Process-Oriented Approach of Teaching Building Information Modeling in Construction Management

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Abstract: It is widely accepted that the evolution of building information modeling (BIM) is increasingly affecting the roles of construction management professionals in the architecture, engineering, and construction (AEC) industry. Since the transition from 2D drafting to BIM is more of a process transformation, the use of BIM also affects how information is managed by and for construction management professionals. Teaching BIM in construction engineering and management (CEM) curriculum requires more emphasis on learning BIM as a process improvement methodology rather than only a technology. This paper describes the implementation of a graduate level course called "Building Information Modeling for Capital Projects" that was developed to educate next-generation construction managers to understand BIM and effectively use an existing BIM in plan execution for building construction projects. This is a project-based course where students gain knowledge on the implementation of BIM concepts throughout the life cycle of a building. A process-oriented teaching approach was applied in the course and is introduced in the paper. Findings and lessons learned to date from the teaching experience are documented.
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Introduction

Building information modeling (BIM) was introduced to the architecture, engineering, and construction (AEC) industry nearly 10 years ago and is continuously evolving with time. BIM is regarded as an innovative approach and integrated process that supports efficient design, information storage and retrieval, model-based data analysis, visual decision making, and communication among project stakeholders (Eastman et al. 2008; Krygiel and Nies 2008). Although the various definitions of BIM have been given with a different focus, most researchers and practitioners believe that BIM is not a product or technology; instead, it is a process that can facilitate project success when utilized throughout the project life cycle (Autodesk 2003). According to McGraw-Hill Construction's Smart Market Report (2009), almost 50% of the AEC industry is using BIM and the biggest challenge to BIM adoption is the lack of adequate BIM training. As the importance of BIM is widely recognized in the AEC industry, it is essential for the new generation of construction management professionals to learn BIM while undertaking studies at universities.

This paper describes the implementation and lessons learned from a graduate level course called "Building Information Modeling for Capital Projects" that was developed to educate next-generation AEC professionals to understand BIM and effectively use an existing BIM in plan execution for a building construction project. This course focuses on BIM as a collaborative process rather than a design tool. There was no requirement for advance modeling since all models using in course work were provided. Students were asked to use existing models to perform tasks including model-based cost estimating, scheduling and 4D simulation, mechanical, electrical, and plumbing (MEP) design coordination, and energy modeling. A process-oriented teaching approach was applied to (1) emphasize the importance of understanding BIM as a process; and (2) provide students with active learning experiences by encouraging self-directed learning and critical thinking throughout the course. The process-oriented teaching approach for BIM education is introduced and lessons learned to date from the teaching experience are documented in the following sections.

Background Research

Approximately 30 years ago, computer-aided design (CAD) was introduced to the AEC industry. Designers and engineers experienced the cultural and technological shift from two-dimensional (2D) hand drawing to computer-aided design and drafting. Many undergraduate programs started to offer classes on designing and drafting with *AutoCAD*. Nowadays, as BIM is gaining wide acceptance and recognition, AEC professionals are facing a new transition from CAD to BIM. BIM represents a new generation of virtual models, which is based on parametric modeling and serves as an information-rich database that stores multidimensional features of a structure. In response to this promising technology and to industry needs for relevant skills, academic institutions are exploring strategies and approaches to incorporate BIM education in their undergraduate and graduate curricula. Researchers found that BIM is one of the most challenging and recent trends for construction management programs but BIM pedagogy is not yet consolidated (Johnson and Gunderson 2009; Casey 2008).

In recent years, an increasing number of academic institutions have started to incorporate this new technology into their programs to respond to industry needs for these skills. Schools such as Penn State, Georgia Tech, University of Southern California, Technion-Israel Institute of Technology, and University of Texas at Austin

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have successfully integrated BIM education in their programs (e.g., Becerik-Gerber et al. 2012; Barison and Santos 2010; Sacks and Barak 2010). A survey conducted by Becerik-Gerber et al. (2011) showed that among 101 U.S AEC programs, 60% of the construction management programs offer BIM courses, while the percentage is 81% for architecture programs and 44% for engineering programs. In architecture and engineering programs, BIM education mostly focuses on design and visualization, especially the transition from CAD to BIM (Berwald 2008; Denzer and Hedges 2008). Students are taught how to create, modify, or analyze the model and the final deliverables are mostly project designs (Berwald 2008; Taylor et al. 2008).

It is important to teach BIM as a design tool in a *Design Studio* or modeling course; however, as BIM is recognized as "the process of creating and using digital models for design, construction, and/or operations of projects" (McGraw-Hill Construction 2009), it should be also taught in construction and facility management. The data-rich nature of BIM enables the model to not only be a digital representation of the design, but also to support quantity takeoff, model-based calculations, clash detection, energy efficiency analysis, and electronic documents. Therefore, in addition to teaching BIM in design education, it is equally important to teach students the potential of BIM application throughout the project life cycle as well as the knowledge and experience of how to manipulate, manage, and make good use of the model. BIM education in construction management is comparatively new. Some institutions integrated BIM into existing courses as a teaching tool (Kim 2012; Meadati and Irizarry 2011) or as a new module (Clevenger et al. 2010; Gier 2008). Only a few institutions offer BIM as a new standalone course (Bur 2009; Dupuis et al. 2008). A survey conducted by Sabongi (2009) reported that less than 1% of the responding institutions offer BIM as a standalone course.

