beams or wall panels) were needed to edit and complete each drawing. Some texts needed adjusting to avoid overlap, and standard CAD lift hook or other manufacturer standard details were imported into the BIM drawings. For sake of comparison, typical durations for CAD drafting of typical wall panels, columns, or beams are between four to eight hours per drawing. Complete data for the project are provided in Table 1.

Temporary features required for fabrication, transport and erection of the precast pieces, which were not part of the final building, were also modelled and shown on the relevant drawings. These included lifting steel "strongbacks" bolted to the back of some panels with large openings (required to strengthen the panels as they are lifted out of the forms, and to secure and stabilize those particular panels during transport to site) and temporary bracing (needed for stability during erection).



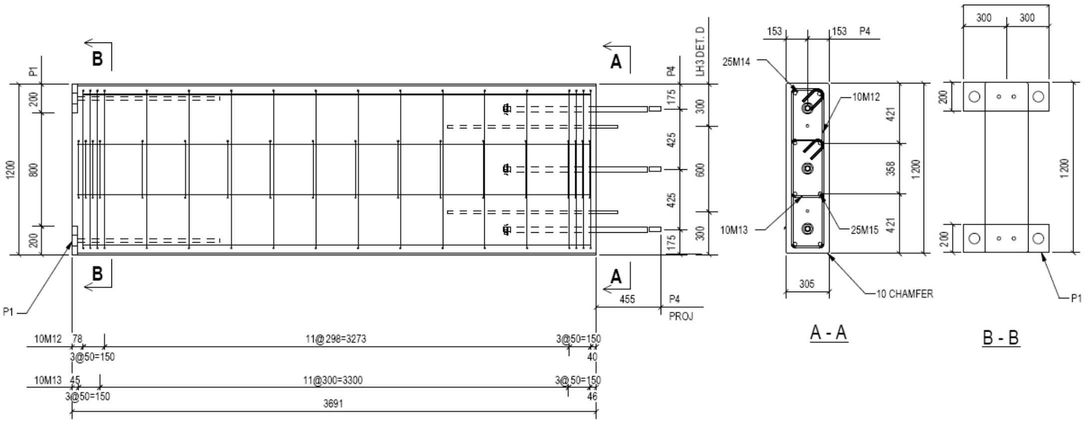


Fig. 8. A typical column from the Eagle Ridge project shown in the model, as detailed in the model and in a shop drawing, and as fabricated and erected.

After the first structure was erected, changes were requested by the architect, the owner, and the precast manufacturer. Changes including revising wall panel reinforcement from rebar to mesh, moving and adjusting the sizes of mechanical blockouts, revising some lift hooks, and minor changes to some connections to make erection simpler for site personnel. All of the changes were made in the model and drawings were updated automatically. Applying the changes and producing all of the drawings for the second building, which was four stories high, required 270 hours. The same work for the third and fourth buildings, both of six stories, required 203 hours and 95 hours respectively.

4.2.2 Modelling difficulties and successes

Technical difficulties were encountered that made it necessary to make ‘manual’ adjustments to the drawings produced automatically, using the available CAD type functions. These included system generation of unnecessary piece numbers (additional mark numbers were generated even when not required) and rebar sketch text callouts overlapping with geometry on the cast-unit drawings (shop drawings). It was also noticed that, in the version of BIM software used, dimensions on these drawings were lost if custom components were revised in the model. As a result, all of the drawings had to be carefully reviewed for presentation.

Cross coordination or checking between drawings has been eliminated with the use of BIM. Drawings are still checked to make sure dimensioning and information is presented correctly, but official checking of all drawings for fit, geometry, alignment is no longer a drafting activity. The model is checked to ensure conformance with the geometry shown on the contract drawings, and the engineer checks the design criteria on the drawings to be issued, but overall “checking” time has been substantially reduced.

Erection layouts were simplified, as only information required for the erection personnel is required on the drawings. This includes geometric layout and connection details. Overall, the amount of dimensioning and information presented on the erection layouts was substantially reduced. Previously, using CAD, a host of details had to be provided on these layout drawings in order to provide enough information for drawing the individual precast pieces, but this information is not relevant to the erectors and is not required using the BIM procedure.

An important result was that throughout erection of the first three buildings, no repairs were required due to errors related to the shop drawings. This was considered a major achievement for the fabricator.

KD&A has gained experience with modelling, and improvements in BIM software are continuing. The difficulties that were encountered in this project with mark numbering, drawing features and other issues have been reduced substantially. The company anticipates that future projects will run more efficiently.

4.3 Modi’in (Star)

In the Modi’in commercial centre project, Star was responsible for detailed design of the precast elements for the parking structure. The precast subcontractor was unable to design and produce the complex precast girders for the project, and so the general contractor solicited bids for the engineering design and fabrication from alternate suppliers. At the time, Star was in the final steps of its initial adoption of Tekla Structures software. The firm therefore felt that its newly acquired BIM capability gave it an advantage over others in design of the complex curved girders, and succeeded in winning the contract. Star`s challenge was to design, detail and prepare shop drawings for 81 precast beams, most of them curved and some of them prestressed, within a very short time frame (2½ weeks). The project was divided into two phases: level -3.50 and level +0.00.

An interesting aspect of this project is that almost all of the beams had unique geometries, as can be seen from the high ratio of shop drawings to precast pieces in Table 1. The primary grids were curved, as can be seen in Fig. 9. Not all beams were at the same levels, which meant that some had to be recessed to support others, as shown in Fig. 10. The unique shape of each beam resulted in the reinforcement layouts for each beam also being unique.

4.3.1 Modelling workflow

At the outset, the project leader and the firm manager calculated estimates of the number of work hours that would have been consumed using the firm's traditional 2D CAD systems. The estimates for each level are listed in Table 1. These estimates showed that it would not have been possible to complete the project within the prescribed time frame using 2D CAD. The firm's perception of the productivity improvement that they achieved in this project is listed in Table 1: an overall productivity gain of 38% was estimated.

