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Incorporating BIM into the upper-division curriculum of construction engineering and management

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ABSTRACT

This pedagogical study aimed to demonstrate an updated Building Information Modelling (BIM) educational activity in CEM (i.e., construction engineering and management) students' final semester project. It investigated students' perceptions of BIM and the project. Student feedback provided insights for linking education to practice, for example, what caused differences between manual estimates and BIM-generated quantity take-off. Four different project deliverable options demonstrated how educational theories could be embedded in BIM education. The novelty of this study lies in two aspects: firstly, this pedagogical research views the CEM education at the curriculum level by linking earlier years' core CEM courses into the final project work; secondly, by designing four different options of BIM-related deliverables, subgroup analyses test how different factors, such as teamwork verse individual work, and BIM application level, could affect students' learning outcomes. The current study also led to more future explorations in research-informed teaching in the CEM curriculum.

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KEYWORDS
Building information modeling (BIM); BIM education; construction engineering and management; teaching and learning; digital construction; research-informed teaching

Introduction

BIM is gaining a wider application in the practice and training of traditional activities in construction engineering and management (CEM), such as cost estimating (Alzraiee 2020), and sustainable construction (Ferdosi et al. 2022). These scholarly outputs could be potentially adopted in BIM education to provide research-informed teaching and learning for AEC students, who will be future industry practitioners. Along with the fast movements of technological innovation in BIM-related applications in the AEC industry, researchers believe that the institutional education of BIM in AEC subjects is another critical part of bridging academia and industry. It was advertised by Ma et al. (2022) that BIM users in China should be offered more technical support. Other studies (e.g. Jin et al. 2017; Liu et al. 2019) conducted on BIM implementation in China also addressed the need for BIM training to establish the information-sharing platform. These studies in the context of the Chinese market all indicated the importance of equipping AEC graduates with the BIM capabilities needed for their future careers.

BIM-related courses have been launched in AEC education worldwide. In recent years, educators have adopted a variety of teaching and learning strategies for CEM students in applying BIM for their

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individual or group projects, for example, experiential learning in a capstone project (Zhang et al. 2019b), and project-based learning (Jin et al. 2018). So far, most of these BIM education-based studies have been emphasizing the framework or case studies of incorporating BIM in the traditional CEM courses, for example, quantity surveys. Different levels of learning for students, such as knowledge and intellectual aspects, practical skills, and transferable skills (Adamu and Thorpe 2016), have been targeted as teaching and learning objectives. However, there has not been sufficient demonstration of extending BIM in a single course (module) level to the curriculum or programme (course) level. Pikas, Sacks, and Hazzan (2013) suggested that BIM education should be upgraded at the programme level rather than staying in the single discipline.

Based on the review of existing BIM pedagogical studies and the limitations identified, research questions are proposed accordingly: (1) what interventions could be implemented to integrate prior CEM knowledge into deliverable options for upper-division CEM courses (e.g. final semester project in this study)? And (2) whether different deliverable options of the final stage CEM project would affect students' perceptions of this integration between prior CEM courses and BIM implementation towards the end of the curriculum? This pedagogical study introduces BIM in the final stage of the CEM undergraduate study to demonstrate how BIM could be extended from earlier years' courses to the final semester project. This study aims to incorporate theoretical and practical guides to offer students a variety of deliverable options in the final semester project. Students in the CEM programme of the university were guided to opt for one of the four different types of final semester project deliverables, namely full BIM application in a group project, partial BIM application based on teamwork in construction planning/scheduling, partial BIM application based on individual work of take-off estimate, and the traditional option of the research dissertation. Setting a variety of deliverable options allowed CEM students to choose the option that best fit their individual interests and needs, for example, developing their cost estimating skills with BIM. This study demonstrates student works in adopting BIM for their high-rise building construction projects.

This current study provides insights with a demonstrated case of how BIM could be better incorporated into the CEM curriculum, especially in the means of integrating the prior core courses into the final capstone project or other top division courses. It offers the latest pedagogical practice of BIM integrated with CEM activities, such as take-off estimate in the last stage of students' undergraduate career, which is considered the transition stage from studying in the CEM subject to their upcoming professional career.

Literature review

Research and practical outputs of BIM in construction engineering and management

BIM has been linked to other contemporary CEM practices such as off-site construction (Abanda, Tah, and Cheung 2017) and other digital technologies, for instance, Geographical Information System (Kim, Cho, and Zhang 2016). Aiming to extend BIM applications from new building design to existing buildings, Gimenez et al. (2015) reviewed existing literature of reconstruction of 3D building models from 2D drawings or plans using different techniques. It was suggested that no solution had yet been able to automatically generate 3D models from 2D plans/drawings (Gimenez et al. 2015). Nevertheless, various studies have been performed since then aiming to address the information management (Zou et al. 2019a) or data interoperability (Andriamamonjy, Saelens, and Klein 2019) between different information reservoirs, and across different project stages (Rodrigues et al. 2018). The information flow and the need for information exchange among project stakeholders require a common file exchange format and the collaborative software connections (Bellido-Montesinos et al. 2019). These information exchange needs are also a key when embedding BIM into other design and construction activities, for example, building sustainability assessment (Kang 2020). Besides the information exchange from the technical perspective (Chen, Jin, and Alam 2018), research gaps from the managerial perspective have been highlighted in other existing scholarly work, such as lack of legal aspects of BIM-involved contracts (Fan et al. 2019), and the need for BIM acceptance and readiness (Lee and Yu 2017). The practices and scholarly outputs of adopting BIM in AEC fields could be applied in the higher education curriculum. On the other hand, BIM in higher education could feed back to the AEC profession in addressing these technical and managerial issues. Tang, Jin, and Fang (2015) stated that BIM education could serve as a pre-career training to save future employers' investments on new employees' BIM skill development.

BIM education

Education plays a key role in the uptake of BIM to meet the increasing industry demand for university graduates with BIM skills or capabilities (Suwal, Jäväjä, and Salin 2014). Various studies (Pikas, Sacks, and Hazzan 2013; Puolitaival and Forsythe 2016) related to BIM implementation have indicated the urgency of bridging the institutional education and industry needs. For example, Oyewole and Dada (2019) revealed the training gap in industrial BIM adoption for design creation and coordination, as-built-modelling, clash detection, and space management. Santos, Costa, and Grilo (2017) found that while existing BIM-related research had significantly highlighted its technical development, such as information exchange and coordination in building design and construction, the education and training-related research in BIM had been under-represented. Jin et al. (2019a) further suggested the need for the continuing BIM pedagogical studies to fill the gap between CEM education and industry practice, for example, the interdisciplinary project-based teamwork as one teaching approach. In this respect, the study by (Olowa, Witt, and Lill 2021) expands upon the constructivist pedagogical approach mentioned above through its investigation based on experiential project-based learning of BIM. The premise is that student engagement with a BIM-enabled cashflow exercise developed for their construction investment course promoted BIM collaboration and professional practice experience within the AEC curriculum. This may serve to bridge the gap between industry and practice. However, as identified, the utilisation of real-world project data was limited owing to time constraints, and further investigation through a longitudinal study is required for a more objective evaluation of the data. The approach of project based learning is also discussed in the study by (Forsythe, Jupp, and Sawhney 2013) which investigates the teaching of BIM to Construction Project Management students in Australia. The vertical integration of real world, project based problems across each year of study allowed students to build and enhance their knowledge of BIM throughout their course.

