Building Information Modeling Education for Construction Engineering and Management. II: Procedures and Implementation Case Study

E. Pikas[1]; R. Sacks[2]; and O. Hazzan[3]

Abstract: The construction industry needs graduate engineers with knowledge and skills in building information modeling (BIM). A detailed set of 39 topics required for BIM competence in construction management, together with specific targets for competency in each topic, was recently compiled on the basis of research into the needs of industry. However, only a handful of universities have introduced BIM topics into their curricula for construction engineering and management (CEM) students. A set of guidelines for the integration of BIM topics into CEM curricula has been developed and tested at the Technion-Israel Institute of Technology. The BIM education interventions in four out of seven courses were planned, implemented, and evaluated over three semesters. The experiments showed that BIM should be introduced not only as a topic in its own right, but more importantly, also as a tool for performing the engineering tasks taught within design, analysis, and management courses. Further, knowledge of the soft skills of information sharing and knowledge management, professional roles, commercial context, etc. are as important as the technology aspects. The work contributes a set of procedures that educators can use to identify their local requirements and build comprehensive BIM education into their CEM degree programs. **DOI: 10.1061/(ASCE)CO.1943-7862.0000765.**

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Introduction

The use of building information modeling (BIM) has become common worldwide (Eastman et al. 2011) and is continuing to grow. Many governmental, public, and private construction clients have established formal requirements for its use in their projects (Khemlani 2012). A recent industry report cites the proportion of heavy users among construction-industry design and management professionals (defined as those using BIM on 60% or more of their projects) to be 44% in Western Europe and 39% in North America (Lee et al. 2012). As a result, there is a growing demand for construction professionals with BIM knowledge and skills. However, without professional education and ongoing training, neither the continuous improvement nor the knowledge management necessary for realizing the value propositions of BIM can be achieved (Sacks et al. 2010).

Several universities are developing BIM-integrated curriculums for students of construction engineering and management (CEM), but they represent only a handful of the large number of such programs available worldwide (Barison and Santos 2010a, b; Becerik-Gerber et al. 2012), and in addition, there is significant diversity in their content. A BIM education framework for CEM programs is needed to aid educators in establishing coherent and comprehensive curricula, both within existing courses and by introducing new courses.

Using the tables of the construction industry's requirements for BIM education for graduate engineers specializing in CEM established in earlier work (Sacks and Pikas 2013), the authors have proposed, tested, and revised such a framework. The framework includes a set of 39 topics in three areas of expertise for BIM-competent construction managers, a set of learning goals for each topic at two levels of education (Bachelor's degree level or Master's degree or equivalent level of continuing education), and a set of courses and course module examples. The learning goals are intended to be used as a benchmark against which proposed curricula can be evaluated. The detailed courses were tested and evaluated at Technion over the course of this research. The set of procedures developed can serve as a guide for educators to integrate the framework topics within the specific contexts of their own programs.

Although the scope of this research was limited to CEM programs, many of the topics are relevant to other disciplines within the architecture/engineering/construction professions. The set of topics and learning goals may serve as starting points for development of BIM curricula for a range of degree courses in architecture and civil engineering.

BIM Education in CEM Programs

Sacks and Pikas (2013) provide a thorough review of the literature covering the state-of-the-art in university-level BIM education for the broad architecture, engineering, and construction (AEC) sector, against the backdrop of university-level civil engineering education

[1]Graduate Research Assistant, Virtual Construction Laboratory, Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel. E-mail ergo.pikas@gmail.com

[2]Associate Professor, Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel (corresponding author). E-mail: cvsacks@techunix.technion.ac.il

[3]Associate Professor, Dept. of Education in Science and Technology, Technion-Israel Institute of Technology, Haifa 32000, Israel. E-mail oritha@tx.technion.ac.il

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and the Civil Engineering Body of Knowledge (Russell 2013). The main findings were that (1) BIM was being adopted gradually, but that most schools were still struggling to understand what and how to teach, and (2) the majority of existing courses implement BIM on a basic level by teaching a specific tool (Barison and Santos 2010b). However, BIM can help students understand the complexity of construction projects from both the product and process perspectives (Boon and Prigg 2011). In the following text, the authors sharpen the focus on CEM. The BIM tool has been used as a vehicle to teach the means and methods of building construction (Deutsch 2011; Kymmell 2008). Nawari et al. (2011) found that using BIM can also deepen students' understading of structures. Lu et al. (2013) concluded that using BIM for construction preparation, to virtually build the facility, affords better understanding of constructions tasks. Furthermore, using BIM can enhance students' spatial perception (Glick et al. 2011). Another similar study that focused on BIM-based estimation concluded that linking building elements with databases reduces mistakes and time for compiling estimates. Given that university students lack experience in construction, teaching BIM methods for quantifying and costing major systems can yield better understanding among students (Sylvester and Dietrich 2010).

Lee and Hollar (2013) conducted a brief survey of industry requirements and exisiting CEM programs. They rated five areas of competence, most of which concern BIM functionality [clash detection, four-dimensional (4D) modeling, etc.]. They concluded that BIM education must be adopted broadly across multiple courses, to satisfy the growing need for BIM-educated engineers.

To realize the promise of BIM education, construction engineers must be equipped not only with the skills of using technology, but also with skills to collaborate in multidiciplinary integrated project-delivery systems. These aspects should be taught in the capstone courses (Solnosky et al. 2013).

Molavi and Shapoorian (2012) proposed a framework for developing a BIM education that will bridge the gap between industry needs and university education. They emphasized that curricula development should also consider innovations such as green building and integrated project delivery.

In a previous case study (Hyatt 2011), three different trends were integrated into a scheduling course, namely, lean construction, sustainability, and BIM. The Last Planner system (Ballard 2000) was used as a general outline for the course, which proved to be highly successful in engaging students in these important topics.

Goedert et al. (2011) used BIM and other innovative technologies to develop a concept for educating CEM students/practitioners in a virtual environment, which simulated the decision-making process for optimizing the resourcing of projects. However, this application cannot be considered BIM education per se, but rather use of BIM as a supporting technology to develop an educational tool.

Becerik-Gerber et al. (2011) mapped the current status of BIM, sustainability, collaboration, and virtual-learning applications within AEC education. They surveyed deans, department chairs, and program directors of 488 U.S. programs accredited by the Accreditation Board for Engineering and Technology, the National Architecture Accrediting Board, American Council for Construction Education, and the American Schools of Construction. They received 101 responses, of which 26% were construction management programs. The first part of the survey focused on the level of BIM integration for programs that already offered BIM courses. The results must be read with caution due to the small number of construction management programs responding and due to the fact that it is likely that those who had already developed BIM content were more likely to respond than those who had not.

The findings show that 60% of construction management programs have some BIM component. Although the number seems high, most of these include a BIM topic in only one or two courses, and most courses with BIM components in construction management programs are elective. Construction management programs are the latest adopters, but have a rapid deployment rate. The teaching methods in construction management programs, with the approximate proportion of programs including each method, include introduction to BIM concepts (40%); BIM assignments merged into the project work in classes (67%); stand-alone BIM courses (67%); BIM immersed into existing courses and design projects (60%); and BIM merged into research projects (28%).

