Automation in Construction 83 (2017) 134–148

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Building Information Modeling (BIM) for green buildings: A critical review and future directions

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ARTICLE INFO

Keywords:
Building Information Modeling (BIM)
BIM software
Green buildings
Life cycle
Review
Sustainability

ABSTRACT

Although a large number of studies on Building Information Modeling (BIM) have been conducted in the past decade, a lack of consensus remains among researchers and practitioners regarding the applications of BIM for the development of green buildings, the activity of making buildings in a way that protects the natural environment. As the usefulness of BIM has been widely recognized in the building and construction industry, there is an urgent need to establish an up-to-date synthesis on the nexus between BIM and green buildings. After an in-depth review of hundreds of journal articles published from 1999 to 2016 and 12 widely used types of BIM software, this study provides a holistic understanding and critical reflection on the nexus between BIM and green buildings, which is systematically illustrated by a "Green BIM Triangle" taxonomy. The proposed taxonomy indicates that the nexus between BIM and green buildings needs to be understood based on three dimensions, namely project phases, green attributes and BIM attributes. Following the proposed taxonomy, this paper systematically illustrated 1) the applications of BIM in supporting the design, construction, operation, and retrofitting processes of green buildings; 2) the various functions of BIM for green building analyses such as energy, emissions, and ventilation analysis; 3) the applications of BIM in supporting green building assessments (GBA); and 4) research gaps and future research directions in this area. Through critical review and synthesis of BIM and green buildings based on evidence from both academic research and industrial practices, this paper provides important guidance for building researchers and practitioners to better align BIM development with green building development in the future.

1. Introduction

The building and construction industry has been driven to adopt green building strategies in light of increasing sustainability concerns such as reducing CO_2 emission and energy dependency on fossil fuels [1,123,124]. As a revolutionary technology and process, Building Information Modeling (BIM) has been regarded by many as a significant opportunity in the architecture, engineering and construction (AEC) industry. BIM emerged as a solution to facilitate the integration and management of information throughout the building life cycle [11], thereby providing an opportunity for making the best use of the available design data for sustainable design and performance analysis [2]. As BIM and green building both continuously gain momentum, growing AEC firms are embarking on green BIM practices [121]. An online survey conducted by McGraw-Hill Construction investigated a wide range of industry professionals who use BIM tools for delivering green buildings, showing that BIM could significantly facilitate green construction and it is expected to be extensively used in the future if relevant challenges could be identified and effectively tackled. Since 1999, when the concepts and technologies related to BIM application were first discussed [1], continuous efforts have been made in exploring the possibility of BIM in facilitating the development of green buildings. Various functions of BIM have been studied, such as energy performance simulation, lighting analysis, and construction and demolition waste analysis. Different management aspects associated with BIM adoption have been highlighted, such as its economic benefits and organizational challenges [2–8]. A number of BIM applications have been proposed and developed to seamlessly integrate sustainability analysis into traditional design, construction, and operation processes.

Although BIM has been advocated for its potential to support green building development in the past decades, few systematic literature review was conducted to delineate the state-of-the-art development of the connections between BIM and sustainable building development based on both academic research and industrial practices [6,9]. Wong and Zhou [11], for instance, presented an important review of the academic research efforts in BIM and green buildings, but paid less

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http://dx.doi.org/10.1016/j.autcon.2017.08.024
Received 3 February 2017; Received in revised form 6 June 2017; Accepted 10 August 2017
Available online 29 August 2017
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attention to systemically comparing the various BIM applications for green buildings in the industry. A number of important research questions concerning the BIM-supported green building development remain unexplored, such as (1) the benefit and additional value of using BIM in green buildings throughout the project lifecycle; (2) the functions that BIM software provides for a specific type of sustainability analysis; (3) the potential of BIM applications to support green building assessments (GBA) frameworks; and (4) the gaps between industry development and academic research in the application of BIM for green buildings.

In order to address the above-mentioned research questions, this study conducts a critical review on the nexus between BIM and green buildings based on both academic research and industrial practices. Specifically, over 500 journal articles from 28 key AEC journals published (1999–2016), as well as 12 commonly used types of available BIM software were critically reviewed. By examining the reviewed articles and BIM software based on a stringent four-step taxonomy process, this study proposes a "Green BIM Triangle" taxonomy to categorize current efforts connecting BIM and green buildings through three dimensions, namely project phases, green attributes and BIM attributes [12]. The taxonomy provides a useful tool for researchers and practitioners to understand the current body of knowledge and helps to stimulate future research.

The structure of the study is organized as follows. Section 2 discusses the research design of this study. Section 3 illustrates the proposed "Green BIM Triangle" taxonomy in detail, discussing the lifecycle of green projects supported by BIM, the latest BIM analytical functions for addressing various green aspects, and BIM-supported GBA. Section 4 identifies the gap of knowledge and future research directions, with Section 5 concluding this article.

2. Research methodology

Connecting BIM and green buildings is the concept of "green BIM", which has been explored by previous studies based on several relevant concepts such as green buildings [13], sustainable design [14], and sustainable construction [15]. Wong and Zhou [11] summarized the previous research on green BIM and defined green BIM as "a model-based process of generating and managing coordinated and consistent building data during its project lifecycle that enhance building energy-efficiency performance, and facilitate the accomplishment of established sustainability goals". To describe the scope and characters of BIM applications for green buildings, this study follows this definition of green BIM, which provides the key criteria for the selection of academic articles and practical BIM software. The selected academic articles and BIM software were examined based on a four-step classification and review process, the result of which is the "Green BIM Triangle" taxonomy. Fig. 1 illustrates the research procedure of this study.