Ghosh, Parrish, and Chasey (2015) proposed the adoption of a vertical integration pedagogy model for BIM education and suggested that vertical integration promoted an understanding of BIM as a collaborative tool for information management and developed a sense of value integration among upper (i.e. postgraduate) and lower division (i.e. undergraduate) students. The study by Zhao et al. (2015) also identified a gap between current teaching of BIM technology and the needs of the construction industry for prospective employees to be trained in the BIM collaboration process. The findings indicate that teaching technology as part of a BIM-integrated learning environment which integrates BIM processes, varied project roles, leadership development and collaboration, led to more successful course outcomes for students and better preparedness for industry.

As suggested by further studies, BIM technology plays a key role in the acquisition of knowledge and skills when used as a platform for interdisciplinary and international collaboration. For example, (Anderson, Dossick, and Osburn 2020) investigated the use of advanced tools for collaboration on a multi-disciplinary project involving students from number of international universities. It was found that exposure to advanced tools for collaboration and planning helped students to understand how globally distributed teams can work effectively together to meet with a defined set of student learning outcomes. The pedagogical approach adopted for this study follows that of the connectivism learning theory, whereby technology played a major part in the learning process when adopted for group collaboration and networking. A potential limitation of this pedagogical approach as concluded in the aforementioned study may be on the over reliance on technology as a primary teaching tool. These tools require adaptation and working around to ensure effective collaboration and avoid issues such as miscommunication due to language differences, which could lead to a straying from defined learning objectives. The approach of promoting the use of BIM tools as a method for BIM learning is further enhanced by the findings of the study by (Suwal and Singh 2018) which emphasise the provision of online learning platforms, hosting free tools and models which are aligned to specific learning outcomes. The use of technological tools for BIM education is further discussed by (Alanne 2016) who proposes a game-based learning approach for Building Services Engineering students in Finland. It is suggested that educational games may enhance the preparedness of building services students for industry by simulating real-life scenarios as learning assignments and encouraging the development of individual competencies for problem solving. However, the study does not elaborate on interdisciplinary collaboration amongst CEM students through the adoption of game-based learning.

A review of existing BIM educational studies (Shi 2019; Zhang, Xie, and Li 2019a) indicates that existing pedagogical research has mostly emphasized a single course within the engineering or CEM curriculum, but still lacks a continuous assessment of students' capability to adopt digital technologies for real-world projects in their later years' study or work. Moreover, there have been insufficient justifications of how educational theories have been incorporated in designing BIM educational activities. Aiming to address this gap based on these prior studies, this BIM pedagogical study focuses on adopting BIM in the last stage of CEM students' undergraduate study by embedding prior years' courses and educations theories (e.g. Chickering and Gamson 1987).

Students' perceptions of BIM

Numerous studies have targeted AEC industry professionals' perceptions of BIM updates in practice, especially related to the opportunities or drivers (Yang and Chou 2018), barriers (Olawumi et al. 2018), and critical success factors (Lin and Yang 2018). Collaboration (Eadie et al. 2013) among stakeholders is generally considered a key to successful BIM adoption. Zou et al. (2019b) extended these prior studies of BIM uptake from the industry professionals' perspective to AEC students' perceptions. Although it was indicated that students could gain some consistent views on BIM adoption as industry professionals did (Jin et al. 2018), students might also have different views on the challenges of implementing BIM due to less practical experience that they had (Zou et al. 2019b). Students' perceptions of BIM practice could be affected by various internal and external factors (Zou et al. 2019b), for example, their field of study. In a pedagogical study with students with similar academic backgrounds, Li et al. (2018) suggested that subgroups of students who chose different options of deliverables in the same discipline could be compared to their perceptions of the completed task, such as BIM final semester project in this study. Extending from these existing studies emphasizing students' perceptions and feedback following BIM educational activities, this study adopted the suggestion of Li et al. (2018) to investigate the effects of deliverable options on students' perceptions of final semester projects.

Materials and methods

This pedagogical study adopts a two-fold approach to demonstrate BIM incorporation in the final semester of the CEM undergraduate curriculum. The first part showcases the typical deliverables of students utilising BIM in the case study of high-rise building projects. Students' reflective thinking from their project report is also included to share their BIM experience. The second part of the study is based on a follow-up questionnaire survey to capture students' perceptions related to their final semester project.

Rationale of designing the four different deliverable options

In the newly updated final semester undergraduate project in CEM of this case study, students were asked to select one of the four options as their project deliverable. Before the start of the final semester project, researchers in this study agreed that although digitalisation in construction, especially BIM, would be largely emphasized, students should be given open options following their individual preference and their career development. For instance, students who had decided to continue their academic career in pursuing a graduate degree tended to opt for the research dissertation, which might or might not involve a BIM application.

In addition to keeping the traditional dissertation option, other factors considered in the pedagogical design of the final semester project emphasized the BIM-related deliverable, specifically, the individual BIM work versus team deliverable. It has been emphasized in multiple prior empirical studies of BIM implementation (Eadie et al. 2013; Liu et al. 2019) that collaborative teamwork is the key to successful BIM practice. Inspired by the industry practice and following the guide of practice-informed learning (GuidHE 2018), the teamwork option of adopting BIM as the digital platform was included. The rationale for researchers to have the teamwork approach was based on several existing education theories, including Chickering and Gamson (1987) and Bloom's Taxonomy Theory (Bloom 1956). Chickering and Gamson (1987) proposed a series of good practices for undergraduate education, including motivating students' active learning, providing timely responses to students' inquiries, and developing the reciprocity and cooperation among students. Bloom's Taxonomy Theory defined six hierarchy levels of the cognitive domain in teaching and learning, namely knowledge, comprehension, application, analysis, synthesis, and evaluation.

The teamwork option could be further divided into the bespoken full BIM application and a partial BIM application, the latter of which was based on a combination of BIM-generated automation and manual work. The full BIM application sub-group utilised common data environments (BSI 2013) with various team members sharing information in a collaborative space. The existing digital facilities could support the full BIM application by linking BIM to other digital technologies such as virtual reality (VR). On the other hand, students' previously completed courses could be better incorporated into the final semester project with the option of partial BIM application; for example, applying the manual skills of cost estimating and comparing the manual outcomes to the BIM-generated outcomes. In this partial BIM approach, students could be motivated in the experiential learning (Borzak 1981) process, which described students' direct encounter with BIM rather than merely thinking about how BIM would affect the cost estimating work. According to Brookfield (1983), experiential learning provide students with the chance to acquire and applying knowledge, skills, and feelings in an immediate and relevant setting. The partial BIM approach also addressed the higher levels of learning defined in Bloom (1956)'s Taxonomy, because students could develop their critical thinking and reflection through the comparison between BIM-generated outputs and the manual outputs by applying knowledge acquired from prior courses, such as cost estimating.