The major reasons cited by those who have not yet incorporated BIM in their programs are that there is no one to teach BIM. Other significant constraints were insufficient resources, no room in the curriculum, and no accreditation requirement for BIM. As shown in Fig. 1, of approximately 27 construction management programs, approximately 65% teach BIM for constructability, 4D scheduling, and model-based estimating, followed by design (55%), visualization (50%), sustainability (40%), and cost control (35%).

Case Study Procedure

In preparation for the case study, the educational approach and the curricula for CEM BIM courses were developed through the following steps:

- Analysis of the existing curricula of CEM track courses at Technion against the set of requirements established for industry, to determine which courses were suitable for experimentation and what BIM educational content should be added. This analysis was performed based on the results of gap analysis carried out in other courses from major universities (Stanford, University of Southern California, Georgia Tech) and reported previously (Sacks and Pikas 2013).
- Selection of potential courses for BIM integration by carefully examining the existing CEM curricula. The logical sequence of courses was kept in mind to enable students' knowledge and skills to mature through the years of their studies.
- Running an introductory seminar to educate the educators in terms of the potential use of BIM in the selected courses.
- Development and preparation of BIM course content for the set of courses selected for experimentation, based on the course syllabi, and abiding by the principle that the original course content should not be degraded. The expected level of outcome for each course was first established subjectively by authors based on the existing course content, and then discussed with the professors who taught each course to identify and correct any misunderstandings. Implementation of the proposed courses and contents during three consecutive semesters and assessment of students' learning. The results of students' achievements were monitored through test scores and interviews with educators and students. Students' skills, knowledge, and confidence were assessed before and after each course using a questionnaire that included tables with the framework topics and achievement levels for each. Some students were also interviewed after completing the courses.
- Evaluation of the results and refinement of the procedures to develop BIM-integrated curriculums.

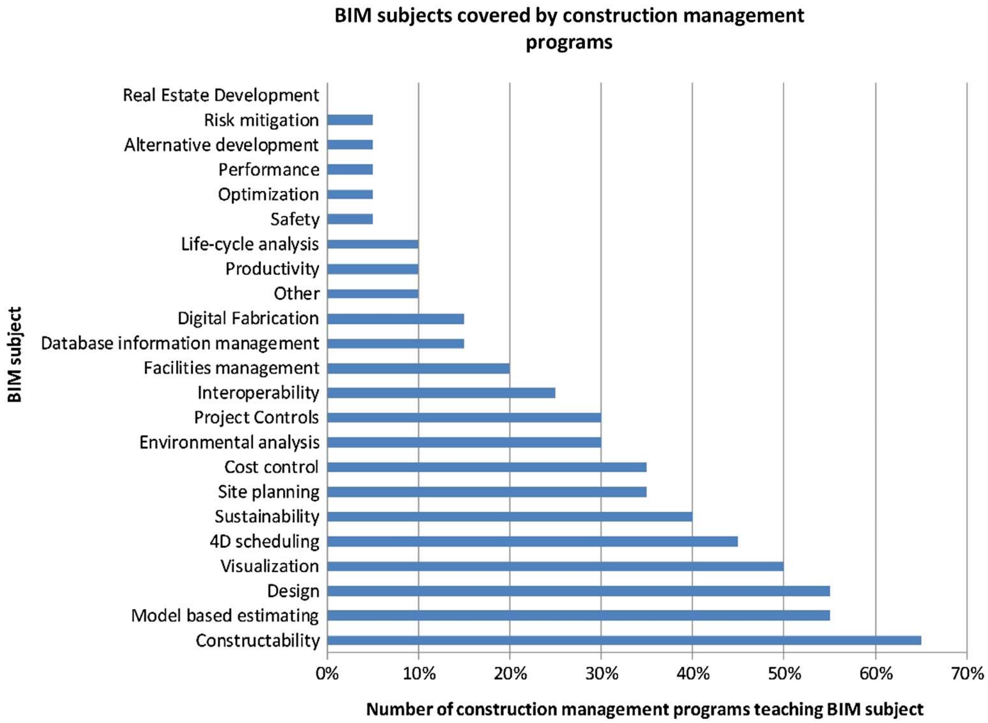

Fig. 1. BIM topics taught by construction management programs (data from Becerik-Gerber et al. 2011)

The cognitive domain of Bloom's taxonomy of educational outcomes (Bloom et al. 1956), applied to each of the 39 topics defined for BIM competence for construction managers (Sacks and Pikas 2013), formed the basis for planning and assessing students' levels of achievement. Six levels are defined as follows: 1, Know; 2, Understand; 3, Apply; 4, Analyze; 5, Synthesize; and 6, Evaluate. For full details of the BIM competence levels, readers are referred to Tables 1, 3, 4 and 5 in the companion paper (Sacks and Pikas 2013).

Selection and Evaluation of Courses for Experimentation

The CEM degree track at Technion is similar to that of most universities that offer CEM as a specialization within civil and environmental engineering. Students are required to complete 156 course credits. These include 40 credits of foundation subjects (mathematics, sciences, etc.), 46.5 credits of mandatory civil engineering subjects, 54 credits in the CEM track, two senior-year capstone projects (one in CEM and the other in a different branch of civil engineering), and 10 credits of elective courses (humanities and others). The seven courses detailed in Table 1 were selected from this program for experimentation. Their selection was based on the following two guidelines: (1) the courses should represent both design and management disciplines; and (2) they should cover the full range of courses from basic freshman year, through the end of the bachelor's degree and extending to graduate studies.

Of the seven courses selected (those listed in Table 1) only three (014008, 014617, and 018625) had any BIM content at the outset (019627—Advanced BIM—was a new course whose curriculum had not yet been determined). The depth and breadth of their content were evaluated according to the defined topics and achievement levels. The evaluation aimed to determine the collective gap that should be fulfilled either through additions to these courses or through a new course (019627—Advanced BIM).

Table 2 provides the detailed analysis of the courses' BIM content. Graphical Engineering Information (014008) is a freshman course that introduces engineering graphics, but whose main content is BIM. It was introduced in this form in 2005 (Sacks and Barak 2010). Although the analysis showed that it is achieving more than planned, for 17 of 21 topics it achieves only either the know or understand level. This indicates that students are introduced to many topics on a basic level but not to any of the following topics in depth. The table also reflects the focus on learning tools for modeling and producing drawings.

Planning and Control of Construction Projects (014617) is an advanced course in which students are required to prepare quantity takeoffs, detailed cost estimates, location-based schedules, site layouts, and cash-flow analyses. At the time of assessment, only quantity takeoff was performed using BIM tools.

