www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

BIM CURRICULUM DESIGN IN ARCHITECTURE, ENGINEERING, AND CONSTRUCTION EDUCATION: A SYSTEMATIC REVIEW

SUBMITTED: May 2016
REVISED: August 2016
PUBLISHED: September 2016 at http://www.itcon.org/2016/17
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SUMMARY*: In the past several years, Building Information Modeling (BIM) adoption has grown significantly in the architecture, engineering, and construction (AEC) industry. In response to this trend, the industry and academia realized that BIM education in university curricula is an important requirement for satisfying educational demands of the industry, and a notable body of research has reported strategies AEC programs implemented to incorporate BIM in their curricula. However, no study has comprehensively reviewed and synthesized the research on strategies adopted by educators. To bridge this gap in the literature, this paper presents a systematic review of research on BIM curriculum design in AEC education. The authors report on the trends of research on BIM curriculum design (e.g. methods, timelines, and contexts) as well as a synthesis of implemented pedagogical strategies with detailed discussions on their implications and effectiveness across different studies and contexts. These strategies address a variety of important pedagogical issues such as enrolment of students, optional or required BIM use, important competencies and skills, tutoring methods, industry engagement, designing assignments, and assessment methods and criteria. This synthesis shows that designing pedagogical strategies for BIM education is complex and challenging, and AEC programs need to make trade-offs between advantages and disadvantages associated with these strategies. The results also highlight the need for more diverse research designs and settings to bridge the gaps identified in BIM curriculum research to date. Finally, the authors present a literature-based framework of BIM curriculum design strategies as well as a set of recommendations that can be used BIM educators and researchers as a guide for designing or assessing their BIM curricula in future research.*

KEYWORDS: *BIM, Building Information Modeling, Education, Training, Curriculum, Review*

REFERENCE: *Hamid Abdirad, Carrie S. Dossick (2016). BIM curriculum design in architecture, engineering, and construction education: a systematic review. Journal of Information Technology in Construction (ITcon), Vol. 21, pg. 250-271, http://www.itcon.org/2016/17*

1. INTRODUCTION AND BACKGROUND

Building Information Modeling (BIM), as a set of technologies and processes, has now a pivotal role in the AEC industry as it enables project team members to virtually represents information required for design, construction, and operation tasks, from early inception stages of projects throughout life-cycle phases of constructed facilities (Eastman et al., 2011). BIM adoption rate in many regions (e.g. the U.S, the U.K, Europe, East Asia) grew significantly in the past several years (McGraw-Hill Construction, 2012, NBS, 2013, NBS, 2015, NBS, 2016, Jung and Lee, 2015) mainly because BIM can effectively address issues such as low productivity, poor functionality, rework, and waste at different project and organizational levels (Deutsch, 2011, Smith and Tardif, 2009). However, such an adoption has not been straightforward, because not only BIM technologies have significantly changed project delivery processes, but also these technologies are complex and evolving, and their implementation requires developing extensive technical and managerial skills. These costly processes of initial skill building, developing training programs, and technology change management are known as the most significant barriers to BIM adoption (Specialist Engineering Contractors Group, 2013, Ku and Taiebat, 2011, McGraw-Hill Construction, 2012, Rohena, 2011, Sacks and Barak, 2008). For these reasons, acquiring BIM skills at the university level is highly valued by the industry as it reduces BIM adoption costs and significantly improves career opportunities of AEC graduates (Wu and Issa, 2014, Russell et al., 2014, Ganah and John, 2014).

In recent years, there has been an increasing interest among AEC educators to integrate BIM into degree programs. A notable body of research has reported strategies AEC programs and instructors implemented in their curricula, challenges they faced, and educational outcomes they perceived. However, so far, no study has critically synthesized existing knowledge and findings on implications of BIM curriculum design strategies in AEC education. This study seeks to conduct this synthesis to assist in the transferability of findings of studies on this topic beyond their immediate contexts. The goals of this study are (1) to highlight trends and gaps in research on BIM education, (2) to critically extract, synthesize, and report existing knowledge on BIM adoption in AEC curricula, (3) to develop a framework of strategies for designing BIM curricula, and (4) to recommend potential areas of future research. This review fills the gap in the literature as it provides a synthesized assessment of strategies BIM educators have implemented in their courses, and it enables AEC degree programs to position or assess themselves in the bigger picture of trends in BIM curricula development. It also provides justification for implementing new strategies in AEC programs that have not yet adopted BIM or seek to adopt it more extensively.

2. RESEARCH METHOD

The authors designed the review method based on steps Denyer and Tranfield (2009) suggested for conducting systematic reviews: (1) question formulation, (2) locating studies, (3) study selection and evaluation, (4) analysis and synthesis, and (5) reporting and using the results (Fig. 1).

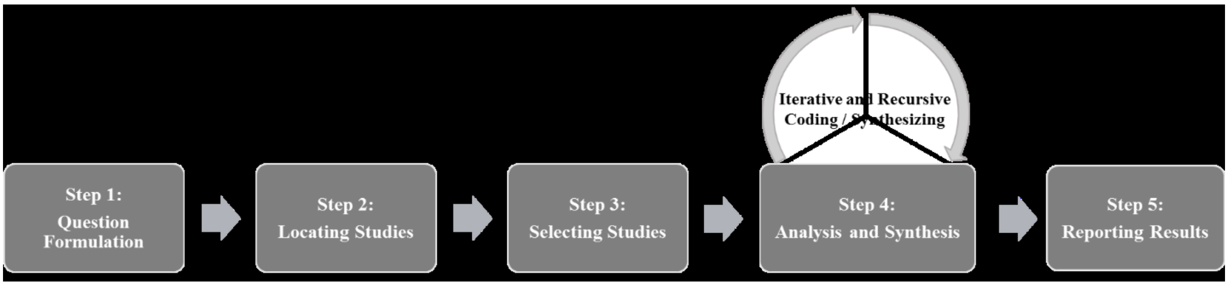


Fig. 1. Steps of Systematic Review in this Research (adapted from Denyer and Tranfield, 2009)

2.1 Step 1: Question Formulation

To provide a critical evaluation of existing literature and draw conclusions based on prior research, the authors first reviewed general research trends in the literature from the standpoints of the number of studies on BIM in AEC curricula, research methods, and context of studies (Day and Gastel, 2012). Second, the authors analyzed research findings on adopted strategies for integrating BIM into AEC curricula. The authors looked into interventions and their impact on curricula, course participants, and educational outcomes, and compared how these strategies relate to the industry's expectations of BIM in AEC curricula. The authors also analyze and synthesize advantages and disadvantages previous researchers reported about each strategy.

2.2 Step 2: Locating Studies

The authors investigated peer-reviewed bibliographic databases by using search strings (Denyer and Tranfield, 2009). The authors used two search keywords, "BIM" and "curriculum," in four major AEC research databases: American Society of Civil Engineers (ASCE), Elsevier, Emerald, and Taylor and Francis (T&F). The authors also included the Journal of Information Technology in Construction, and proceedings of Associated Schools of Construction (ASC) in this process as well because these venues publish technical papers on AEC education. This study covers papers published before March 2015. It is important to note that the choice of keywords and databases listed here, like other systematic reviews of this type, may pose limitation to the generalizability of findings on research trends.

2.3 Step 3: Study Selection and Evaluation

In order to assess the relevance of each study to the topic, the authors set inclusion and exclusion criteria based on contents of each paper. First, the authors identified and excluded manuscripts that did not report research on BIM in AEC Education (e.g. editorial notes, book reviews). Second, the authors reviewed the remaining manuscripts and selected those that discussed at least one of the following topics: (1) industry requirements and expectations of AEC graduates, (2) challenges of integrating BIM into AEC course, (3) adopted strategies for designing and implementing BIM-enabled courses in AEC curricula, and (4) advantages/disadvantages associated with BIM curriculum design strategies. As the authors incrementally evaluated and added papers from different databases to our analysis, a saturation point was reached, which signaled that there was little need for more sampling because new data only confirmed perspectives, categories, and conclusions in the reviewed literature (Suter, 2011). Table 1 presents the number of located and selected papers in each database and publication venue. A total number of 59 papers out of 375 papers were selected and included in the analysis.