Teaching BIM in construction management is challenging for several reasons. First, it is critical to help students form a correct understanding of BIM. As noted by Kymmell (2008), the problem of misunderstanding BIM concepts is the most important hurdle to overcome in BIM education. BIM is not simply new software or a standalone tool that supports an individual discipline. Hence, understanding how BIM streamlines the collaboration process of a construction project is much more important than mastering software (Hietanen and Drogemuller 2008; Kymmell 2008). Second, considering the ever increasing evolution speed of information technology, it is very likely that the *content* taught in class especially the hands-on training on BIM applications will be outdated in the near future. Therefore, it is important for university educators to place more emphasis on students' ability of self-directed learning by focusing on the learning *process* rather than strictly the *content*. Furthermore, as BIM is still emerging, critical thinking should be strongly encouraged throughout the teaching process. In response to these challenges, the authors developed the course "Building Information Modeling for Capital Projects" and applied a process-oriented teaching approach, which is presented in the following sections.

Traditional teaching tends to focus on the content (knowledge and/or skills), while process-oriented instruction also deals explicitly with the process of acquiring this content (Bolhuis 2003). In learning theory, process-oriented instruction aims at fostering and facilitating self-directed lifelong learning among students. The teacher activates students to participate, practice on their own, learn from others, work productively as a group, and question the formal knowledge. Previous research demonstrates that students learn more by engaging them actively "to explore, to question, to experiment, and to formulate their own solutions" (Li and Liu 2004). Process-oriented teaching was first introduced in language learning. Because the *content* of a language is unlimited, only when grasping the *process* (learning methods/strategies) can a student achieve continuous learning. Learning evolving information technology is similar to *process* learning. Thus, traditional teacher-centered teaching should be replaced by teacher-assisted learning.

Course Description

Course Overview

This is a graduate-level course for students interested in construction management and information technology in the AEC industry. This course focuses on the skills and information needed to effectively use an existing BIM in plan execution for a building construction project. This is a project-based course where students gain knowledge on the implementation of BIM concepts throughout the life cycle of a building, from planning and design, to construction and operations.

Learning Objectives

This course is designed to provide construction management students with core concepts of BIM, the knowledge of implementing BIM as a process and as a new way of thinking throughout the project life cycle, hands-on experience with BIM software and the opportunity to develop international team collaboration and critical thinking through group projects and individual assignments. By taking this class, students will be able to (1) define BIM, (2) describe workflow in using BIM in the building life cycle, (3) describe the process of model-based cost estimating, (4) perform 4D simulations, (5) apply BIM to reduce error and change orders in capital projects, (6) evaluate the use of 3D point clouds to support construction and asset management, (7) perform building energy performance simulations, and (8) evaluate and communicate ideas related to the use of BIM in the building life cycle.

Course Organization and Instructional Approaches

Instructional approaches include lecture (topic instruction and lab tutorials), team-based learning (time-for-questions workshop, hands-on exercise, case study, group presentation, and discussion) and individual learning (reading assignments and synthesis report). An innovation of this course compared to previous efforts is that the teaching approach and evaluation principle are process-oriented, which means the emphasis is placed on understanding BIM as a new construction management process as well as its impacts on project success. BIM is not only a technology but also a methodology. Especially with information technology booming, BIM products are also advancing rapidly; mastering one or more software should not be the focus in BIM education in universities. Process-oriented approach encourages students to grasp the role of BIM in different project phases so that they know why this tool is used, how it improves the project performance, and how it can be further improved. For example, the model-based cost estimating module is designed to familiarize the students with the *recipes-methods-resources* approach, which is the basis of model-based cost estimation. This module was first offered using *Vico Constructor* and *Vico Estimator* along with paperback RSMeans (Waier 2010) in Fall 2010 and Spring 2011. To enhance the ease of use, *Assemble* was later introduced as an alternative quantity takeoff software solution in Spring 2013. In Fall 2013, students used *Assemble* along with the online version of RSMeans, which enables direct import of cost data from RSMeans to an estimation software or spreadsheet. Although different software systems have been used in different offerings of the class, the basic concept of BIM-enabled cost estimating remains the core of this module. The evaluation mechanism of lab-based assignments is also based on the students' discussion on the process and the understanding of tasks based on practice, rather than the result itself. The assessment rubrics were developed by the instructor for each assignment. As an example, Table 1 shows the rubric for the scheduling and 4D simulation assignment.

Course Structure

The course content is organized as learning modules covering various topics. Every module is composed of four sessions:

1. Topic introduction: Introductory lecture supplemented by additional reading assignments;
2. Lab session I: Step by step hands-on tutorial lead by a teaching assistant (TA);
3. Lab session II: Time for question workshop when students seek for help, ask questions, work in groups, and interact with other groups; and
4. Reflection and discussion-assignment delivery and presentation.