Table 1. Technion Courses Selected for Experimentation

Code	Course	Credits	Status	Semester
014008	Graphical Engineering Information	3.0	Foundation: Compulsory	1 (4)
014123	Concrete Structures 1	3.5	Mandatory civil engineering	4
014617	Planning and Control of Construction Projects	3.0	Construction engineering and management track	5 (6)
014609	Construction Mechanization	2.5	Construction engineering and management track	7
014601	Senior-Year Project in Construction Management	2.5	Capstone project	8
019627	Advanced Building Information Modeling	3.0	Graduate elective	Graduate
018625	International Collaboration in Construction Management	2.0	Graduate elective	Graduate

Table 2. Evaluation of the BIM Content of the Selected Courses before Experimental Intervention

Requirement Number	Knowledge area covered	Required achievement level: First-degree	Required achievement level: Graduate courses	Assessed achievement level in courses: 014008	Assessed achievement level in courses: 014617	Assessed achievement level in courses: 018625
1.1	Overall construction design, management and contracting procedures	3	4	2	3	3
1.3	Advantages and disadvantages of BIM for design and construction processes	3	4	2	3	2
1.7	Information integrity	2	3	1	1	2
1.10	Management of information flows	3	5	—	1	2
2.1	Basic BIM operating skills	3	4	3	3	2
2.2	Modeling with standard catalog elements	3	3	3	—	—
2.4	Massing/solid modeling	3	4	2	—	—
2.6	Interoperability (file formats, standards, and structure for data sharing)	2	3	1	1	3
2.7	Communication tools, media, channels, and feedback	3	5	2	—	3
2.9	Choose right BIM technologies/processes/tools for specific purposes	3	5	2	1	3
3.3	Energy analysis	2	2	1	—	—
3.4	Structural analysis	2	2	1	—	—
3.5	Automated quantity takeoff and cost estimation	3	4	3	3	3
3.6	Check code compliance	2	—	1	—	—
3.8	Clash detection	3	4	2	2	—
3.9	Automated generation of drawings and documents	2	3	3	—	—
3.13	Discrete event simulation	1	2	—	1	—
3.14	4D visualization of construction schedules	3	5	1	3	2
3.16	Export data for computer-controlled fabrication	2	3	1	—	—

Note: Numerical achievement level codes are defined in Table 1 of Sacks and Pikas (2013); requirements that are not addressed are not listed in the table.

The International Collaboration in Construction Management course (018625) is a project-based course in which teams composed of students from multiple universities dispersed around the world prepare schedules, cost estimates, and risk analyses (Soibelman et al. 2011). The specifications for the buildings used for the term projects are provided as sets of building information models (architectural, structural, and mechanical, electrical and plumbing models). Students use a variety of BIM tools to collaborate on their projects. The models were used for preparing product breakdown structures, work breakdown structures, development and proposal of design changes, selection of construction methods, quantity takeoff, cost estimation, scheduling, and risk assessment. In general, most of the expected BIM objectives for this course were achieved, although for some, the level of achievement differed from the planned baseline. For example, the assessed level of achievement for *interoperability* (Topic 2.6) was understand instead of apply as was expected. The same applies to *rapid generation of multiple design alternatives* (Topic 3.2) and *4D visualization of construction schedules* (Topic 3.15). This shows that the learning and consequent use of BIM for collaborative working was insufficient. Thus, the potential for introducing additional BIM topics, such as *BIM standardization* (Topic 1.15), *cloud computing, networking, big-room equipment* (Topic 2.8), *selection of BIM technologies/processes/tools* (Topic 2.9), and *clash detection* (Topic 3.8), was recognized.

As can be seen in Table 2, the levels of achievement required were only met for a small number of the topics (1.1, 1.3, 2.1, 2.2, 3.5, and 3.9), all of which represent basic BIM skills. Review of the content over the three areas (work processes, BIM technology, and BIM functionality) revealed that the area of BIM work processes is covered less well than the others.

The gap between what industry expects and what engineering students were being taught was clear. Overall, this result matched with the findings of the gap analysis of the state-of-the-art of BIM education internationally (Sacks and Pikas 2013). A small number of universities offer BIM content in just one to three courses, and most include only a limited number of topics. In light of the requirements for BIM skills expressed by the construction industry, this is clearly insufficient.

BIM Education Interventions

In the next step of the research, interventions in specific courses were planned, prepared, implemented, and evaluated to test ways in which the BIM requirements defined by industry could be integrated into the curriculum as a whole. Of the seven possible courses, four were selected for experimentation. Target achievement levels were set for each, as outlined in Table 3.

The first challenge was to involve and educate the professors and teaching assistants (TAs) who had little or no background in BIM. A series of workshops were held in which the concepts were taught and tools were introduced. However, the primary task was to define appropriate ways to introduce new teaching methods that would enhance the teaching of the core subjects. Some professors expressed concern that introducing BIM might consume time that should be spent teaching the underlying engineering topics. This was a particular concern for a course such as Concrete Structures, the core purpose of which is to teach the basics of reinforced concrete design, and not information modeling. Direct involvement of the course faculty was perceived to be essential to achieving an appropriate balance, and this was one of the key issues monitored and evaluated through the experiments.

Depending on the course content and needs, BIM-related study materials, tutorials, and lectures were developed. These were introduced to courses at different times and using different approaches, as was agreed with the professor of each course. In some cases, educators were trained to teach BIM content, whereas in other situations the authors participated in the lectures or tutorials to teach specific topics.

Validation: Experiments, Case Studies, and Discussion

This section summarizes the experiments conducted in the courses that were selected for investigation. It includes details of the contents planned, their implementation, monitoring of students' progress and evaluation of the results.

Table 3. Achievement-Level Targets Set for Courses Included in the Experimentation Trials