Table 1. Number of Reviewed and Selected Studies and Their Publication Venues

Database/#Selected Papers	Journals and Proceedings	# Papers
ASCE (31 out of 90)	Journal of Construction Management and Engineering	2
	Journal of Professional Issues in Engineering Education and Practice	9
	Journal Computing in Civil Engineering	1
	Practice Periodical on Structural Design and Construction	1
	ASCE Conference Proceedings	18
Elsevier (2 out of 75)	Automation in Construction	2
Emerald (1 out of 14)	Journal of Engineering, Design and Technology	1
Taylor &Francis (9 out of 117)	International Journal of Construction Education and Research	6
	Engineering Project Organization Journal	1
	Architectural Engineering and Design Management	1
ITCON (2 out of 15)	Journal of Information Technology in Construction	2
ASC (15 out of 73)	Proceedings of Associated Schools of Construction	15
	Total	**59**

2.4 Step 4: Analysis and Synthesis

The authors analyzed each individual study based on questions and criteria formulated in step 1 (Table 2) and conducted an iterative and recursive process for coding and analyzing findings of the selected papers. This process enabled the authors to synthesize findings of individual studies and create a framework of curriculum design issues for integrating BIM into AEC courses.

Table 2. Question Formulation and Analysis Criteria for BIM in AEC Education

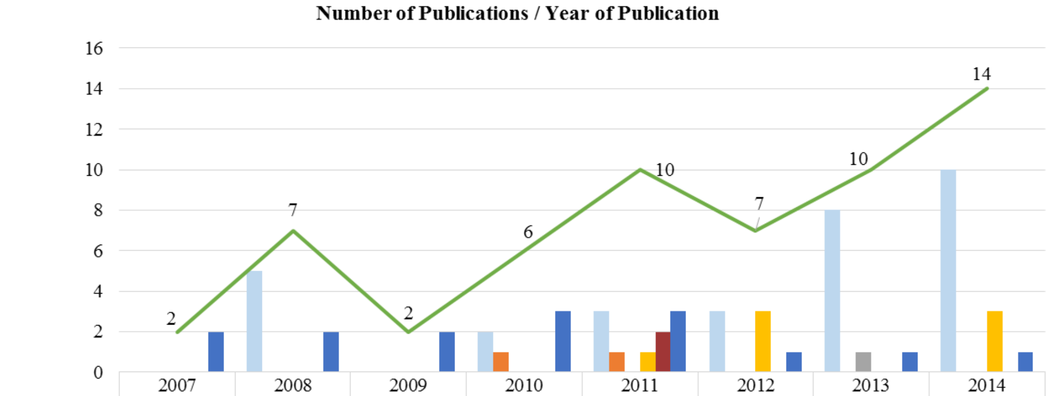
	Question 1: What are the trends and contexts of existing research?
Analysis Criteria	Number of Studies Publication Dates Research Methods Geographic Location (Country) Majors (Architecture/Engineering/Construction) Levels (Undergraduate/Graduate)
	Question 2: What are findings, arguments, and claims in existing research?
Analysis Criteria	AEC industry's perceptions and expectations of BIM in AEC curricula and graduates Adopted strategies for designing and implementing BIM-enabled courses. Outcomes, advantages, and disadvantages associated with each adopted strategy. Challenges in implementing strategies and integrating BIM into AEC curricula and courses.

2.5 Step 5: Reporting and Using Results

Per our literature review methodology, a review paper needs a topic-specific structure for summarizing and presenting findings (Rosnow and Rosnow, 2011). Accordingly, this paper first presents the results of research trend analysis as well as identified gaps in the research methods and designs (Question 1 in Table 2). Next, it reports the critical synthesis of curriculum design strategies as well as the advantages and disadvantages associated with them (Question 2 in Table 2). Finally, the authors present conclusions and recommendations for future research.

3. FINDINGS-PART I: REVIEW OF RESEARCH TRENDS

As shown in Fig. 2, the authors of this review found a growing trend of research on BIM in AEC curricula. As conferences are major publication venues for papers on this topic, a possible explanation for the dip in 2009 is that the number of conferences (especially ASCE conferences) in 2009 was fewer than other years. In this dataset, 45 out of 59 studies were conducted in the U.S (Fig. 3). This aligns with the fact that this study consists of papers written in English, and 55% percent of the papers were presented in conferences held in the U.S. In addition, this growth corresponds to the surge of BIM adoption in the U.S over the same time period. As BIM adoption rate is significantly growing outside of the U.S. more recently (McGraw-Hill Construction, 2014), the authors expect to see more scholarly research on BIM in education from other countries in near future.



	2007	2008	2009	2010	2011	2012	2013	2014
ASCE	0	5	0	2	3	3	8	10
Elsevier	0	0	0	1	1	0	0	0
Emerald	0	0	0	0	0	0	1	0
T&F	0	0	0	0	1	3	0	3
ITCON	0	0	0	0	2	0	0	0
ASC	2	2	2	3	3	1	1	1
Total	2	7	2	6	10	7	10	14

Fig. 2. Number of Publications and Year of Publication

From the standpoint of research methods implemented in prior research, a majority of papers present case studies (39 out of 59 studies) (Fig. 4). This is followed by surveys (15 studies), which are mostly focused on industry participants' expectations of BIM education and the general status of BIM in AEC programs. This paper summarizes these studies to determine the current strategies for integrating BIM into AEC curricula, and it can support future surveys among educators to study educational strategies and analyze the achieved level of success.

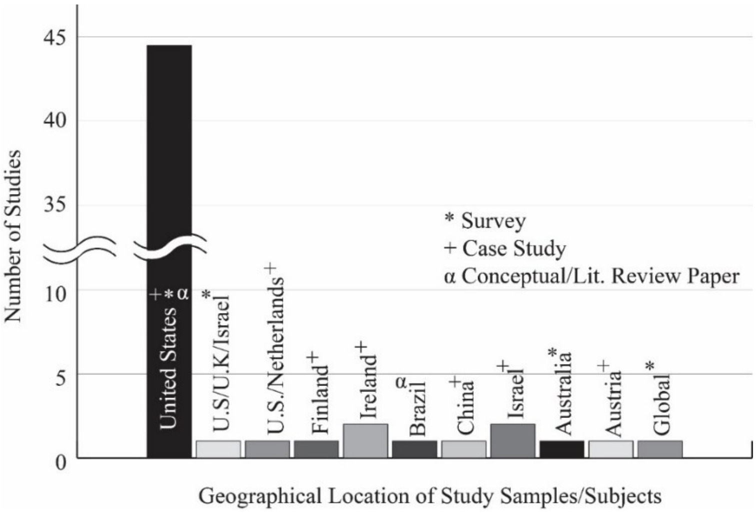


Fig. 3. Geographical Location of Studies

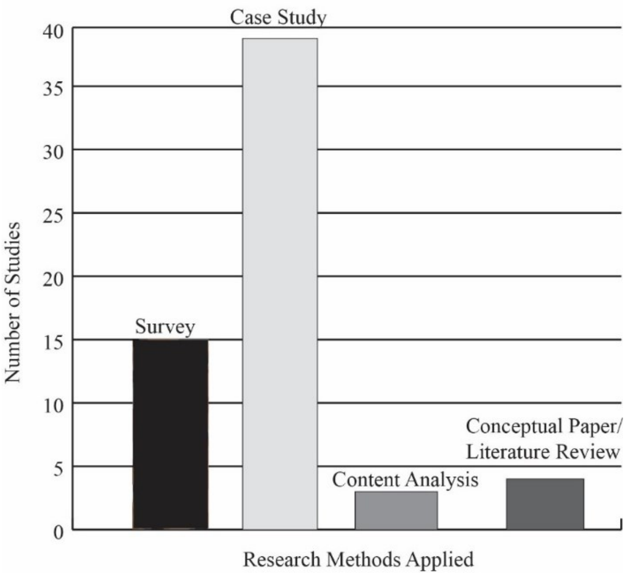


Fig. 4. Research Methods Used in Prior Research on BIM in AEC Curricula[1]