2.1. Selection of academic publications

The selection process of academic publications in this study draws on the methodology adopted in other review articles, such as [144,145]. The commonly adopted literature selection processes in review articles include several steps, namely defining the used literature database and search rules, preliminary search and double-check screening (literature filtration). To make the review results dependable and rigorous, many review articles in the construction field only review literature published in peer-reviewed academic journals with high reputation in the field, which are deemed to be of higher quality than conference papers. In accordance with this principal, this study only reviews journal articles on green BIM. Then, a process similar to [144,145] was adopted to conduct preliminary search and literature filtration, thereby identifying the articles most relevant to green BIM. This process involves reading the titles and abstracts of the articles first to exclude the apparently irrelevant articles, and then reading the whole articles to assess whether they directly analyze green BIM. The detailed procedures are as follows.

Step 1: Select target journals. In order to acquire all possible papers pertaining to BIM and green buildings, this study adopted three criteria to select the journals for academic review. (1) The journal is included in the Science Citation Index (SCI)-Expanded database or Engineering Index (EI) Compendex database. (2) The journal is recognized or encouraged by two world-recognized international associations for civil engineering and built environment, namely the American Society of Civil Engineers (ASCE) that is dominated by American researchers, and the International Council for Research and Innovation in Building and Construction (CIB) dominated by European scholars. And (3) the journal has an important impact and prominent position in the research community of either BIM and sustainability or building and construction industry. Based on the above criteria, 28 widely acknowledged peer-reviewed journals were identified as target journals for paper selection, as shown in Table 1.

Step 2: Perform a search on BIM-related studies. This step aimed to screen all BIM-related articles by using the search keywords of "Building Information Modeling" or "Building Information Model" or "BIM". To determine the eligibility and level of relevance of the article, all articles published in the above 28 journals from 1999 to 2016 were searched for the keywords via specific domains, such as "title", "keywords" or "abstract". By manually selecting articles specifically related to BIM, a total of 550 BIM-related articles were identified in this step.

Step 3: Identify the BIM application on green buildings based on the definition of green BIM. In this step, 92 papers pertinent to green buildings in the pre-identified BIM-related studies were rigorously reviewed, while the remaining articles were partially reviewed as supporting records. The distribution of the 92 articles in the 28 journals is shown in Table 1. It is worth mentioning that this study mainly investigates the converging points between BIM and green buildings, so overwhelming studies that only emphasize on either one of the topics were referred only when needed.

2.2. Selection of BIM software used in AEC industry

In addition to academic studies, this study also reviews current BIM software and applications that are developed to improve the sustainability performance of buildings throughout their lifecycle phases. To this end, based on the definition of green BIM, 12 types of popular BIM software specifically designed and developed to address green and sustainable building issues were selected from the *BIM Tools Matrix*, the industry-shared knowledge compiled by *BIM Forum* [16]. Table 2 presents an overview of the 12 types of BIM software.

It is important to note that there is no single satisfactory definition of BIM [125]. An extensively referred definition is provided by Succar, B. [128], who defined BIM as "a set of interacting policies, processes and technologies producing a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle." This definition reveals that BIM is a methodology comprised of interacting processes and technologies, serving for the entire life cycle of buildings from architectural design to facility management, demolition and refurbishment of buildings. Various BIM applications exist, with some emphasizing the aspect of architectural design while others may focus on sustainability analysis. Based on a systematic review of the literature, a structured questionnaire survey, action learning, focus group discussions and email surveys, Abanda et al. [126] provide one of the most holistic reviews of BIM applications, listing 122 BIM software systems including BIM systems for architecture such as Vectorworks, for structural engineering such as Tekla Structures and Robot Structural Analysis; for building service such as Revit MEP and MagiCAD, for project management such as Synchro,

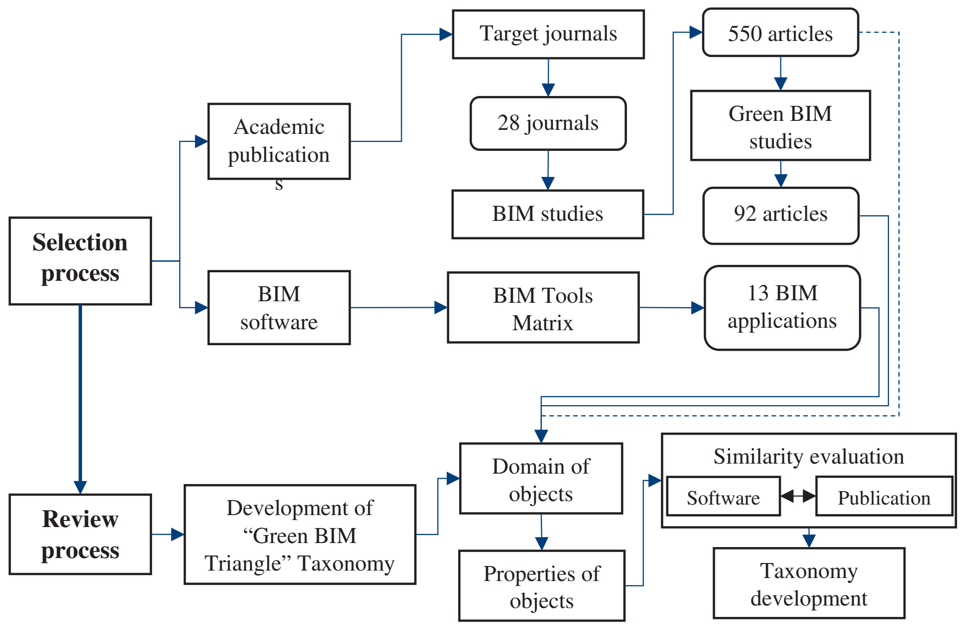

Fig. 1. Research methods and procedure of this study.