It was evidenced from prior education studies such as Herrera, Vielma, and Muñoz (2018) that individual work significantly contributed to BIM-based project delivery. Following defining the subcategories of BIM teamwork – full BIM and partial BIM- the researchers agreed that offering teamwork options did not mean downplaying the individual motivation. The full BIM application approach would not work in the individual context because full BIM application refers to information sharing among team members. Instead, the partial BIM application could be based on the individual option by exploring the consistencies or differences between BIM-generated outcomes and manually-created outputs.

Finally, based on the variables considered in this pedagogical study, including traditional dissertation versus BIM-involving project, teamwork versus individual work, and full BIM versus partial BIM adoption, these four options of the final semester project were designed by the researchers, namely: (1) working with full BIM application in a case study group project; (2) working in a group adopting partial BIM application in construction planning/scheduling; (3) working as an individual with partial BIM application in quantity take-off and cost estimating; and (4) the traditional option of a research dissertation. The rationale for keeping the traditional dissertation option included: (1) providing an adequate option for students who would pursue their graduate studies; (2) serving as a control variable for the comparative study in this pedagogical research.

Details of the deliverable options

Before their final semester, CEM students had completed an introductory BIM application course by using Autodesk products (e.g. Revit and Navisworks). For this project, BIM tools from Glodon (Glodon Company Limited 2018), another domestic BIM software package supplier, were also provided to students in the computer laboratory of the university. Students were not limited to any software package in performing their project. Using at least two different software systems, students could experience the information exchange and data compatibility between different digital files.

Figure 1 illustrates a typical workflow of a full BIM application group, starting from converting the 2D Computer-Aided-Design (CAD) drawings from an existing high-rise building project in China. The reason for adopting the high-rise building project for BIM application was based on the facts that: (1) high-rise buildings are typical construction types in China's commercial and residential sectors. Thus, the students would be more likely to work in high-rise building projects in their future careers, as evidenced by alumni; and (2) adopting the high-rising building for delivering the BIM-related work package was considered reasonable to meet the credit hour requirement according to the delivered outcomes from the prior year's final semester. A typical 30-story high-rise complex building would provide a student group with an appropriate level of challenges and task allocations among five to six members. Multiple tasks were required in the group project deliverables, including simulation of construction activities, scheduling, site planning, virtual walkthrough/rendering, and the interface of BIM linked to virtual reality. BIM must have assisted all these activities for the full BIM application group.

Compared to the full BIM application group project, the group of partial BIM applications focusing on construction planning/scheduling also adopted a similar BIM digital package to assist site

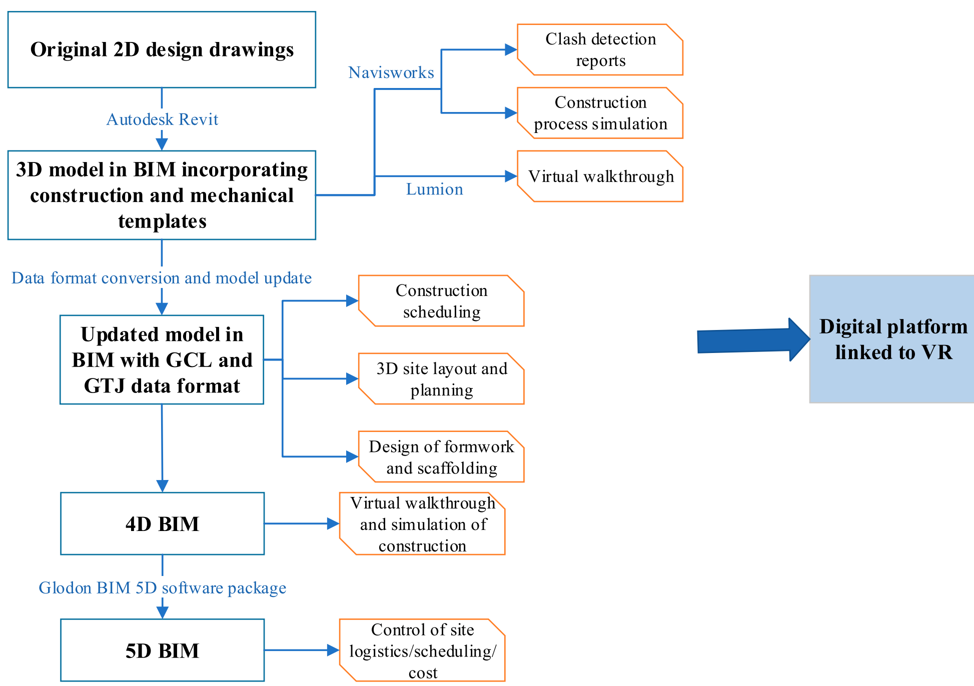


Figure 1. An example of workflow of the team work in full BIM application group.

Note: 4D BIM refers to linking the 3D model into scheduling; 5D BIM means adding cost-related items to the existing BIM platform.

planning, scheduling, resource allocation, design and calculation of formwork and scaffolding, and construction walkthrough/rendering. The main differences were that the partial BIM application groups or individuals had to also conduct manual work, for instance, a manual estimate of take-off quantities of certain items such as formwork and comparing/combining them to the outputs from BIM. For the partial BIM application, manual estimate or calculation, such as the load path analysis of formwork and other temporary structures, was also required as part of the final deliverables. The pedagogical objectives of adopting both manual and BIM work in the partial BIM application work included: (1) enabling students to appraise how BIM could complement the traditional CEM activities such as construction planning and cost estimating; and (2) critically evaluate the effect of BIM in the traditional construction-related activities.

Both full and partial BIM applications focused on construction planning/scheduling adopted a teamwork approach with five or six students working in a group. Each group was assigned with a different high-rise building project located in China. Auto CAD 2D drawings of the assigned project were provided to each group at the beginning of the semester. Each group member was required to clearly present their individual contributions to the team in their final group presentation. The final semester project was developed for students to apply their prior knowledge and skills obtained from previous key courses to the project. It aimed to motivate students' higher cognitive learning through application, analysis, synthesis, and evaluation, which would be reflected in various deliverables, for instance, a project report showing the technical details and reflective thinking.

Although it was up to each group to allocate the tasks to each individual member, typical distribution of tasks to each individual in a collaborative group can be found. For example, in a full BIM application group, a five-member team could be allocated with the following individual tasks: (1) modelling of the surrounding building (other than the main building) and topographic site, using Autodesk Revit and Glodon, as well as establishing the background in virtual walkthrough; (2) modelling (including rendering) the main building's standard floors in Revit and Glodon, as well as the planning of formwork/scaffolding; (3) modelling the main building's 1st to 3rd floors' and simulating the construction activities with rendering and videos; (4) modelling the construction process of the basement, programing the construction activities incorporating rendering; and (5) modelling and simulating the 4th–6th floors and creating the 5D BIM platform displayed in videos and other digital formats. Slightly different from the full BIM application group, in a typical task allocation for the partial BIM application group focusing on construction planning/scheduling, as demonstrated in Figure 2, at least one person in the group would work on manual calculation and analysis of formwork and scaffolding.