In this review, case studies of BIM curriculum design in undergraduate courses is significantly larger than the cases of BIM curriculum in graduate courses (38 cases vs. 7 cases) (Fig. 5). Since post-graduate level BIM courses have their specific challenges (such as diverse educational backgrounds, work experience, and exposure to BIM technologies among students), reporting case studies of graduate level BIM courses is a gap in the literature that could be addressed with further studies. There is a need to determine how AEC programs can provide graduate students with more advanced education than undergraduate students, as expected from both the industry and academia (Lee et al., 2013, Sacks and Pikas, 2013). Furthermore, 29 cases (65%) report on BIM

[1] Two studies that triangulated content analysis and survey methods were counted both categories.

integration into civil engineering and construction management courses[2], while 16 cases (35%) report on BIM in architecture, architectural engineering and building science courses. This shows that there is still a need for more research on the implications of educational strategies and their outcomes in BIM courses in architectural design and architectural engineering majors. Although research on design computing methods (e.g. parametric form generation) in architectural design has been growing, the number of studies on pedagogical issues of BIM-based collaboration and object-based platforms in architectural education is relatively small.

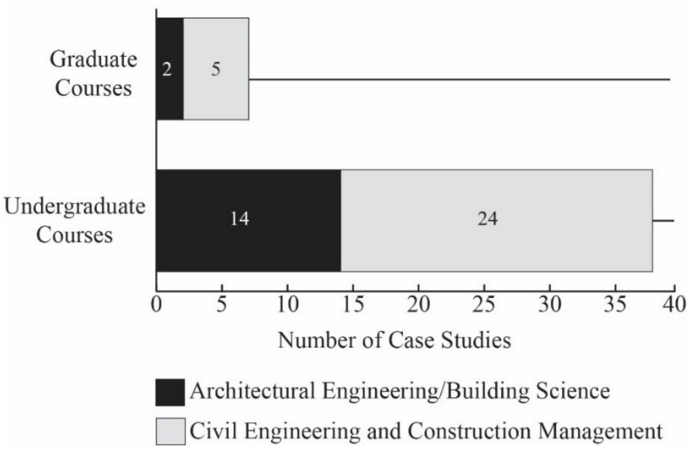


Fig. 5. Majors and levels of courses in case studies of BIM implementation in AEC curricula[3]

3.1 Chronological Development of BIM in AEC Education Scholarship

A few threads of research develop over the time span between 2007 and 2015. Early studies focused on making a transition from teaching CAD to teaching BIM in standalone courses (e.g. Berwald, 2008, Denzer and Hedges, 2008, Livingston, 2008). These were followed by studies that analyzed the impact of integrating BIM into core courses (e.g. Azhar et al., 2010, Clevenger et al., 2010, Sacks and Barak, 2010, Sharag-Eldin and Nawari, 2010). Survey analysis of industry participants' and academics' perceptions and expectations of BIM education has been another major theme on this topic since 2010 (e.g. Taiebat and Ku, 2010, Becerik-Gerber et al., 2011, Bhattacharjee et al., 2012, Wu and Issa, 2014, Gerber et al., 2015). Two major themes recognizable in recent BIM curriculum research include: (1) analyzing issues of realizing cross-disciplinary collaborative BIM processing (e.g. Kovacic and Filzmoser, 2014, Solnosky et al., 2014b, Solnosky et al., 2014a, Ghosh et al., 2015), and (2) in-depth analysis of innovative pedagogical strategies (adapted from other disciplines or originally designed) to improve educational outcomes of BIM course (e.g. Wang and Leite, 2014, Clevenger et al., 2015).

3.2 BIM Education and Industry's Expectations

The studies that used survey methods on this topic investigated one or more of the following areas: (1) industry participants' expectations of BIM education, (2) the status of BIM integration into AEC curricula, and (3) perspectives on future of BIM education in AEC courses. Table 3 presents a summary of information on the survey studies (e.g. sample size, characteristics of samples, research goal). Herein, the authors present a synthesized summary of findings and implications of these surveys.

According to the literature, whether or not technical BIM skills are more important than conceptual BIM knowledge for AEC education is still an open question. According to Wu and Issa (2014), industry professionals rank BIM software skills as the most desired learning outcome of BIM education at the university level. However, others found that BIM concepts and BIM process knowledge are considered more important than

[2] It is important to note that the authors mapped civil engineering and construction management together because, in most papers, either these two majors were analyzed together or construction engineering and management was a track under civil engineering majors. As these majors may vary greatly from one region, nation, or university to another, the collected data do not represent the differences between these two majors.

[3] Two studies covered both graduate and undergraduate CEM courses, and two studies covered collaboration of CEM and AE students in integrated studios. The authors counted these studies in both categories as applicable.

software skills for AEC graduates because BIM technologies are continuously evolving and mastering them in a BIM course is not effective for long-term BIM implementation (Dossick et al., 2014, Sacks and Pikas, 2013, Ku and Taiebat, 2011). Despite these conflicting findings about the relative importance of BIM concepts and software skills, most scholars and professionals, though to varying degrees, recommended that BIM instructors cover both technical and conceptual skills in their courses.

In addition, some of the surveys found that industry participants believed that socio-technical BIM skills, such as collaborative and interdisciplinary BIM processes, are as important as BIM concepts and software skill and that there is a need to integrate such competencies to the core AEC topics to prepare students for BIM implementation (Dossick et al., 2014, Gu and London, 2010). Accordingly, current deficiencies in BIM education, as reported in the surveys, include the lack of understanding of inter-disciplinary collaboration in BIM, lack of experience in BIM-enabled projects, and lack of understanding of work-sharing and BIM-based communication (Wu and Issa, 2014). In contrast, when surveyed, instructors believed that interdisciplinary BIM processes are best covered in internships and professional practice since AEC programs are not able to satisfy these varying expectations of BIM competencies within current curriculum requirements (Sacks and Pikas, 2013, Wu and Issa, 2014).

While Becerik-Gerber et al. (2011) found that there is not clear pattern among AEC programs regarding how and when BIM is integrated into AEC curricula, more recent studies suggest a convergence around how and when to introduce BIM concepts. What appears to be emerging is that the expected level of BIM competency for undergraduate students is recommended to be at basic and intermediate levels (understanding and applying), while for graduate-level courses, Sacks and Pikas, 2013 and Joannides et al., (2012) recommend that BIM competencies be more demanding (analysis, synthesizing, and evaluation). Many studies agree that undergraduate students need both technical and managerial skills, and Lee et al. (2013) recommend that general knowledge and general operations are covered early in a curriculum, while specialty BIM uses, collaboration, and integration are topics for senior-level courses. However, Becerik-Gerber et al. (2011) found that there is no consensus among AEC programs regarding how and when BIM should be integrated into AEC curricula. These questions require more in-depth investigations in future research.

In regard to the status of BIM in AEC courses, findings of Becerik-Gerber et al. (2011) showed that the coverage of required BIM courses in undergraduate programs is more than graduate programs. However, in more recent surveys from Gerber et al. (2015) and Dossick et al. (2014), scholars reported a shift towards graduate programs. From Gerber et al.'s study, among a sample of 115 AEC programs (51% architecture, 30% engineering, and 19% construction) around the globe, the percentage of graduate level programs that offer BIM courses is higher than undergraduate programs (57% vs. 35%). Dossick et al. (2014) analyzed syllabi of courses only in CEM graduate programs (47 accredited programs in the U.S.), and showed that only 14 universities (30%) offered graduate-level BIM-enabled courses. Despite the inconsistency of numbers across these studies, which is a result of research designs and sampling methods (see Table 3), this combination of findings supports the fact that there still appears to be a need for offering more BIM courses as a requirement for AEC degrees at the both graduate and undergraduate levels in the studied contexts as many programs still do not include BIM coursework.