Requirement number	Knowledge area	Target achievement levels (assessed levels) 014123 Concrete structures	014617 Planning and control	014601 Capstone project	019627 Advanced BIM
1.1	Overall construction design, management, and contracting procedures	2	3 (3)	4	5
1.2	Facility maintenance and management	—	—	—	2
1.3	Advantages and disadvantages of BIM for design and construction processes	1	2 (3)	3	4
1.4	Model progression specification and level of detail concepts	2	2	3	4
1.5	Change management procedures	—	2	—	4
1.6	Data security	—	1	—	3
1.7	Information integrity	—	2 (1)	2	3
1.8	Design coordination	—	2	2	4
1.9	Constructability review and analysis	—	2	3	4
1.10	Management of information flows	—	2 (1)	2	4
1.11	Contractual and legal aspects of BIM implementation	—	—	—	3
1.12	BIM standardization (in organizations and projects)	—	—	—	3
2.1	Basic BIM operating skills	3	3 (3)	3	4
2.2	Modeling with standard catalog elements	3	2	3	4
2.3	Creating and modeling with custom elements	—	—	3	4
2.4	Massing/solid modeling	—	—	—	2
2.5	Central databases/information repositories	—	2	2	2
2.6	Interoperability (file formats, standards, and structure for data sharing)	—	1 (1)	3	4
2.7	Communication tools, media, channels, and feedback	3	2	3	4
2.8	Ways to store and share information (cloud computing, networking, big-room equipment, etc.)	—	2	—	3
2.9	Choose right BIM technologies/processes/tools for specific purposes	2	2 (1)	3	5
2.10	Laser scanning	—	—	—	3
3.1	Create renderings and representations for aesthetic evaluation	—	—	2	3
3.2	Rapid generation of multiple design alternatives	—	—	2	4
3.3	Energy analysis	—	—	—	2
3.4	Structural analysis	1	—	—	5
3.5	Automated quantity takeoff and cost estimation	—	3 (3)	4	5
3.6	Check code compliance	—	—	—	2
3.7	Evaluation of conformance to program/client values	—	—	—	3
3.8	Clash detection	—	2 (2)	—	5
3.9	Automated generation of drawings and documents	3	—	—	3
3.10	Multiuser editing of a single discipline model; multiuser viewing of merged or separate multidiscipline models	—	—	—	3
3.11	Rapid generation and evaluation of construction-plan alternatives	—	2	4	5
3.12	Automated generation of construction tasks	—	—	—	3
3.13	Discrete-event simulation	—	1 (1)	—	—
3.14	4D visualization of construction schedules	—	3 (2)	4	5
3.15	Process status monitoring and visualization	—	2	—	4
3.16	Export data for computer-controlled fabrication	—	—	—	5
3.17	Integration with project partner (supply chain) databases	—	—	—	3

Note: Numerical achievement level codes are defined in Table 1 of Sacks and Pikas (2013); data provided in brackets are the existing achievement levels, wherever relevant.

Concrete Structures

This is a typical design course, and as such BIM tools were introduced through several tutorials and individual consultation as an alternative way for students to prepare their final project drawings. Participation in the experiment was voluntary as the course policy was not to restrict students' choice of tools, whether hand drafting or two-dimensional computer-aided design (2D CAD), or now, BIM. A competition with prizes was instituted as a motivating factor for developing BIM. The competition called for students to develop their project design, model the project, and produce drawings in *Tekla Structures* software. They were required to fill out an initial survey, to submit a progress-monitoring report once every week, and to deliver the project and publish the model to *Tekla BIMSight*. Four 2-h training sessions on the use of the software were provided and students were given the opportunity to consult when needed.

The intervention in this course was tried over a single semester, using *Tekla Structures*. At the end of the semester, each of the students was interviewed. None of them had any prior experience with 2D CAD. They found that while the thinking behind the BIM tool was simple to understand, some aspects of using the tool for modeling were more complicated than they expected. They felt that these obstacles, related to ease of use of the tool, could have been mitigated if there were better self-learning materials, more hands-on experience on sample projects through tutorials, better alignment of course objectives, and if the teaching staff were more experienced with the tool and able to demonstrate more real-world examples.

The students all stated that there was a relatively steep learning curve, and therefore, great commitment was required to study the tool. A significant benefit that they cited was that using a BIM application helped them understand the structure, and more

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Table 4. BIM Content in Selected Courses in the Category of Processes and General Knowledge Area

		First-degree courses									Graduate courses			
			014008	014123		014617		014609	014601		Required	019627		018625
Number	BIM-related knowledge/skill: processes/general knowledge area	Required	Assessed	Planned	Actual	Planned	Actual	Assessed	Planned	Actual	Planned	Actual	Assessed	
1.1	Overall construction design, management, and contracting procedures	3	2	2	1	3	3	2	4	4	4	5	4	2
1.2	Facility maintenance and management	1	—	—	—	—	—	—	—	—	2	2	1	—
1.3	Advantages and disadvantages of BIM for design and construction processes	3	2	1	1	2	2	2	3	2	4	4	4	—
1.4	Model progression specification and level of detail concepts	3	—	2	2	2	2	1	3	2	4	4	3	—
1.5	Change management procedures	3	—	—	—	3	2	—	—	2	3	4	2	—
1.6	Data security	2	—	—	—	1	—	—	—	—	3	3	—	—
1.7	Information integrity	2	2	—	—	2	—	—	2	2	3	3	3	—
1.8	Design coordination	2	1	—	—	2	—	—	2	2	4	4	4	—
1.9	Constructability review and analysis	3	—	—	—	2	—	2	3	3	4	4	4	—
1.10	Management of information flows	3	—	—	—	2	2	2	2	2	4	4	4	2
1.11	Contractual and legal aspects of BIM implementation	2	—	—	—	—	—	—	—	—	3	3	1	—
1.12	BIM standardization (in organizations and projects)	2	—	—	—	—	—	—	—	2	3	3	1	—

Note: Numerical achievement level codes are defined in Table 1 of Sacks and Pikas (2013); the table data provide planned versus achieved for experimental courses, assessed for existing courses; industry requirements are summarized in Tables 3–5 of Sacks and Pikas (2013).

particularly, how reinforcement should be placed in concrete elements. Despite the difficulties, all three students received very high grades relative to their classmates who used 2D CAD or manual drafting. High grades are given in the course not for the quality of engineering drawings but for ability in reinforced concrete engineering. That ability was presumably enhanced by the deeper understanding of the three-dimensional (3D) structure that they reported gaining from the authors of this study. They rated their level of achievement for use of tools as 3 (apply), meaning that they felt confident that they could use BIM in the future for reinforced concrete modeling.

Tables 4–6 summarize students' achievements in relation to what was planned with respect to all of the four courses. With respect to the Concrete Structures course, for three items in particular, whose targets were not met (1.1, 2.9, and 3.4), an evaluation showed that the targets set were unrealistic. For example, the target *structural analysis* (3.4) was not achieved, because there was no room in the course content for discussion of the possibilities of integrating structural analysis tools. Integrating analysis tools should be an objective of a subsequent course on concrete structures.

Planning and Control of Construction Projects

This is the penultimate course in the CEM track, preparing students for their capstone project. All aspects of management and methods are integrated and applied for solving problems and making decisions for delivering construction projects. As explained in the aforementioned analysis, BIM was already used within the course, but only for quantity takeoff. Intervention in this course consisted of introducing use of a comprehensive BIM-based software package for quantity takeoff, estimating, location-based scheduling, site layout, cash-flow analysis, work breakdown and cost analysis, and for process visualization (4D CAD) and construction control.

This intervention was trialed over two consecutive semesters, with both local and international students. With the exception of two introductory homework still done using critical-path method software, all homework and the term project were now to be delivered using the BIM software. The experiments were implemented by training TAs to use the software, adapting the tutorial, homework, and project assignment definitions to reflect the new ways of working, and supporting the professor and TAs during the course with advice on training and procedure. The course staff were introduced to the software in three sessions, whose content was as follows:

- Introduction, user interface, model management, model-based takeoff items and takeoff quantities, node concept, formula editor, and cost estimation with assemblies.
- Location breakdown structure, location systems, creation of project task list, and mapping tasks to resources in cost estimation.
- Scheduling environment, Gantt and flow-line schedules, program networking (schedule logic), types of task dependencies (location, organizational, and technological), assignment of resources to tasks, cash-flow analysis, and risk analysis.