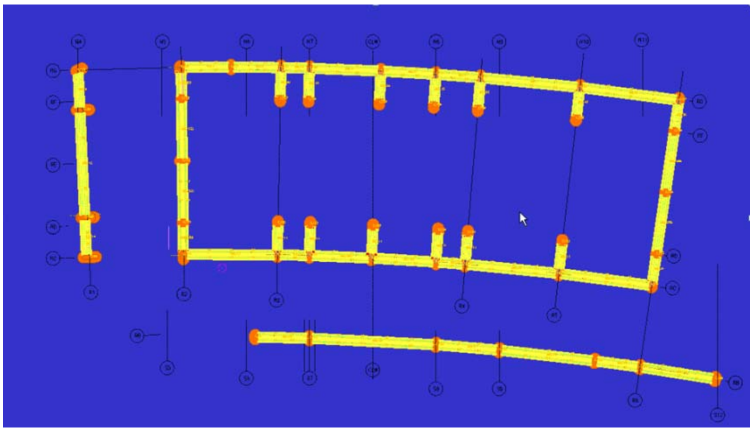


Fig. 9. Plan view of girders at level -3.50 showing curved grids.

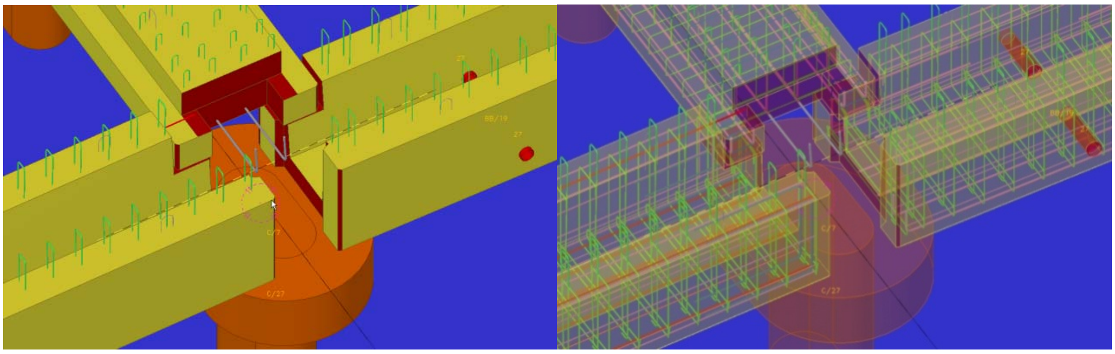


Fig. 10. Modi'in project - prestressed concrete girders. Girders were supported at different levels.

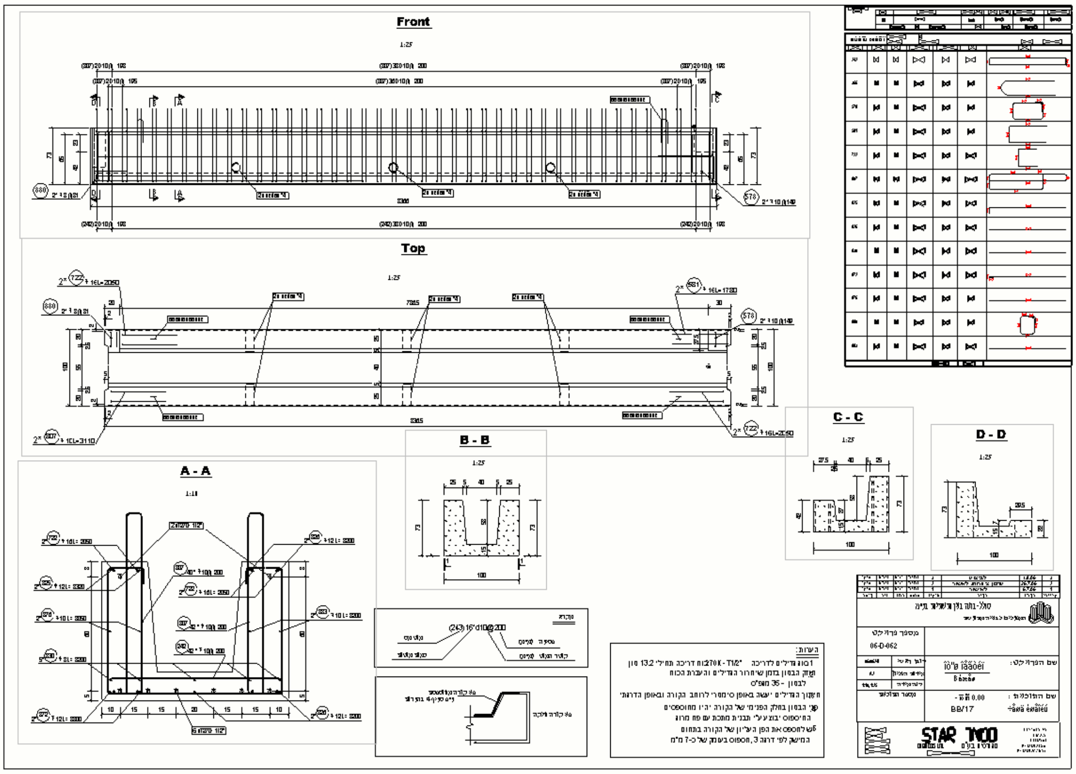
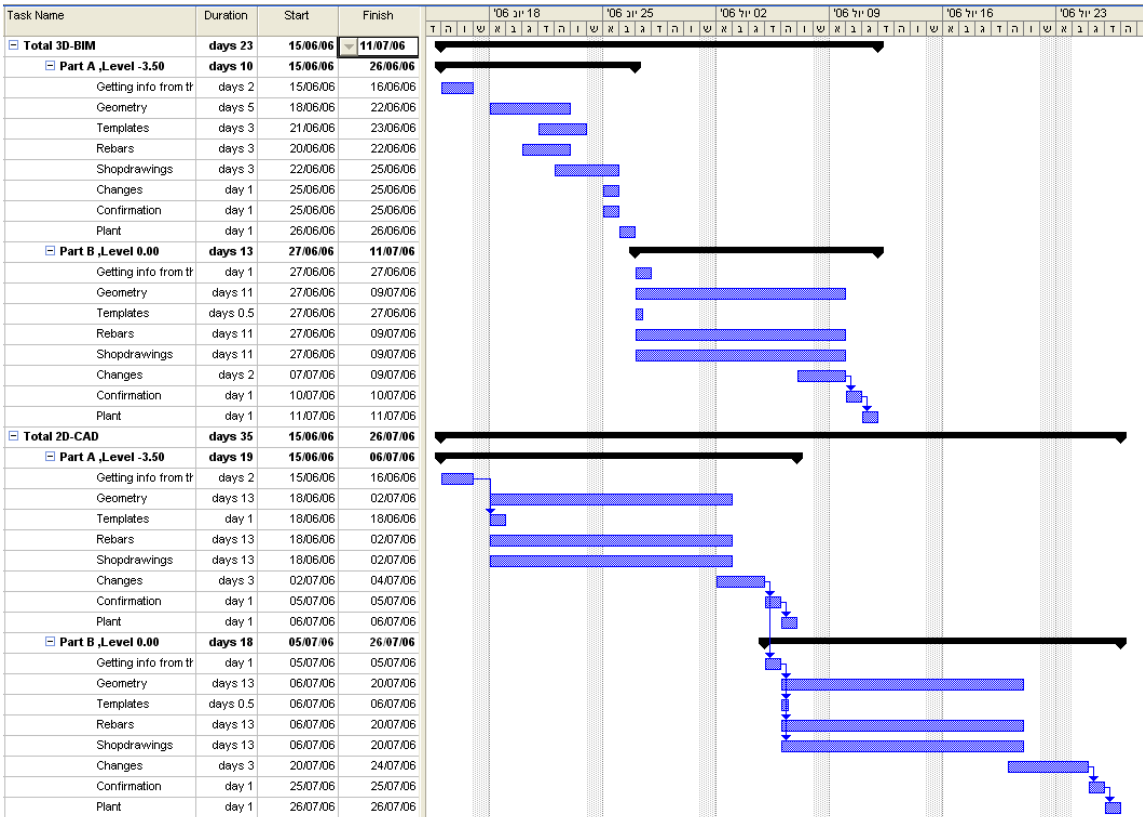