According to Figure 2, at least one group member would work on manual calculation and analysis of formwork and scaffolding.

Beyond the two teamwork options, the other two options in the final semester project were individually-based. Students who opted for partial BIM application could also select the cost estimating work involving both manual quantity take-off and BIM-assisted estimate. Similar to the other option partially adopting BIM, this individual project deliverable included various digital files in Revit and Glodon, a project report, a final presentation, an essay reflecting their project experience, and other manual calculation logs.

Results from demonstration of student work

The project timetable was given during the induction week, labelled as Week 1, as shown in Table 1. Table 1 demonstrates the timeframe for the partial BIM application group focusing on construction planning/scheduling.

Students working on other BIM groups or for individual deliverables had the same arrangement in Weeks 1–4, and 14–15. However, detailed tasks during Weeks 5–13 would differ. For example, during Weeks 11–13, the full BIM application group would focus on 4D and 5D BIM platform creation, involving simulation, virtual reality, and interfaces. Student deliverables from the three different BIM-related options are partly shown in Figures 3–7 and Table 2.

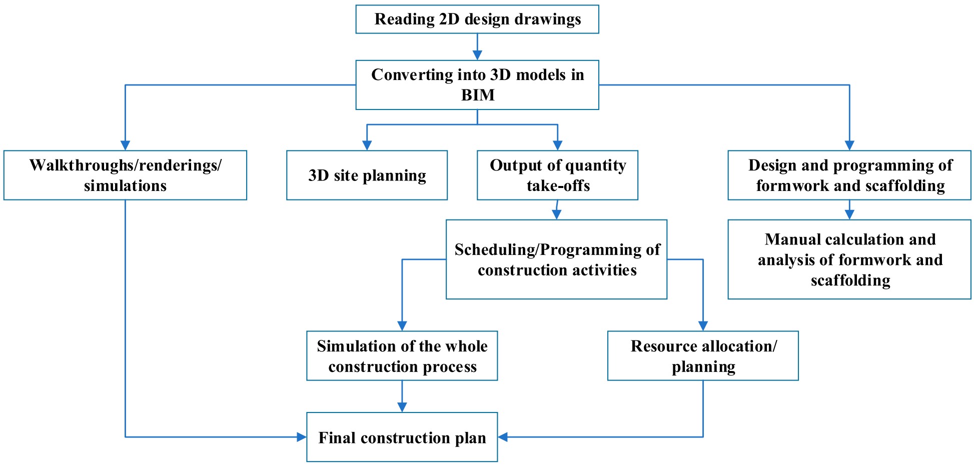


Figure 2. Tasks involved in a typical partial BIM application group working on construction planning.

Students working in the full BIM application group

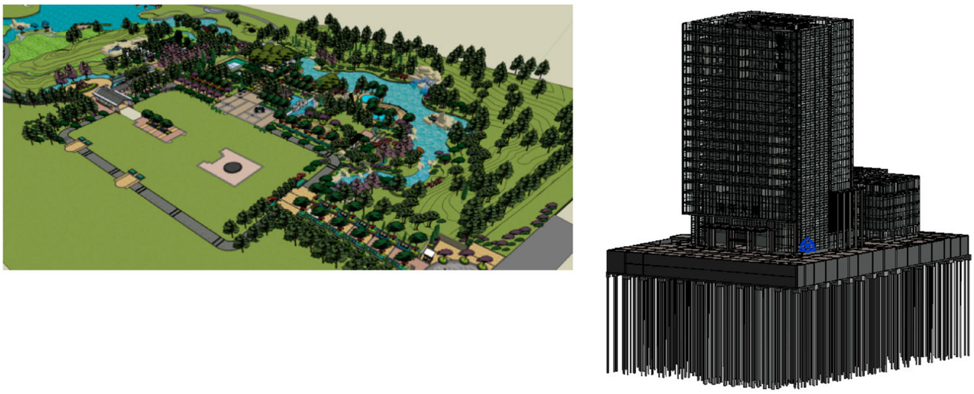
Students working in the full BIM application group had to place the main building in the given topographic site (e.g. Figure 3a). Digital models, as shown in Figure 3, were created in different file formats to be later linked to other construction activities, such as site planning and scheduling.

For this high-rise building shown in Figure 3 with, a construction area of 13,000 m^2 and a total floor area of 72,000 m^2, students also had to create the family files in the digital library, for example, the irregularly-shaped windows, curtain walls, and other modular building components.

Unlike the partial BIM application group or individual work, the full BIM application groups had to link BIM into VR with an interface guiding end-users to the virtual walkthrough of the building project. The interface shown in Figure 4 allowed users to click the menu and be guided to the observation point. Connected to the virtual reality headset, the user would undergo the immersive walkthrough to tour around the site and the building. Semantic or non-graphic information could be obtained by clicking the selected building component, such as the strength of the shear wall in the building structure.

Table 1. Timetable of the 15-week final semester undergraduate project.

Week	Content/tasks
1	Induction week, including receiving the original 2D AutoCAD drawings of the assigned project, learning the tasks and deliverables for the final semester project, and becoming familiar of all the resources needed to complete the tasks; Further starting reading drawings/plans, and proposing the initial construction plan
2	(1) Software tutorial and practice in the computer lab; (2) starting the modelling work in the BIM environment
3–4	Field trips and site study
5–7	(1) Group work of discussing and confirming the construction plan, determining the work-breakdown structure, calculating quantity take-off (manual estimate required), and estimating labour resources; (2) writing up the project opening report; (3) writing up the literature review work related to BIM for construction management
8	(1) Creating the site plan for the given construction project; (2) determining the durations of each activity and the relationships among them in the plan; preparing the schedule with networking cross-diagrams; (3) preparing the resource plans, including labour, materials, and equipment
9	Design and calculation of formwork
10–11	Design and calculation of scaffolding
12–13	(1) Creating the plan and drawings for formwork; (2) Simulation of major construction activities in the construction process
14	(1) Preparing for submission of project deliverables including project report, literature review, manual calculation and analysis, videos and other digital files, etc.; (2) defence of the final semester project to be evaluated by the academic panel
15	Final submission



a) b)

Figure 3. Digital models of the case study project saved in different file formats.

Figure 4. Interface involving BIM and VR.

Students working in other options of the final semester project

Similar digital models, as shown in Figure 3 for the case study building project, would also be created in the BIM partial application groups or individual works. Both full BIM application and partial BIM application groups adopted the 5D BIM approach to simulate construction activities, as demonstrated in Figures 5 and 6.

The site layout changed according to the construction stages, e.g. the foundation construction stage, the main building's structural construction, and the interior finish. Students from the construction planning/scheduling groups reflected that lack of site experience had caused some challenges in their initial site planning. As a digital process, BIM helped check their site layout and update the site planning.