Table 1
Review sources of 28 academic journals and the identified articles during 1999 to 2016.

Journals	Number of articles (1999–2016)	
	BIM[a]	BIM & green buildings
Architecture Science Review	1	1
Advanced Engineering Informatics	49	9
Architectural Engineering and Design Management	15	3
Australasian Journal of Construction Economics and Building	11	1
Automation in Construction	183	28
Building and Environment	6	5
Energy and Buildings	14	14
Building Research and Information	3	0
Built Environment Project and Asset Management	7	0
Construction Innovation	19	3
Construction Management and Economics	9	1
Computer-Aided Civil and Infrastructure Engineering	3	0
Engineering, Construction and Architectural Management	9	0
Facilities	5	2
International Journal of Project Management	4	1
ITcon - Journal of Information Technology in Construction	84	8
Journal of Building Performance Simulation	14	4
Journal of Civil Engineering and Management	12	1
Journal of Computing in Civil Engineering	47	2
Journal of Construction Engineering and Management	29	3
Journal of Engineering Design and Technology	1	0
Journal of Management in Engineering	17	3
Proceedings of Institution of Civil Engineers - Civil Engineering	4	1
Project Management Journal	1	0
Smart and Sustainable Built Environment	1	1
The International Journal of Construction Management	2	1
Total	550	92

[a] Note: no relevant papers are found for the following journals, including *Intelligent Buildings International*, and *International Journal of Disaster Resilience in the Built Environment*.

Vico and BIMMeasure, for facilities management such as Bentley Facilities and ArtrA, and for sustainability analysis such as Green Building Studio and DesignBuilder. Similarly, Kassem et al. [127] propose protocols for BIM collaborative design that can be utilized at project level to increase the consistency of information flow and BIM deliverables, by using several BIM systems including Revit, Integrated Environmental Solutions Virtual Environment (IES-VE) and Navisworks as an example. These studies indicate that the family of BIM software systems should holistically cover the various aspects of buildings, and tools for sustainability analysis such as IES-VE are part of the BIM family. This is further illustrated in Azhar and Brown [129] and Azhar et al. [95], which found that there are three commonly used BIM-based sustainability analyses software, namely Autodesk Ecotect™ (which has been ended since 2015), Autodesk Green Building Studio (GBS)™, and IES-VE. Similarly, these sustainability analysis tools are named as "BIM analysis tools" in the *BIM Tools Matrix*, compiled by BIM Forum. In accordance with the above studies, this study selects and reviews 12 BIM analysis tools from *the BIM Tools Matrix*.

Most software programs are specially developed for the design phase and used by architects, designers or engineers. Few can be used at the construction or operation phase. In regard to the functionality, these 12 types of software programs can contribute to the sustainability analysis of green buildings in six aspects, including energy consumption, carbon emissions, natural ventilation, solar radiation and lighting, acoustics, and water usage. The first four aspects can be addressed by around ten types of software, while the last two aspects are only supported by certain types. The details of these 12 types of BIM software programs will be discussed in Section 3.2.

2.3. Review method and the development of "Green BIM Triangle" taxonomy

The review of the academic research and 12 types of BIM software identified above follows a stringent four-step process proposed by Fleishman and Mumford [12]. The outcome of this rigorous review process is the development of a "Green BIM Triangle" taxonomy, which synthesizes the connections between BIM and green buildings into an overarching framework. The details of the four-step process developing the "Green BIM Triangle" taxonomy are as follows.

Step 1: Specify the domain of objects to be classified. A classification

Table 2
12 popular types of BIM software and their functions used for green analyses.

BIM software	Green analyses[a]						Users[b]	Users[c]	Supplier web link
	E	CE	NV	SD	A	W			
Autodesk® Green Building Studio	√	√	√	√		√	A/D	De/OM	www.autodesk.com
Integrated Environmental Solutions® Virtual Environment	√	√	√	√		√	A/D/E/O	De	www.iesve.com
Bentley Hevacomp	√	√	√				D/E/C	De	www.bentley.com
AECOsim	√	√		√			E/C/D	De	www.bentley.com
EnergyPlus	√	√		√		√	E/A	De	www.apps1.eere.energy.gov
HEED	√	√					O/A/D/C	De	www.energy-design-tools.aud.ucla.edu/heed
DesignBuilder Simulation	√	√	√	√			C/E/A	De	www.designbuilder.co.uk
eQUEST	√		√	√			A/E/C	De/C/OM	www.doe2.com/equest
DOE2	√		√	√			A/E/C/U/G	De	www.doe2.com
FloVENT			√				E	De	www.mentor.com
ODEON Room Acoustics Software					√		A/E	De	www.odeon.dk
TRNSYS	√		√	√			A/E	De	www.trnsys.com

[a] E for energy, CE for carbon emissions, NV for natural ventilation, SD for solar and day lighting, A for acoustic, W for water.
[b] A for architects, D for designers, E for engineers, O for owner, C for consultants, U for utility companies, G for government.
[c] De for design, C for construction, OM for operation and maintenance.

system describes the structure and relationships among a set of objects drawn from a certain domain, in which similar objects can be assigned to a smaller number of categories [12]. In this study, the domain of objects is the previously identified research articles and BIM software.