Fig. 11. A typical precast girder shop drawing. Note the detailed rebar schedule with callout shapes at the top right.

4.3.2 Modelling difficulties and successes

One of the first lessons learned on this project was that for design work of this nature, single piece flow is superior to batched work (Hopp and Spearman 1996), which was the norm for the 2D CAD process. Level -3.50 was modelled first, using the whole batch approach for the full set of beams on the level. The work was performed in six main stages: a) structural design including reinforcing sketches for all of the beams, b) modelling of the geometry of all of the beams, b) creation of reinforcement custom components and special details (lifting hooks, holes for pipes), c) application of reinforcing and other details and generation of 2D drawings, d) review by the engineer, e) application of the engineer's corrections to the model and regeneration of the drawings. However, the Star engineers and modeller realized that the result was a great deal of rework that became necessary because the engineer only became aware of the full complexity of the geometry, and its impact on the reinforcement details, once the drawings were produced. They realized that if the geometry was modelled first, and then the design was pursued for each beam one by one through all of the steps of design, detailing, drawing generation and review, then the amount of rework was minimized and indeed almost eliminated, as the modeller and engineer understood the work well for all subsequent beams. The impact of this change to a leaner approach was measurable. As can be seen from the productivity calculations in Table 1, the productivity improvement estimated for the first level was 28%, while that for the second level was 47%. Naturally, some improvement was to be expected from the general learning curve effect, but the engineer and modeller reported that this specifically was a significant change.

The comparative Gantt chart shown in Fig. 12 reveals not only the difference in design duration between the 3D BIM (the upper part of the chart) and the 2D CAD processes (the lower part of the chart), but also the change in strategy that was implemented between the two levels in the BIM process.



Task Name	Duration	Start	Finish
⊟ **Total 3D-BIM**	**days 23**	**15/06/06**	**11/07/06**
⊟ **Part A ,Level -3.50**	**days 10**	**15/06/06**	**26/06/06**
Getting info from th	days 2	15/06/06	16/06/06
Geometry	days 5	18/06/06	22/06/06
Templates	days 3	21/06/06	23/06/06
Rebars	days 3	20/06/06	22/06/06
Shopdrawings	days 3	22/06/06	25/06/06
Changes	day 1	25/06/06	25/06/06
Confirmation	day 1	25/06/06	25/06/06
Plant	day 1	26/06/06	26/06/06
⊟ **Part B ,Level 0.00**	**days 13**	**27/06/06**	**11/07/06**
Getting info from th	day 1	27/06/06	27/06/06
Geometry	days 11	27/06/06	09/07/06
Templates	days 0.5	27/06/06	27/06/06
Rebars	days 11	27/06/06	09/07/06
Shopdrawings	days 11	27/06/06	09/07/06
Changes	days 2	07/07/06	09/07/06
Confirmation	day 1	10/07/06	10/07/06
Plant	day 1	11/07/06	11/07/06
⊟ **Total 2D-CAD**	**days 35**	**15/06/06**	**26/07/06**
⊟ **Part A ,Level -3.50**	**days 19**	**15/06/06**	**06/07/06**
Getting info from th	days 2	15/06/06	16/06/06
Geometry	days 13	18/06/06	02/07/06
Templates	day 1	18/06/06	18/06/06
Rebars	days 13	18/06/06	02/07/06
Shopdrawings	days 13	18/06/06	02/07/06
Changes	days 3	02/07/06	04/07/06
Confirmation	day 1	05/07/06	05/07/06
Plant	day 1	06/07/06	06/07/06
⊟ **Part B ,Level 0.00**	**days 18**	**05/07/06**	**26/07/06**
Getting info from th	day 1	05/07/06	05/07/06
Geometry	days 13	06/07/06	20/07/06
Templates	days 0.5	06/07/06	06/07/06
Rebars	days 13	06/07/06	20/07/06
Shopdrawings	days 13	06/07/06	20/07/06
Changes	days 3	20/07/06	24/07/06
Confirmation	day 1	25/07/06	25/07/06
Plant	day 1	26/07/06	26/07/06

Fig. 12. Gantt chart showing comparative durations of the BIM (upper) and estimated CAD processes. Note the change in the BIM process from batch work for the first level to single piece flow for the second level.