During the first trial, the TAs encountered technical difficulties associated with incompatible versions of BIM files, in which the BIM-authoring software was upgraded but the CEM package did not yet have the appropriate import routine available. This is typical of interoperability problems encountered in industry from time to time. The result was that the final homework reverted to use of the non-BIM software used previously. In the second trial, software was updated and students were able to finish their projects as planned, despite challenges imposed by aging hardware in computer classes.

Table 5. BIM Content in Selected Courses in the Category of BIM and Related Technology

		First-degree courses									Graduate Courses			
			014008	014123		014617		014609	014601		Required	019627		018625
Number	BIM-related knowledge/skill: BIM and related technology	Required	Assessed	Planned	Actual	Planned	Actual	Assessed	Planned	Actual	Planned	Actual	Assessed	
2.1	Basic BIM operating skills	3	3	3	3	3	3	—	3	3	3	4	4	3
2.2	Modeling with standard catalog elements	3	3	3	3	2	3	—	3	3	3	4	4	—
2.3	Creating and modeling with custom elements	3	1	—	—	—	—	—	3	3	3	4	5	—
2.4	Massing/solid modeling	3	2	—	—	—	—	—	—	—	3	2	3	—
2.5	Central databases/information repositories	2	—	—	—	2	3	2	2	2	4	2	1	—
2.6	Interoperability (file formats, standards, and structure for data sharing)	3	1	—	—	—	2	—	3	2	5	4	4	2
2.7	Communication tools, media, channels, and feedback	4	1	3	3	3	2	—	3	2	5	4	4	3
2.8	ways to store and share information (cloud computing, networking, big-room equipment, etc.)	2	—	—	—	2	3	—	—	—	3	3	3	—
2.9	Choose right BIM technologies/processes/tools for specific purposes	3	2	2	1	2	—	1	3	2	5	5	4	—
2.10	Laser scanning	2	1	—	—	—	—	1	—	—	3	3	2	—

Note: Numerical achievement level codes are defined in Table 1 of Sacks and Pikas (2013); the table data provide planned versus achieved for experimental courses, assessed for existing courses.

At the end of each semester, teaching staff and students were interviewed. The TAs of the first trial were frustrated by the need to divert their students' attention to technical issues, but they nevertheless highlighted the potential advantages of the software in presenting the different practical CEM actions in a holistic manner, rather than as disparate parts. An important difference between the two semester groups that came to light was that the students in the second trial, those of the international engineering school, found the learning curve for operation of the BIM tools to be significantly less steep than the students of the first trial. The international students had studied the Graphic Engineering Information course just one semester before studying the Construction Planning course, whereas the students of the first trial had a gap of three semesters between the courses. This not only indicates the value of the first course in preparing students, but also highlights the fact that it may be offered too early in their degree program.

Senior-Year CEM Project

The senior-year project is a compulsory capstone project for CEM students. Students are expected to integrate all their knowledge and perform management functions including cost estimation, budgeting, proposing and choosing between technological alternatives, planning production and site layout, choosing proper machinery for construction, organizing work, choosing, and assigning necessary resources, etc.

The intervention planned for this course was to offer students the possibility to deliver their project using BIM tools as an alternative to traditional methods. It was tried over two consecutive semesters. Students who selected BIM were given additional requirements, such as location-based scheduling using the model and preparation of 4D visualizations, and therefore, they were offered additional training in the use of the tools. Approximately one-third of the students elected the BIM option. Their motivation was clarified in a short survey distributed to the students in this and other courses. The 39 respondents rated the requirements of industry and potential advantage when seeking employment as the most significant motivating factors for studying BIM tools, with average scores of 4.23 and 4.17 on a scale of 1–5, respectively; the least motivating factors were an interest in technology (3.69) and the software supports learning in the coursework (3.46).

One of the project mentors from industry and the volunteer students were given two refresher courses in *Autodesk Revit*, and three training sessions in *Vico Office*, structured in the same way as those described previously for the Planning and Control course. The students were also coached by a TA who specialized in the BIM-delivery track.

Fig. 2 presents examples of the different CEM tasks that students completed. The initial modeling stage took a relatively long time (half of the semester), but students found that modeling helped them improve their understanding of the projects as they were actually virtually building them. This gave them a good basis for performing management functions subsequently, which underscores the value of requiring students to model their own projects, rather than providing them with preprepared design models.

Some of the benefits students highlighted in their postcourse interviews are extraction of accurate quantities, visualization of alternatives for equipment selection and site layout, location-based production planning, cash-flow analysis, and risk analysis (Monte-Carlo simulation), all based on the same database. Fig. 3 compares the workflow taught before the intervention with that implemented in the experiment, showing both iterations and additional steps that the latter process facilitated. Once the building model was compiled and the construction process was planned,

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Table 6. BIM Content in Selected Courses in the Category of BIM Applications/Functionalities

		First-degree courses										Graduate courses		
			014008	014123		014617		014609		014601		Required (App. I)	019627	018625
Number	BIM-related knowledge/skill: BIM and related technology	Required (App. I)	Assessed	Planned	Actual	Planned	Actual	Assessed	Planned	Actual		Planned	Actual	Assessed
3.1	Create renderings and representations for aesthetic evaluation	2	1	—	—	—	—	—	2	—	3	3	3	—
3.2	Rapid generation of multiple design alternatives	2	—	—	—	—	—	—	2	2	3	4	4	1
3.3	Energy analysis	2	1	—	—	—	—	—	—	—	3	2	2	—
3.4	Structural analysis	2	1	1	—	—	—	—	—	—	3	5	3	—
3.5	Automated quantity takeoff and cost estimation	3	3	—	—	3	3	2	4	4	5	5	5	3
3.6	Check code compliance	2	1	—	—	—	—	—	—	—	—	2	2	—
3.7	Evaluation of conformance to program/client values	2	—	—	—	—	—	—	—	—	—	3	3	—
3.8	Clash detection	3	2	—	—	—	—	2	—	—	5	5	2	—
3.9	Automated generation of drawings and documents	3	3	3	3	—	—	—	—	—	—	3	—	—
3.10	Multiuser editing of a single discipline model; multiuser viewing of merged or separate multidiscipline models	3	—	—	—	—	—	—	—	—	—	3	—	—
3.11	Rapid generation and evaluation of construction plan alternatives	3	—	—	—	2	3	—	4	—	5	5	3	—
3.12	Automated generation of construction tasks	—	—	—	—	—	—	—	—	—	—	3	4	—
3.13	Discrete-event simulation	1	—	—	—	1	1	—	—	—	2	—	—	—
3.14	4D visualization of construction schedules	3	1	—	—	3	3	2	4	—	5	5	4	2
3.15	Process status monitoring and visualization	3	—	—	—	2	2	2	—	—	5	4	3	—
3.16	Export data for computer-controlled fabrication	2	1	—	—	—	—	—	—	—	3	5	5	—
3.17	Integration with project partner (supply chain) databases	2	—	—	—	—	—	—	—	—	3	3	—	—

Note: Numerical achievement level codes are defined in Table 1 of Sacks and Pikas (2013); the table data provide planned versus achieved for experimental courses, assessed for existing courses.

