Project-based Pedagogy in Interdisciplinary Building Design Adopting BIM

Abstract

Purpose – This study aims to present a pedagogical practice in the project-based assessment of AEC students' interdisciplinary building design work adopting BIM. This pedagogical practice emphasizes the impacts of BIM, as the digital collaboration platform, on the cross-disciplinary teamwork design through information sharing. This study also focuses on collecting students' perceptions of BIM effects in integrated project design. Challenges in BIM adoption from AEC students' perspective were identified and discussed, and could spark further research needs.

Design/Methodology/Approach – Based on a thorough review of previous pedagogical practices of applying BIM in multiple AEC disciplines, this study adopted a case study of the Solar Decathlon residential building design as the group project for AEC students to deliver the design work and construction planning. In total 13 different teams within the University of Nottingham Ningbo China, each group consisting of final year undergraduate students with backgrounds in architecture, civil engineering, and architectural environmental engineering, worked to deliver the detailed design of the solar-powered residential house meeting pre-specified project objectives in terms of architectural aesthetics, structural integrity, energy efficiency, prefabrication construction techniques, and other issues such as budget and scheduling. Each team presented the cross-disciplinary design plan with cost estimate and construction scheduling together with group reports. This pedagogical study collected students' reflective thinking on how BIM affected their design work, and compared their feedback on BIM to that from AEC industry professionals in previous studies.

Findings – The case study of the Solar Decathlon building project showed the capacity of BIM in enabling interdisciplinary collaboration through information exchange and in enhancing communication across different AEC fields. More sustainable design options were considered in the early architectural design stages through the cross-disciplinary cooperation between architecture and building services engineering. BIM motivated AEC student teams to have a more comprehensive design and construction plan by considering multiple criteria including energy efficiency, budget, and construction activities. Students' reflections indicated both positive effects of BIM (e.g., facilitating information sharing) as well as challenges for further BIM implementation, such as some architecture students' resistance to BIM, and the lack of existing family types in the BIM library, etc.

Research limitations/implications – Some limitations of the current BIM pedagogy were identified through the student group work. For example, students revealed the problem of interoperability between BIM (i.e., Autodesk Revit) and building energy simulation tools. To further integrate the university education and AEC industry practice, future BIM pedagogical work could recruit professionals and project stakeholders in the adopted case studies, for the purpose of providing professional advice on improving the constructability of the BIM-based design from student work.

Originality/value – This work provides insights into the information technology applied in the AEC interdisciplinary pedagogy. Students gained the experience of a project-based collaboration and were equipped with BIM capabilities for future employment within the AEC job market. The integrated design approach was embedded throughout the team project process. Overall, this BIM pedagogical practice emphasized the link between academic activities and real-world industrial practice. The pedagogical experience gained in this BIM course could be expanded to future BIM education and research in other themes such as interoperability of building information exchange among different digital tools.

Keywords - Building Information Modeling, construction education, design management, Information and Communication Technology (ICT) Applications, simulation, integration

Paper Type: Technical paper

1. Introduction

Building information modelling (BIM), as the emerging digital technology in the global architectural, engineering, and construction (AEC) market, is gaining wider application in industrial practice. The popularity of BIM as an integral concept in the AEC industry has motivated its necessary inclusion within relevant education (Ghosh et al., 2015). BIM movements and multiple BIM related areas (e.g., sustainability) have resulted in a higher demand on competent BIM professionals and college graduates with BIM skills (Jäväjä and Salin, 2014). Educational institutions play a significant role in providing the industry with BIM-equipped graduates (Tang et al., 2015). However, there is still insufficient institutional education resources to train and educate AEC students to meet industry needs in countries like China, where the industry demand for BIM professionals is growing.

BIM education is not simply changing the pedagogical tool from 2D Computer-Aided Design (i.e., CAD) to 3D visualization (Tang et al., 2015), but the way of collaboration among project team members through information management and teamwork (Sacks and Pikas, 2013). Recent trends of AEC movements, including prefabrication in construction and energy efficient “green” building, are gaining momentum along with BIM in some developing economies’ AEC markets (e.g., China). These state-of-the-art practices are interlinked. For example, BIM digital libraries could be established to incorporate the information of various building prefabricated members (e.g., precast concrete walls), and BIM could be used to support the building energy performance analysis through data sharing. Nevertheless, communication, coordination, and collaboration, as keys for BIM implementation, have not been fully integrated into existing BIM training or education through project-based or experimental learning approach.

Previous relevant pedagogical practices mostly adopted BIM in single disciplines, such as architecture in the studies of Mathews (2013) and Solnosky and Parfitt (2015), structural engineering in the study of Nawari (2015), and construction engineering in the studies of Kim (2011) and Ghosh et al (2015). So far there has been limited pedagogical practice in recruiting all the aforementioned disciplines by exploring BIM's capacity in enhancing interdisciplinary project design and construction planning through information sharing and management. This BIM pedagogical study aims to: 1) implement the project-based approach to adopt BIM as the digital platform to enhance the multidisciplinary project teamwork for final year undergraduate AEC students; 2) incorporate the real-world scenario (i.e., off-site construction elements and solar energy) into the project team design; 3) apply multiple criteria in the student project work including architectural design, structural analysis, technology, cost estimate, and construction planning; and 4) gain insights from the feedback and reflective thinking of AEC students on BIM's impacts on cross-disciplinary team project. The overall goal of this BIM pedagogical work is to provide students' with not only BIM operational skills, but also the initial BIM-based collaboration experience which could help their future professional career in the AEC industry.

2. Literature review

2.1 Application of ICT in AEC fields 2.1.1 ICT movement in AEC industry

Barriers and constraints of ICT (Information and Communication Technology) implementation in the construction industry identified by Peansupap and Walker (2006) have been overcome and advanced towards BIM adoption in terms of technology, cultural and behavioural change management worldwide (Benjaoran and Bhokah 2009; Khosrowshahi and Arayici 2012; Jensen and Hohannesson 2013; Ding et al. 2015; Rogers et al. 2015). Gajendran and Brewer (2007) emphasised the influence of ICT integration on the change of cultural environment. Through a BIM experience survey in Australia (2007-2010) and Finland (2012-2014), Singh and Holmstrom (2015) established the congruence between Maslow's motivational theory of needs and Roger's theory of technology adoption and innovation diffusion. Individuals and organisations have distinct aspects of adoption and innovation-related needs for being career champions and industry leaders to meet market demands and maintain competitive advantage.

2.1.2 Benefits of BIM adoption

BIM enables digital forensic tracking of high-quality information to support business outcomes through true collaborative effort amongst all stakeholders (clients, designers, contractors, building occupiers and managers). BIM collaborative processes will significantly improve the efficiency of design, construction and operation, and provide a platform for continuous upskilling for all (Strong and Burrows, 2017). Focusing on commercial construction, Farnsworth et al. (2015) surveyed executive, mid-management, and BIM practitioner level employees on application, advantages, and methods associated with the use of BIM in the sector. Top advantages of using BIM were identified as communication, scheduling, coordination, visualization, and clash detection. Efficiency with regards to time, resources, materials, and reduced construction costs were also acknowledged. Companies reported a positive impact on profitability, construction time, and marketing. The 4D and 5D capabilities of BIM in simulations for resources, time, safety, space, risk, construction layout and buildability analyses have been used with the outcomes of reduced cycle times, reduced Request for Information (RFIs), reduced wastes and increased safety in some work tasks (Aziz and Tezel, 2016).

2.1.3 BIM applications in building design and construction

BIM can also be linked to building sustainability. Wong and Kuan (2014) noted that BIM-based sustainability analysis was regarded as a potentially useful vehicle for helping project stakeholders to capture complete design and project information. The latest review of sustainability by Chong et al (2017) highlighted the demands of new BIM tools for assessing sustainability criteria, improved interoperability among BIM software package and energy simulation tools. Further impacts of BIM on various AEC practices can be found in further studies. For example, Brathen and Moum (2016) facilitated the use of “BIM-kiosks” for construction site workers to obtain a better understanding of the design material, navigate to get information about specific details or problem in the 3D model and efficiently handle complex elements. Amuda-Yusuf and Mohamed (2015) created a building service standard method of measurement (BSSMM) framework for managing the cost of building services by quantity surveyors/cost consultants. Li et al. (2015) developed a 4D automated simulation tool based on simulation by using a game engine for construction resource planning, which was different from traditional construction planning that relies upon the critical path method and bar charts embedded with visualization and timing issues. These multiple studies indicated that BIM could play a role within different AEC fields. There could be further work to adopt BIM to enhance interdisciplinary collaboration across AEC fields.