These modules provide students with core BIM knowledge, hands-on practice with the state-of-art BIM solutions, and collaboration experience with students from different countries with various backgrounds. All lab-based assignments are done in groups. At the beginning of the class, students form groups of three to four. Students are encouraged to create teams with varied industry experience levels and background. Detailed explanations of each session in the learning modules are presented as follows.

Topic Introduction—The goal of lectures is to introduce basic concepts of BIM to students, providing the necessary knowledge for them to effectively accomplish course requirements. Subjects such as model-based cost estimating, construction scheduling and 4D simulation, design coordination, construction progress monitoring with 3D point clouds and energy simulation are covered. In order to support, broaden, and strengthen knowledge on specific subjects, book chapters, articles, journal papers, and other documents are provided to the students as supplementary learning material. Lectures are presented by the instructor, with group discussions on various topics related to the class materials or assigned readings.

Lab Session I: Tutorial—In-class demonstrations of software tools are presented for all hands-on exercises. These step-by-step tutorials are intended to provide students with an introduction to the tools, not to fully train students on the use of tools. Students need to self-study in order to work effectively with the tools. This session not only provides student with hands-on experience with the state-of-art BIM solutions, but also trains them on self-directed learning.

Lab Session II: Workshop—These sessions are held in the lab allowing students to work in groups, exchange ideas with other groups, and solve issues they have on the assignments by discussing with classmates or the instructor or TA. Through these workshops, students are able to develop social learning skills and communication skills. Frequently asked question (FAQ) files are developed by the TA during the process to provide sufficient guidance to the students. These files are also stored as references for future course development. The FAQ file was continuously updated, as new questions were posed to the instructor or TA, and the latest version of the FAQ file was posted on the course website. Some examples of the FAQs are "How can I attach the same activity to different elements at multiple times without losing the attachments that are previously made? "How do I check the recipe assignments" and "How do I save the model in *Vico Constructor* as an .ifc file?"

Reflection and Discussion—Each group is required to submit a report summarizing their work and discussing the problems they had, how they solved them and developing a wish list for future technology improvement. Each team chooses one assignment to present during the course. This session is critical for applying process-oriented instruction. Students are encouraged to share and discuss their experience with software manipulation, the process

Table 1. Scheduling and 4D Simulation Rubric

Assignment	Competent	Somewhat competent	Not yet competent
First schedule	Logical and detailed schedule (activities considering who, what and where)	Logical schedule but not all activities are detailed as to who, what and where	Schedule not considering order of activities (e.g., columns before slab in same floor)
Fast-track schedule with sculpture installation problem	Logical and detailed schedule (activities considering who, what and where)	Logical schedule but not all activities are detailed as to who, what and where	Schedule not considering order of activities (e.g., columns before slab in same floor)
First 4D	All objects have a link to a specific activity in the schedule; objects were disaggregated in each floor to reflect the level of detail in the schedule	All objects have a link to a specific activity in the schedule; no disaggregation of objects in a single floor	Not all objects are linked to the schedule/several objects do not show up in the simulation
Fast track with sculpture 4D	All objects have a link to a specific activity in the schedule; objects were disaggregated in each floor to reflect the level of detail in the schedule	All objects have a link to a specific activity in the schedule; no disaggregation of objects in a single floor	Not all objects are linked to the schedule/several objects do not show up in the simulation
Report: schedule discussion	Discussion regarding selection of level of detail of each activity, stating assumptions and information used from estimating assignment. Discussion on resource balancing for fast-track schedule.	Limited or no discussion regarding selection of level of detail of each activity. Some assumptions discussed. Some discussion on resource balancing for fast-track schedule.	No discussion regarding selection of level of detail of each activity. No assumptions discussed. No discussion on resource balancing for fast-track schedule.
Report: 4D discussion	Discussion on possible ways of keeping track of an as-built schedule aligned with an as-planned schedule. Discussion on mapping process and limitation of the 4D system they used.	Mention that it might be possible to keep track of an as-built schedule aligned with an as-planned schedule, but no discussion on how. Only discussed mapping process.	No mention that it might be possible to keep track of an as-built schedule aligned with an as-planned schedule, but no discussion on how. Did not mention mapping process.

of accomplishing certain tasks, the benefits, and challenges of BIM implementation during the process, collaboration methods used among group members and suggestions for future improvements on the technology used. Some examples of the discussion points are "how to incorporate sculpture installation analysis in the 4D model," "what are some characteristics of a project that would benefit the most from a 4D system?" "discuss a wish list containing five to 10 items that you would like to have in an ideal 4D system," and "what should be taken into consideration when creating a BIM in order to obtain more accurate results in automatic clash detection?"

Five modules are developed for this course. In additional to the learning modules, a case study is required for each group to help them enrich the knowledge with real world examples. Industry professionals were also invited to give guest lectures, providing practical applications of BIM in real-world projects. Moreover, a synthesis report due at the end of the course motivates innovative and critical thinking on specific BIM-related topics. Details of the modules, case study, and synthesis report are presented in the "Course Assignments" section.