Step 2: Define and measure the essential properties of objects. However, the selection of essential properties which represents the basic building blocks of the taxonomy has seldom been studied. There are few guidelines on defining what characters are admissible and useful in classifying objects. One source of selecting variables is from the body of underlying theories [17]. Based on the keywords of reviewed papers and their underlying theories, this study categorized all current functions and practices of green BIM based on three dimensions, namely "project phases", "green attributes", and "BIM attributes". Specifically, the project phases were identified based on the theory of project management; the green attributes were proposed from the sustainability baseline; and the BIM attributes were derived from vital BIM features referred by keywords of the reviewed papers.

Step 3: Appraise the similarity and differences of the reviewed papers and BIM software respectively based on the "project phases" and "green attributes" identified above. For the research articles, according to their research topics and aims, they were categorized into different groups based on their level of similarity in the dimensions. For instance, Schlueter and Thesseling [18] as well as Shrivastava and Chini [19] focused on the application of BIM for energy analysis in the design phase, and thus were classified into the same category, i.e. "energy-design group". Likewise, other groups of articles could be generated such as "carbon emission-design group" and "energy-construction group". For the 12 types of BIM software, they were similarly examined and compared according to their features in the "project phases" and "green attributes" dimensions. For instance, both types of BIM applications, i.e. DOE2 and TRNSYS, could conduct energy analysis and natural ventilation analysis for the design phase.

Step 4: Determine whether the reviewed papers and applications display sufficient similarity to permit assignment to a common category. After identifying the specific groups, this study critically examined the research articles and BIM applications within each group, to reveal the research aims, contributions and gaps of knowledge in each group of study or software. Subsequently, a taxonomy was developed to synthesize the themes of the current academic and industrial efforts in connecting BIM with green buildings, as shown in Fig. 2, which is discussed in detail in the next section.

3. The nexus between BIM and green buildings

There are two entities associated with green BIM, namely BIM and green buildings. In terms of BIM, the key features of BIM are captured by the "BIM attributes" dimension in the taxonomy, which represents the analytical functions that BIM software can provide to the built environment. The essential features of BIM can be summarized into four aspects, namely integrating with various databases, facilitating document management, visualizing analytical processes and results, and providing sustainability analyses and simulations.

In terms of green buildings, two important dimensions, namely the "project phases" and "green attributes" are adopted to describe green buildings. The "project phases" dimension captures the perspective of project lifecycle. Any green project experiences a lifecycle process that starts with project design, through construction, operation, maintenance, and ends with the demolish phase. The "green attributes" dimension includes sustainability considerations that could be addressed by using BIM software, such as energy, thermal comfort, carbon emissions, water, material waste, daylighting, natural ventilation, and acoustics analysis.

As shown in Fig. 2, the three dimensions form a triangle where BIM and green buildings have interactions. The interactions could be decomposed into two aspects, namely how BIM could support the different phases and the whole lifecycle of green buildings (i.e. BIM attributes-project phases); and how BIM could support the various sustainability aspects of green buildings (i.e. BIM attributes-green attributes). The dark green arrow in Fig. 2 denotes such impacts of BIM on green buildings. Highly relevant to the "green attributes", GBA, such as the LEED framework, can provide a holistic evaluation on the various green attributes. Therefore, a discussion on integrating BIM software with various popular GBAs was provided in this study as well. To summarize, the following sub sections address three important aspects of BIM-green building nexus, namely 1) BIM-supported green project lifecycles, 2) BIM functions for green issues, and 3) BIM-supported green building assessment.

3.1. BIM-supported lifecycles of green buildings

3.1.1. BIM-supported designs of green buildings

Sustainability of buildings has become a critical consideration for building design as decisions made in the early design stages has a significant influence on the actual environmental impacts of buildings [28–29]. Traditional design methods are limited in term of continually analyzing sustainability during the design process due to fragmented information [1]. A BIM model can be used as a database for data

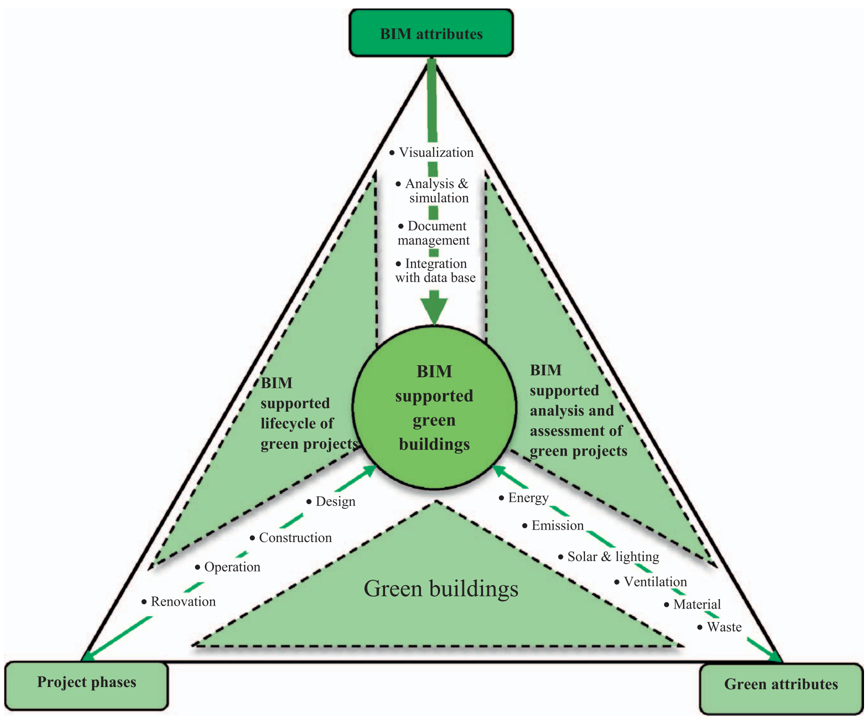

Fig. 2. Green BIM Triangle taxonomy. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