2.2 BIM education in AEC disciplines

ICT has been establishing its role in the AEC education. For example, by viewing the real environment augmented with computer-generated information layers, students in the construction management field have significantly improved perception of reality through the combination of their ability to understand the complexity of construction products and associated jobsite processes (Shanbari et al. 2016). Nevertheless, it still remains a question as to how the perceived BIM benefits and their applications within AEC practices can be incorporated in BIM education. For example, how AEC students would experience the challenges and the needs in addressing the information exchange issue when adopting BIM in building energy simulation? How students would experience the BIM impact on design management? How students would learn to embrace holistic design through BIM processes instead of traditional 'silo' approach? And how collaborative working process can be better embedded when teaching BIM not only as a tool but also a platform and an environment where such collaboration is facilitated?

2.2.1 BIM pedagogical cases

Earlier studies have showcased BIM-based education in AEC fields. Zhao et al. (2015) shared their investigation on training students' collaborative construction skills through BIM-integrated learning environments in the "Integrated Construction Studio". The ICS environment is designed to simulate the real-world working conditions of the preconstruction phase of a project. Students would obtain employer's new expectations of soft skills, while simulating self-directed or team-based learning, mentoring, and collaboration. A mixture of students from four specific courses at difference levels (sophomore, junior, senior, and graduate levels) all participated in the integrated studio study. Similar BIM education programs can be found in the cases of Clevenger et al. (2012) and Ghosh et al. (2015). Review of existing literature indicates a lack of a focused pedagogical approach to link BIM education to BIM industry practice by addressing the state-of-the-art BIM implementation and challenges.

2.2.2 Rational of BIM interdisciplinary pedagogy

Based on a review of BIM-curriculums and surveys from industry, Lee and Hollar (2013) concluded that a collaborative learning environment through purposeful integration of BIM would be best suited for future industry needs. However, there have been limited pedagogical case studies (e.g., Udeaja and Aziz, 2015) to showcase how BIM, as a digital platform, could enhance interdisciplinary group work for students among different AEC disciplines. PAS 1192-

2 published by The British Standards Institution (2013) emphasized the need of information exchange among multiple AEC subjects. There is an urgent need to update the BIM pedagogy to train students in the real-world scenarios addressing challenges stressed in PAS 1192-2 such as building information exchange and interoperability. Using BIM-based interdisciplinary pedagogy could bridge the gap between academic course delivery and industry practice based on the consistent digital design approach and construction standards.

3. Research methods

, This pedagogical research design consists of steps guided by Creswell (2013) as described in Table 1.

Table 1. Research design steps of BIM pedagogy

Steps	Strategy
Preliminary considerations	• Literature review of previous case studies in BIM pedagogy; • Case study approach adopting the 2018 Solar Decathlon (SD) project aiming to incorporate the state-of-the-art practices within the AEC industries (e.g., prefabrication construction, renewable energy facilities, and human wellbeing) to the BIM-based group project; • Theories including Bloom's Taxonomy (1956) and Chickering and Gamson (1987)'s principles for good practice in undergraduate education
Purpose statement	• The research focuses on the BIM pedagogical practice aiming to enhance the building project design by bridging multiple AEC disciplines.
Research hypotheses	• AEC students could gain the experience through project-based learning on how BIM impacts their design; • The BIM pedagogy could link education to industry practice by comparing students' perceptions towards BIM impact in project delivery to that of AEC professionals.
Methods	• AEC student teams will be asked to perform the group design and construction planning for the residential building by meeting pre-described project specifications. • The deliverables of students' group design included their design documents, presentations reflecting their experience on how BIM affects their group design, as well as benefits and challenges in BIM practice.

Details on the research design are described in the following sections, including students' academic background, group project information, assessment approach of team design, pedagogical strategies.

3.1.Students' academic background

In the autumn 2016, 72 final year undergraduate students from the Faculty of Science and Engineering at University of Nottingham Ningbo China enrolled on the BIM and Management course. These AEC students came from three major disciplines, namely, Architecture, Architectural Environmental Engineering (AEE), and Civil Engineering (CE). They were divided into 12 groups, each group consisting of students from the three different disciplines. Another group consisting of graduate students in the Geospatial Engineering with BIM master program also formed an extra design team to deliver the project design. It was known that the majority of students had little previous BIM academic or professional experience. Before they formed groups to perform the BIM-based group design, all AEC students within this BIM course were provided with four-week intensive teaching focusing on BIM software skills using Autodesk Revit and Navisworks. During these four weeks, each student was provided with three-hour BIM laboratory training every week. Regardless of students' own discipline, they were exposed to the design or construction planning work that was not from their own field. For example, architecture students were learning the reinforced concrete structural visualization in Revit Structure Template, and CE students were also made aware of how building services systems (e.g. air-conditioning and heating) were designed and integrated within the building.

3.2. Group project background

The Solar Decatholon (SD) project was adopted in the project brief aiming to enhance the AEC students' interdisciplinary collaboration through a real-life holistic design approach. The project brief was prepared and released to student groups, with the main objective of focusing on adopting BIM tools to enhance the multi-disciplinary design by achieving the visualized building model incorporating architectural, structural, and building services elements and by associating the design proposal with construction scheduling, cost, and building sustainability. As part of the SD project requirements, solar photovoltaic (PV) panels had to be installed as a source of renewable energy. The information of all building elements (e.g., modular construction members and PV panels) were required to be saved in the BIM-based design. Therefore, students were motivated to acquire the building product information by investigating the local AEC market and contacting relevant suppliers or manufacturers. The detailed project brief can be summarized in Table 2.

Table 2. Summary of Solar Decathlon project requirements

Project site	• Within the 25 m × 25 m pre-defined boundary line • All site components on the project site must stay within the 8.4-meter-high solar envelope, with the first story set least 0.3 meter above grade. • The house components within the defined boundary line should not restrict a neighbour's right to the sun.
Architecture	• One story • Architectural merits to embrace the residential architecture feature for senior citizens • Building floor area between 120 m^2 and 200 m^2
Structure	• The concrete foundation will be adopted in this project. The foundation type, size, and location to be designed by each team • Structurally sound with visualized design approach and analysis • Resistant to natural disaster (e.g. typhoon) based on the local climate condition
Building services	• Renewable energy facilities to be considered (e.g., solar panel, and/or wind turbines) • The overall balance to be met between building energy consumption and the renewable energy supplied
Construction	• Prefabricated members for on-site assembly • Construction site assess to be evaluated given the site layout • Site assembly to be completed within 12 working days from the start of site construction
Others	• Costing • Procurement of appropriate building materials and prefabrication members considering the transportation cost and local availability in China

As summarized in Table 2, this SD project had specific requirements for adopting renewable energy technologies and off-site construction. Students were guided on utilizing BIM as a digital platform to perform the team design, and linking BIM into building energy simulation.

3.3. Assessment of BIM-based team project design

The workflow of the team design is presented in Fig.1, which illustrates the four key major stages of the project.