4.4 Precast Shelter (Star)

This project, a public air-raid shelter in southern Israel, was the second designed by Star using BIM. The case study is unique because it underlines the importance of modelling skill when using BIM software; it clearly shows the impact of formal advanced training on BIM operators' productivity. It transpired that the engineer modelling the project completed the first phase (floor and vertical pieces) before receiving advanced training, and the second phase (horizontal elements) after the training.

The structure has overall dimensions of 50m x 35m, with a footprint area of approximately 1,500 m^2 and an overall height of 8m. It has an unusual geometric shape, as can be seen in Fig. 13. The building's foundations were cast-in-place and the walls and roof were made from panels with a single uniform U shape cross section (Fig. 14).

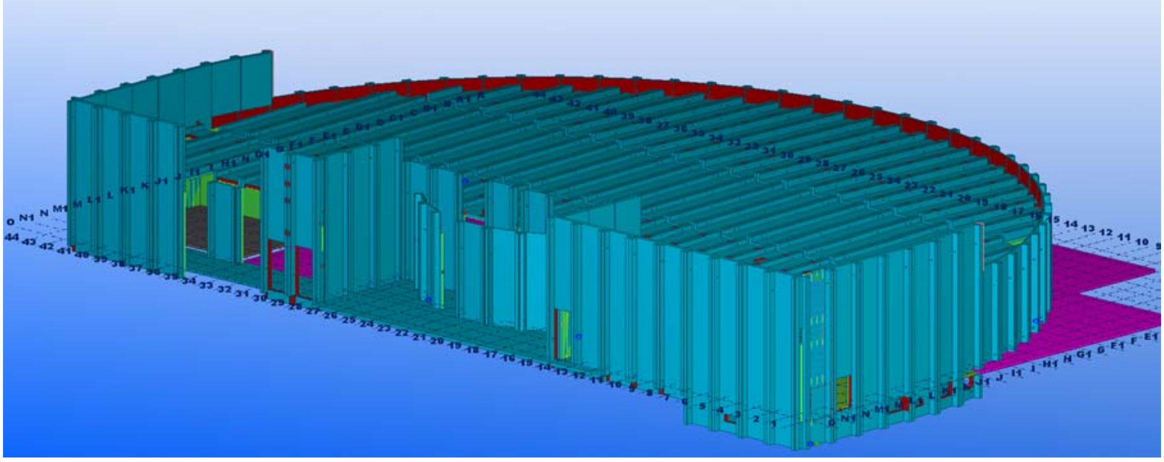


Fig. 13. Isometric view of the shaded Shelter model

4.4.1 Modelling workflow

The project was begun by an architect, who prepared CAD layout drawings for the vertical pieces. Star's project engineer understood that, due to the semi-circular shape and varying heights, almost every piece would be unique and require its own shop drawing (Fig. 14 show a typical piece). Thus BIM would have a clear advantage for preparing shop drawings. However, he decided that for this single story building, modelling of the precast structure should only begin once the iterations of schematic layout design were substantially complete. He reasoned that with only one operator available, and an architect, an owner and an MEP consultant with no BIM experience and no access to the model, collaboration over multiple iterations of the layout using Star's model would create a wasteful workflow.

Modelling began once the layout was substantially fixed. The detailed design was done in two stages, in accordance with the production and erection sequence: the walls were designed in the first phase (vertical panels) and the roof (horizontal panels) in the second phase. During the first phase, the modeller encountered many modelling issues that arose from ignorance of the right modelling practices, i.e. what types of software objects should be used for which building objects, and what aggregation relationships were appropriate. As a result, when shop drawings were generated after modelling was substantially complete, the automated piece numbering features did not function as expected, part lists were not as required, and other problems became apparent. With much frustration the drawings were completed and the precast panels of the first phase went into production. The overall productivity, measured in hours per shop drawing, was over 16 hours per drawing, as can be seen in the first phase column reported in Table 2

During the natural break in the design work between project phases, the operator was given formal advanced training in modelling and drawing production. With the appropriate modelling techniques (correct use of custom components, appropriate application of parameters to parts and components, etc.), modelling of the second phase went smoothly and almost all of the shop drawing content could be produced automatically. The overall productivity for this phase reached 2.5 hours per drawing (Phase 2 column in Table 2).

4.4.2 Modelling difficulties and successes

The change in modelling practice as a result of the formal training resulted in a jump in productivity of more than 600%. This made it clear to management that despite their earlier reticence concerning training (due in part to the expected language barrier, their assumption that self-study would suffice for a highly skilled CAD operator, and the difficulty of releasing a productive employee from everyday work), the return on investment in professional training was very high. BIM software is more complex than CAD; to exploit it correctly requires formal professional training.

Drawing templates had been improved since the company's first project, and the precast plant reported that the drawings were clear and contained all of the data needed for fabrication, but no more than was needed. The erection team at the site reported that the pieces and drawings were entirely error-free, a situation that they had never experienced before.

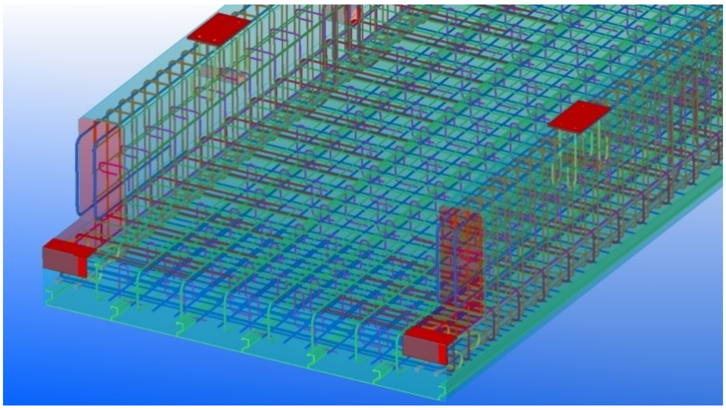


Fig. 14. A typical U profile piece, showing corrugated metal sheet base, embed plates, reinforcement and lifting hooks.