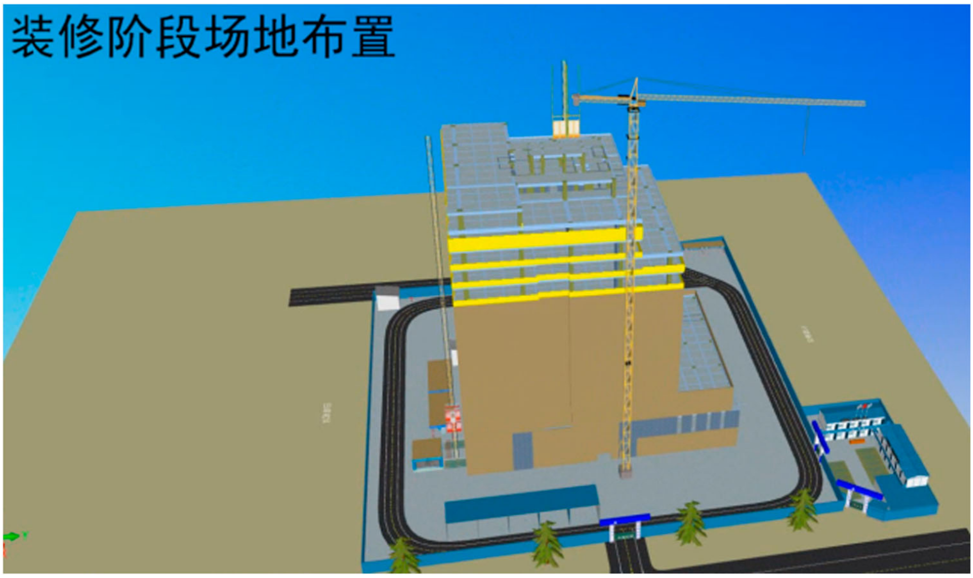


Figure 5. Site layout in the main building's interior finish stage.

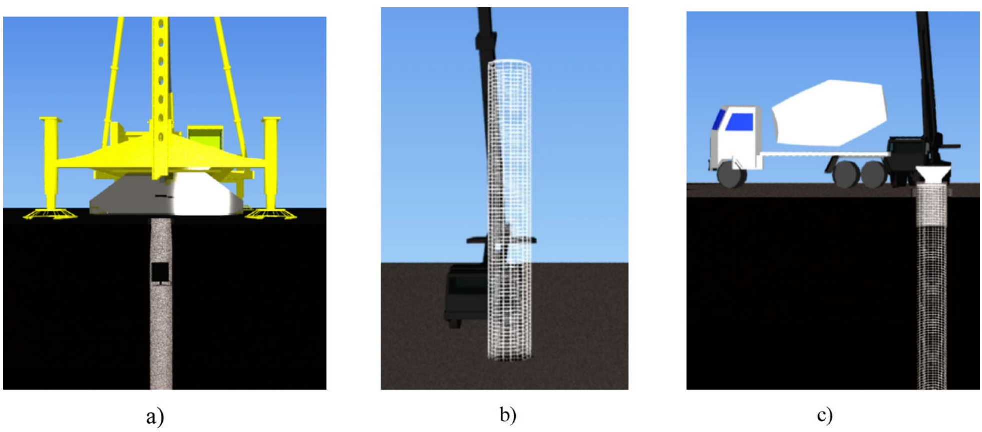


Figure 6. The process of creating construction simulations.

The construction planning/scheduling group adopted both manual and BIM-driven scaffolding design. Figure 7 illustrates the steps and a visualisation example of the building in designing the formwork and scaffolding.

According to the steps described in Figure 7-a), initially the structural 2D drawings had to be converted into the BIM file using software tools provided by Glodon in the GCL format. The construction planning/scheduling group member(s) performed both parametric and geometric design of formwork. BIM was applied in the calculation and analysis of the scaffolding parameters in ensuring that the design met the requirements of relevant specifications, e.g. Unified Standard for Safety of Scaffold in Construction (GB51210, 2016). One of the challenges encountered by the partial BIM application groups, as reflected in the final presentation and project report, was how to quickly and accurately determine the parameters of scaffolding by combining the manual calculation and BIM-generated outputs. Examples of these parameters included the type and materials of scaffolding components, geometric size and spacing requirements, and their spatial setup in the context of the formwork and structural building members.

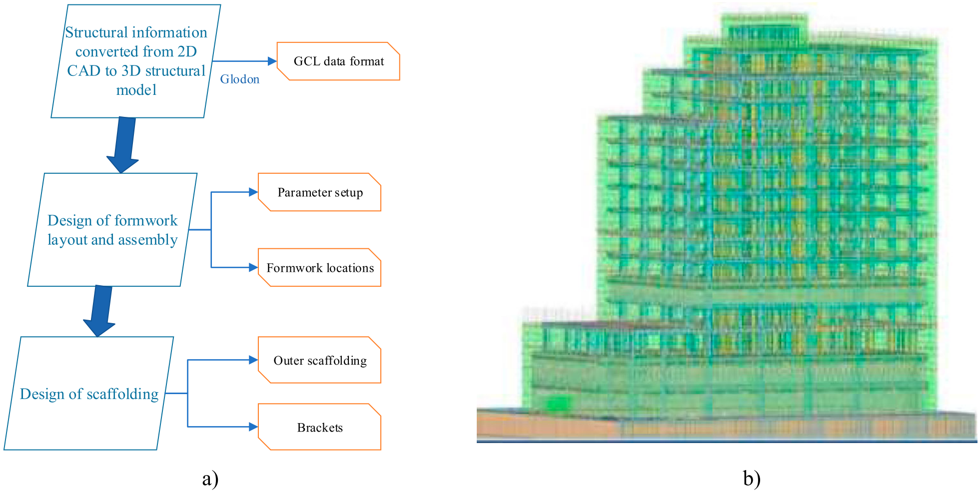


Figure 7. Illustration of the planning/scheduling for building formwork and scaffolding.

Similar to those engaged in teamwork, the individuals who opted for take-off estimate work also started by modelling the building from 2D drawings for quantity take-off. The visual reinforcement details were used to generate quantity take-offs compared to the manual estimate. Consistent standards or guidelines were provided to students involved in take-off estimates, such as the Code for Calculation of Housing Construction and Decoration Engineering (NTSBPRC 2013).

An example of adopting BIM in quantity take-off and comparing it to the manual estimate is displayed in Table 2.

The student demonstrating the comparison shown in Table 2 also investigated the difference between the BIM-generated output and the manual work. Table 2 indicates that either manual work or the BIM-generated outputs could be evaluated as being the more reliable outcome. On the other hand, both methods could be flawed. For example, human errors occurred due to omission, such as concrete volume in slabs; BIM-based estimate might have not included the scope of the quantity take-off, for instance, concrete volume in basement shearwall. Marginal differences were found when both methods were properly implemented. It was hence inferred that with proper modelling in the digital platform, BIM could save time and maintain or even improve the estimate accuracy. Students, by trying both methods and the follow-up investigation, developed their BIM-integrated cost estimating skills through experiential learning (Borzak 1981) and practice-informed learning (GuidHE 2018).