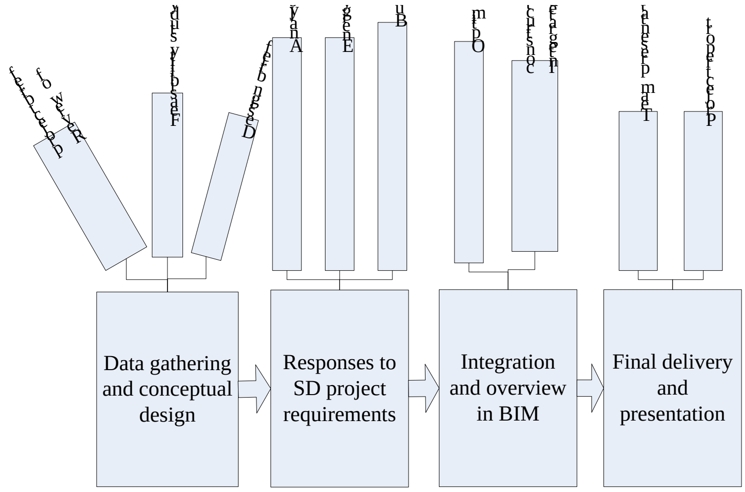


Fig.1. Key stages with deliverables in the BIM-based student team project

In the conceptual design stage, each team was guided to explore possible architectural schemes/ideas/concepts with effort not only from architecture members, but also AEE students in considering building energy efficiency and CE students in off-site construction techniques. The micro-climate analysis of the project site was also required. Available local suppliers or manufacturers of building materials and prefabricated elements (e.g., precast wall panel or timber framing) were to be searched by student teams. Informal team discussions were encouraged led by each group's project manager at this initial stage. Following the conceptual design stage was the schematic design, where student teams were guided to generate their detailed responses to project requirements in BIM. According to AIA California Council (2007), BIM could be adopted to evaluate different design options and to test "what-if" scenarios in the integrated project delivery (IPD) system. Students were guided and motivated to explore the optimal project design plan at this stage by considering multiple criteria, including building energy simulation and project costs. BIM was also required to generate the model combining architectural, structural, and building services systems. At the later stage of integration and overview, the optimized design was to be identified considering multiple criteria, including architectural merits, local availability of building components/materials, energy simulation results, and construction cost estimate. At this stage, clash detection should be completed and the detailed design work should be free from any spatial conflicts among building elements. Finally, the group design was presented both verbally by presentation and in a written report, both of which contributed to a summative assessment of the project and contributed to final marks.

3.4. Pedagogical strategies

Several teaching strategies were applied to deliver this project-based BIM course. Fig.2 lists the five main teaching strategies to nurture AEC students' active learning and critical thinking.

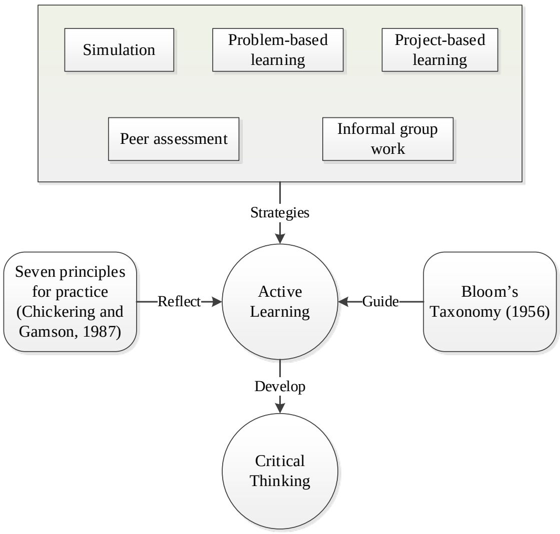


Fig.2. Teaching strategies in the BIM-based student team project

Some of the teaching strategies and theories adopted from other educators (e.g., Bloom, 1956; Chickering and Gamson, 1987) are described below.

- BIM enables simulation related activities within the building design and construction stages. In this team project, energy simulation was required to determine the optimized energy efficiency design. The 4D scheduling was also encouraged to display the assembly of pre-fabricated construction members on site.

- Peer assessment and informal group work were incorporated in the project design process. Peer-assessment could stimulate students to become independent learners (Falchikov, 2005). Informal group work would enhance student collaborative work as learning should be collaboration-based (Dolmans et al., 2005).

- The principles for good practice in undergraduate education proposed by Chickering and Gamson (1987) were reflected in the BIM pedagogy, including encouraging active learning, giving prompt feedback to students during different design stages of SD project, encouraging contacts between students and faculty, as well as developing reciprocity and cooperation among students.

- Bloom's Taxonomy Theory defined six hierarchy levels of cognitive domain (i.e., knowledge, comprehension, application, analysis, synthesis, and evaluation). Students enrolled on this BIM course had all been equipped with subject-specific skills and knowledge through their own field of core curriculums. For example, CE students had learned and practiced building structural design, take-off estimate, and construction scheduling; architecture students have been trained, through studio work, in architectural design; and AEE students had been trained through their first three years' undergraduate study in building services design and environmental sustainability. This project-based collaborative work was designed to apply their own fields of knowledge to contribute to the team design adopting BIM as the communication platform through information sharing.

Finally, students' critical thinking was reviewed in the group project report. The critical thinking could cover topics such as their understanding of how BIM impacted the project delivery process compared to the traditional design approach, and existing problems in applying BIM. The researchers also viewed students' digital models, clash detection results, and group presentation contents to check the consistency between their reflections and their project design deliverables. For example, when a group claimed that BIM improved design quality with clash detections. Their clash detection reports would be checked by the researchers to verify the detailed spatial clashes identified and how were they resolved. Similarly, when a group described the lack of family (e.g., solar PV panel) in BIM library as one challenge in using BIM, the researchers would check the building model to pinpoint how the lack of family was addressed. Only these consistent reflections from student group work would be considered reliable and adopted for analysis of students' perceptions towards BIM at later stages.

4. Results

By the end of the autumn semester in 2016, 12 undergraduate student teams and one graduate team presented their team design proposals. Fig.3 showcases an example of one student group's workflow.

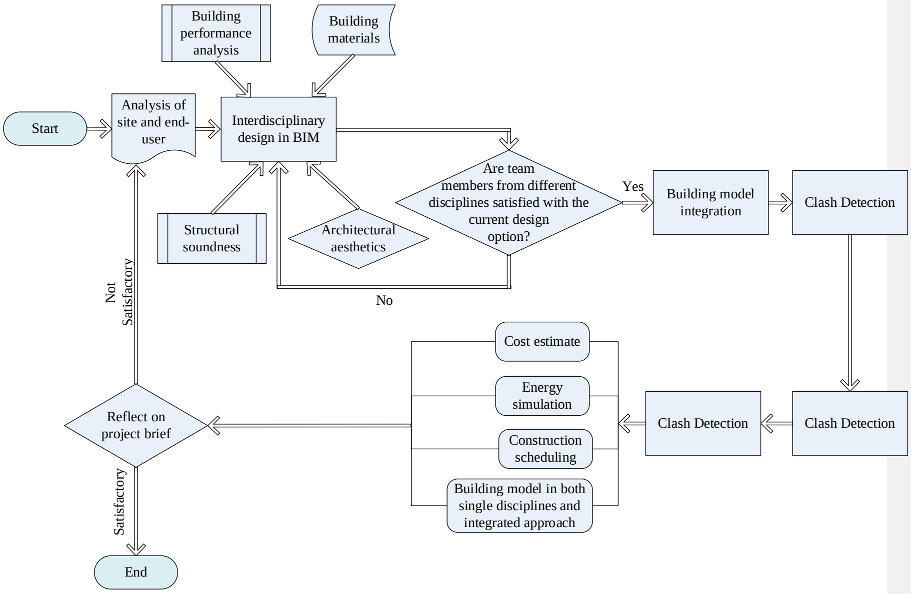
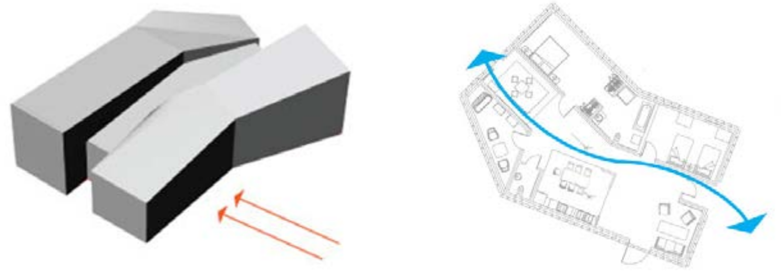


Fig.3. An example of workflow in the BIM-based team design

According to the given group work procedure described in Fig.3, the team design started from a comprehensive understanding of the project requirements summarized in Table 1, to finally provide the design deliverables including architectural rendering, cost estimate, construction scheduling, and integrated digital models. The key of the BIM group design based pedagogy was AEC students' interdisciplinary collaboration adopting BIM as the digital platform.