Table 2. Shelter project data

		Phase 1 (vertical panels)	Phase 2 (horizontal panels)
Total unique panels	un	78	98
Unique panels –shop drawings	un	41	58
Total panels	m^3	355.6	422.4
Total unique panels	m^3	212.0	233.2
Engineer working hours	hours	297	
2D Cast in place working hours	hours	605	
3D precast modeller	hours	674	142
3D-working hours/ m3 concrete	hours/m^3	1.89	0.34
3D-working hours/ m3 unique concrete	hours/m^3	3.18	0.61
3D hours/shop drawing	hours/ shop drawing	16.4	2.44

5. ADOPTION PROCESS

5.1 KD&A

KD&A's decision to adopt BIM grew out of the partners' observation of the use of 3D modelling in the structural steel industry and their participation in the PCSC. The firm's adoption strategy was predicated on their assumption that the long-term commercial benefits were clear, and therefore that being an early adopter would give the firm a competitive advantage. The result was a strong leadership and a commitment to overcome any obstacles through persistence. This attitude is reflected in the firm's approach to training and the willingness to work around the problems presented by early bugs in the BIM software.

The company decided to stage its adoption, in terms of gaining skills, in four main stages: 1) basic 3D modelling, 2) automation of drawing production, 3) preparation and use of sophisticated parametric components, and finally 4) use of integrated structural analysis functions.

From the start, junior drafting technicians were selected for training rather than experienced drafters or engineers, on the assumption that they would have less difficulty in "un-learning" work patterns suited to 2D CAD. This was based on the understanding that the workflows best-suited to BIM would be different to those that had evolved for CAD. The training was aligned with this overall strategy. A careful analysis was made of what functionality was essential for basic modelling and drawing production, and only those aspects were taught. Training for, preparation and use of sophisticated parametric components was postponed until numerous projects had been completed; use of structural analysis functions has not yet commenced and will only be attempted once the firm has achieved efficiency with BIM modelling. All of the training was undertaken in-house by the principal engineer, who had the benefit of extensive prior experience with the software through his participation in the PCSC activities.

The conviction of the firm's leadership in the viability of BIM led them to apply it to actual projects from the start, without ghosting projects that were already underway using CAD. This 'sink or swim' approach forced them to develop skills and working methods rapidly. The partners' decision to proceed in this way was bolstered by the support they received from a major client (a large precast fabricator), who shared their vision and understood the benefits that KD&A's adoption of BIM would bring to their own business (the first benefit they wanted to achieve was short lead times for the provision of shop drawings, which could not be achieved with CAD). The client's management were willing to accept that there would be teething problems and to guarantee a flow of work while they were ironed out. Indeed, a strongly symbiotic relationship has resulted, where the client is now eager to provide KD&A with work in order to prevent the firm offering its new expertise to the client's competitors.

The main problems encountered in the adoption process were software bugs and the use of incorrect modelling procedures. Both reduced productivity and resulted in much rework. The lack of formal training and effective online support meant that the firm honed its modelling methods through trial and error before an optimal approach was formed. Difficulties with logical numbering of precast pieces for production and producing bills of material were common because the software's ability to identify like pieces for production is sensitive to the way in which they are modelled. In retrospect, focussed advanced formal training may have alleviated some of these problems.

The shortage of skilled operators was identified as a threat, and so trainees were initially asked to commit in writing to remain with the company for a fixed period of time before being trained in BIM. Indeed, some of their operators have been hired away since gaining BIM skills.

During the first stage, during which emphasis was placed on modelling alone, custom components were only created ad hoc as they were needed for each project. To date there has been little re-use of components because each project has been sufficiently different that it was not worthwhile to build extensive libraries.

Although it has the capacity to apply multiple users to any project, the firm has not found it necessary to exploit this capability of the software. Using BIM, a single modeller assigned per project can produce shop drawings within short lead times and at a sufficient rate. With CAD the need often arose to employ a number of drafters on each project at the shop drawing stage.

5.2 Star

Star was the first engineering design firm in Israel to adopt BIM for precast concrete. As such, the firm decided to begin with caution. The adoption process included a six-month period of 'on-the-job' training for one engineer, after which a previously designed project was 'ghosted' for two months. A further two months were then required for adapting drawing and report templates to suit local needs.

The trainee was a civil engineer highly skilled in 2D CAD software and precast design. He was trained by the first author for one full day each week throughout the six month period, while attending to other projects for the majority of this time. Due to the language barrier and the firm's reluctance to invest in what was perceived to be a risky outlay, he was not sent to Europe for formal training. In retrospect, the lack of continuity and of daily practice made the process highly inefficient.

Once a reasonable level of proficiency was attained, the engineer began modelling a precast project that he had recently completed using CAD. The purpose of the ghosting was to give the modeller and the design team experience and to discover any obstacles that might arise in a real project. The modeller experimented with modelling precast objects in a variety of ways, using both standard objects (such as beams, panels and columns) and with parametric custom components. At this stage he encountered several difficulties, most of which related to the need to change his conceptions of how the work should be done from a 2D CAD approach to one suited to BIM. Two significant aspects of preconceived notions that are barriers:

- The sequence of preparing precast drawings in 2D CAD involves paying attention sequentially to general arrangement plans, then cross sections, then piece views and finally rebar bending schedules. Much effort is required to coordinate between the different pieces. In BIM, the approach is holistic, with attention paid to a single model, in three dimensions.

- He found it difficult to relinquish the standard methods of notation and layout for drawings, particularly when the BIM approach offered efficient ways of presenting information on drawings. Fig. 15 shows a typical example of the restrictions that conservative thinking can impose. The left hand image shows the traditional way of calling out rebars on piece drawings. This style is used because the same drawing must be used both for fabricating the rebar and for tying it in place; the detailed call out is needed because no bending schedule is provided. However, the BIM system was able to produce a detailed bending schedule automatically, which means that the rebar callout tag on the section can contain just the rebar mark number, as shown on the right hand side of Fig. 15. It was therefore no longer necessary to provide all the information about each rebar within the tag on the piece drawing. Nevertheless, the engineer invested significant time and effort 'forcing' the system to generate the detailed rebar tag. It was only much later, after site engineers who were consulted confirmed that they in fact preferred the BIM schedule and annotation, that the practice was abandoned.