Results of follow-up questionnaire survey

Background of survey participants

Following the completion of student projects, a questionnaire survey was sent out to all students in the final semester project. Within the valid survey sample ($N = 64$), *20* of the students worked in a full BIM application group, *21* students in a partial BIM group focusing on planning/scheduling, *10* of them worked individually in the cost estimating, and the remaining *13* students adopted the research dissertation option.

Student perceptions towards other prior courses linked to the final semester project

The questionnaire survey asked students' views on how close the core courses in the CEM curriculum were connected to the final semester project. The Likert scale question included ten items corresponding to each core course. Before starting the final semester project, each student had

Table 2. An example concrete quantity take-off between manual quantity take-off and BIM-generated output.

Cost item	BIM-assisted estimate	Manual estimate	Cause analysis of difference
Shearwall concrete in the basement /m^3	189.77	155.71	Basement was treated as a building separated from the superstructure in the manual estimate, and concrete beyond the exterior wall was not included. In the BIM-based estimate, all building components were recognised and included in the quantity take-off. Therefore, the BIM-generated estimate turned out higher compared to that of manual work. The project estimate was recommended to not include what was beyond the exterior wall. Therefore, the manual work in this case was more reliable.
Beam and slab concrete in the basement/m^3	200.61	231.62	Double-checking the manual work revealed that the opening area within the slab had not been deducted when estimating the concrete volume, resulting in the higher estimate from the manual work. After revision, the manual estimate was corrected as 200.69 m^3, with only 0.04% difference from the BIM-generated work.
Shearwall formwork in a standard floor/m^2	1,051.54	1,055.59	The difference between the two estimates was only 0.40%. The shearwall boundary lines were corrected located in the BIM-based model converted from the original 2D CAD drawings. The difference could be considered marginal.
Concrete quantity in basement columns/m^3	33.04	31.85	The difference between the two estimates was 3.60% which could be considered relatively low. Generally the concrete columns' geometric shapes were correctly recognised in the digital model.

completed these mandatory courses. Students were asked to rank their perceived connection between the given course and their final project, with *1* being that 'the given course had little to do with the final project', *2* meaning limited connection, *3* meaning some application, *4* denoting that the course was fairly important for the final project, and *5* indicating that the course had been very important for the final project. These core courses listed in Table 3 were evaluated based on the rationale that: (1) they needed to be ranked in the importance from students' perspective; (2) hypotheses needed to be tested on the subgroup differences of student perceptions depending on their selected deliverable option; and (3) it fulfilled one of the main research motivations of this study to view the BIM education by extending from a single course level to the CEM curriculum level. The overall sample analysis based on the Cronbach's Alpha values is displayed in Table 3. The Cronbach Alpha value (Cronbach 1951), which ranged from 0 to 1, was adopted to measure the internal consistency of multiple items under each Likert-scale question. An ideal Cronbach Alpha value should be between 0.75 and 0.95 (DeVellis 2003), meaning that a student who chose a numerical value for one item would likely select a similar score for other items.

Seven out of ten courses received an average score of over 4.000, suggesting that most courses were perceived as highly important for students' own projects. The top-ranked course was the fieldtrip and site study, suggesting that students highly appreciated the practical fieldwork. In contrast, the real estate related course received the lowest average score. The overall Cronbach's Alpha at *0.8826* indicated an excellent internal consistency among the ten courses, meaning that a student who chose a numerical score to rank one course would be likely to assign a similar score to other courses. The only exception is the cost estimating course, with its Cronbach's Alpha value higher than the overall one. Its lowest item-total Correlation also suggests that students tended to have more different views on this course. Further subgroup analysis is summarised in Table 4 to explore the differences among students choosing different project options.

As seen in Table 4, for the cost estimating course, students who chose the take-off estimate option had a significantly higher perception of its importance compared to the other three subgroups. A few other courses viewed differently by students included engineering design, CAD, BIM, and construction technologies (CT). Students' perceptions were largely different in viewing how these core CEM courses were connected to their final semester project. For example, students who focused on quantity take-off tended to perceive their previous course in cost estimating as more important. The post-hoc

Table 3. Overall sample analysis in the question of students' perceptions on the degree of application of each prior course in the final semester project (Overall Cronbach's Alpha = 0.8826).

Prior course in the CM curriculum	Mean	Std.	Ranking	Item-total Correlation	Cronbach's Alpha
Field Trip and Site Study (FTSS)	4.279	0.915	1	0.5700	0.8744
Construction Technologies (CT)	4.197	0.963	2	0.6261	0.8705
Cost Estimating (CE)	4.164	1.036	3	0.3594	**0.8886***
Computer Aided Design (CAD)	4.066	1.031	4	0.6543	0.8682
BIM Technology and Application (BIM TA)	4.066	1.109	4	0.6269	0.8701
Construction Planning (CP)	4.049	0.990	6	0.7071	0.8648
Project Management (PM)	4.049	1.040	6	0.5442	0.8760
Engineering Drawing (ED)	3.705	1.085	8	0.7066	0.8641
Engineering Structures (ES)	3.672	1.193	9	0.7549	0.8596
Real Estate Development and Planning (REDP)	3.525	1.233	10	0.5947	0.8734

*: An individual Cronbach's Alpha value higher than the overall value suggests that survey participants had more differed perception towards this course.

analysis revealed that the full BIM application group generally perceived all core courses as necessary for their projects, followed by two partial BIM application subgroups. In contrast, it seemed that the subgroup of research dissertations generally perceived all core courses with a lower level of importance. In addition to those courses showing significant differences according to the *p* values presented in Table 4, other prior courses, such as CP (i.e. Construction Planning), also had different effects on the final semester project. The full BIM application group also perceived CP with significant influence on their teamwork, followed by the construction planning/ scheduling group. In comparison, groups focusing on take-off estimate perceived CP with the lowest influence because their teamwork did not focus on planning/scheduling. CT and CP were core courses before the final semester project. This project was not only about adopting BIM but, even more importantly, technically feasible construction processual activities to be simulated within BIM. Therefore, students also had to implement their knowledge acquired in CP to properly organise site activities in the 4D BIM platform, including site logistics. Students reflected in their final group presentations that BIM was the multi-dimensional platform but could not replace the core skills needed from other core courses, for example, CT and CP.

Discussions

Researchers in this pedagogical study updated the assessment of the final semester project for CEM students. Various pedagogical approaches were included in the study, for instance, teamwork versus individual work and full BIM application versus partial BIM group. Students were

Table 4. Statistical results for subgroup analysis of students' perceptions of how each prior course is linked to the final semester project.