exchange and integration based on the industry foundation classes (IFC) [23]. Regarding the design phase, BIM allows for multi-disciplinary information to be superimposed on one model, which creates an opportunity for sustainability measures to be incorporated throughout the design process [20]. With the aid of these BIM applications, architects and engineers can more effectively share information related to sustainability, such as daylighting and energy consumption, and thus the sustainability analysis can be seamlessly integrated into the design process. BIM can also help designers utilize the existing building data sets to optimize the default configuration for building performance simulations during early phases of new building design [33].

To be specific, various BIM applications have been developed to address sustainability issues in the design process. The majority of green BIM applications are designed for building performance analyses and simulations, such as energy performance analyses [8,18,19,34–37], CO_2 emission analyses [28,38], lighting simulations [39] and some integrated building performance optimization [40]. These BIM applications help designers by providing more integrated and visualized views of building performance in the early design phase. For instance, Schlueter and Thesseling [18] presented a prototypical tool, the Design Performance Viewer (DPV), which enables instantaneous energy calculations and graphical visualization of the resulting performance indices, thereby assisting designers to make energy conservation decisions. Another example illustrated the use of BIM to provide a powerful visualized workflow in control systems [24]. BIM also has great potential in helping to minimize construction waste during project design phases, especially at the concept and design development stages [42–44]. For example, various BIM-based estimation systems of construction waste, which extract and process the component information of each building element in a BIM model, have significantly improved waste estimation and planning [45–47]. Similarly, BIM-based material analysis tools have also been proposed to enable designers in simulating architectural and structural design requirements and making necessary design adjustments to reduce material waste, such as rebar waste [48].

Based on the above-detailed sustainability analyses, BIM can be used to assess the impacts of various design alternatives on the building performance so that designers can make more rational decisions environmentally. For instance, Jrade and Nassiri [30] integrated BIM with a decision-making approach (Entropy-TOPSIS), which can efficiently optimize the selection of sustainable building materials at the conceptual design stage of building projects. Inyim et al. [31] introduced a design optimization tool integrating BIM with Simulation of Environmental Impact of Construction, to help designers fulfill multiple sustainable objectives in their decision-making process, such as objectives related to construction time, initial construction cost, and CO_2 emissions. Similarly, Oti and Tizani [41] provided a BIM integrated system combining three green indicators, i.e. life cycle costing, ecological footprint and carbon footprint, to aid structural engineers in the sustainability assessment of alternative design solutions.

3.1.2. BIM-supported construction of green buildings

It is widely acknowledged that construction process has a major impact on the environment in terms of many aspects, such as carbon emission [49], noise pollution, resource consumption and waste generation [42,146]. BIM software provides various efficient solutions to mitigate these environmental impacts of the construction process. For instance, a 3-D BIM model was proposed to measure the CO_2 footprint in a house construction process and to provide recommendations for improving construction activity schedule and to reduce associated emissions [49].

Existing studies highlighted that BIM technology could contribute to waste reduction which is an important aspect of sustainable construction [51,52]. For instance, Shanghai Center, the tallest building in China, has benefited from a new BIM-based lifecycle data management approach that has helped the project to achieve a material waste rate of 4%, compared with the average level of 10% in China [50]. Similarly, a BIM-based system was developed to provide early alerts of construction waste to contractors [48], and likewise, a real-time BIM and System Dynamics based methods was proposed to minimize construction waste generated due to rework, lack of coordination, and poor integration of building subsystems during the construction process [53].

3.1.3. BIM-supported operations of green buildings

Monitoring the sustainability performance of buildings in the operation phase is very important as it could verify the actual performance compared with the targets set in the design phase. This is a complicated task as the information of buildings within operation phase must be collected from different stakeholders in various phases. BIM can support the supply, integration, and management of information throughout the building lifecycle [57]. Consequently, BIM has been considered as an invaluable tool in monitoring the sustainability performance of buildings in their operation phase [58]. In a case study, BIM was used as an enabling technology for cloud-based building data services that integrated building data in the operational phase with a focus on energy management [59]. Similarly, Yang and Ergan [60] presented a BIM-based automated approach to help facility managers streamline the process of troubleshooting HVAC-related problems.

However, the use of BIM for facility management (FM) during the operation phase is still limited. Three major reasons have been identified: (1) lack of awareness about the benefits brought by using green BIM for operation management; (2) lack of clear definition of the data exchange for operation management; and (3) lack of clearly defined use cases in compliance with industry standards/guidelines for practitioners to follow [61].

3.1.4. BIM-supported renovations and retrofit of green buildings

Practitioners believe BIM applications provide feasible solutions to address sustainability issues on project renovations [58]. Researchers have also demonstrated examples of using BIM on retrofitting/renovation projects. For example, Akbarnezhad et al. [62] proposed a sustainable deconstruction strategy which uses the information provided by BIM to enable the retrieving of energy and capital invested in building components. Similarly, Lagüela et al. [63] presented a hybrid method based on BIM and other information technologies to support energy rehabilitation processes ranged from energy usage diagnoses to retrofitting decision-making. Woo and Menassa [64] provided the Virtual Retrofit Model (VRM), an affordable computational platform integrating BIM, energy simulation and other technologies to support streamlined decision making of building retrofit projects. Likewise, Larsen et al. [21] proposed a new approach for analyzing energy performance of retrofit projects using BIM and 3D laser scanning.