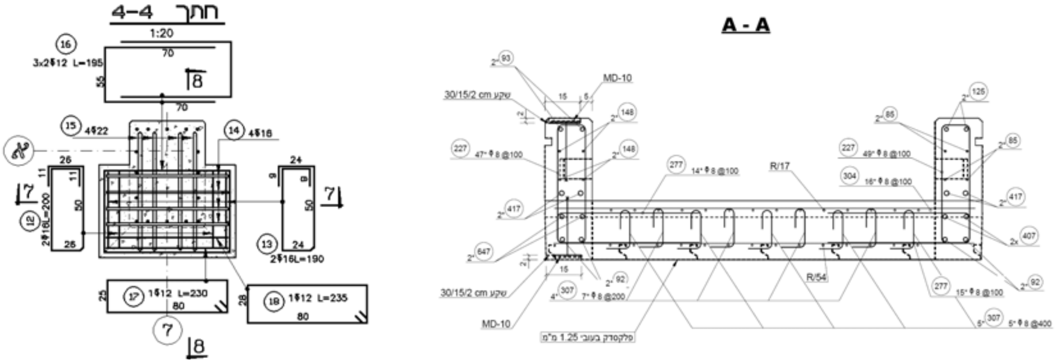


Fig. 15. Rebar annotation in traditional CAD practice (left) and a simpler BIM approach (right).

The ghosting stage was very important: it gave the modeller time to adapt to the new way of thinking, to improve his level of proficiency in operating the software, and not least, it improved the level of confidence within the firm that a project could be executed using BIM. However, during this period, the engineer was still required to execute a significant workload using 2D CAD. The resulting slow pace, with its interruptions, made it harder to assimilate the software than might have been the case. It was only when a project for which BIM was deemed to be essential – due to its unique and complex geometry – that a 'point of no return' was reached and the management decided to commit the engineer full time to following through on an entire project using BIM. The Modi'in project described in section 4.3 above was this firm's point of no return.

The final part of the adoption process was to compile templates for 2D drawings and reports according to the firm's needs. Here too, much time was invested in attempting to achieve templates as close as possible in style and content to those traditionally used in the firm. However, in the final analysis, it was generally agreed that this was unnecessary, as many of the standard templates provided with the BIM software made better use of the 3D modelling paradigm. In many ways, this firm gained experience in BIM the hard way, which is inevitable to a degree for any pioneer.

6. DISCUSSION

Both companies cited engineering productivity and improved quality of design and documentation as primary motivating factors behind their move to BIM. The four case studies show that the second target was attained almost immediately by both companies, with erection crews reporting zero or negligible erection delays and waste resulting from design errors. However, the goal of enhanced productivity takes more time to achieve. The learning curve for both companies was steep with productivity increasing significantly from project to project and even from phase to phase within the projects (productivity gains grew from 2% to 20% between KD&A's first and second project, and from 28% to 47% between the phases of Star's first project – see Table 1).

The levels of productivity reached and the pace of productivity gain are highly dependent on the degree of formal training provided. Formal training and less formal ghosting and acclimatization periods appear to be essential. Both companies reported that their BIM operators had to undergo a significant change in thinking from their CAD approach to precast engineering to a BIM approach. A second common thread is that productive use of BIM requires careful planning of how a building is to be modelled, which is a level of sophistication unnecessary for CAD operation. The choice of objects used, the way parameters are applied to custom components, the way that embeds and rebars are aggregated within details and applied to precast pieces, and the way in which parametric connections are modelled and applied between pieces all have strong impact on the ways in which drawings appear, the level of automation that can be achieved, and the types of material reports that can be obtained. A corollary is that professional support, preferably in the modeller's native language, is of cardinal importance during and immediately after the adoption phase.

A goal stated implicitly by both KD&A and Star was the ability to shorten the duration required for preparation of precast engineering documentation. In the Eagle Ridge and Modi'in projects this was the key criteria for winning the projects; BIM provided both companies with a clear commercial advantage over their competitors. Star stated a related advantage explicitly– the ability to absorb changes late in the process and produce accurate shop drawings rapidly with minimal rework. However, exploitation of this advantage is limited to the degree to which drawings can be produced automatically. Both companies encountered limitations in this regard with the versions of software used in the case studies, with the need to manipulate drawings 'manually'.

For both firms, the first exclusive use of BIM on projects occurred only when they were confronted with projects in which the geometry was sufficiently complex to provide an apparently clear advantage to BIM. The subsequent projects were simpler, but the hurdles had been overcome. It appears that each company's management and staff required a high level of confidence before they were able to make the leap of faith needed in order to abandon the tried and tested methods of CAD drafting. Both companies focused their initial use of BIM on a single engineer operator, and in both cases this rapidly became a limiting factor. Dependence on a single individual is to be avoided, not only due to the risk it entails, but because all but the smallest projects require more than one operator to achieve the goal of shortening project duration.

Widely differing approaches can be discerned in terms of the use of BIM for collaboration at the early stages of design. While KD&A leveraged their BIM capability to assist the design team in the Eagle Ridge project, Star viewed the lack of BIM hardware, software and experience on the part of their clients to be a barrier. Interestingly, Star report that the precast fabricator on the Shelter project subsequently acquired BIM viewer software in order to exploit the model directly for fabrication and erection. This is a use that was reported as a goal by KD&A, but was not implemented in their projects.