To determine BIM educational requirements, a few studies analyzed contents of BIM syllabi and BIM-related job descriptions. Their results corroborate the survey findings. For example, Barison and Santos (2011) analyzed job descriptions for BIM-related positions in AEC companies. They found that teamwork, communication skills, and analytical thinking are as important as skills in using BIM tools, knowledge of BIM workflows and standards, and BIM coordination. Sacks and Pikas (2013) compared the contents of 18 CEM course syllabi against industry expectations and found that although the best-practice CEM curricula can satisfy most educational expectations of the industry, there is still a need for covering BIM process management aspects (e.g. contracting and collaborative change management) in the curricula. Table 4 presents a summary of the studies that used content analysis in their research.

Taken together, knowledge on BIM concepts, technical skills in BIM tools, BIM-enabled collaboration, and the integration of AEC disciplines are complementary to each other, and they have a synergic effect on BIM learning. Based on this literature review, the authors conclude that in AEC education these BIM competencies should be aligned with core AEC topics to provide the best educational outcomes. Additionally, due to the low BIM adoption rate in AEC degree programs, there is still a need for offering more BIM courses in AEC curricula at both graduate and undergraduate levels.

Table 3. Summary of Survey Studies on the Topic

Study	Survey Population	Sample Size	A	B	C	Topics of Interest
Johnson and Gunderson (2009)	ASC Affiliated Programs (U.S.)	43	■			Status of educating students in regard to recent trends in AEC
Sabongi (2009)	ASC Affiliated Programs (U.S.)	45	■	■		Status of BIM in graduate courses and barriers to integrate BIM into curricula.
Gu and London (2010)	AEC Professionals (Australia)	21			■	Challenges the industry has faced for BIM implementation
Becerik-Gerber et al. (2011)	Department chairs and directors of AEC programs (U.S.)	101	■			Level of BIM integration into the current AEC curricula
Becker et al. (2011)	Construction and Owner Companies (U.S.)	64			■	Trends in construction industry and their implications for AEC education.
Ku and Taiebat (2011)	Construction Companies (U.S.)	31		■	■	Expected BIM knowledge competencies and skills from new hires - status of BIM use in the practice
Ahn et al. (2012)	Construction Companies (U.S.)	100			■	Competencies Required for Construction Graduates
Joannides et al. (2012)	AEC programs (U.S.)	43	■		■	Status and Expectations of BIM education in AEC programs (e.g. courses, students, faculties, topics, software)
Ahn et al. (2013)+	Construction Companies (U.S.)	8			■	Importance of different BIM uses, knowledge, and skills when making new hires
Lee et al. (2013)	Construction Companies (U.S.)	17			■	Status of BIM implementation, training, and software; Expectations from BIM Education
Sacks and Pikas (2013)*	Construction Professionals (U.S. and U.K)	34			■	Educational outcomes expected from CEM courses (undergraduate and graduate) on BIM competencies
Dossick et al. (2014)*	Construction Professionals (U.S.)	42			■	Relevancy of Core CEM topics to BIM concepts- Integration in graduate or undergraduate levels
Wu and Issa (2014)	AEC-Academics & Professionals (global)	120	■		■	BIM Adoption in the Industry and Academia – Comparing Opinions/Expectations of Two Samples
Gerber et al. (2015)	AEC programs (global)	115	■	■		Computing at Undergraduate and Graduate Level Courses (BIM as a sub-area in computing)

Note:

A: **Current Status of BIM in AEC education**

B: **Perspective on Future of BIM Education**

C: **Demands and Expectations (Required BIM Competencies)**

*** Triangulation with Content Analysis**

+ **Interview**

Table 4. Summary of Content Analysis Research on the Topic

Study	Analyzed Documents	Sample Size	Goal
Barison and Santos (2011)	Job descriptions/ads	31	Investigating Expectations of the industry
Sacks and Pikas (2013)*	Syllabi of courses in CEM programs	18	Investigating gaps between best-practice courses and expectations of the industry.
Dossick et al. (2014)*	Syllabi of courses in CEM graduate programs	47	Investigating Patterns and Level of BIM adoption in CEM graduate programs

* Triangulation with Surveys

4. FINDINGS-PART II: CRITICAL REVIEW OF CURRICULUM DESIGN ISSUES

The authors developed a literature-based framework of curriculum design strategies implemented for incorporating BIM into AEC curricula (Table 5). The balance of this paper provides a synthesis of the literature relevant to each set of strategies. The findings are accompanied by detailed discussions on the implications of these strategies for BIM education, advantages and disadvantages associated with them, and their impact on course participants and educational outcomes.

4.1 Incorporating BIM into Curricula

According to Clevenger et al. (2010), three strategies have been adopted for incorporating BIM into AEC curricula: (1) developing standalone BIM courses to cover different BIM uses, (2) updating existing courses with a focus on specific BIM uses for the core topic(s) of each course, (e.g. introducing 4D modeling in a scheduling course), and (3) a combination of both strategies along with a BIM-enabled capstone course. Previous studies suggest that offering standalone BIM courses without any follow-ups in other courses do not support students' long-term learning because students rarely find the opportunity to re-use BIM skills in different courses, and they do not retain software skills after learning and using them for a single course (Ghosh et al., 2013, Gier, 2008, Clevenger et al., 2010). Furthermore, a standalone BIM course can be disruptive because although BIM topics are associated to other courses, students experience a learning environment very different from other AEC courses (Wu and Issa, 2014).

Updating existing modules alone, as the second strategy, may not be effective either as Clevenger et al. (2010) and Sharag-Eldin and Nawari (2010) found that existing core courses cover a significant amount of information, leaving insufficient time for educators to cover the full potential of BIM in a class project. Furthermore, CAD and BIM impose additional cognitive loads to users, making the learning curve of computer commands more salient than that of the core topics (McLaren, 2008, Pikas et al., 2013). For instance, Pikas et al. (2013) reported that in a cost estimation course, students believed that their background in BIM significantly improved their learning experience, while students who had not taken a basic BIM course faced a steep learning curve for utilizing BIM tools. Despite these challenges associated with BIM modules in core courses, Livingston (2008) asserts that this strategy is still more beneficial than harmful if there is no other way for adopting BIM.

To address the limitations of the standalone course and the BIM modules in core AEC courses, Clevenger et al. (2010) recommend combining these two strategies as students can learn about general BIM concepts and skills in a standalone course, and that will prepare them for more advanced BIM concepts and skills in updated modules of existing courses. Additionally, students can also fully apply their BIM knowledge and skills in a capstone course. However, there are few challenges associated with this strategy. First, due to the requirements for maintaining accreditation status, AEC programs have a limited ability to modify their curricula to match the speed of advances in the industry (Sharag-Eldin and Nawari, 2010). For example, the current criteria of Accreditation Board for Engineering and Technology (ABET) do not support some essential BIM concepts (Hedges and Denzer, 2008), and although BIM can satisfy some accreditation criteria of The National Architectural Accrediting Board (NAAB) (Livingston, 2008), there is no explicit criteria regarding the appropriate level of BIM adoption in degree programs (Becerik-Gerber et al., 2011). Second, integrating BIM into AEC courses requires significant upgrades in classroom equipment and software/hardware infrastructure, followed by the needs for continuous technical support, maintenance, and logistics (Clevenger et al., 2010). It is not only because students need to use computers and tools, but also they need classrooms that facilitate team communication for improving interactions (Mathews, 2013a, Leicht et al., 2009, Dossick et al., 2012). Third, challenges associated with the capabilities and preferences of instructors would affect the selection of all aforementioned strategies (Pikas et al., 2013, Suwal et al., 2014, Sabongi, 2009). In summary, for standalone BIM courses or BIM modules in core curriculum courses, requirements of each course restrict learning opportunities of students, while for the combinational strategy, accreditation requirements and availability of resources are barriers that inhibit the wider adoption of BIM (Table 6).