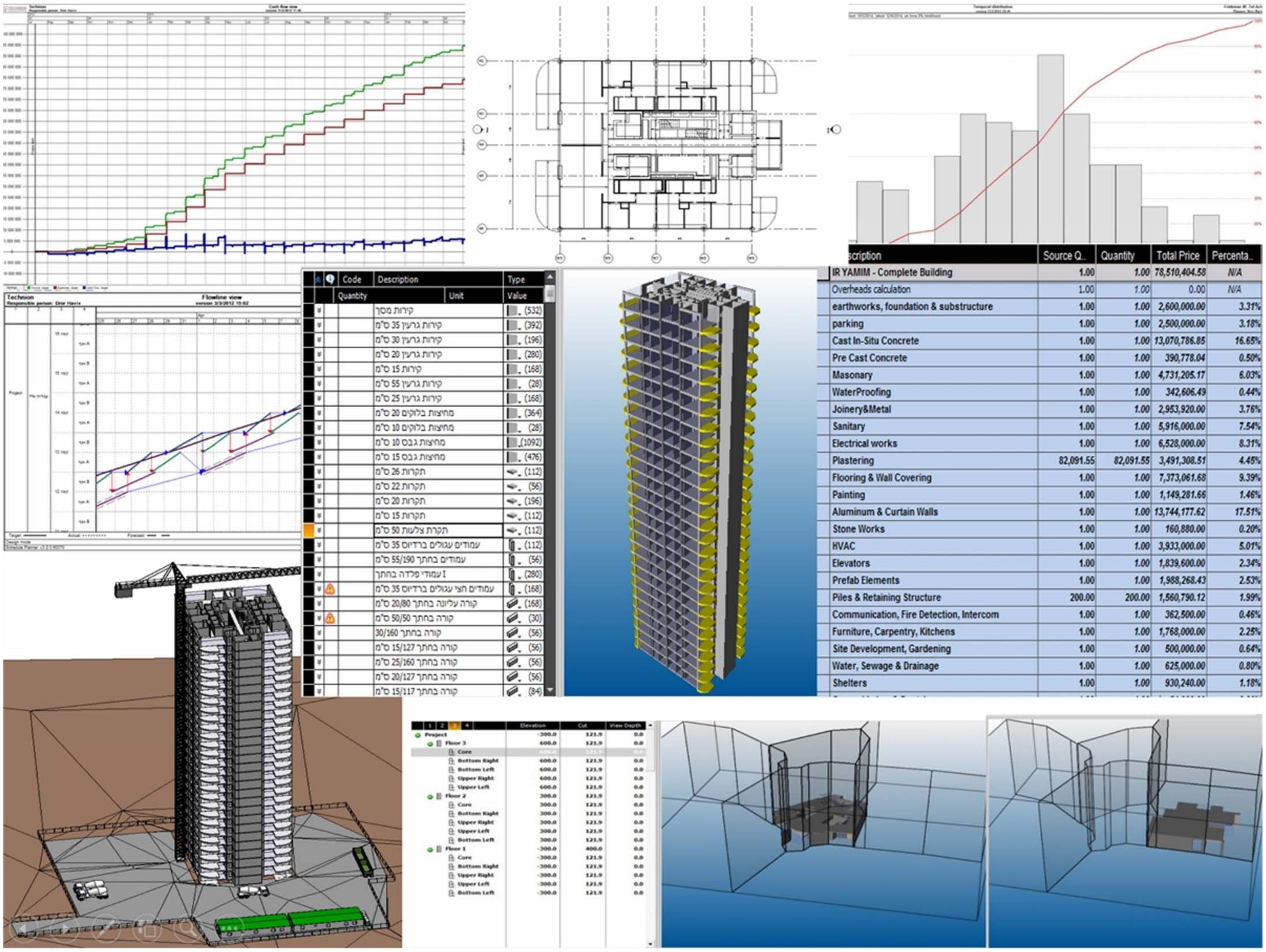

Fig. 2. Examples of students' final project work, including (clockwise from top left to center): cash-flow analysis, floor plan, resource planning, quantity takeoff, location breakdown, site layout, location-based scheduling, and 4D process visualization

students were able to perform the additional tasks (cash-flow analysis, risk analysis, and 4D visualization) with minimal effort. One of the most significant successes of the intervention was the judgment of the teaching staffs, as reflected in the final grades in both semesters, that the quality of the projects produced in the BIM process was, from a professional standpoint, significantly superior to that of the other students' projects.

One of the students' review comments had particular insight: "These tools help you give a better understanding of the big picture but still make detailed information available. I think the more experienced people are in construction management, the more they can benefit from the BIM process as they have more real-life knowledge to apply within the models." Many indicated that BIM would increase the importance of preplanning, as now the building can be built first virtually, before being built in reality, enabling a more holistic view of project delivery and identification of potential risks and action where necessary. One of the students added that BIM would change interpersonal communication: "I mean how the communication will take place between different parties involved. The new tools facilitate the processes with the platform; they provide a common language between all the parties."

The evaluation of the difference between the content of the course as planned and the actual level of achievement is detailed in Tables 4–6. In general, the BIM education objectives were met, with some exceptions, which are as follows:

- Change management (1.7) was not initially planned, but was introduced in the tutorials to explain the impact of model change to management aspects.
- BIM standard workflows (1.15) had to be introduced because of the dependence of the BIM application for CEM on appropriate modeling (in the model-authoring tool) of objects in a way suitable for cost and task classifications.
- Issues of interoperability (2.6) were not dealt with because a custom direct one-way translator that used the application programming interface of the authoring tool was used to export the models to the CEM application.
- Select BIM tools and processes (2.9) were not learned because students were given only one alternative process. Expectations that they could exercise judgment in this regard were premature.