The case studies support the hypothesis that the workflow on a precast project designed using BIM is different to that on one designed using CAD. The main difference is in the change of focus of the modeller/drafter. The process chart shown in Fig. 16 presents the essential difference between CAD and BIM workflows as observed in these and other case studies (Sacks et al. 2007). As Fig. 16 illustrates, for much of the BIM workflow, the focus is placed on the building as a whole, with all the work performed on the model. Drawings are secondary. This is in contrast to CAD, where all of the work must be performed on the drawings, and the whole building is only modelled in the designers' minds. As such, design using BIM becomes largely top-down, as opposed to a hybrid, iterative approach using CAD (Sacks et al. 2005b). A major part of the work in BIM is to create parametric libraries of details, connections and objects, so that modelling can be made efficient and in order to ensure geometric compatibility between adjacent pieces. The modeller concentrates more on the design and engineering aspects of the project and less on document production.

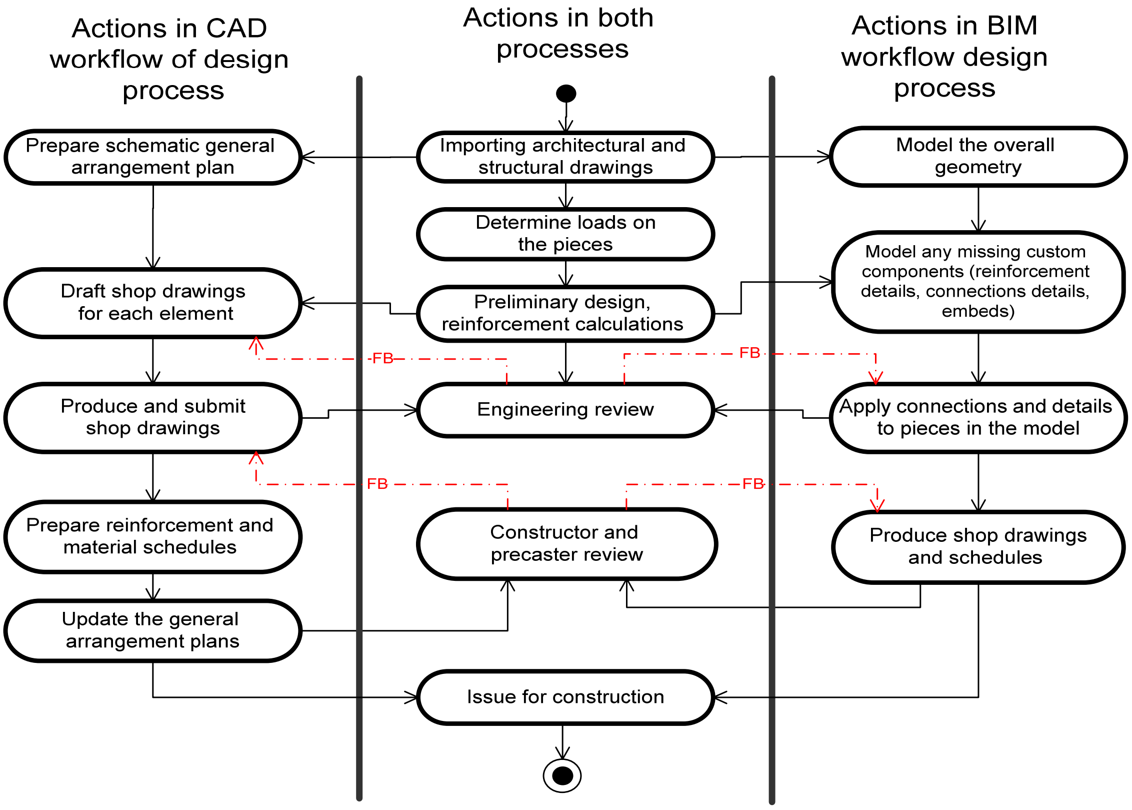


Fig. 16. Detailed comparison of CAD and BIM workflows.

An aspect conspicuous by its absence from all four case studies is the use of the BIM data describing the structures for engineering analysis and design. Despite the fact that BIM vendors have made integration of structural analysis and design software with their BIM tools a priority, neither firm used the functions in practice. The reasons for this at Star were that the finite element software integrated with the BIM software (Tekla Structures) does not support the local standard code, while conversely the software commonly used in Israel, and which conforms to its standard code, has not been integrated with the BIM tool. The investment of overhead time required to train the structural engineer (who did not otherwise operate the BIM software) to use the analysis functions, was considered unjustified. No attempt was made to transfer data between the BIM and the legacy structural engineering applications.

KD&A on the other hand, made a conscious decision to postpone the start of use of structural analysis within the modelling software. In their case, the same analysis package that has direct data links with their BIM package is already used in their firm. Nevertheless, they wanted to focus first on gaining expertise in modelling, then on automation of drawing production and parametric components, delaying exploitation of the structural analysis functionality. This sequence is reasonable given that 83% of labour hours were traditionally expended on drawings while just 10% was devoted to engineering, as reported in section 3 above.

Similarly, neither firm reported demands from building owners for BIM data to serve for facility management. It appears that the facility management industry is not yet sufficiently aware of what is available. As structural engineering firms establish BIM as their mainstream tools, it is expected that their clients will develop new ways to exploit the rich information that can be delivered. An early indicator of this was found, in that both the design firms reported that following their second projects, their precast fabricator clients had introduced BIM within their own organizations for production management and other purposes. Using the SWOT analysis method (Armstrong 1990), Fig. 17 presents the strengths and weaknesses of typical structural engineering firms and the opportunities and threats that they face when considering adopting BIM. The two engineering firms investigated in this research both shared all three strengths and it is apparently these, and particularly the confidence of their engineering leadership, that enabled them to be early adopters. Although neither performed a SWOT analysis before embarking on BIM adoption, both adopted the same strategy to cope with their inherent weakness in making capital investments and the threat of varying workloads – they sought long term arrangements with precast fabrication companies to ensure stable demand for their new services. Engineering firms considering BIM adoption may use Fig. 17 as a template for their own SWOT analysis, by adapting the strengths and weaknesses with those peculiar to their specific business context.