Table 5. Curriculum Design Strategies for Incorporating BIM into AEC Courses

Curriculum Design Issues	Scope of Strategies
Incorporating BIM into AEC Curricula (Clevenger et al., 2010)	- Standalone BIM Courses - Updating Existing Courses - Combination of Both
Criteria for Selecting Courses for BIM Implementation (Pikas et al., 2013, Wu and Issa, 2014)	- Having design and/or management concepts - Selected courses cover all years of a curriculum - Industry Preferences and Known Career Paths
Enrollment of Students (Becerik-Gerber et al., 2012, Solnosky et al., 2014b)	- Required/Elective - Open /Closed Registration (interview by major/educational background)
Making BIM Use Optional (Mathews, 2013a, Pikas et al., 2013, Becerik-Gerber et al., 2012)	- BIM use being optional for students - Students being free to choose BIM platforms
Required BIM Competencies/ Level of Competency (Based on Bloom's Taxonomy) (Sacks and Pikas, 2013)	BIM Competencies: - BIM Processes - BIM Technology - BIM Application Competency Levels: - Know - Understand - Apply - Analyze - Synthesize - Evaluate
Pedagogical Strategies for BIM Concepts (Ahn et al., 2013)	- Instruction and Lecture - Reading Assignment - Case-Study Presentation by Guest Lecturers - Group Discussion - Field Trips
Software Tutoring Methods (Russell et al., 2014, Becerik-Gerber et al., 2012, Clevenger et al., 2010, Lewis et al., 2014, Taylor et al., 2008)	- Step-by-step Instruction (Virtual/Physical Setting) - Handouts- Reading Materials - Audio/Video Tutorials - Interactive Simulations - Day-to-Day Coaching
Industry Engagement/Faculties' Contribution (Solnosky et al., 2014b, Suwal et al., 2014)	- From the industry - Faculty Members - Guest Lecturer for Topic/BIM Use (from industry or from the faculties)
Types of Assignments (Settings) (Becerik-Gerber et al., 2012, Solnosky et al., 2014b)	- Individual/Team/ or Combination of Both - Vertical/Horizontal Integration of Students - Virtual or Local Setting for Team Work - Local/International Collaboration - Working on Real-World Problems or Educational Scenarios
Types of Assignments (Format and Content) (Shenton et al., 2014)	- BIM Use/Implementation Assignment - BIM Project Case Study/Interview - BIM Concept Summary/Narratives
Assessment Methods and Criteria (Becerik-Gerber et al., 2012, Solnosky et al., 2014b)	- Conventional Assessment by Instructors - Assessment by Invited Faculty Jurors - Self-assessment by Students - Team Assessment by Students - Peer-Assessment by Students - Assessment by Invited Professionals - Verbal/Written

Table 6. Constraints Associated with Strategies for Incorporating BIM into AEC Curricula

Internal Constraints (Educational Standpoint)	A	B	C
Lack of opportunity to re-use BIM in other coursework for retaining knowledge and skills (Clevenger et al., 2010, Gier, 2008)	■		
Specificity of core topics leaves insufficient time for covering BIM (Clevenger et al., 2010, Sharag-Eldin and Nawari, 2010)		■	
External Constraints	**A**	**B**	**C**
Demanding significant upgrades in classrooms/computer infrastructure (Clevenger et al., 2010)		■	■
Limitations due to requirements to maintain accreditation/No room in curricula (Sharag-Eldin and Nawari, 2010, Sabongi, 2009)	■	■	■
Constraints associated with capabilities and preferences of instructors (Pikas et al., 2013, Suwal et al., 2014)	■	■	■

Note:
A: Standalone BIM courses to cover different BIM uses
B: Updating existing courses with a focus on specific BIM uses
C: A combination of both strategies with a BIM capstone course

Although many studies have listed the BIM uses and BIM tools that educators incorporated into AEC courses, very few studies have reported the underlying criteria for prioritizing courses for BIM adoption. Pikas et al. (2013) recommended three criteria for selecting courses for BIM integration: (1) covering both design and management concepts, (2) addressing the logical sequence of building BIM knowledge and skills, and (3) covering all years of a curriculum (from freshman years to senior years followed by graduate studies). As some AEC programs cannot modify a whole curriculum for BIM integration (due to the external constraints outlined in Table 6), Wu and Issa (2014) suggested that programs can prioritize and select courses based on direct inputs from the industry and benchmarks of BIM career paths in the job market.

4.2 Enrollment of Students

Different strategies for enrollment of students in BIM courses have been implemented in AEC curricula. In some cases, BIM is integrated into core courses required for a degree (Clevenger et al., 2010), while in some cases BIM courses have been offered as elective courses (Lewis et al., 2014). Covering BIM concepts and tools only in elective courses would raise the concern that some students miss the opportunity to learn the minimum required BIM knowledge and skills. This is a valid concern since Becerik-Gerber et al. (2011) found that the number of AEC programs that offer elective BIM courses is significantly higher than programs that require BIM courses for a degree.

A challenge in graduate-level courses is that some students have the experience of working with BIM in their undergraduate studies or in the industry, while some students do not have such experience. Therefore, it is usually necessary to introduce some basics in order to keep the latter group on track, while it might not be very effective for the former group (Sharag-Eldin and Nawari, 2010). This issue might also be observed in undergraduate courses, in which students from different AEC majors or even non-AEC majors are new to BIM, and this negatively influences their learning and collaboration outcomes. For this reason, the individual needs of students with diverse backgrounds should be taken into account. Additional support such as office hours by teaching assistants or instructors, more inter-team sessions, and more BIM tutorials (videos/presentations) should be considered in such cases (Zhao et al., 2015).

In some BIM courses, course registration may not be open for all students from different majors and educational backgrounds. For instance, Becerik-Gerber et al. (2012) selected students through an interview process to ensure that interdisciplinary integration and collaborative BIM implementation could be realized in an elective course. Criteria for student selection were academic success, level of BIM understanding, and professional and teamwork experience. In another example, Solnosky et al. (2014b) asked for volunteers from different engineering tracks (construction, lighting/electrical, mechanical, and structural) to join design studios in order to build fully integrated teams. Taken together, AEC programs should consider: (1) if they offer BIM courses as required or elective courses, (2) how they address educational demands of students with varying backgrounds and majors, and (3) whether they restrict enrollment of students by applying criteria for selecting students for BIM courses.

4.3 Making BIM Use Optional in a Course

Prior research shows that some instructors allow for optional BIM use in core AEC courses. The authors of this paper found two formats for optional BIM use in AEC courses including (1) choosing between BIM vs. non-BIM options for delivering assignments, and (2) having the freedom to choose BIM software platform if using BIM is not optional. The first format has provided researchers with an opportunity to assess the impact of integrating BIM into AEC curricula from the standpoint of learning outcomes. For instance, four studies found that achievement scores of students in BIM-enabled courses were higher than scores in non-BIM courses (delivered by the same instructor). These studies analyzed students' scores on their understanding of construction documentation and results of quantity take-off (Kim, 2012), visualizing of structural elements and understanding of structures (Barham et al., 2011), communication of design ideas and identifying design issues (Mathews, 2013a), and results of a series of construction management tasks in a capstone course (Pikas et al., 2013). The challenge associated with optional BIM use is that students who choose non-BIM options miss the opportunity to improve their learning outcome and appreciate the best-practice BIM implementation.