BIM Graduate Course

Advanced Building Information Modeling was an entirely new course that was developed and prototyped during this research (to date, it has been offered two times). The objective was to teach students to apply theoretical knowledge of BIM in the development of a building project from conceptual design, through engineering

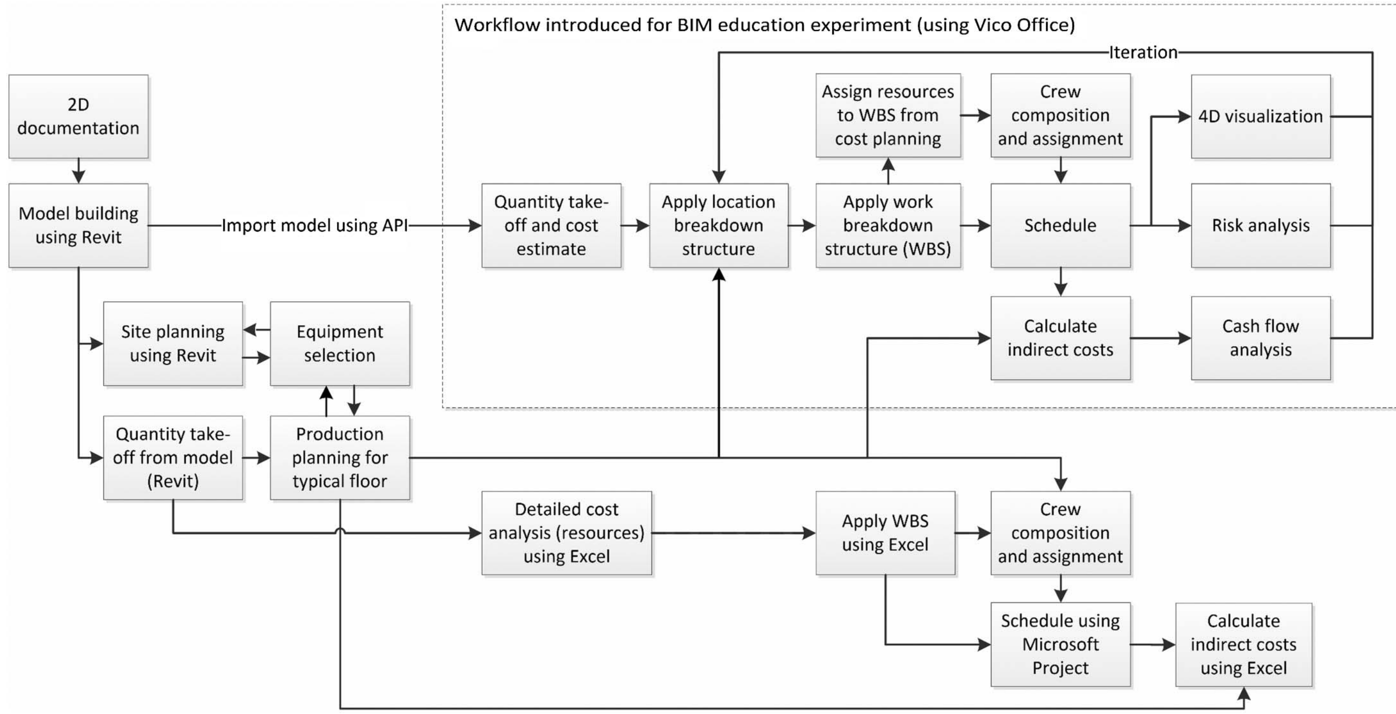

Fig. 3. Alternative workflows for the capstone project, with and without comprehensive BIM tools

and construction-engineering analysis, to detailed design and fabrication of models using rapid prototyping technologies. It uses formal lectures, tutorials, and a hands-on multidisciplinary group project. The course is a joint offering of the Faculties of Civil and Environmental Engineering (Structural Engineering and Construction Management Unit) and the Faculty of Architecture. In addition to advanced BIM concepts and technologies, the course also aims to provide understanding of how various but interdependent disciplines work and think, and how they can collaborate.

The weekly content includes a 2-h lecture, 2 h of hands-on tutorial, and group and individual homework. The modules covered are the following:

- Introduction to BIM
- BIM in architectural design and manufacturing
- BIM in structural engineering
- BIM in CEM
- Parametric design and modeling
- Collaboration and interoperability
- BIM-supported design simulations and analysis
- BIM-supported construction engineering simulations and analysis
- BIM contract provisions
- Detailing and manufacturing
- Production of 3D prototypes and use of computer numerical control machines

The primary deliverable, and the vehicle for collaboration among student teams, is the course project. The project requires students to design, analyze, and detail a small structure, and to fabricate a scale model of it. The project brief called for a ticket sales kiosk at the entrance to a nature reserve. In addition to defining the buildings' function and intent, specific process requirements were set, including, design the building parametrically, with nonrepetitive parts; coordinate the design among the different disciplines; present the whole building solution to the faculty using immersive virtual reality in the cave automatic virtual environment (CAVE); produce a small-scale model of the building using 3D printing.

As a prototype, the course was limited to one group of graduates consisting of three CEM students (who each focused on different aspects), one structural engineering student, one architecture student, and one digital prototyping and manufacturing student. Students had individual learning assignments as well as the group project. After some introduction to BIM applications, tutorials were dedicated to the development of the term project. The team members developed a schematic design for their project through a number of iterations.

In the design development phase, structural analysis was performed using *Atir STRAP* software. The architectural model was exported from *McNeel Rhinoceros (Rhino)* to *STRAP* using DXF file format. The project team then prepared the model for final reporting, including design of the interior (performed in *Revit*, exchanged through *DWG*), shell detailing for manufacturing (Grasshopper within *Rhino*), model coordination (*Autodesk Navisworks*), visualization in the CAVE (Autodesk 3DS Max and *EON Studio*), cost estimating and scheduling (*Vico Office*), and digital prototyping/3D printing (in *AlphaCAM* and *ZCorp* software). Fig. 4 illustrates the sequence of use of the software tools and the data exchanges made between them.

In the staff members' and students' evaluations of the course, they highlighted the following lessons learned:

- Various disciplines think and work in different ways;
- The variety of BIM tools available for complex projects is limited;
- Traditional BIM tools are inefficient for producing complex and free-form designs;
- Interoperability and information-exchange management is a key aspect of BIM projects; and
- Model coordination for developing and sharing the right content at the right time is a major management challenge for BIM projects.

The content of the course lectures appeared to be timely and well developed. However, students pointed out that some BIM topics they considered relevant were omitted, such as national BIM

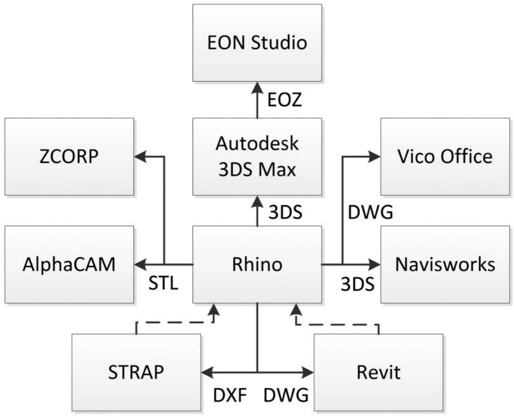

Fig. 4. Digital project environment for delivering the multidisciplinary term project

standards, model coordination management, and BIM standardization within organizations and projects. The biggest challenge during the course was the complexity of the term project. Whether because of the problem posed or poor choice of potential solution, the team spent relatively more time on designing the facility than on anything else, leaving less time to deal with other BIM aspects. From the perspective of collaboration between disciplines it was instructive, but from the perspective of using advanced BIM technologies for delivering projects, it was less successful. The recommendation was to assign a simpler project-design task to balance collaborative design and use of BIM technologies.