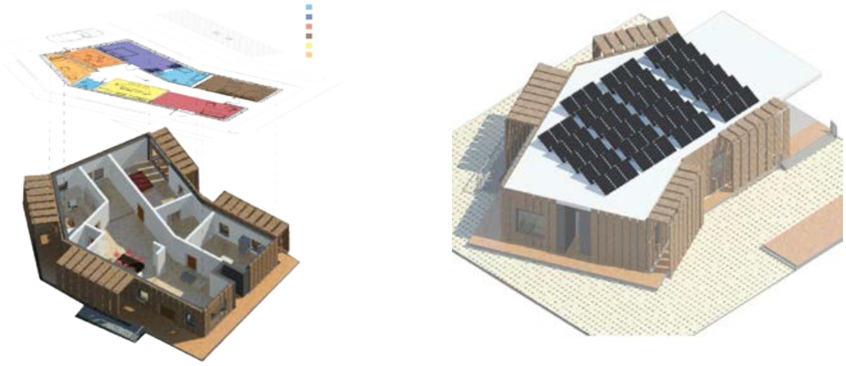
4.1.BIM-driven interdisciplinary collaboration

Following the given topographic information of the project site and analysis of end-user needs, the design team applied multiple criteria into the early design stage. For example, AEE students would be involved in the conceptual design stage working with architecture students to provide strategies for potential energy savings. These strategies provided by student teams included building orientation and building envelope, which were also mentioned by Kriegel and Nies (2008) to emphasise how BIM could aid in sustainable design. It was also mentioned that the early design and preconstruction stages are the most critical phases for decision making in sustainability (Azhar, 2010). Fig.4 shows an example of how one team integrated the passive design and renewable energy facilities in the early design stage.



a) Determining the building orientation

b) Cross ventilation



c) 2D plan linked to 3D visualization

d) Integration of solar panels

Fig. 4. Interdisciplinary collaboration in the early design stage

Note: All the figures or images generated in Fig.4 come from students' original work in this BIM course without modification, with the purpose of demonstrating students' interdisciplinary practice within BIM. The same rule applies to following figures in Section 4 from Fig. 5 to Fig. 16, except Fig.10 which is the researcher's work.

As showcased in Fig.4, an early stage input of AEE subjects was enabled in this integrated design approach, for instance, determining the building orientation, or the roof shape for energy efficiency purposes. Certain BIM tools (i.e., Autodesk Revit) and building simulation tools (e.g., Ecotect) could be linked to explore more sustainable architectural solutions. As the teamwork moved to schematic and detailed design stages, design responses to the multiple criteria (e.g., cost estimate and energy performance) would become more accurate. Fig.5 illustrates one example of how one of these student teams coordinated multiple BIM or BIM-extended software tools across the whole design process.

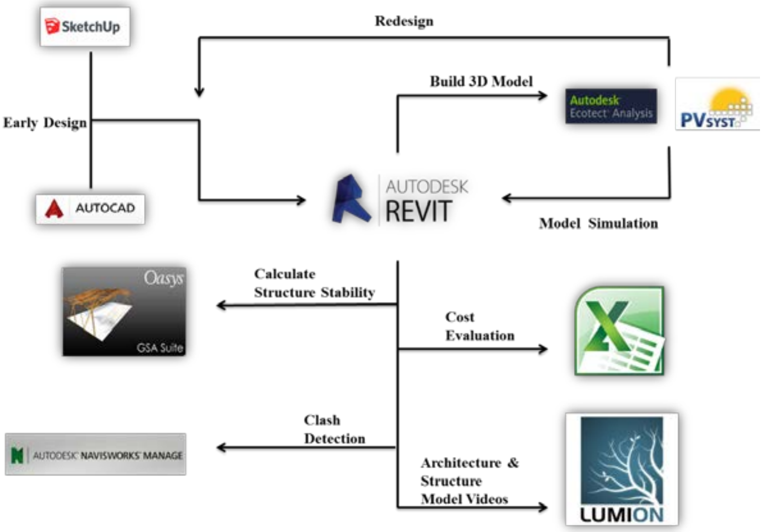


Fig.5. One example of team design with multiple BIM-based tools

The group work shown in Fig.5 started the conceptual design involving Autodesk Revit, which was further linked to multiple tools in solar panel integration, structural analysis, quantity take-off, clash detection, and architectural rendering. It is worth noticing that students were not restricted to any specific software tools in the design process, except that Revit and Navisworks were adopted as the tools in the earlier BIM workshop training.

Informal group meetings were scheduled periodically to allow prompt feedback from faculty to students as illustrated in Fig.2. Generally, student teams were motivated in a BIM-driven collaborative environment while contributing to the project design with their own field of knowledge. The team design of the 13 groups are summarized based on their team presentations and corresponding project reports in the following subcategories.

4.2.Architectural design

As indicated by some previous studies in both pedagogical and professional work (e.g., Thomsen, 2010; Jin et al., 2016), architects' traditional role in project design would be affected by BIM adoption due to the multi-disciplinary involvements. The influence of AEE and CE subjects in architecture could be seen in all 13 groups' work, for example, the input of structural engineering subject to define the grid system in the architectural form within the BIM platform, and the adjustment of roof angle to accommodate solar panels ensuring the structural soundness. One group stated that the initial design underwent several rounds of discussion between architecture and structural engineering students to meet the specific structural requirements while maintaining architectural merits using Revit as the communication tool. Fig.6 show an examples of technical collaborations across different disciplines.

Commented [RJ1]: Does this part need to be re-written?

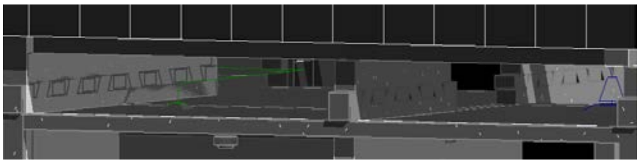


Fig.6. Spacing for air conditioning and piping

Various technical inputs of AEE or CE subjects into architectural models could be found in the team group design, for example, the adjustments of roof height and angle to accommodate building service facilities, window sizes and locations to enable cross ventilation, and integration of renewable energy technologies, etc. Teams widely reflected on how BIM functioned as the communication tool enhancing interdisciplinary collaboration. A few architecture students from multiple teams perceived BIM as a coordination method rather than a design solution in their project reports.

4.3.Structural engineering

Besides coordinating with architecture team members in the early design stages, structural engineering students were mainly responsible for performing the structural calculation and analysis adopting certain software packages (e.g., Oasys GSA). Revit was utilized to achieve the visualization of the structural form and to be integrated to the architectural and building services model for further clash detection analysis. The interdisciplinary collaboration could also be found in the structural analysis. One of these collaboration examples can be found in Fig.7.

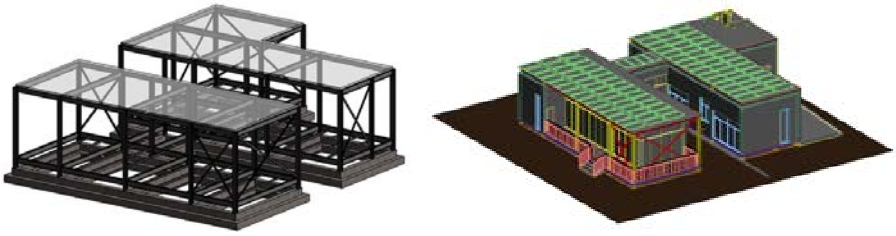
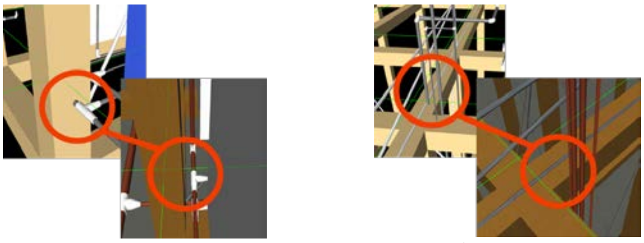

a) Structural model
b) Integrated model

Fig.7. Interdisciplinary collaboration in the structural design

Fig.7 shows an example of architectural input in the structural design. The architecture student on that team suggested to relocate the originally designed steel columns and bracings to outdoor spaces in order to enhance the living experience by allowing residents to view the aesthetics of steel members. The architectural design suggestion was adopted by CE students in this case within the BIM platform.