	Subgroup									
	Full BIM application		Construction planning/ scheduling		Take-off estimate		Research dissertation		Statistical comparison	
Course name[a]	Mean	Post-hoc group	Mean	Post-hoc group	Mean	Post-hoc group	Mean	Post-hoc group	*F* value	*p* value
ED	3.895	A	3.600	A and B	4.050	A	2.917	B	**3.36**	**0.025***
CAD	4.579	A	4.100	A	4.300	A	2.833	B	**11.74**	**0.000***
ES	4.000	A	3.900	A and B	3.650	A and B	3.000	B	1.96	0.130
PM	4.263	A	4.100	A	3.700	A	4.250	A	1.19	0.322
CP	4.526	A	4.000	A and B	3.750	B	3.833	A and B	2.44	0.074
CE	3.895	B	3.800	B	4.900	A	3.667	B	**6.55**	**0.001***
REDP	3.526	A	3.400	A	3.400	A	3.833	A	0.34	0.796
FTSS	4.421	A	4.200	A	4.250	A	4.167	A	0.23	0.872
BIM TA	4.579	A	4.000	A	4.350	A	2.833	B	**9.68**	**0.000***
CT	4.579	A	4.200	A and B	4.200	A and B	3.583	B	**2.87**	**0.044***

[a]The acronyms used for each course are defined in Table 3.
*A *p* value lower than *0.05* indicates significantly differed perceptions of students from different project options.

given a clear guide to select their options according to their individual career options or preferences.

Collaborative nature of student teamwork

This pedagogical study incorporated the collaborative nature of BIM through student group works. In the group of full BIM applications, students played the role of construction managers/engineers in teamwork by compiling BIM-based technical standards into the final report. Each group member had clearly defined tasks contributing to the project technical report. For example, the individual contribution(s) could be initial modelling from 2D CAD into BIM, quantity take-off, 5D BIM, and virtual rendering. These individual tasks were usually dependent on each other, and each member had to collaborate closely to achieve the joint deliverables. The final assessment of each member was not only based on the individual tasks but also on the overall project outcomes. The collaborative group work assessed not only the software or specific digital skills but also their applications of construction standards (e.g. quantity take-off), communication, teamwork, and presentation of outcomes. In the partial BIM application group focusing on planning/scheduling, students also worked in a team environment by undertaking the roles of construction engineers or managers. They were also asked to perform individual tasks to integrate each other's work to form the final report, including scheduling documents. These tasks embedded steps and methods of construction site planning and critical activities, which were presented in the BIM-assisted digital platform. Similarly, in the group of BIM partial adoption focusing on the cost estimating, students worked as cost engineers/estimators to establish the bidding documents for the given high-rising building following pricing standards or quotation benchmarks. Students applied their construction cost pricing and control skills, knowledge of establishing construction bidding, and information technologies, including BIM.

BIM pedagogy linked to educational theories

In the current final semester project adopting BIM, all teams or individuals had to undergo the highly time-consuming modelling process from given 2D CAD drawings to 3D virtual models. Students reflected that they gained modelling experience when converting 2D CAD into different BIM authoring tools, including Revit and Glodon. Although the highly manual conversion could be considered part of the learning curve for BIM pedagogical activities, this time-consuming process would not be practical when industry practitioners needed to create a more efficient information exchange process using an enhanced automatic approach. More state-of-the-art research could be introduced in the future to strengthen the research-informed teaching, for instance, automating the semantically-rich models from existing 2D plans or drawings (Bortoluzzi et al. 2019).

The demonstration of student deliverables, especially BIM-related works, demonstrated how the introductory core courses, such as cost estimating, had been applied in the final semester that are either driven or assisted by BIM. This reflected the researchers' pedagogical aim by extending BIM pedagogy from a single course level to the CEM curriculum perspective. Educational theories, including the good practices of undergraduate education (Chickering and Gamson 1987) and Bloom's Taxonomy (Bloom 1956) were implemented in this study, highlighting students' BIM-driven learning process from application to reflective thinking. For example, by comparing the BIM-generated outputs to that of manual outcomes, the partial BIM adoption motivated students to critically think about how BIM had been creating a difference in the project work. Students involved in the full BIM application developed their understanding of information exchange among team members and between different digital tools. As reflected in the definition of the common data environment (CDE), McPartland (2016) described that CDE contents include documentation, graphical model, and non-graphical assets. CDE aims to enhance the information collaboration between project team members (McPartland 2016). The current BIM full application shown in Figure 1 maximised the data sharing between different tools (e.g. Revit-initiated clash detection, simulation, and virtual reality),

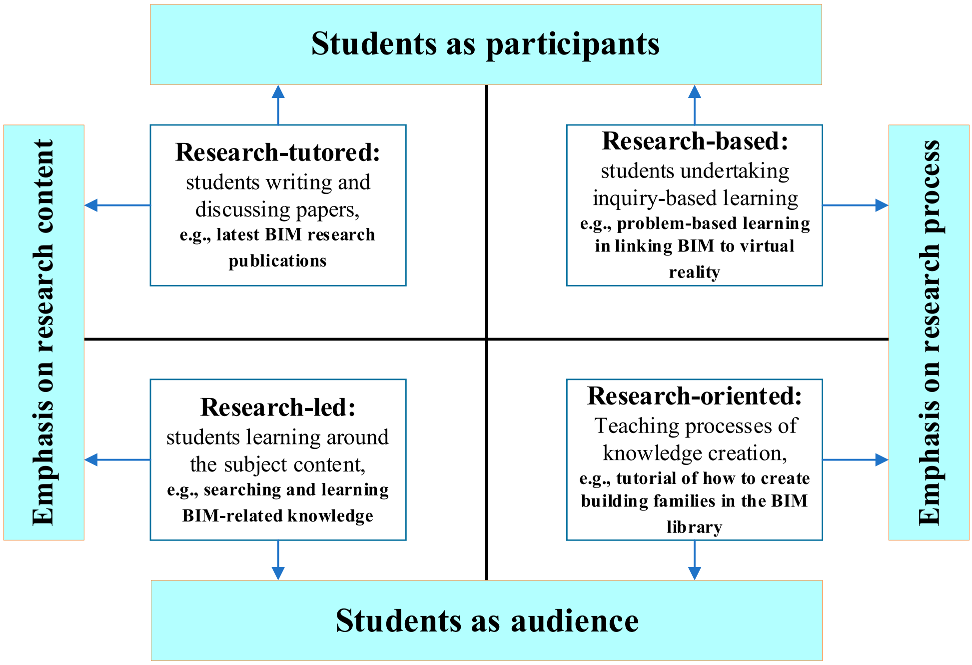


Figure 8. Four different types of research-informed teaching that could be applied in BIM education (adapted from Healey 2005).

and integrated different skillsets (e.g. cost estimating and scheduling from the integrated models in the BIM environment). This current educational study focused on the construction stage. To extend it into the life cycle stages of a real-world construction project, more principles on information management using BIM described in the ISO 19650 (BSI 2019) can be incorporated in the future, such as exchange information requirements and asset information model. Based on the research-informed teaching illustrated in Figure 8, more teaching-informed research in BIM education could be generated to facilitate knowledge sharing. Researchers in this study believe that research and teaching form a mutually-informed cycle to enrich the knowledge base of BIM education.