Strengths Skilled engineering staff experienced in CAD and other software Appropriate IT infrastructure, access to advanced software Leadership with vision	Weaknesses Skilled operators are in short supply and are costly to train Adoption requires capital investment
Opportunities Increased engineering productivity Enhanced competitiveness of engineering services through reduced design lead times and virtual elimination of geometry and design consistency errors Provision of new services for owners and contractors (e.g. visualization for conceptual design, rapid and accurate quantity take-off and estimating, data for monitoring and managing production and erection)	Threats Varying workloads Dependence on a small number of engineers skilled in BIM Staff that are unable or unwilling to adapt may feel threatened Drawings cannot be produced fully automatically: ‘manual’ editing is still needed Inability to remain profitable without BIM if competitors adopt

Fig. 17. SWOT analysis of BIM for precast concrete engineering.

7. CONCLUSIONS

The four detailed case studies, provided by two mid-sized structural engineering firms, show that adoption of BIM is challenging but certain. Of the goals established at the outset, only the goal of improved quality of engineering information appears to have been achieved in full. BIM unequivocally improves the quality of precast engineering design, in terms of accuracy and reliability of the documents. Fabrication and erection are essentially error-free, and the effort required for checking drawings has declined drastically.

BIM also clearly improves the productivity of design documentation, but the results predicted have not yet been achieved in full. The trend toward increasing productivity from project to project is evident from the data gathered. An important observation in this regard is that once the first level of basic proficiency has been reached, formal advanced training is needed to improve the modelling methodology used and can have a strong impact on improving productivity. Continued productivity improvements in producing documents are the most important internal goal, because with CAD design documentation consumed as much as 83% of the labour inputs of engineering design firms.

The most important value of BIM cited by the precast fabricator clients of the firms investigated was the benefit of shortened lead times for preparing shop drawings highly. However, the owners of precast buildings have not yet demanded BIM data for facility management.

Adoption of BIM in carefully measured stages is important. Both firms focussed first on gaining basic modelling and drawing production skills before progressing to productivity enhancing functions such as the use of parametric custom components. Structural analysis using BIM data is considered to be a medium to long term goal.

BIM is a powerful but complex technology. To make progress in adoption, firms must establish and maintain their organizational knowledge. It is important to develop, document and teach the modelling procedures that enable production of accurate drawings and material reports with as little manual editing effort as possible. While formal training by or consultation with an expert experienced in precast concrete can avoid incurring the costs of low productivity and rework as this knowledge is developed, the procedures must be developed by internal staff.

Leadership by management is critical at the early stages, where human resource issues arise and frustration may be felt. For example, BIM tools can be exploited best in workflows that are different to those that have evolved for work with paper drawings and CAD tools. With BIM, documentation is produced rapidly and cheaply, so that multiple reports and drawings can be prepared that provide the exact information needs of their various consumers. Changing the format of documents can be difficult for the information consumers, whether within a firm or among its clients

8. REFERENCES

Armstrong, M. (1990). "Management Processes and Functions." Management Studies Series.

Census. (2005). "Other Concrete Product Manufacturing: 2002." *EC02-31I-327390 (RV)*, Manufacturing Industry Series, U.S. Census Bureau, Washington DC, <http://www.census.gov/prod/ec02/ec0231i327390.pdf>.

Eastman, C. M. (1999). Building Product Models: computer environments supporting design and construction, CRC Press, Boca Raton, FL, USA.

Eastman, C. M., Sacks, R., and Lee, G. (2003). "Development and Implementation of an Advanced IT Strategy for the North American Precast Concrete Industry." *ITCON - International Journal of Construction Information Technology*, 8, 247-262.

Eastman, C. M., Teicholz, P., Sacks, R., and Liston, K. (2008). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Architects, Engineers, Contractors, and Fabricators, John Wiley and Sons, Hoboken, NJ.

Gallaher, M. P., O’Connor, A. C., John L. Dettbarn, J., and Gilday, L. T. (2004). "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry." *NIST GCR 04-867*, National Institute of Standards and Technology, U.S. Department of Commerce Technology Administration, Gaithersburg, Maryland.

Hopp, W. J., and Spearman, M. L. (1996). *Factory Physics*, IRWIN, Chicago.

IAI. (2007). International Alliance for Interoperability. <http://www.iai-international.org/index.html>, last accessed April 2007

Karstila, K., Laitakari, A., Nyholm, M., Jalonen, P., Artoma, V., Hemio, T., and Seren, K. (2002). "Ifc2x PCC v09 Schema in EXPRESS." PCC-IFC Project Team, EuroSTEP, IAI Forum Finland.

Kiviniemi, A. (2006). "Ten Years of IFC Development; Why are we not yet there?" *Building on IT – Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, ISCCBE (International Society for Computing in Civil and Building Engineering), ASCE (American Society of Civil Engineers), CIB-W78 & CIB-W102 (International Council for Building), Universite du Quebec, Ecole Polytechnique Federale de Lausanne, Montreal, Canada.

NBIMS. (2007). National BIM Standard. <http://www.facilityinformationcouncil.org/bim/index.php>, last accessed April 2007

NIBS. (2007). Architectural Precast. <http://www.facilityinformationcouncil.org/bim/pdfs/bim_fs_ap.pdf>, last accessed August 2007

PCSC. (2003). Precast Concrete Software Consortium. <http://dcom.arch.gatech.edu/pci>, last accessed November 3rd 2005

Sacks, R., and Barak, R. (2007). "Impact of Three-dimensional Parametric Modeling of Buildings on Productivity in Structural Engineering Practice." *Automation in Construction*, in press.

Sacks, R., Eastman, C. M., Lee, G., and Orndorff, D. (2005a). "A Target Benchmark of the Impact of Three-dimensional Parametric Modeling in Precast Construction." *Journal of the Precast/Prestressed Concrete Institute*, 50(4), 126-139.

Sacks, R., Kaner, I., and Esquenazi, A. (2007). "Improving the Competitiveness of Industrialized Components in Construction using Building Information Modeling." *#5235239*, Israel National Building Research Institute, Haifa.

Sacks, R., Wessman, R., Eastman, C. M., Lee, G., and Orndorff, D. (2005b). "3D parametric modelling of precast structures - a revolutionary change." *18th BIBM International Congress and Exhibition*, M. Borghoff, A. Gottschalg, and R. Mehl, eds., bfbn, Netherlands, Amsterdam, Netherlands, 115-116.