4.4.Building services engineering

AEE students in each team were responsible for integrating the building services facilities and sustainable technologies into the SD house design including the solar panels. Groups' building services design work typically covered the micro-climate analysis of the project site in Northern China, daylighting analysis, MEP system design applying clash detection, and energy simulation. Fig.8 displayed typical examples of spatial clashes identified in the plumbing design.

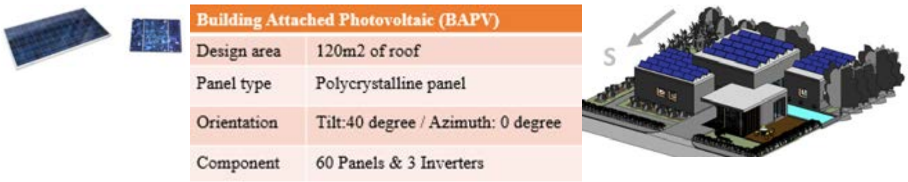


a) Clash between pipes and structural column

b) Conflict between pipes and structural beam

Fig.8. Spatial conflict detected in MEP design

Teams were encouraged to contact local suppliers of all building service equipment to integrate the product parameters into their digital models and designs. Fig.9 shows an example of one team's work of integrating solar panels into the building design.



Building Attached Photovoltaic (BAPV)	
Design area	120m2 of roof
Panel type	Polycrystalline panel
Orientation	Tilt:40 degree / Azimuth: 0 degree
Component	60 Panels & 3 Inverters

a) Polycrystalline panels

b) Some product parameters

c) Integrated building model

Fig.9. An example of integrating the solar panel into the building model

Building energy consumption was estimated by conducting energy simulations. Before the simulation, typically within teams, AEE students would discuss with CE members on adjusting the building fabrics information (e.g., external wall thickness and U-Values) to meet certain design standards such as CIBSE (i.e., Charted Institute of Building Services Engineers, 2016) Guide A. Some AEE students stated that this process was time-consuming as they had different goals in the design. For example, AEE students targeted on building energy efficiency but CE members focused more on structural integrity, material costs and construction effectiveness.

Although students were not restricted in choosing building energy simulation methods or software applications, they were aware of linking BIM-based tools (i.e., Revit) to energy simulation. Some building information, such as geometrical data and building fabrics, could be transported from BIM into energy simulation tools (e.g., IES-VE) to save time in rebuilding models for energy performance analysis. Data could be output from Revit to other energy simulation tools in certain format, such as gbXML. In this schematic design stage, some teams adjusted the building design details by comparing different design options in order to achieve the energy consumption optimization. BIM would allow them to compare the energy performance of different design options, for example, constructing curtain wall at façades, adjusting cooling and heating schedules, and night-time ventilation according to the local climate, etc.

Generally, teams designed the solar panel parameters (e.g., roof areas, tilting angles and number of solar modules) based on the building demand from simulation. The details of each team's renewable energy generation and the annual energy demand are presented in Fig.10.

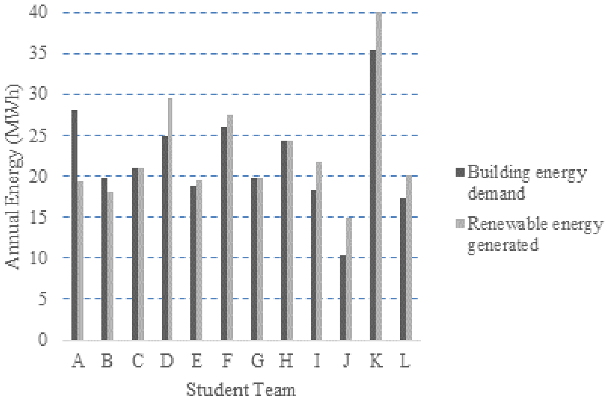


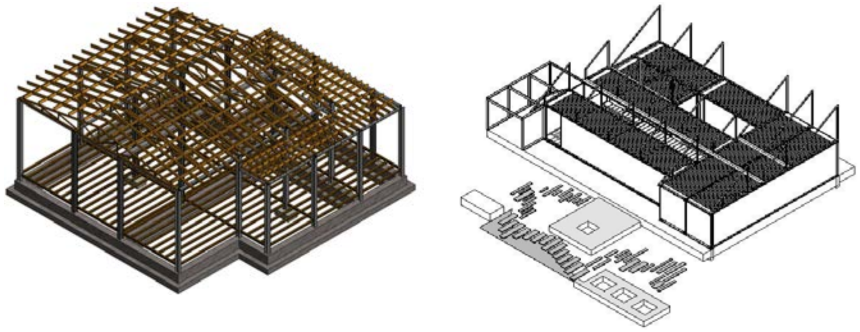
Fig.10: Different teams' simulation results of building energy demand and renewable energy generation

Note: only 12 teams' simulation results are available and presented in Fig.10, the other team consisting of graduate students did not provide the results.

Fig.10 shows that the majority of teams designed the solar panels to meet or even exceed the building energy demand. The ratio of annual renewable energy supply to building energy consumption ranged from 69% to 144%, with the average value at 107%. The building energy demand simulated by different teams also varied significantly, ranging from 10.34 to 35.47 MWh/year, with an average simulation value at 22.0 MWh/year and the standard deviation at 6.3 MWh/year. Different design options or parameters could generate significantly varied energy consumption results. Four out of 12 teams also provided the payback period analysis of SD house, with the payback of their designed solar panels ranging from 6 to 20 years. Their views on the investment effectiveness of solar panels also varied according to the return on investment analysis. It could be inferred that the evaluation on the cost effectiveness of solar panels is design-related and highly dependent on the product chosen.

4.5.Prefabrication construction

As prefabrication was the construction method required to deliver this SD project, each team was guided to choose their own building structural materials based on their investigation within China's construction industry. Teams also had to consider the local availability and transportation cost of prefabricated members. Among these 13 teams, six of them chose a steel frame, three teams designed a timber frame structure, and two teams chose precast concrete construction. The remaining two teams chose a mixed structural system, namely steel framing with timber roofing and flooring, and a recycled steel container with steel framing. Fig.12 displays the visualization of the mixed structures.



a) Steel framing with timber roofing b) Steel container with steel frame

Fig.12. Two mixed structural systems in SD team design

Although two out of the 13 teams chose a mixed structural system, both of them implemented steel as the main structure. It could be found that the steel-based materials and structure were the dominating option to satisfy the prefabrication construction needs of this SD project. Teams all provided a rationale for their selections. For example, those teams who selected the steel frame stated that steel is high in strength, fitting the fast construction needs, and is recyclable, etc. The team that proposed to use a steel container in Fig.12 explained that the locally available supplier could prepare the building services facilities (e.g., electrical wiring) in the containers when they are being manufactured in factory, and the floors/walls are integrated in the container therefore achieving time saving during on-site construction.

Teams were strongly encouraged to incorporate scheduling into the site-assembly for prefabricated construction members on-site. Typically teams used Work Breakdown Structure (WBS) in a Gantt Chart and 4D BIM to simulate construction activities on site. Fig.13 and Fig.14 show an example of traditional scheduling approach and 4D BIM assisted simulation respectively.