Course Assignments

Table 2 shows a summary of course evaluation items, deliverables and weights for the course in Fall 2011, which include individual assignment (e.g., assemblies estimate and synthesis report), group assignments (e.g., lab-based assignments and case study), one quiz and class participation.

Lab-Based Assignments and Learning Modules

The learning modules developed for this course were model-based cost estimating, scheduling and 4D simulation, MEP design coordination, 3D point clouds and energy simulation. As introduced above, each learning module contains one lab-based assignment. All necessary software, drawings, specifications, models, and instructions are provided. For the model-based estimating module, *Vico Constructor* and *Vico Estimator* were used to conduct the computer-aided estimation tasks in Fall 2010 and Spring 2011; *Assemble Systems* and *Autodesk Revit* were used in Spring 2013 and Fall 2013. For scheduling, Microsoft Project was used, with Primavera as an optional choice. *Autodesk Navisworks Manage* was used for 4D simulation and *MEP Design Coordination*. *Autodesk Photofly* (now called *Autodesk 123D Catch*) and *Autodesk AutoCAD* were used for the 3D Point Clouds module. *Autodesk Green Building Studio* was used for the energy simulation module.

Module 1: Model-Based Cost Estimating:. In this module, students are introduced to the concept of model-based cost estimating by automatically linking a quantity takeoff from a provided model to an existing cost database. Teams are responsible for estimating the cost of building columns, beams, slabs, walls, and windows for a section of a commercial building. Students start with an .ifc (buildingSMART 2013) file of the project and use blueprints as a reference for design specifications and generate an estimate for the given scope of a structure. For the practice of cost estimation, teams need to choose one element to prepare a full recipe by specifying construction methods, resources, and associated costs based on RSMeans (Waier 2010). In addition to an estimate, the groups are asked to discuss questions such as

- "What are the benefits and limitations associated with using *Vico Estimator* for cost estimating purposes?"
- "How did this tool improve the estimating task?"
- "What features of the system need improvement?"
- "What are the considerations you must make while using *Vico Estimator* to estimate, as opposed to paper-based estimating?"
- "At what point in the design process would the current version of this tool be most useful (i.e., is this tool more useful for 90% complete design versus 30%)?"
- "What construction environments would benefit most from this tool?"
- "What do you see are the opportunities and challenges of file-exchange between multiple software packages in the AEC industry?"

Module 2: Scheduling and 4D Simulation:. Because of the data-rich nature of BIM, the model serves as a repository of information and provides easy and anytime access to insert, extract, update, or modify digital data. BIM fosters a four-dimensional (4D) simulation by facilitating integration of 3D model with time. The 4D modeling provides a virtual reality environment and improves the ability of students to comprehend and learn construction processes. In this module, students are asked to use MS Project for scheduling and *Autodesk Navisworks Manage* 2012 for 4D modeling. In this assignment, students learn how to link activities to model components to visualize and analyze construction processes. They are asked to develop two schedules for the construction of slabs, walls, columns, beams and windows of a section of a commercial building. The first schedule should be created assuming that there is not a major time-constraint on the job site. The second schedule should be an improved fast-track schedule that aims at completing the project in minimum time frame. The second schedule should also contain activities and sequences associated with the installation of a sculpture. The students are asked to bring both schedules to a 4D environment and analyze the construction processes generated to identify any possible constructability issues in their schedules and improvement opportunities to deliver the facility in a shorter duration. The advantages and challenges of using 4D simulation for scheduling and planning are discussed in the reports and also in class on the presentation day.

Module 3: MEP Design Coordination:. MEP design coordination is the task in which BIM is currently most widely used in the AEC industry, usually lead by the general contractor (GC) and coordinated among the subcontractors. This assignment has

Table 2. Evaluation Summary Table (Fall 2011)

Evaluation type	Deliverable	Value (%)
HW 1: manual cost estimating	Individual assemblies estimate	5
HW 2: scheduling and 4D simulation	Group presentation + report based on lab assignment	10
HW 3: MEP design coordination	Group presentation + report based on lab assignment	10
HW 4: 3D point clouds	Group presentation + report based on lab assignment	10
HW 5: energy simulation	Group presentation + report based on lab assignment	10
Case study	Group presentation + report	15
Quiz	Quiz	10
Synthesis report	Individual report in the format of a conference paper	20
Class participation	Class participation (instructor's discretion)	10

students explore BIM-based clash detection using *Autodesk Navisworks Manage*. Through hands-on demonstration, the teaching module introduces how to use Navisworks to automatically detect clashes between trades, as well as analyze which of the automatically identified clashes are true positives. Students are quickly impressed by the instant check of clashes performed by the software; however, the objective of this module is to emphasize the truth that BIM as a tool is never perfect. The most challenging and time-consuming work for clash detection is the identification of true positive clashes. Professionals and researchers agree that MEP coordination using BIM leads to less rework during installation compared to the traditional 2D design coordination process which is inefficient and error-prone. At the same time, it is also important to notice that automatic clash detection process using BIM provides a more complete identification of clashes, but with the cost of false positives (Leite et al. 2011). This module not only presents the fundamental effectiveness of automated clash detection, but also points out the presence of false clashes and forces students to think critically and not to blindly rely on technology. The precision and recall methodology of evaluating the performance of clash detection is introduced to the students (Leite et al. 2011).