BIM technology can benefit waste management in demolition and renovation projects [65]. For instance, a BIM-based prototype system was developed for contractors to automatically and accurately estimate the amount of renovation and demolition waste [66]. However, the estimation of construction waste in new projects cannot be achieved, and more efforts are needed to extend the applicability of existing BIM-based system.

3.1.5. Summary of BIM-supported project lifecycles

To summarize, BIM could support various facets of green buildings during their lifecycle, as shown in Fig. 3. Overall, current research suggests that the benefits of using BIM in the lifecycle process of green projects can be categorized into three aspects. First, BIM data can be exchanged among multi-disciplinary users with different analysis tools of sustainability. For instance, a BIM-based modular web service framework can integrate the information necessary for green building design, automate the design evaluation processes, and facilitate simple updates on the building model on a common but distributed platform. Second, BIM applications can provide visual information related to building performance and process and thus enable project participants, such as designers, contractors and owners, to make more environmental-friendly decisions. For instance, a BIM-based energy consumption assessment of a building was designed to provide a graphical visualization of energy performance indices [18]. Third, BIM could enhance the communication and collaboration of various stakeholders associated with green design, construction, and operation [25]. This integrated platform offers a new paradigm for all stakeholders who are working on the same project for a shared vision [26]. This strengthens ties among all project parties who, in the building and construction industry, had previously experienced fragmented relations.

Although various benefits brought by green BIM applications have been perceived, there is still debate on using BIM for green buildings. A group of design and construction professionals believes that sustainability is not the primary application of BIM, and instead they believe project coordination and visualization are [67]. During the construction process, BIM is considered by many as a means of improving quality management and scheduling rather than sustainability [68]. Similarly, an investigation revealed that, most BIM-enabled construction projects are tightly coupled technologically, but divided organizationally [27]. This organizational division may be aggravated by some technical issues of the BIM software, such as the weak interoperability between different BIM software and across organizational boundaries. Besides, mentality issues may also lead to a dissuasive attitude towards BIM-based collaboration for sustainable construction. For instance, construction practitioners may reject the use of BIM software as they believe BIM is currently too complicated to use and not a necessity within the industry [8]. However, as more design and construction professionals understand the potential benefits of BIM for green buildings, it will become a vital tool for sustainable design and construction [67].

Existing BIM software and its green features are also mostly limited to the project design phase and seldom extend to the project construction or operation phases. Given that more types of BIM software have developed the analytical capacity for an entire project lifecycle [50], one can expect that the green BIM applications supporting the whole lifecycle of green buildings will experience growth as well. For example, eQUEST has begun to support detailed energy performance analyses throughout the phases of construction documentation, commissioning, and post-occupancy [130].

3.2. BIM functions for major green issues

This section presents a detailed discussion of 12 types of BIM software and investigates they can assist green buildings in 6 aspects, namely energy consumption, carbon emissions, natural ventilation, solar and lighting analysis, acoustics, and water usage.

The selected 12 types of software are highly diverse in their own features, end users, and applicable stages, which are listed in Table 2. For instance, ODEON Room Acoustics Software is designed for acoustic analyses for special professionals. Other BIM software provides broad and comprehensive sustainability analyses, such as Green Building Studio (GBS). GBS is mainly used in the design phase, but it also serves various end users, including architects, designers and engineers, as well as other project participants whose work can benefit from using BIM

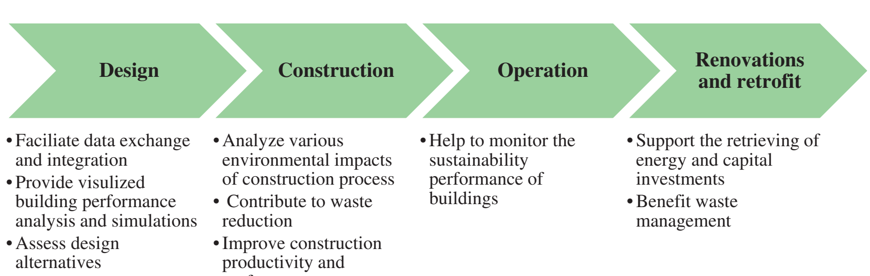

Fig. 3. BIM-supported lifecycles of green projects.

applications, such as consultants, owners, and contractors [70]. Another example is Integrated Environmental Solutions® Virtual Environment (VE), which visualizes sustainability issues in project delivery and helps owners determine the most optimized green-design solutions [71].

3.2.1. Energy performance analyses and evaluations

BIM software provides four major functions on energy performance analyses and evaluations, namely 1) a whole building energy analysis, 2) detailed analyses for different energy conservation measures, 3) a feasibility evaluation of renewable energy and, 4) a more effective detection and diagnostics of energy faults.