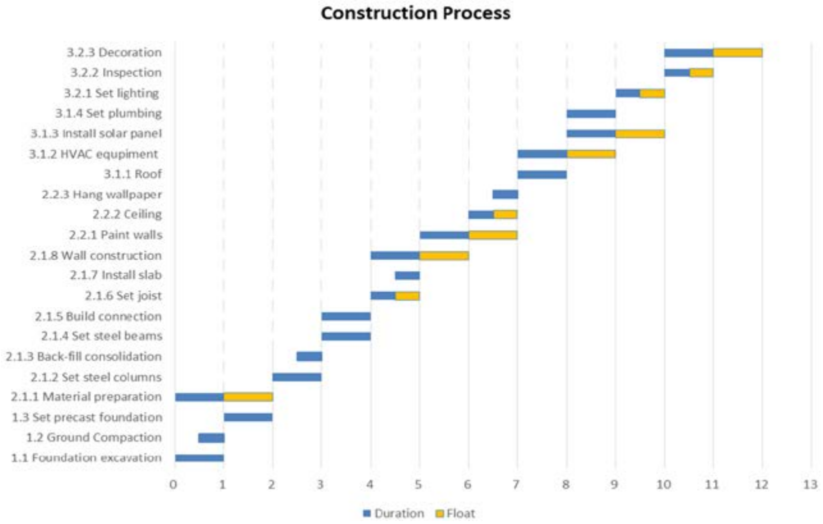


Fig.13. A demonstration of 12-day on-site construction scheduling

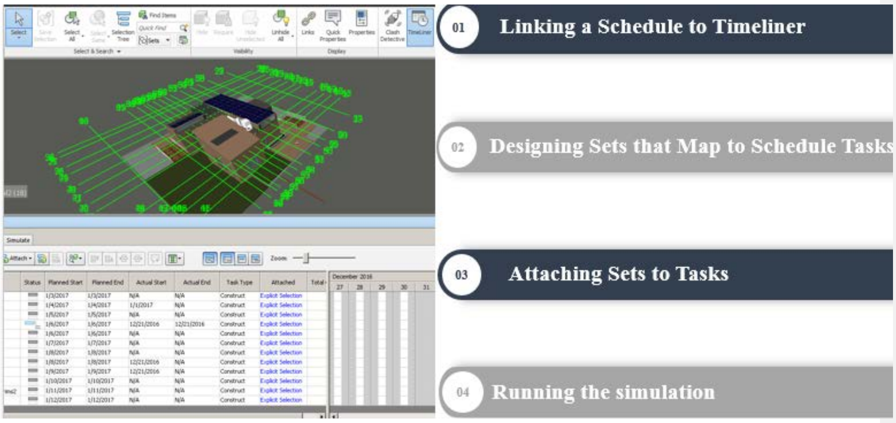
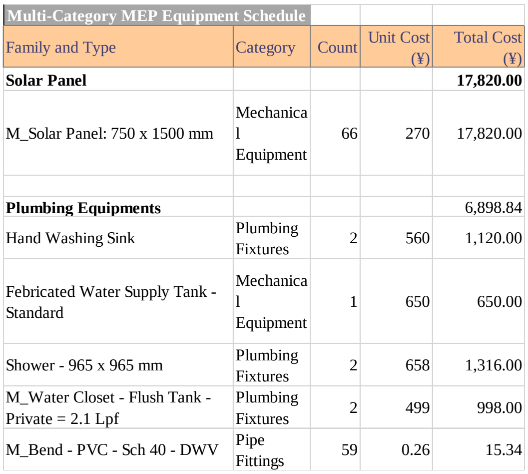


Fig.14. A description of the procedure to simulate 4D scheduling from Microsoft Project to Autodesk Navisworks

4.6.Cost estimate

As part of the assessment criteria, each team was required to provide the take-off estimate spreadsheet from the digital model created in BIM. Fig.15 shows one example of the cost break-down within the mechanical, electrical, and plumbing (MEP) system.

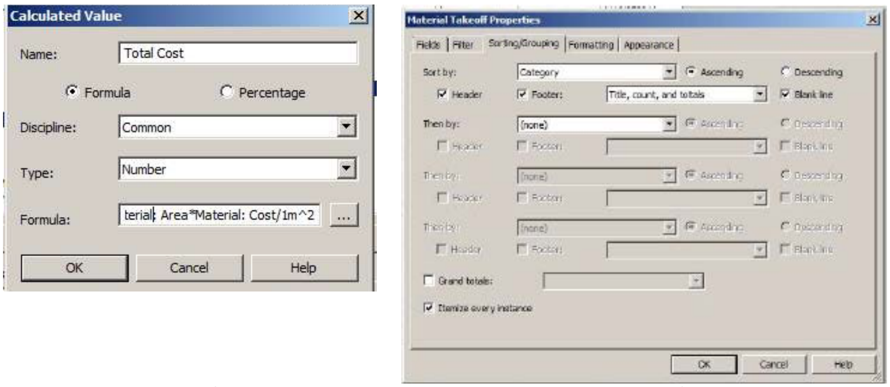


Multi-Category MEP Equipment Schedule				
Family and Type	Category	Count	Unit Cost (¥)	Total Cost (¥)
Solar Panel				**17,820.00**
M_Solar Panel: 750 x 1500 mm	Mechanical Equipment	66	270	17,820.00
Plumbing Equipments				6,898.84
Hand Washing Sink	Plumbing Fixtures	2	560	1,120.00
Febricated Water Supply Tank - Standard	Mechanical Equipment	1	650	650.00
Shower - 965 x 965 mm	Plumbing Fixtures	2	658	1,316.00
M_Water Closet - Flush Tank - Private = 2.1 Lpf	Plumbing Fixtures	2	499	998.00
M_Bend - PVC - Sch 40 - DWV	Pipe Fittings	59	0.26	15.34

Fig.15. A captured example of take-off spreadsheet in Excel according to the quantity generated from Autodesk Revit

Note: only part of cost items were displayed in Fig.15 to show the example of the budget sheet, some other items (e.g., electrical facilities and structural members) are not captured in this figure.

The family and types as well as quantities of each building element listed in Fig.15 came from the take-off information automatically generated in Revit model. The unit price came from either published sources in China or local suppliers. It is also worth noticing that although students were only taught with the basic Material Take-off function in Revit, some student teams demonstrated their self-motivation to edit the existing formulas or format in the default set-up of quantity take-off within Revit according to their own project needs. Fig.16 displays the examples of students' work in handling Revit functions in the process of generating a material take-off sheet.



Name: Total Cost

● Formula ○ Percentage

Discipline: Common

Type: Number

Formula: terial: Area*Material: Cost/1m^2

Sort by: Category ● Ascending ○ Descending

☑ Header ☑ Footer: Title, count, and totals ☑ Blank line

Then by: (none) ● Ascending ○ Descending

☐ Header ☐ Footer: ☐ Blank line

Then by: (none) ● Ascending ○ Descending

☐ Header ☐ Footer: ☐ Blank line

Then by: (none) ● Ascending ○ Descending

☐ Header ☐ Footer: ☐ Blank line

☐ Grand totals:

☑ Itemize every instance

a) Adding formula b) Changing format

Fig.16. Students' work on editing existing quantity take-off functions in Autodesk Revit

With the assistance of BIM, further cost estimate codes (e.g., Spon's Architectures' and Builders' Price Book, 2015) could be applied to obtain the cost information as shown by Jin et al. (2016).

4.7.Reflection

As indicated in Fig.2, this BIM course was developed to motivate students' active learning and to nurture their critical thinking focusing on how BIM affected their team design and management in this SD case study project. Students were guided to share their BIM usage experience through this SD project. Based on the qualitative analysis of the 13 teams' project deliverables, i.e. reflective reports, building digital models and drawings, clash detection results, and group presentation contents, both positive and negative perceptions that teams held towards how the adoption of BIM impacted their teamwork were categorized and counted as shown in Table 3.