Having the flexibility to choose BIM software platform has been usually implemented in design studios and capstone courses. Since there is a variety of tools available for design modeling and creating construction documents, Berwald (2008) suggested that students should have the freedom to select their choice of tools, and instructors should only specify requirements of deliverables. However, some studies indicate that BIM restricts design creativity and solution generation due to its strong visual representation (Dossick et al., 2012, Sebastian, 2011). For instance, Denzer and Gardzelewski (2011) observed that most students in design studios take a linear approach from manual sketching to BIM, and they stop sketching or drawing manually once they develop models in BIM. For this reason, the timing of BIM use should be managed carefully if students have the freedom to plan and use BIM (Mathews, 2013a). Denzer and Gardzelewski (2011) found that a cyclic process of design sketching and BIM modeling improved the alternative generation process because students could model and analyze design sketches with BIM tools and then print BIM generated views for continuing manual sketching and refining ideas.

As students used a wide range of CAD and BIM tools in design studios, the varying capabilities and affordances of these tools can also induce bias in the process and products of design (Berwald, 2008). As Denzer and Gardzelewski (2011) put it, instead of emerging from creativity of students, design solutions may become mere outputs of the functionality of tools. Stacey and Eckert (1999) asserted that these tools may impose certain decision-making orders, design development processes, and modeling structures, and they might make some aspects of a design more salient than others, resulting in negligence in identifying some design issues.

Optional BIM use would also raise the question on how instructors can effectively build BIM skills for students when students have the freedom to choose among different BIM platforms. For instance, Becerik-Gerber et al. (2012) reported in their case that students had the flexibility to choose from trending BIM tools, though instructors taught only a few tools, and self-learning was required for other tools students opted to use. In contrast, Solnosky et al. (2014b) provided their students with lectures, seminars, and day-to-day coaching as well as software tutorial sessions when students needed to work with different tools. Taken together, these studies suggest that instructors should determine whether the use of a single platform, instead of having the flexibility to choose among different platforms, could provide students with a more effective learning environment or not, and whether instructors have sufficient resources to support learning of various BIM tools in a single course.

4.4 Required BIM Competencies and Competency Levels

4.4.1 Prerequisites of BIM Learning

The issue of prerequisites of BIM learning has been a controversial subject within the field of BIM education. One of the main questions here is whether students need to learn manual engineering and CAD drawing (2D and 3D) before learning BIM. In early BIM adoption timeframe, McLaren (2008) found that learning manual drawing before using CAD enhances knowledge and skills students need for creative design (quality of design) and appreciating drawing conventions and standards (quality of drawings). However, as BIM became more prevalent, some studies suggested that learning 2D and 3D CAD is not essential for BIM education, though learning manual engineering drawing and fundamentals of BIM is still required. These studies reported that students will not need CAD once they learn to utilize BIM tools (Sacks and Barak, 2010, Russell et al., 2014), and use of BIM would increase to eventually replace CAD (Wong et al., 2011). Interestingly, Sacks and Barak (2010) found that students with CAD experience had more difficulties in learning BIM tools because they expected that processes, commands, and workflows in BIM to be similar to those of CAD tools. In contrast, some researchers suggest that learning manual sketching, reading and understanding drawings, working with physical models, and learning CAD are prerequisites for learning BIM (Kim, 2012, Weber and Hedges, 2008, Sharag-Eldin and Nawari, 2010). These researchers argue that, in BIM platforms, users still have to produce, read, and understand 2D views and drawings, while building these skills is time-consuming, and it should be independent of teaching BIM software platforms as BIM imposes additional cognitive loads to students.

Prior research suggests that students should appreciate that BIM is different from CAD because recent advances in parametric design and object-based information modeling have evolved the traditional CAD practice (Hubers, 2010). In parametric design tools, shapes and geometries have physical behaviors and quantifiable characteristics, and the relationships among components can be determined mathematically (Autodesk, 2005, Eastman et al., 2011). Object-based software platforms deal with properties and attributes of components, considering that each component can have different characteristics and contain technical information (Hubers, 2010). Therefore, scholars proposed that in contrast to learning CAD, learning BIM is not limited to creating shapes and geometries, and it requires a deep understanding of how buildings and their components work and relate to each other (CRC Construction Innovation, 2009, Woo, 2007). BIM users need to have more trade-specific knowledge than conventional CAD technicians as all information required for realization of buildings must be aggregated in BIM (Russell et al., 2014). To clarify this argument in an educational context, Wetzel (2012) reported that some students use BIM to create digital models of building components early in their freshmen year, but their models are not accurate and useful due to their limited knowledge of the trade. the authors of this paper conclude that manual engineering drawing, 2D CAD (and 3D CAD though not strongly supported), and basic knowledge about buildings and building components are prerequisites for learning BIM and understanding its fundamental concepts. As there are some differences in findings in the literature, this topic also provides a subject of future study to clarify the importance of these prerequisites for BIM learning.

4.4.2 Required BIM Competencies

The survey studies in this review showed that most industry professionals believe that BIM concepts, collaborative implementation processes, and skills in BIM tools are complimentary to each other, and that they should be integrated into AEC core topics to result in the best learning outcome. The review of case studies showed that some BIM courses (especially existing courses in which BIM itself is not the core topic) heavily focus on technical BIM skills (e.g. Barham et al., 2011). Courses that are limited to software skills in BIM tools do not address the real-world challenges of BIM implementation, and they were not effective in transferring essential BIM knowledge to students (Molavi and Shapoorian, 2012). Therefore, several have argued that BIM and CAD should be taught as a process which integrates technical concepts with technological, managerial, and collaborative aspects of project delivery, and they should not be underrated as a set of “picks and clicks” in software or a product of a specific tool (Field, 2004, Petrina, 2003, Wang and Leite, 2014).

Sacks and Pikas (2013) developed a framework of required BIM competencies and competency levels for CEM graduates and professionals. BIM competency groups included BIM processes (integrating BIM to core topics), BIM technologies (general operations), and BIM application (technical BIM use implementation). Competency levels in each group included knowing, understanding, applying, analyzing, synthesizing, and evaluating the aforementioned competency groups (defined based on Bloom’s Taxonomy; Bloom et al., 1956). Although Sacks and Pikas (2013) made no attempt to determine the relative importance level of each competency, some survey studies have reported that a number of BIM uses and competencies have been considered more important than others in the industry and in AEC degree programs. For instance, Gerber et al. (2015) reported that BIM authoring, energy simulation, BIM-based collaboration, model-based estimation, and 4D simulation are respectively the most taught BIM uses and competencies. Ku and Taiebat (2011) found that constructability and visualization are currently required BIM uses and model-based estimating and cost control are near term BIM uses, while facility management and energy analysis are longer-term priorities as they are less prevalent in practice. Taken together, the industry professionals considered several BIM uses and competencies, though ranked differently in different studies and disciplines, as the most important subjects in BIM curricula. Based on these studies, educators can prioritize courses for BIM implementation when there is insufficient room for a comprehensive integration of BIM into AEC curricula.

4.5 Pedagogical Strategies for BIM Concepts

According to Gier (2008), instructors in BIM-enabled courses need to help students engage in experiencing and constructing knowledge of BIM implementation workflows. This necessitates instructors act more as coaches and facilitators rather than as keepers of knowledge. Students should assume more responsibility in BIM courses, and instructors should carefully design course activities and materials to enable the self-construction of knowledge. Russell et al. (2014) suggested that case study presentations and discussions can enable students to learn and think about real-world challenges and solutions as well as standards and conventions in BIM implementation. Collaborative learning through team assignments, knowledge sharing platforms, and web-based media is also gaining momentum in BIM education. For instance, creating a blog or an online forum can enhance group discussion and peer learning opportunities, and it can raise stimulating topics for sharing knowledge and lecturing in class (Shenton et al., 2014, Mathews, 2013b).