Module 4: 3D Point Clouds:. This is a new module developed for the class in Fall 2011. This assignment has students explore *Autodesk Photofly* (now called *Autodesk 123D Catch*) software package to generate 3D models from 2D photographs. The students are asked to take photographs of two structures on campus using a handheld digital camera. The photographs are then imported into Autodesk Photoscene editor to generate a draft mesh. The students use the generated models to create the envelope of a specified element in the two structures, set the scale of the models, and then compare the dimensions that they get from the model with the actual dimensions of the element. This enables them to analyze the accuracy of the modeling process using photographs. Finally they import the models into *AutoCAD* and generate animations of the 3D models. While completing the models, the students are asked to describe the process of generating a 3D model using *Autodesk Photofly* highlighting the benefits and limitations of the modeling process, comment on the number of photos taken, compare the level of effort required to generate the two models and the camera setting used. They are also asked to compare the benefits and limitations of such a tool with that of a laser scanner, comment on the accuracy, give improvement suggestions for the system, and discuss what types of construction environments would benefit most from this tool.

Module 5: Energy Simulation:. In this module, the teams are asked to perform building energy simulation and conduct energy consumption analysis using Autodesk's Green Building Studio (GBS) on an existing building. Teams are responsible for exploring a design strategy to improve the energy efficiency of their assigned building and reduce the energy cost by at least 20% as compared to the base model. The students optimize the energy performance by changing the properties of roof, wall, or glazing, and evaluate which would be a better investment for the building owner in terms of energy savings. The evaluation of this assignment is not based on the final percentage of saving that the team achieve but the process of analysis and their learning from this energy simulation process described in the report.

Case Study

The case study provides students an opportunity to connect and communicate with industry professionals, learn from the practical experience and strengthen the knowledge learned in class with real world practices. Students are asked to directly contact, with the support of the course instructor, one company and develop one case study on a project that utilized BIM in any way. The questions they need to discuss include, but are not limited to: what challenges the project team faced which led to the use of BIM, what technologies were used, why were these technologies pertinent to the problem they were addressing, how was BIM implemented in the project and in which phase of project life cycle, how did these technologies facilitate project success, were there any measurable improvements, and what challenges were faced in BIM implementation. The groups address these questions by interviews, site visits, and project document analysis.

Synthesis Report

Students choose a topic discussed in class or any BIM-related topic of their choice, being it technical, managerial, case study related or a combination, to write a synthesis report in the format of a conference paper. It is an important opportunity to practice critical thinking, initiate their own ideas on BIM-related topics, and highlight their lessons-learned from this course. It also provides an opportunity for the students to conduct an in-depth and individual study on the topics they are interested in and develop academic writing skills. Students discuss their selected topics with the course instructor at the beginning of the semester and an outline and progress mid-semester. The final report is due at the end of the semester.

Course Evaluation

This course was first offered in Fall 2010 and has been offered and fully evaluated for five semesters, in Fall 2010, Spring 2011, Fall 2011, Spring 2013 and Fall 2013. Enrollment has been offered on a limited basis (23 in Fall 2010, 12 in Spring 2011, 22 in Fall 2011, 21 in Spring 2013 and 23 in Fall 2013). Students are mostly Master's students or Ph.D. students from the Construction Engineering and Project Management (CEPM) program, a graduate program in the Department of Civil, Architectural, and Environmental Engineering at the University of Texas at Austin. In order to keep a record of the student profiles and the learning outcomes of each semester, two surveys were conducted, one at the beginning of the semester and the other at the end of the course with a similar set of questions. The results of the survey are presented as follows.

Student Profiles and Experience Levels

Area of Specialization

Combining the results of five semesters, 72% of the students taking this course are from the CEPM program, 13% of students majored in Architectural Engineering, 7% are Civil Engineering undergraduates, 5% in Structural Engineering, and 3% in other majors such as Construction Materials or Mechanical Engineering. The main reason is that this is a graduate level course with a focus on using BIM to support decision making in construction management process. Including students with multidisciplinary background can add value to the course in terms of simulating real world situations and fostering students' ability to collaborate in multidisciplinary teams.

Industry Experience

As shown in Fig. 1, more than 78% of the students have professional work experience, most of which were intern positions. Industry experience helps students better understand the role of BIM in specific tasks and the benefits and drawbacks of the systems.