Table 3. Reflections of student teams on BIM adoption in SD project design (N=13)*

Positive Perceptions	Number of teams	Negative perceptions	Number of teams
Improved collaboration and communication	12	Lack of family elements in existing BIM library	3
Improved design quality with clash detection	9	Demands on training and software skills	2
Enhanced details from visualization	5	Architects being restricted by other disciplines	2
Improved sustainability in building design	3	Interoperability problem among different BIM-related tools	2
Faster design process	3		
Consistency and efficiency of generating quantity take-off	1		

*: Totally 13 student teams provided their perceptions on how BIM affected the team project

Table 3 counts the number of teams that provided the given perception towards BIM impacts on their team project. The most frequently perceived positive effect of BIM within the team project was the improved collaboration and communication. As teams reflected, BIM worked as a platform for cross-disciplinary communication starting from the conceptual design to the later clash detection. There were more motivations for collaborations among the major disciplines (i.e., architecture, structural engineering, building services engineering, and construction management) in the BIM-driven environment, through information sharing and coordination within the digital building models. The second most frequently recognized BIM impact on teamwork was the improved design quality with clash detection. Teams were able to modify their models by correcting detections automatically identified within the BIM system. One of the fundamental BIM features, 3D visualization, was also frequently listed by teams as one major impact on project design. Besides these three major positive effects of BIM, a few teams also had positive perceptions on the effects of using BIM in building sustainability and design delivery. AEE students in this project were responsible for integrating solar panels into the building service facilities and analyzing the building energy demand. BIM, up to a certain level, assisted the building performance analysis through data sharing (e.g., building geometric information). The interdisciplinary design approach, as stated by several teams, enhanced the design efficiency.

Some negative comments on BIM effects were also provided. One main barrier of adopting BIM during this project work was the lack of families in the exiting BIM library. Students had to perform extra work to build the family (e.g., solar panel) within the existing library. A few groups demanded more software skill trainings before working on this SD project. Teams also discussed the interoperability issue when linking BIM into building energy simulation, specifically in the information loss when sharing the data among different software tools. Besides these comments regarding technical factors, the factor within design management was also concerned by student teams when adopting BIM. Some architecture students stated that their design was restricted by both AEE and CE disciplines. For example, in one group work, the AEE students declined the architecture teammates' proposal of applying larger-sized glazing for a better view, as it would result in more heat loss in the winter. On another team, one architectural student claimed that the worst part of BIM was that the architectural design was interfered with by team members from other disciplines.

5. Findings and Discussion

This pedagogical practice adopted the project-based approach to bring the interdisciplinary teamwork approach to AEC students. The results were summarized from students' project work and their reflection on how BIM functioned and influenced their teamwork of the SD project. AEC students' work was presented based on multiple disciplines' contributions, namely architectural design, structural engineering, building services engineering, prefabrication construction, sustainability, as well as take-off estimate and scheduling. These various disciplinary works were inter-linked using BIM as the communication tool. Teams were highly encouraged to provide their creative design to meet multiple project criteria (e.g., selection of prefabricated elements). Student teams' perception might vary towards certain design criteria. For example, one team claimed that it was worthwhile investing in solar panel, while the other team held opposite views. Students were trained on BIM skills and interdisciplinary teamwork capacity in this SD project through an experiential learning approach. For instance, some teams compared a few design options in earlier design stages to decide the most efficient option through simulation. Some other teams applied the 4D scheduling to simulate the construction activities. Major findings of this pedagogical research can be described as students' perceptions towards BIM's positive impacts on project design, challenges encountered, as well as the similarities and differences between students and AEC professionals in terms of these perceptions.

This BIM pedagogical practice also aimed to collect insights from AEC students' perceptions on BIM effect in the building project design and management. The SD project, deemed as a small-sized building project, was selected as the case study. It has been previously demonstrated by Sebastian et al. (2009) in industrial practice that BIM could be applied in small-scale housing sector and enhance the interdisciplinary design and engineering. The consistent perceptions regarding BIM impacts on project design between AEC students in this pedagogical study and industry practices from a few previous case studies including Sebastian et al. (2009) and Sebastian (2010) are summarized below:

- the 3D visualization assisted to enhance coordination and communication;
- facilitating information sharing and exchange across disciplines;
- integrated multidisciplinary design among architecture, structural engineering, energy analysis, cost estimate, and planning;
- selection and optimization of design options against the project requirements;

- BIM linked with cost estimate
- a 3D model integrating the prefabrication solution
- accommodation of building service facilities within the 3D building model
- several techniques to achieve data sharing among multiple BIM-related software tools
- early discovery of design errors through clash detection.

This BIM pedagogical practice also identified certain issues or challenges which could spark future research needs or raise industry concerns, including:

- interoperability issue when sharing the building information between the building digital model and building energy simulation;
- architects' resistance to BIM due to their potential loss of leadership in the design process as their architectural decisions might be disapproved by other disciplines;
- lack of family types in the existing BIM library, leading to the extra work by converting the existing local suppliers' building product information (e.g., solar panels) into the BIM library;
- insufficient BIM software skill training to deliver project design applying digital technologies;
- drawbacks within existing software tools, for example, some of these spatial conflicts detected might not necessarily need any modification (e.g., installation of electrical wiring within internal partition walls).

Some of these students' feedback on challenges encountered in the BIM-based project design were also highly consistent with the views from AEC industrial practice. As identified by multiple other sources (e.g., Porwal and Hewage, 2013 and Jin et al., 2017) from the AEC industry perspective, interoperability remained one major barrier for wider application of BIM in enhancing multidisciplinary collaboration. The architecture students' resistance to BIM was also consistent with the architects in the study of Thomsen (2010) who stated that BIM limited the design choices and added extra requirements to architects. It could be inferred that through the project-based experiential learning approach, AEC students could gain consistent perceptions as industry professionals do on how BIM could influence their team design. This BIM pedagogical practice not only served as the software skill training, teamwork capacity, but also the real-world scenario for students to gain their initial experience in BIM interdisciplinary project work. Students developed their critical thinking on BIM through their reflective feedback, which in return, provided insightful suggestions on how to embrace more effectively different aspects of AEC practices (e.g., off-site construction and green building) into interdisciplinary BIM pedagogy.

6. Conclusions

To fill the gap of limited BIM-based interdisciplinary teaching and learning at institutional level, this BIM pedagogical work was developed to recruit students from multiple AEC disciplines to deliver a solar-powered residential house within the real-world scenario. BIM was adopted as the digital platform for cross-disciplinary communication, coordination, and collaboration. Prefabrication and renewable energy facilities were incorporated in this residential project as part of the BIM-driven cross-disciplinary cooperation among architectural, structural, building services, and construction engineering work. It was found that AEC students were generally motivated in the teamwork approach assisted by BIM-enabled visualization and information sharing. With the experiential learning procedure, students were able to provide their perceptions and feedback which were highly consistent to that of AEC professionals from other studies regarding BIM influences on project design and management. Generally, BIM was found to have positive effects in terms of enhancing team communication, improving design through clash detection, assisting sustainable design, and providing visualization. Challenges in BIM adoption were also identified consistently to what had been found from the industry's standpoint, such as the lack of interoperability among BIM related tools, insufficient BIM library database for design needs, and the challenges to the traditional role of architects, etc.

The AEC students in this BIM course gained not only software skills but more importantly, the interdisciplinary collaboration experience needed before they enter the industry. The properly designed BIM pedagogy could provide AEC students with state-of-the-art skills and help, further at some point, saving some resources of their future employers on employees' BIM skill training. The limitations identified from this pedagogical practice could be linked to research needs, such as the interoperability issue. Future BIM pedagogy could involve AEC industrial professionals to assess student teams' feasibility in design or construction planning by providing more constructive feedback. More project-based case studies could be provided from the industry to continue applying the real-world scenario in the pedagogy, which in return provides design proposals to project stakeholders for their appraisal.

References

AIA California Council. (2007), "Integrated Project Delivery: A guide", pp. 20-30.

Amuda-Yusuf, G. and Mohamed, S.F.(2015), "Essential features of a building services standard method of measurement in Malaysia." *Engineering, Construction and Architectural Management*, 22(6), pp.749-770.

Azhar, S. (2010), "BIM for sustainable design: results of an industry survey", *Journal of Building Information Modeling*, 4 (1), pp. 27–28.

Aziz, Z. and Tezel, A. (2016), "Lean and BIM – A Synergistic Relationship." UK Construction Excellence, 2016 (1), pp. 40.

Benjaoran, V. and Bhokha, S. (2009) "Enhancing visualization of 4D CAD model compared to conventional methods." *Engineering, Construction and Architectural Management*, 16 (4), pp.392-408.

Bloom, B.S. (1956), "Taxonomy of Educational Objectives, the Classification of Educational

Goals – Handbook I: Cognitive domain.” New York, McKay. pp.16.