1) First, BIM software has advantages in analyzing whole building energy performance. One advantage is that BIM software improves the usability of the whole building energy calculation by using standard processes and parameters. Traditional analysis and assessment methods of energy performance, for instance, the CAD-based method, take a substantial amount of time and effort for modeling. The implementation of these methods is largely dependent on the assessors' skill and experience, and thus is subject to problems associated with objectivity [72]. On the contrary, BIM software follows a standard process to calculate whole building energy consumption based on various parameters such as building use patterns, building shape, materials, and weather conditions [131]. These are generally default parameters retrieved from an external database where information has already been collected from surveys of standard practices. Consequently, such a calculation is less dependent on an individual user's experience and knowledge.
2) Second, BIM software supports detailed analyses for different energy conservation measures. For instance, during the building operation phase, occupant behaviors have a significant influence on the whole building energy use. Therefore, simulation applications of building energy have incorporated occupant effects into the energy analysis process to evaluate energy savings based on different scenarios of schedules [73]. Factors associated with occupants such as occupancy and equipment schedules are considered in the applications. By comparing the results of various energy-saving measures provided by BIM software, users of the software can better optimize the original solution.
3) Third, some types of BIM software, such as GBS and VE, can also estimate the feasibility of adopting renewable energy, such as photovoltaic and wind power [20,70,71]. In most cases, the estimation result is significantly influenced by the local context and thus requires project-specific data to achieve higher accuracy. Due to the difficulty of data collection, some critical factors have not yet been fully incorporated and considered in current BIM-based renewable energy analyses. For instance, most types of BIM software have a limited capacity of estimating the co-effects of shelters around the building. This has led to a strand of research investigating the concept of Inter-Building Effect (IBE). For instance, it has been revealed that building's energy performance can be significantly impacted by surrounding buildings through mutual reflection and mutual shading [132]. Even though some studies e.g. [133] have contributed to the understanding of IBE and how it may impact building energy consumption, few studies have explored how IBE impacts the potential of utilizing renewable energy in buildings.
4) Fourth, BIM software can support an online real-time fault detection and diagnostics (FDD) of building energy to achieve more effective energy performance maintenance over the lifecycle of buildings. Such BIM-supported FDD approach provides a scalable and adaptable information infrastructure that can integrate other energy performance analysis and simulation technologies to streamline the information exchange process, thereby closing the information gap between facility managers and designers [61].

Although BIM software can contribute to energy performance analysis in various areas, as discussed above, the direct application of BIM with preloaded energy performance properties in existing buildings is still challenging because heat transfer condition of building elements gradually degrades during the operational phase [74]. In order to address this limitation, both semi-automated and automated methods for BIM reconstruction are proposed, such as automatic as-is 3D modeling methods from point clouds [75–78] and image-based thermal BIM reconstruction methods [79,80]. By using as-is BIM as an input of BIM-supported energy analysis, the gap between the energy performance information in the as-designed BIM and as-is building conditions can be significantly shortened [80], and designers can model the current energy performance of existing buildings in a more reliable way.

In addition to the above technical functions, BIM software is also capable of presenting energy analysis information in various ways. Energy analysis results are typically presented on a yearly, monthly, daily, and hourly basis. Most types of BIM software provide a user-friendly interface that does not require users to have expertise in energy analysis or computer programming. Several types of BIM software, such as GBS, can even automatically convert estimated energy usage into energy costs by using default utility rates [70]. However, some types of BIM software, such as EnergyPlus, still provide a text-based user interface in which the software can only read and output the information as text files [68].

3.2.2. Carbon emissions analyses and evaluations

BIM software provides carbon emissions analyses and evaluations to help the project achieve carbon neutrality. Current BIM software has incorporated both building-system components and the external environment into carbon emissions analyses by using information such as local electricity emissions, hydrocarbon production in the construction site, and other energy conversion approaches. In order to assess how such factors affect a building's carbon emissions throughout its lifecycle, some types of BIM software use standard data from an external global database. A typical case is the VE software which uses a global database of weather information [71].

Besides carbon emissions analyses, current BIM software also provides alternative designs for carbon emission reduction, thereby helping designers and engineers optimize their original designs towards carbon neutrality. For instance, GBS can provide suggestions in selecting local utility providers who discharge fewer emissions by using renewable energy [70]. Liu et al. [82] developed a BIM-based multi-objective optimization model, which aids designers to identify and choose the optimal design scheme balancing carbon emission and cost for their clients. Similarly, BIM software can simultaneously estimate embodied and operational carbon over the life span of buildings, so designers can make better decisions on material selection [81].

3.2.3. Natural ventilation system analyses and optimization

BIM software is applicable for ventilation analysis and optimization to reduce building energy use as well as to raise a building's thermal comfort level. Built on the key effects of building occupancy and equipment, BIM software can estimate the potential capacity for natural ventilation to handle the heating and cooling loads of buildings [20]. Based on the predicted results, BIM software helps users evaluate the feasibility of using natural or mixed modes of ventilation strategies, e.g. single-sided ventilation, cross-ventilation, whole-building ventilation, chimneys, and opening controls. Such evaluation of the ventilation strategies can assist users to select a reliable mechanical ventilation system for the target project.

3.2.4. Solar radiation and lighting analyses

BIM software provides lighting impact analyses for both the exterior and interior of buildings. Externally, BIM software incorporates a detailed solar radiation analysis module to help designers and engineers understand and optimize the impact of sun on a building. First, BIM software could display the sun's position and path relative to a building model at any time and location, which enables designers and engineers to optimize the building's position and orientation at an early stage of design. Second, BIM software supports the assessment of solar gain, temperatures, and radiant exchange on the building surfaces. The assessment results can be visualized and presented at any time interval of the building thermal analysis. Third, several types of BIM software, such as VE, can test the internal and external solar shading effect and compare the simulated results with the expected design [71]. The comparison can then be used as evidence to help designers select appropriate shading systems.