Previous BIM Experience

56% of the students did not have any BIM experience before taking this course. Among those who had knowledge about BIM, some

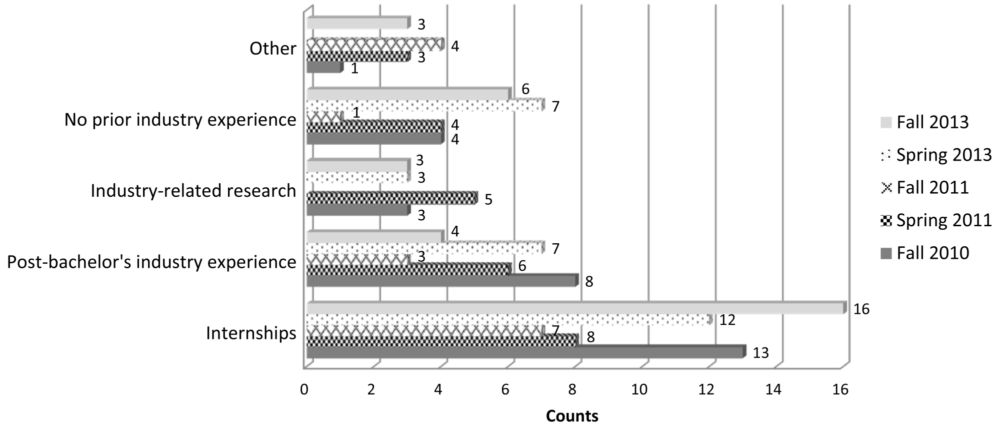

Fig. 1. Construction engineering industry experience

shared experiences include Revit modeling, 4D simulation, general introductory webinars and previous research or courses. The percentage of students without any BIM experience has dropped from 77% in Fall 2011 to 39% in Fall 2013. The instructor also observed that the level of knowledge of students changed throughout the years. More students are now familiar with BIM and understand BIM concepts at the start of the semester, as compared to the early offerings of this class.

Learning Outcomes

Over the course of a semester, students were able to (1) understand BIM as a process improvement rather than just a new software product; (2) describe workflow in using BIM in the building life cycle; (3) understand the process and gain practical experiences on performing tasks such as model-based cost estimating, 4D simulations, MEP design coordination, 3D point clouds generation with photographs and building energy performance simulations; (4) evaluate the use of BIM to support construction and asset management; and (5) evaluate and communicate ideas related to the use of BIM in the building life cycle.

The students were asked to define BIM at the beginning of the course and refined it at the end of the course. Results were synthesized to compare the differences of the students' understanding of BIM before and after taking the course. Based on the survey results, the majority of students were able to understand that BIM is a process or method rather than simply a modeling tool. Table 3 shows the result comparison from one semester (Fall 2010). 59% of the students were able to understand BIM as a process at the end of the course. Similar improvements were also observed in other semesters.

The major misconception is considering BIM as a set of computer programs or software systems or 3D modeling tool. As the recognition and accessibility of BIM is increasing in the AEC industry in recent year, this trend is also reflected in the class survey results throughout the five offerings of this course. For example, in Fall 2010, 77% of students considered BIM as only a modeling tool. However, the percentage has gradually decreased throughout the years (40% in Fall 2011, 37% in Spring 2011, 14% in Spring 2013 and 8% in Fall 2013). In Fall 2013, 52% of the students already understood BIM as a process before taking the course. More benefits of implementing BIM were recognized and fewer misunderstandings were found.

Regarding each module, rubrics were used to assess student attainment of learning objectives. Table 1, shown previously, is the rubric used in the assessment of the scheduling and 4D simulation module. The most common limitations in student work for this module were related to (1) fast-track 4D with no disaggregation of the slab object; and (2) scheduling report section with limited discussion on level of detail of each activity.

Student Assessment and Recommendations

For course evaluation and improvement purposes, students are actively involved in the course development. They state their expectations for this course at the beginning of the semester. The most commonly cited expectations include (1) hands-on experience of BIM application; (2) better and in-depth understanding of BIM; and (3) knowledge of practical application of BIM in real projects. Based on the course assessment at the end of the semester and informal conversation between the instructor and students, those expectations were well addressed in the course. At the end of

Table 3. Result Comparison on BIM Definition by Students (Fall 2010)

Definition	Start of the semester	Response rate (%)	End of the semester	Response rate (%)
BIM is	4D/5D/nD modeling	77	A process/concept/collaborative method	59
	A digital management tool	14	A model-based information management system	23
	A software	5	The digital representation with parametric data	12
	An assembly of databases	4	4D or 5D modeling tool	6
BIM can	Integrate building information	41	Cost estimating, MEP detection, scheduling, 3D visualization and planning	43
	Facilitate management in project life cycle	27	Facility management, energy analysis and increase constructability	25
	Run simulation and clash detection	18	Better communication, trade integration and data transparency	18
	Improve evaluation and decision making	5	Others (intuitive decision making, data storage, faster response to RFI and more computing power)	14
	Cost and schedule control	5		
	Facilitate preconstruction planning	4		

the semester, students are asked to provide suggestions for future course improvements. Their concerns and advice were taken into consideration of course modifications. In order to enhance the quality of the course, minor changes were made every semester based on the learning outcomes and the student feedback. Some examples are as follows.