Bråthen, K. and Moum, A.(2016,) "Bridging the gap: bringing BIM to construction workers." *Engineering, Construction and Architectural Management*, 23(6), pp.751-764.

Chickering, A.W. and Gamson, Z.F. (1987), “Seven principles for good practice in undergraduate education. American Association for Higher Education & Accreditation Bulletin.” March, 39 (7), pp. 3-7. Available from www.aahea.org/bulletins/articles/sevenprinciples1987.htm [Accessed 18 December 2016]

Chong, H., Lee, C. and Wang X. (2017), “A mixed review of the adoption of Building Information Modelling (BIM) for sustainability.” *Journal of Cleaner Production*, 142, Part 4, pp.4114–4126.

CIBSE Guide A. (2016), “Environmental Design 2015.” GVA/15.

Clevenger, C., Glick S. and Puerto, C.L.D.P. (2012), “Interoperable Learning Leveraging Building Information Modeling (BIM) in Construction Education.” *International Journal of Construction Education and Research*, 8(2), pp. 101-118.

Creswell, J.W.(2013), “Research design: Qualitative, quantitative, and mixed methods approaches.” Sage publications.

Ding, Z., Zuo, J., Wu, J. and Wang, J.Y.(2015), "Key factors for the BIM adoption by architects: a China study." *Engineering, Construction and Architectural Management*, 22(6), pp.732-748.

Dolmans, D. H., De Grave, W., Wolfhagen, I. H. and Van Der Vleuten, C. P. (2005), “Problem-based learning: Future challenges for educational practice and research.” *Medical education*, 39(7), pp. 732-741.

Falchikov, N. (2005), “Improving assessment through student involvement: Practical solutions for aiding learning in higher and further education.” London: Routledge & Falmer.

Farnsworth, C.B., Beveridge, S., Miller, K.S. and Christofferson, J.P. (2015). “Application, Advantages, and Methods Associated with Using BIM in Commercial Construction.” *International Journal of Construction Education and Research*, 11(3), pp.218-236.

Gajendran, T. and Brewer G. (2007), "Integration of information and communication technology: Influence of the cultural environment." *Engineering , Construction and Architectural Management*, 14(6): 532-549.

Ghosh, A., Parrish, K. and Chasey, A.D. (2015), “Implementing a vertically integrated BIM curriculum in an undergraduate construction management program.” *International Journal of Construction Education and Research*, 11, pp. 121–139.

Jäväjä, S.S.P. and Salin, J. (2014), “BIM Education: Implementing and Reviewing "OpeBIM" - BIM for Teachers. Computing in Civil and Building Engineering.” *©ASCE 2014*, pp.2151-2158.

Jensen, P.A and Jóhannesson, E.I. (2013) "Building information modelling in Denmark and Iceland." *Engineering, Construction and Architectural Management*, 20 (1), pp.99-110.

Jin, R., Tang, L., and Fang, K. (2015), “Investigation of the current stage of BIM application in China’s AEC industries.” WIT Transactions on The Built Environment, 149, pp. 493-503.

Jin, R., Tang, L., Hancock, C.M. and Allan, L. (2016), “BIM-based multidisciplinary building design practice-a case study.” 7th International Conference on Energy and Environment of Residential Buildings, November 20-24, 2016, Brisbane, Australia.

Jin, R., Hancock, C.M., Tang, L., Chen,C., Wanatowski, D. and Yang,L. (2017), “Empirical study of BIM implementation-based perceptions among Chinese practitioners.” *Journal of Management in Engineering*, 33(5), DOI: 10.1061/(ASCE)ME.1943-5479.0000538.

Khosrowshahi, F. and Arayici, Y. (2012), "Roadmap for implementation of BIM in the UK construction industry", *Engineering, Construction and Architectural Management.*” 19 (6), pp.610-635.

Kim, J. (2011), “Use of BIM for effective visualization teaching approach in construction education, *Journal of Professional Issues in Engineering Education and Practice*.” 138(3), pp. 214-223.

Kriegel, E., and Nies, B. (2008), “Green BIM”, Wiley Publishing, IN, Indianapolis.

Mathews, M. (2013). “BIM collaboration in student architectural technologist learning.” *Journal of Engineering, Design and Technology,* 11(2), pp.190-206.

Nawari, N.O. (2015), “The role of BIM in teaching structural design.” *Structures Congress*

2015, pp. 2622-2631.

Lee, N., and Hollar, D.A. (2013), “Probing BIM education in construction engineering and management programs using industry perceptions.” 49th ASC Annual International Conference Proceedings, California.

Li, H., Chan, G., Skitmore, M. and Huang, T.(2015), "A 4D automatic simulation tool for construction resource planning: a case study." *Engineering, Construction and Architectural Management*, 22 (5), pp.536-550.

Peansupap, V. and Walker, D.H.T. (2006) "Information communication technology (ICT) implementation constraints: A construction industry perspective." *Engineering, Construction and Architectural Management*, 13(4), pp.364-379,

Porwal, A., & Hewage, K. N. (2013), “Building Information Modeling (BIM) partnering framework for public construction projects.” *Automation in Construction*, 31, pp.204-214.

Rogers, J., Chong, H. and Preece, C. (2015), "Adoption of Building Information Modelling technology (BIM): Perspectives from Malaysian engineering consulting services firms." *Engineering, Construction and Architectural Management*, 22 (4), pp.424-445.

Sacks, R. and Pikas, E. (2013), “Building information modeling education for construction engineering and management. I: industry requirements, state of the art, and gap analysis.” *Journal of Construction Engineering and Management*, 139(11), 04013016.

Sebastian, R. (2010), “Changing roles of the clients, architects and contractors through BIM.” *Engineering, Construction and Architectural Management*, 18(2), pp. 176-187.

Sebastian, R., Haak, W., and Vos, E. (2009), “BIM application for integrated design and engineering in small-scale housing development: a pilot project in The Netherlands.” International symposium CIB-W096 future trends in architectural management, pp. 2-3.

Shanbari, H., Blinn, N. and Issa, R.R.A. (2016), "Using augmented reality video in enhancing masonry and roof component comprehension for construction management students", Engineering, Construction and Architectural Management.” 23(6), pp.765-781.

Singh, V. and Holmström, J. (2015), "Needs and technology adoption: observation from BIM experience." *Engineering, Construction and Architectural Management*, 22 (2), pp.128-150.

Solnosky,R.L and Parfitt, M.K. (2015), “A curriculum approach to deploying BIM in Architectural Engineering.” *AEI 2015*, pp. 651-662.

Spon’s Architectures’ and Builders’ Price Book. (2015), Edited by AECOM, One hundred and fortieth edition. CRC Press, Taylor & Francis Group.

Strong, D and Burrows, V. (2017), “A whole-system approach to high-performance green buildings.” Artech House, Norwood, MA, pp. 281.

Tang, L., Jin, R. and Fang, K. (2015), “Launching the innovative BIM module for the architecture and built environment programme in China.” *Building Information Modelling (BIM) in Design, Construction and Operations*, 149, 145.

The British Standards Institution. (2013), “PAS 1192-2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling.” BSI Standards Limited.

Thomsen, A. (2010), “The role and influence of the Architect in industrialized building.” Second cycle, A2E. Alnarp: SLU, Landscape Management, Design, and Construction.

Udeaja, C and Aziz, Z (2015), “A case study of fostering multidisciplinary in built environment using BIM.” In: Raidén, A B and Aboagye-Nimo, E (Eds) Procs 31st Annual ARCOM Conference, 7-9, September 2015, Lincoln, UK, Association of Researchers in Construction Management, 701-710.

Wong, J.K.and Kuan, K (2014), “Implementing ‘BEAM Plus’ for BIM-based sustainability analysis.” *Automation in Construction*, 44, August 2014, pp.163-175.

Zhao, D., McCoy, A.P., Bulbul, T., Fiori, C. and Nikkhoo, P. (2015), “Building Collaborative Construction Skills through BIM-integrated Learning Environment.” *International Journal of Construction Education and Research*, 11(2), pp. 97-120.

Corresponding author

Dr Ruoyu Jin can be contacted at: R.Jin@brighton.ac.uk