4.6 Software Tutoring Methods

In AEC curricula, step-by-step instruction (as an instructor-led method), handouts and reading materials, audio - video tutorials, coaching, and interactive simulations (as self-paced methods) have been implemented as software tutoring methods. For choosing among the methods of tutoring, educators must consider the expected learning outcome of each course and availability of resources (e.g. amount time needed for preparing materials) because these methods have different effectiveness levels.

Instructor-led tutoring in the form of giving step-by-step instructions to students, in a virtual or physical class, has been the most common BIM tutoring approach in AEC degree programs. Nevertheless, according to the literature, learning a new software with instructions and a sequence of skill-building steps is very frustrating for students. Some students learn software very quickly, while some students need more time than other students to fully understand and pick up the steps (Lucas, 2014). This approach significantly impacts the students' perception of their learning experience in earlier sessions, and instructors have to resolve the issues each student faces during the instructions (Becerik-Gerber et al., 2012). Therefore, Lewis et al. (2014) suggested that instructors first demonstrate all steps at once, and then students follow step-by-step instructions.

Some studies have reported that students ask for self-learning tutorials as these resources enable them to plan and manage their skill-building process (Pikas et al., 2013), and they can refer to the materials whenever needed (Ghosh et al., 2013). If students have the flexibility to choose among BIM software platforms, use of self-learning tutorials is essential because instructors cannot teach several BIM software platforms in a class (Becerik-Gerber et al., 2012, Pikas et al., 2013). However, the use of self-learning materials alone would cause frustration among students, especially for students from non-AEC majors (Zhao et al., 2015). BIM software platforms are complex and self-learning materials cannot cover the whole range of roadblocks students face in BIM implementation (Lucas, 2014, Taylor et al., 2008).

Interactive software simulations can capture and integrate audio, visual, and textual instructions into a simulated environment of BIM platforms. Clevenger et al. (2010) developed software simulations for a few modules in construction management courses, and they listed their advantages as follows: (1) simulations can be used as standalone computer applications, independent of native BIM software platforms, mitigating the need for expensive software/hardware; (2) they reduce time and effort required for preparing materials and teaching software; and (3) they facilitate self-paced learning, and can be used in class and/or online. However, only in some modules students did perceive that these simulations are more effective than conventional tutoring methods (Clevenger et al., 2010, Clevenger et al., 2012).

In project-oriented courses, in which students have to use a wide range of BIM uses on a series of interdependent problems, coaching can help students with roadblocks and case-specific BIM problems. For instance, Solnosky et al. (2014b) provided day-to-day coaching to students in integrated studios as some students did not have much experience in BIM and studio projects were more complex than conventional BIM assignments. This approach is similar to on-the-job trainings, in which less-experienced BIM users apply knowledge and skills acquired from formal trainings to real-world projects under BIM experts' supervision (Kent, 2014, CRC Construction Innovation, 2009, Haron, 2013). Some instructors have used social networks and web-based forums for discussing technical BIM issues. These strategies enabled students to learn from conversations and also ask questions from their peers and instructors (Kang and Ryoo, 2012).

Very few scholars have so far attempted to statistically analyze the effectiveness of different BIM tutoring methods. Research methods and designs of educational studies from other disciplines may facilitate such experimentations. For instance, measuring achievement scores, performance on a follow-up or retention examination, attitudes toward tutoring methods, attitudes toward instruction, attitudes toward course topics, course completion rates, and the amount of time needed for instruction can show how different tutoring methods impact course participants and their learning outcomes (Kulik and Kulik, 1991). Furthermore, AEC scholars could also assess the effectiveness of tasks that other fields have found useful in developing their training programs. For instance, Yi and Davis (2001) from the business management domain found that adding retention enhancement activities to software training programs (e.g. coding and writing steps required for utilizing a software) can enhance general comprehension and cognitive learning outcomes of students.

4.7 Industry Engagement and Faculties' Contribution

Joannides et al. (2012) reported that more than 70% of faculty teaching BIM in the U.S. are either tenured/tenure track or adjunct faculty members. One issue that relates to tenured faculties is the reluctance of experienced faculty to adopt new BIM tools and to make changes to their existing syllabi (Sharag-Eldin and Nawari, 2010). Another issue is the lack of skilled BIM educators because most instructors are experts in using CAD platforms and/or CAD deliverables (Suwal et al., 2014, Pikas et al., 2013). For these reasons, there is a need to provide training opportunities for faculty members in order to align course topics and materials with BIM adoption status in the industry (Russell et al., 2014).

There is consensus among industry participants and educators on the need for financial, technological, and educational support from the industry to overcome the conservative and slow adoption of BIM in AEC education (Wu and Issa, 2014, Suwal et al., 2014). This support can be realized in many different forms. For instance, Suwal et al. (2014) organized a course development workshop in close collaboration with experts from the industry. It was a successful strategy to improve instructors' knowledge on BIM concepts, implementation processes, and strategies to integrate BIM to existing courses. Nationwide BIM competitions supported by the industry, like the case Li et al. (2013) reported in China, can be an impetus for spreading BIM education into university programs. Solnosky et al. (2014b) reported that in their integrated studio, financial support, informational support (bringing in real-world projects for assignments), and educational support in and out of the classroom (e.g. tutoring, instructing, coaching, and problem solving) the industry was essential for the success of the course. Molavi and Shapoorian (2012) suggested that partnerships with the industry would be valuable not only for learning BIM and integrated practices, but also for establishing professional relationships, internships, and employment opportunities. Students usually found these opportunities very helpful and informative, and prior research in AEC education suggests that such collaboration with the industry improves educational outcomes (Shenton et al., 2014, Li et al., 2013). However, only few studies have so far discussed details of industry-academic collaboration processes in BIM education, and this appears to be an opportunity for future research.

4.8 Types of Assignments: Settings

4.8.1 Individual Assignments or Team Assignments

Team assignments in BIM courses enable students to experience and learn collaboration, integration, and teamwork. Mathews (2013a) reported that these success factors of BIM implementation have some characteristics that can utilize the most effective learning activities such as "discussion group[s], practice by doing, and teach others with immediate use". However, Parfitt et al. (2013) found that "the team version of the capstone is not in the best interest of all students" in terms of comprehensive learning, because each student may focus only on one aspect of a whole assignment, i.e. divide and concur strategies. In order to avoid this issue, Li et al. (2013) argued that students should be re-grouped at each stage in order to experience a change in their role in other teams. Interdisciplinary capstones or teams can alleviate this issue as well, because students work in their own discipline while they exchange knowledge with students from other disciplines.

While the benefits of teamwork for learning outcomes are proven, realizing a collaborative environment can be very challenging. For instance, Solnosky et al. (2014b) faced a challenge in building teams and assigning team-members as some students were reluctant to work in such a configuration due to their unsatisfactory experience with other students. Kovacic and Filzmoser (2014) suggested that instructors should not expect student teams to organize themselves for collaborative work without any support for team-building, holding progress meetings, and preparing collaboration spaces because these issues can significantly affect team-spirit and joint-vision. Instructors should carefully consider capacity and configuration of computers and tables in collaboration spaces before designing BIM-enabled assignments (Parfitt et al., 2013). For integrated processes and teamwork, building a collaborative environment is crucial at the beginning because integrated processes require more work early in the process than conventional design processes, and students may perceive a low-productive and negative environment without appropriate support (Solnosky et al., 2014a, Dossick et al., 2012).

Ghosh et al. (2015) applied a vertical integration form of collaboration in a construction management BIM-enabled course, in which freshmen students had to collect and prepare information (BIM inputs) for senior-level students who had to use BIM for a site logistic planning assignment. Although freshmen students did not use BIM software in such a configuration, they developed an appreciation of collaborative information management and BIM implementation. Senior students were directly involved in all BIM implementation aspects. In another example of vertical integration, Becker et al. (2011) studied integrated studios in which sophomore and junior-level students utilized BIM respectively for structural and mechanical system design, and senior and graduate students had to consolidate all models from the perspective of a general contractor. This strategy can be successful from the standpoints of discipline integration and collaboration, use of different BIM processes and roles, and collaborative learning for students with different skill and knowledge levels (Zhao et al., 2015).