Module Modification

In order to reach a generally balanced work load for each lab-based assignment, the model-based cost estimating assignment was removed in Fall 2011 because students spent too much time navigating the software due to operational issues and software glitches. This module was offered again in Spring 2013 using another application (*Assemble Systems*). In addition, an energy simulation model was added to the syllabus upon students' request in Spring 2011, a 3D point cloud module was added in Fall 2011 and a Revit modeling module was included in Fall 2013. The experience shows that the following software applications are most appropriate for this course in terms of usability and learning curve: *Assemble Systems* and Autodesk Revit for cost estimating, *Microsoft Project* for scheduling and *Autodesk Navisworks Manage* for 4D simulation and *MEP Design Coordination*.

Case Study

The case study requirements were also modified based on students' suggestions. Groups are now asked to conduct one case study instead of two. The students should directly contact the company to obtain information on the project, which provides students a good chance to connect and communicate with industry professionals, and learn from real-world problems.

Quiz on Reading Assignments

Since most assignments are carried out in groups, a mid-term quiz was added to assess individual learning. According to the instructor's observation, the quiz helps differentiate students' performance on self-directed learning and facilitate group discussions in class on the reading assignments.

By considering student feedback in the course development and refinement, progress was observed in the survey results. For example, in Fall 2011, nearly 50% of the students indicated that the course organization is well-structured and does not need any further improvement. discussed above, several students' suggestions have been successfully adopted and other common suggestions include having more guest lectures, field trips, or other practical exposure to BIM use in live projects, or introducing more software applications and techniques in the class. Students' suggestions will be carefully considered and the course will be continuously improved to accommodate evolving needs.

Industry Perspective

While the emergence of BIM is stimulating a strategic and cultural shift in the AEC industry, AEC companies and owners are looking for employees who have considerable knowledge of BIM. University education provides great opportunities for students to gain basic knowledge of BIM before they enter the job market. A better understanding of the industry needs in terms of BIM education can help educators develop their BIM course in the direction that will benefit industry. Therefore, a survey was developed to elicit industrial expectations for Construction Engineering and Management (CEM) graduates in terms of BIM knowledge. The survey was sent to the Austin BIM Peer Group, guest lecturers of the BIM class, Engineers at the United States Army Corps of Engineers (USACE). A total of 33 responses were received. The respondents include owners (9%), design firms (31%), general contractors (27%), subcontractors (9%), and others (24%; e.g., the federal government). The average year of the companies' history is approximately 78 years. Respondents include CAD/BIM managers, BIM directors, BIM coordinators, senior project managers, client executives and lead architects.

In the survey, the respondents were asked to check all BIM knowledge requirements of their future employee as a BIM manager/engineer and a project manager. The results are shown in Fig. 2.

Based on the survey results, a BIM manager/engineer is required to understand the general concept of BIM and how it changes the work process, with the ability to perform data analysis with existing BIMs and use BIM as a visualization and communication tool. The ability to create BIM and hands-on experience of specific BIM software are also considered as important prerequisites for a qualified BIM manager/engineer. Other requirements include

- Understand construction trends and code issues;
- Improve interoperability and data exchange between different software and file types; laser scanning and surveying;
- Ability to facilitate to sharing and leveraging of models and information they contain to further traditional construction activities;
- Understand database and data structure; ability to use databases;