The four types of research-informed teaching are recommended in different levels of BIM courses in the CEM curriculum. Research-led teaching is suitable in BIM lectures to introduce the state-of-the-art scholarly work in BIM, for instance, building a life cycle approach incorporating BIM for facility management (Rodrigues et al. 2018); research-tutored teaching is suggested for final year undergraduate or graduate courses on adopting BIM to assist the construction activities, such as cost estimating; research-based teaching and learning are considered appropriate in capstone projects; research-oriented teaching is preferred in courses like research methodology in the CEM discipline. In the BIM learning curve, students will be able to switch their roles between an audience and a participant corresponding to the different levels of learning defined in Bloom's taxonomy (Bloom 1956). Students will be guided with different learning objectives to capture the knowledge itself, such as the BIM family, or to be trained with the skill to capture the knowledge, for example, the process of creating a BIM family member. These four different research-informed teaching types fit the education aim in digital construction, extending the digital AEC education from the single course level to the curriculum perspective. Overall, the four different types are recommended to be applied in different courses depending on the learning objectives. For example, research-based teaching, which is highly related to the problem-based learning defined by Wood (2003), is suitable for students to develop their own research question, methodology, and research skills. This should be considered before CEM students start their final year research project or a graduate research project. These different teaching and learning methods, as reflected by the research-informed teaching types (Healey 2005) and educational theories such as Bloom's taxonomy (Bloom 1956), are expected to result in students' varied perceptions of the same digital platform or technology, for example, BIM.

Findings from the questionnaire survey

The questionnaire survey provided several insightful findings. For example, it was found that students in the full BIM application subgroup held the most significant view of all core CEM courses in terms of the courses' importance to the final semester project. It was inferred that these different application levels of prior CEM courses influenced students' perceptions. Nevertheless, researchers did not aim to recommend a certain deliverable option in preference to another. Instead, this pedagogical study provided an unbiased list of options for CEM students incorporating their interests and career development needs. In contrast, students from the subgroup of research dissertation held the least significant view of these core courses. In fact, those who chose research dissertation were more likely to continue their academic career in pursuing a graduate degree. Those who chose research dissertation tended to conduct more scholarly work to seek answers to their research questions, but with less practice in adopting BIM authoring tools or other empirical work. As a result, those working on research dissertation typically experienced less connection of their final project to their previous core courses. This is not to deny the importance of the core courses to these students' career development. Instead, it is inferred that the final semester project deliverable options influence students' learning behaviour and the follow-up perceptions on integrating their prior courses into the final project. This is also to address the suggestion of Pikas, Sacks, and Hazzan (2013) that BIM education should be viewed at the programme or curriculum level, rather than staying in a single course level.

The follow-up survey also revealed that while emphasizing BIM in the CEM curriculum, the importance of practical experience from site work should not be weakened. Instead, BIM cannot replace other key skills needed to complete a group or individual CEM project. Students were aware that BIM could assist their work by enhancing their work efficiency, but could not replace their practical experience. In other words, BIM should complement their practical experience or other key skills, but should not replace other experience or skills. It is inferred that the full BIM application deliverable tends to motivate students to apply their prerequisites and make them hold positive visions of the future technological movement.

Conclusions

Researchers updated the ongoing BIM pedagogical research by highlighting BIM incorporation in students' final semester projects in the construction engineering and management (CEM) curriculum. This pedagogical study aimed to link the core CEM courses from earlier years of undergraduate study into the final semester project using BIM as the vehicle. More options were provided for students to select depending on their personal preferences and career development needs. Four BIM-related options included full BIM application in teamwork, partial BIM application focusing on construction planning/scheduling in a group, individual work utilising BIM for cost estimating, plus the traditional research dissertation. Four different deliverable options allowed a variety of learning and practices for CEM students, such as teamwork versus individual work, and different levels of BIM applications. The full BIM application aimed to maximise the use of the digital platform, by creating interfaces linking BIM to virtual reality. The partial BIM group work or individual work combined BIM-generated outputs and manual work, for example, comparing the quantity take-off between manual work and BIM-generated estimate. Students provided their reflective thinking through their final-week presentation and project report. The experience shared was valuable not only for other students, but also for BIM educators, for instance, the typical causes of differences between BIM-generated quantity take-off and the manual work.

The follow-up questionnaire survey with statistical analysis revealed further findings about how the subgroups perceived prior core CEM courses linked to the final semester project. Compared to other subgroups, students from the subgroup of full BIM application held the most positive perceptions of linking their prior core courses. It was inferred that the level of information exchange caused the differences in the application levels of prior core CEM courses to the final project. Nevertheless, students perceived consistently that all these defined key skills or experience such as practical experience were important for their project. Although BIM was highlighted in the final semester project, students reflected that the practical experience was with top importance to complete their work. It was indicated that introducing BIM did not diminish the importance of other key skills or experiences. More reflections from students following the project completion were obtained, for example, the need to embed state-of-the-art research in automating the conversion of existing 2D CAD drawings into BIM, rather than manually rebuilding the digital model.

This pedagogical study implied that different education theories could be integrated to address multiple teaching and learning objectives in the BIM-involved curriculum, for example, students' different levels of BIM learning from understanding, applying, to reflective thinking. To enhance the processual learning, a variety of teaching and learning methods could be employed, such as research-informed teaching to spark problem-based learning. These educational theories and pedagogical strategies could be embedded to boost the understanding, application, and evaluation of key BIM concepts. Informed by these theoretical and practical guides in BIM education, different variables could be designed in the pedagogical study, for instance, full BIM versus partial BIM application based on the level of information exchange defined in BIM maturity levels. Based on these educational theories, practical guides, and teaching strategies, this pedagogical study could be generalised in the global academic community of digital construction. Specifically, the paper provides suggestions for enhancing existing BIM-related education in the CEM curriculum worldwide, including: (1) incorporating the digitalisation education not only at the single course level, but also at the programme level to integrate different courses; (2) setting up a variety of teaching and learning methods such as teamwork versus individual work; and (3) addressing the different levels of learning and different teaching strategies such as research-led teaching in BIM. Overall, the findings and the current experience released from this study conducted could be used by other institutions to update their BIM education and other disciplines such as architecture and civil engineering.

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No potential conflict of interest was reported by the author(s).

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Appendix: Part of questionnaire survey to students following their final semester project.

(1) Please select your final semester project deliverable type. (Single choice)

A. Full BIM application; B. Construction planning/scheduling; C. Take-off estimate; D. Research dissertation

(2) Please select one of the five numerical values to rank how each of the following prior year's courses helped the final semester project. The score from 1 to 5 measures the degree of application of the given course on the final semester project, i.e. importance level or how closely it is connected to the final project. (1: the given course had little to do with the final project; 2: the given course had limited effect on the final project; 3. the given course had been applied to some degree on the final semester project; 4. the given course was fairly important for the final semester project; 5. the course had been very important for the final project).

Activity	Importance of the given course to the final semester project (please select a number from 1 to 5)
Field Trip and Site Study (FTSS)	
Construction Technologies (CT)	
Cost Estimating (CE)	
Computer Aided Design (CAD)	
BIM Technology and Application (BIM TA)	
Construction Planning (CP)	
Project Management (PM)	
Engineering Drawing (ED)	
Engineering Structures (ES)	
Real Estate Development and Planning (REDP)	