4.8.2 Virtual or Local Setting for Team Work

Offering collaborative BIM courses between two or more universities in a virtual setting is gaining momentum in AEC education. For instance, Becerik-Gerber et al. (2012) developed collaborative team assignments for students distributed in two campuses in the United States. Although students did not have consensus on the level of success of this strategy, instructors believed that it was successful in terms of collaborative BIM implementing and dealing with challenges associated with distributed teams (e.g. time-zone difference, task coordination, interoperability and data-sharing issues, and building interpersonal relationships through virtual worlds). AEC programs have also experimented global collaboration between students from different countries. Although this form of collaboration has some advantages over other teamwork settings in terms of learning about international construction, globalization, and BIM developments in different countries, it is very challenging in respect to scheduling and preparation across different schools, defining the scope of work, managing communication technologies, and language barriers (Liu and Kramer, 2011).

4.8.3 Working on Real-World Problems or Educational Scenarios

Some researchers argued that AEC education should not be detached from the realistic context of design and construction projects, and students must realize that professional practice requires multidisciplinary collaboration, decision-making in a dynamic environment, and processing information developed by other project participants (Becerik-Gerber et al., 2012, Pikas et al., 2013). AEC students should face the same medium (e.g. models, spreadsheets, documents) they will receive as professionals (Peterson et al., 2011) to learn that practitioners usually do not experience a perfect modeling or information-exchange process even in professional practice (Taylor et al., 2008). Instructors can provide students with information of real-world cases, or they can ask students to contact a pool of suggested AEC firms to obtain information (Peterson et al., 2011). In contrast to the advocates of real-work scenarios in BIM courses, Ghosh et al. (2013) indicated that by working on scenarios received from the industry, students may fail to develop a sense of ownership because they can only work on a limited scope of BIM use in a complex project, and this can impact their learning outcome. Overall, the literature is inconclusive as to whether or not real-world scenarios are more helpful than custom-tailored educational scenarios.

4.9 Types of Assignments: Format and Content

Using BIM tools for modeling and model analysis is the most common type of assignment in BIM-enabled courses. As mastering these tools requires a steep learning curve, Kang and Ryoo (2012) suggested that facilitation is required to motivate the need for BIM technologies among students (e.g. by inviting industry partners to the class). They also recommended that instructors make assignments fun and exciting. In one such example, Shenton et al. (2014) asked students to prepare commercials for selling BIM to different industry participants.

Previous studies suggest that design and planning problems in AEC courses should be simple to enable students to push the boundaries, make improvements in their deliverables, and create a balance between the process of developing a solution and the iterations of BIM use. However, students should still be exposed to a less predictable environment than a typical classroom to acquire critical-thinking abilities and practical experience that resembles their future work (Pikas et al., 2013, Peterson et al., 2011). For instance, to maintain a balance between these two requirements, Solnosky et al. (2014a) provided students in integrated studios with overall massing of a building as a starting point for a design project. Due to challenges in model development, interoperability, and interdisciplinary data exchange, students might become reluctant to collaborate or go through iterative design improvement cycles. Instructors must ask students to pro-actively develop a BIM Execution Plan to avoid such issues (Kovacic and Filzmoser, 2014).

Written assignments in BIM-enabled courses can take many forms. For instance, instructors asked students to summarize BIM definitions and BIM processes after reading technical papers (Ahn et al., 2013), or to prepare a “synthesis report” as a term paper that enables students to critically think about different aspects of BIM implementation, initiate their own ideas, and reflect on lessons-learned (Wang and Leite, 2014). In addition to the conventional BIM assignments (lab, presentations, and narratives), in some courses students were asked to interview BIM professionals from the industry to learn about their BIM implementation cases (Shenton et al., 2014). According to Wang and Leite (2014), case studies of BIM practices provided students with an opportunity to connect and communicate with professionals, learn from real-world experience, and strengthen knowledge they develop in the course. A case study can lead the students to investigate challenges or opportunities professionals faced that provide a basis for the use of BIM and determine the perceived benefits and improvements from BIM implementation. Data collection methods suggested for such case studies include interviews, field trips (observation), and project document analysis (Ahn et al., 2013, Wang and Leite, 2014). In summary, in this literature review, the authors identified a gap in the literature insofar as an appropriate balance between different types of assignments (e.g. BIM use vs. narrative or case study) in different settings (e.g. individual or team, virtual or local) has not yet been determined.

4.10 Assessment Methods and Criteria

In addition to conventional assessment by instructors, assessments by industry professionals, peer assessment, and self-assessment methods have been deployed in BIM courses. Assessments by industry professionals can improve the learning experience of students since professionals can bring new perspectives to BIM courses and make constructive comments on students’ deliverables (Shenton et al., 2014). For instance, Solnosky et al. (2014b) reported that in an integrated studio, industry professionals from different disciplines and organizations evaluated integrated teams, individual students, and the whole class throughout a semester. These evaluations can be verbal (formal or informal; face-to-face) and/or written (formal). Administering self-evaluation, team-evaluation, and peer-evaluation surveys is also recommended because assessment of students’ contribution to group work is challenging and students usually have concerns regarding commitments of their teammates (Solnosky et al., 2014b). These forms of assessment require developing inclusive criteria such as quality of discipline technical contents, quality of integration contents, graphics, clarity of work, demonstration of BIM, answering questions, presentation skills, and the amount of effort spent on projects and teamwork. Despite these insights, there is a general gap in the research on advantages, disadvantages, and challenges associated with assessment strategies and criteria in BIM courses.

5. CONCLUSION

In order to highlight the trends, advances, and gaps in research on BIM education in AEC curricula, the authors conducted a systematic literature review and critically extracted, analyzed, and reported existing knowledge on this topic. This enabled the authors to develop a framework of curriculum design issues, which served as the basis for synthesizing findings on BIM curriculum design strategies and finding gaps in the literature. The major limitation in this study, like other systematic reviews of this type, is the specific keywords (‘BIM’ and ‘Curriculum’) and bibliographic databases chosen for locating relevant studies (Denyer and Tranfield, 2009). It is likely that papers in other publication venues or using other search strings (e.g. ‘education’, ‘teaching’, and ‘training’) may offer other insights on this topic, though this study reached a saturation point in the analysis of more than 375 studies.

The authors present the major implications of this study for current practice and particularly for future research as follows. First, for some curriculum design issues, only few scholars have reported details of strategies they implemented, and some scholars only listed their strategies without discussing their impact on educational outcomes. Therefore, there is a gap in educational assessment regarding some strategies (e.g. assessment methods). There is an opportunity for further research with a narrower - yet more detailed - scope in almost all identified curriculum design issues. Second, further studies need to investigate how instructors and AEC programs can manage to mitigate externally induced challenges to BIM education such as accreditation requirements (Hedges and Denzer, 2008). Third, although online-courses and distant learning programs are gaining momentum in AEC education (e.g. Wu et al., 2013), no research has addressed pedagogical strategies for BIM-enabled courses in a distant setting, in which all student-instructor and student-student interactions and instructions are virtually mediated. Lastly, AEC scholars could use more diverse research designs and settings to bridge the gaps the authors of this paper have identified in the BIM education research trends. The authors specifically recommend conducting case study research on graduate-level BIM courses in different AEC domains and in different research contexts and locations. In conclusion, this study has shown that developing pedagogical strategies for BIM education is complex and challenging. Programs and instructors should consider many curriculum design issues and carefully trade-off between their advantages and disadvantages in educational outcomes. BIM educators and researchers can use the framework and discussions presented in this study as a basis for designing or assessing their BIM curricula.

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