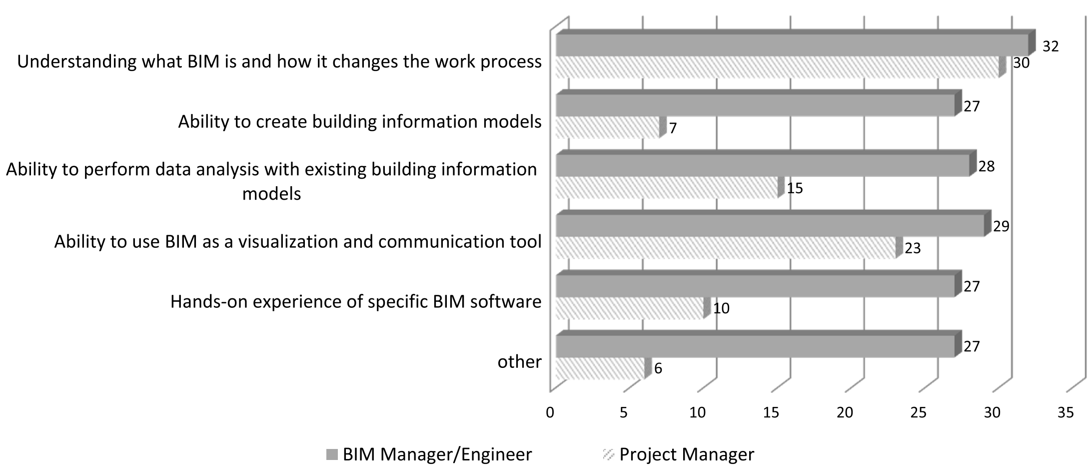

Fig. 2. BIM knowledge requirements

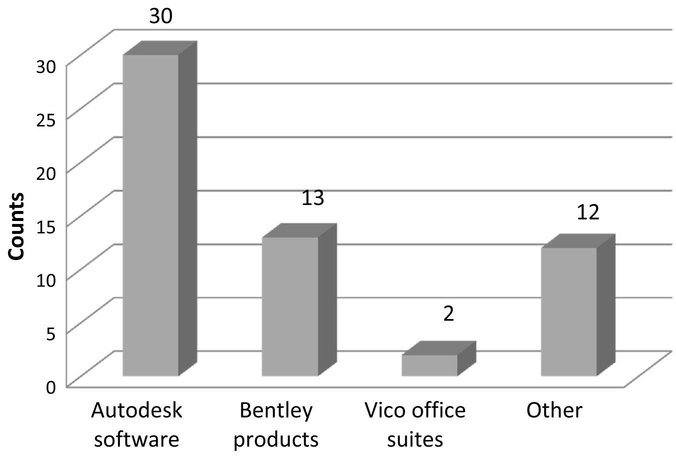

Fig. 3. Software packages used in companies

- Well-rounded knowledge of construction, understands the technical side of the business; and
- Basic understanding of the roles of all disciplines in the building design and construction industry.

Three to five years of experience is preferred for a BIM manager/engineer. A few companies only require one to two years of experience for BIM engineers, while the position of BIM manager requires more experience and skills, approximately five to 10 years.

A project manager (PM) may or may not directly use BIM but is also required to understand BIM and the working process involved or influenced by BIM. 91% of the respondents indicated that a project manager should understand BIM and how it changes the work process. 70% of the respondents indicated that a project manager should also have the ability to visualize BIM and use it for communication purposes. 45% of the respondents thought that it is necessary for a project manager to know how to perform data analysis with BIM. The skills of modeling and software navigation are not required for project managers in most companies. One respondent mentioned that "the PM of the future will be 'BIM Enabled', which means he/she should be able to leverage BIM to perform typical project management tasks; in other words, BIM has become the new and better 'pencil' for the construction manager." Five to 10 years of experience is recommended for a project manager.

Fig. 3 shows a summary of the BIM software packages used by the responding companies. Various Autodesk products (e.g., *Revit*, *Navisworks*, *AutoCAD*, and *Civil 3D*) are used in most companies, followed by Bentley products. Other BIM-related software systems mentioned include *Vela*, *Tekla*, *Synchro*, *D-Profiler*, *Google SketchUp*, *Assemble*, and *Solibri*. Results show that although the majority of AEC companies use Autodesk products, many companies also utilize other software systems. Future construction professionals need to grasp the fundamental ideas behind software systems in order to effectively communicate with various project participants. This way, regardless of the specific software solutions a company implements, the professional is able to adapt, since the fundamental knowledge from a project management perspective is independent of the software system.

Concluding Remarks and Lessons Learned

This paper documents the course design, instructional approaches, and learning outcomes of a graduate level course on BIM for Capital Projects. This course emphasizes learning BIM as an integral process which influences the overall project success from various aspects. Understanding the core value of BIM and its far-reaching influences with specific training on innovative and critical thinking is much more important than mastering a piece of software. Reflecting on the course over five semesters, the main lessons learned include (1) process-oriented teaching and learning, (2) modular structure of the course design, and (3) constant tracking of learning outcomes.

Process-oriented teaching emphasizes the importance of learning the *process* rather than the *product*, which provides students with active learning experiences by encouraging self-directed learning and critical thinking throughout the course. A combination of lectures, team-based learning and individual learning not only provides students with well-structured knowledge but also enables them to practice working and learning in a collaborative environment supplemented by self-reflections. For emerging technologies and trends as BIM, university education should put more emphasis on *why* and *how* in addition to *what* (e.g., Why is the BIM process better than the traditional process? Why is the software application good or not good? How can you improve it?). Students would benefit more by knowing how to learn and think with a tool than simply knowing how to use it.

The modular structure used in this course establishes a standard format for each learning module but also enables flexibility in terms of course content. Students get adequate training in each module through lectures, readings, lab tutorials, lab-based exercises and reflection and discussions, while the content of learning modules can be updated as required.

Also, tracking learning outcomes was important, so as to assess the effectiveness of course design and teaching approaches. Adjustments can be made accordingly to improve the course. Several changes were successfully made over semesters based on course evaluation results. The instructor also observed that the level of knowledge of students changed throughout the years. More students are now familiar with BIM and understand BIM concepts at the start of the semester, as compared to the early offerings of this class. The course content may need to be updated as the technology evolves.

Furthermore, familiarizing students with industry practice and expectations is also important. In addition to a well-directed course, case studies and guest lectures were also good ways for students to expand their vision and stimulate innovative ideas.

With continuous modification and improvement over five semesters, the proposed process-oriented BIM teaching approach was successfully implemented and well received by the students. The end-of-semester course evaluation and students' learning outcomes both demonstrate the benefits of this approach. In summary, this course can be considered a successful educational experience for teaching BIM in CEM programs. The process-oriented teaching approach, the modular structure of course design and lessons learned described in this paper can provide useful insights for educating next generation AEC professionals on emerging information technologies and innovations like BIM.

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