Results

In general, the use of BIM enhanced students' learning of engineering topics. This was declared by students in the Concrete Structures, the Project Control, and the capstone project courses, who commented on the learning benefits afforded by clear visualization of product and process information using BIM.

Tables 4–6 provide an overview of the state of BIM content across the seven courses selected at the end of the research period. For the courses in which experiments were conducted, it shows the planned versus the achieved levels. The values for the other courses reflect the assessments of their status at the same point in time. Although it appears that a significant portion of what was planned was achieved, some topics require more attention.

In the area of BIM processes, teaching of the following topics must be improved: change management (1.7), data security (1.8), contractual and legal aspects of BIM implementation (1.14), and BIM standardization (1.15). The last three topics refer to the management of BIM models. They could be improved in the Advanced BIM course by introducing students to legal implications and standards of BIM adoption, and by requiring students to plan and monitor their project BIM process.

In the area of BIM technologies, most of the expected competencies were achieved. This reflects the focus on technology in the existing courses.

In the area of BIM applications and functionalities, planned levels were not achieved for structural analysis (3.4), process status monitoring and visualization (3.16), clash detection (3.8), and rapid generation and evaluation of plan alternatives (3.12). These are topics that should be integrated into bachelor's degree courses, and must be taken into consideration for future improvement. Multiuser editing of a single discipline model (3.10) and multiuser viewing of merged or separate multidiscipline models (3.11) were not given enough attention, and should be incorporated in the Advanced BIM course.

Refined Proposal of Procedures to Develop BIM-Integrated Curricula

The overall approach for developing a BIM-integrated curriculum followed the plan–do–check–adjust (PDCA) cycle (Azhar et al. 2010; Calado et al. 2009). As laid out in the "Case Study Procedure" section, the overall process for integrating BIM was as follows: analysis of existing courses and curricula, selection of courses for BIM integration, involvement of educators, development of BIM content for selected courses and defining the expected levels of achievement, implementation and monitoring, and finally improvements. This methodology was applied through three consecutive semesters of studies, with three PDCA cycles.

The refined procedure can therefore be stated as follows:

- Review the industry requirements laid out in Tables 1, 3, 4, and 5 of the companion paper (Sacks and Pikas 2013) and adjust to local context if necessary.
- Define the objectives of your school in relation to the industry requirements—determine for each item what level your school aims to achieve.
- Assess existing curricula to identify the current state of BIM content and the gap between your goals and the existing content. Itemize the gap using a table such as Table 2.
- In consultation with all the course educators, identify and select existing courses, and define new courses as required to fulfill the goals.
- Compile curricula and implement courses.
- Monitor and measure achievements in each course implemented using Tables 4–6.
- Review the courses and determine any changes that are needed in the curricula and/or the requirements.
- Repeat the process for continuous improvement.

Note that the first two steps should result in a set of requirements that is specific to the educational goals of each school or department. This will commonly require adjustment of levels of achievement, but it may also prove necessary to extend the range of topics. The procedure, and the requirements framework itself, by their nature cannot be considered prescriptive. They do not absolve educators of their responsibility to determine the goals and contents for BIM education according to the capabilities and needs of their students and the local industry conditions.

Conclusion

In this section, several lessons learned from the analysis of the case studies described in this paper are suggested. The authors do not argue for any generalization, but do propose that the appropriateness of these guidelines should be examined when the introduction of BIM into a study program is considered:

- BIM education should be continuous: This is reflected by the fact that those students who took part in the senior-year capstone project course had to invest a considerable amount of time to catch up with the tools and applications that they studied during their freshman year. The international students, who had only one semester gap between Engineering Graphics and Planning and Control of Construction Projects, did not experience the same difficulties. Students delivering senior-year capstone projects must focus on engineering rather than on studying new or remembering old applications. They must acquire the knowledge of proper tools and concepts before entering the final project.

- BIM can enhance students' learning of engineering topics: While there is a certain overhead for students to apply BIM tools within engineering courses if they have not previously learned the specific application required, this appears to be more than offset by the advantages gained in terms of their improved ability to grasp the engineering concepts themselves that modeling affords. The benefits appear to flow from the parametric modeling, intelligent object behavior, and clear visualizations provided by BIM tools.
- TAs must have hands-on experience with BIM: Students stated that they could have benefited more if the instructors and TAs had been more experienced with the applications. It is recommended, therefore, to give the teaching staff the needed technical assistance or alternatively, to employ experienced professionals in the field to teach the said courses.
- Integrate real project examples in the courses: Students said that more realistic examples from real projects could have helped them improve their understanding of the benefits of using BIM applications. Here too it is recommended to employ a professional with experience in the construction industry to be involved in the design and teaching of courses where appropriate. Such examples may increase students' motivation when they feel that their learning is meaningful.
- Obsolete hardware and improper software setup can harm students' motivation: The entire study environment needs to support students' learning commitment and experience. The support from faculty, teaching staff, working software, and hardware all must support the creation of a healthy study environment.
- Encourage students to make use of the opportunity to self-learn operation of BIM software: BIM education includes principle and theoretical aspects, and these must be conveyed by the professor and the TAs. However, there are also technical and/or operational topics that students can study by themselves, especially because most of the software vendors have well-developed step-by-step tutorials for learning their software. The process of self-learning will prepare them also for future employment situations in which they will have to become familiar with new tools.

In addition, teaching BIM may elevate students' learning of teamwork and other soft skills. Therefore, the teaching of BIM should not be limited to technology, but should also cover the ways in which technology should be aligned with processes and people in organizations and projects. In courses that invite project-based learning, it is recommended to take advantage of the BIM tools as a vehicle for integrating other human aspects of CEM into the courses.

In practice, two general scenarios for future improvements in BIM content for Technion's CEM programs are proposed. First, integrate more BIM topics within a variety of courses to emphasize collaboration between interdisciplinary or multidisciplinary processes and integration. Second, add an elective course between the introductory BIM course (Graphical Engineering Information at Technion) and the junior or senior advanced CEM courses (Planning and Control of Construction Projects and Senior-Year Construction Management capstone at Technion). This course should deliver the message that BIM is a common language between project parties and emphasize how project/facility-related information is created, compiled, and shared to support decision making through complex construction-project processes. Such a course will reduce the time invested in the capstone project course on learning the software and enable students to focus on the actual construction-engineering analysis and use the tool as an environment that reinforces their learning and understanding of CEM processes.

This research differs from other similar studies in that it focused on the entire construction-engineering and management curriculum rather than just on isolated courses. Most previous studies studied the use of BIM in the context of a single course. This work contributes tried and tested guidelines for universities to develop BIM-integrated curriculum by considering all the years of civil engineering studies. The main limitation of this study was the time and effort required to conduct experiments and aggregate results. The research was conducted over two academic years. To gain better understanding of the appropriateness of the procedures, a longer study—ideally following students' progress through an entire degree program and on into industry—is recommended.

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