Internally, BIM software adopts a detailed lighting-condition analysis to improve the utilization of natural daylight and visual comfort of buildings. BIM software provides an overview of lighting conditions for the whole building so that designers and engineers can visually appraise how their lighting designs will perform. Besides, BIM software provides a detailed point-by-point simulation by comparing natural and artificial light. In addition, the calculation can be adjusted based on different weather conditions. To better simulate the local context, BIM software such as DesignBuilder Simulation enables users to manually set customized parameters, such as the radiance level [83].

Despite the benefits discussed above, one major issue has been identified in the integration of green BIM with lighting and solar radiation simulation, i.e. the lack of information for simulations. Most researchers argue that BIM does not have all the information that is necessary for creating the input files for lighting simulation tools, such as Radiance and DAYSIM. To solve this issue, a new methodology, ThermalOpt, was proposed as an automated BIM-based simulation method intended for use in multidisciplinary design optimization environments [84]. Meanwhile, Landry and Breton [85] presented a detailed workflow of doing daylighting analysis using 3ds Max Design from BIM software. Kota et al. [86] provided a new method to enable direct integration of BIM with Radiance and DAYSIM. However, all the above efforts focus on the integration of BIM with specific types of lighting and solar radiation simulation tools. Therefore, future studies could develop a general method applicable for the majority of existing simulation tools.

3.2.5. Water usage analyses

BIM software supports water usage analyses mainly at design phase. BIM software estimates water usage based on relevant factors e.g. the type of building and number of occupants, and could automatically convert the estimated results into water cost reports [70]. However, the estimation is still rough due to limited factors considered in the analyses. Factors such as the project location and users' behavior may cause large variances to the estimated result. It is suggested that future BIM software should consider the full spectrum of effects impacting water use. In addition, BIM software can help optimize a building's water distribution system. For example, to help users make decisions on future renovation of the waste systems, BIM software could provide fast water capacity tests based on the water flow data that stored in its model [88]. Similarly, a newly developed BIM-based application, LicA, was proposed to perform the automated design code checking of water distribution systems of buildings [87].

3.2.6. Acoustics analyses

BIM software enables architects to simulate acoustic performance at earlier stages. Connecting BIM data with existing acoustic simulation system can increase the level of automation and save simulation time. For instance, a prototypical BIM-based acoustic simulation application was proposed to reduce the simulation time from a few days to a few minutes while maintaining or increasing accuracy [45]. Besides, this application can re-simulate the result immediately whenever any update is made in the original BIM model [45].

BIM-based acoustic simulation software provides multiple types of outputs. For instance, visualized maps could be generated based on simulation results to show various acoustic effects of the building. Furthermore, some BIM software, such as ODEON Room Acoustics Software, can present simulated acoustics in 3D audio effects and vividly broadcast over headphones or loudspeakers according to users' customized requests [89]. Future BIM-based acoustic simulation software could further integrate with emerging technologies, such as virtual reality, to provide visual and audial experience in a more vivid way.

3.2.7. Thermal comfort analyses

Green buildings are only effective when the occupants in the buildings feel comfortable, which indicates the high importance of assuring thermal comfort in green buildings. According to the ANSI/ASHRAE Standard 55-2013, thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [134]. There are six primary factors that directly affect thermal comfort, including metabolic rate, clothing level, air temperature, mean radiant temperature, air speed and humidity [135]. Through simulating or monitoring these factors, BIM applications help to evaluate occupants' thermal comfort.

For instance, a framework for the integration between wireless sensor network (WSN) and BIM-based model was developed to measure and record temperature and humidity in a spatial manner, thereby partially monitoring thermal comfort and enabling asset managers in facilities inspection [136]. Similarly, a case study is provided on the official website of IES-VE, showing that IES thermal models could be used to evaluate buildings with comfort issues, such as overheating and underheating, and help to identify the reasons behind comfort issues [137]. BIM applications could not only contribute to post-occupancy monitoring of thermal comfort through integrating various sensors, they can also help simulate and optimize thermal comfort in the design stage. For instance, BIM could be used to conduct Computational Fluid Dynamics (CFD) simulations to examine the air temperature and speed around occupants in different positions in the office, thereby optimizing thermal comfort through properly arranging the occupants' positions [138]. Similarly, based on models generated in Revit, IES-VE could be used to simulate Fanger's predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD), which are widely used to reflect thermal comfort, thereby enabling the evaluation of indoor thermal comfort through comparing the simulated data and comfort requirements in the standards [139].

3.2.8. Summary of BIM functions for green issues

The above-mentioned BIM applications are designed and developed for various sustainability analyses, such as energy performance, CO_2 emissions and lighting analyses. A few BIM applications have also proposed solutions for water conservation and indoor air improvement. Fig. 4 has summarized the main functions of BIM for green analyses. However, most of these applications are designed specifically for one type of analysis and cannot address others. As a result, industry practitioners may underutilize their capabilities in using these BIM applications [67]. In the future, a generic and integrated green BIM application is needed that would allow a systematic analysis of a building's whole environmental sustainability.

The dependence of BIM software on external database could generate potential risks for sustainability analysis. If the external database has incomplete data, BIM software then has to use unmatched data to input the default parameters, which leads to deviations in its calculations. For instance, Green Building Studio (GBS) may not be reliable to conduct a whole building energy analysis for residential or industrial buildings, as no data has been collected from residential or industrial buildings in GBS's external database, i.e. the Commercial Buildings Energy Consumption Survey (CBECS) [70]. Moreover, out-of-date data provided by the external database also weakens the reliability of relevant analyses. It is suggested that timely maintenance and update of the external database for BIM software is very important and should be

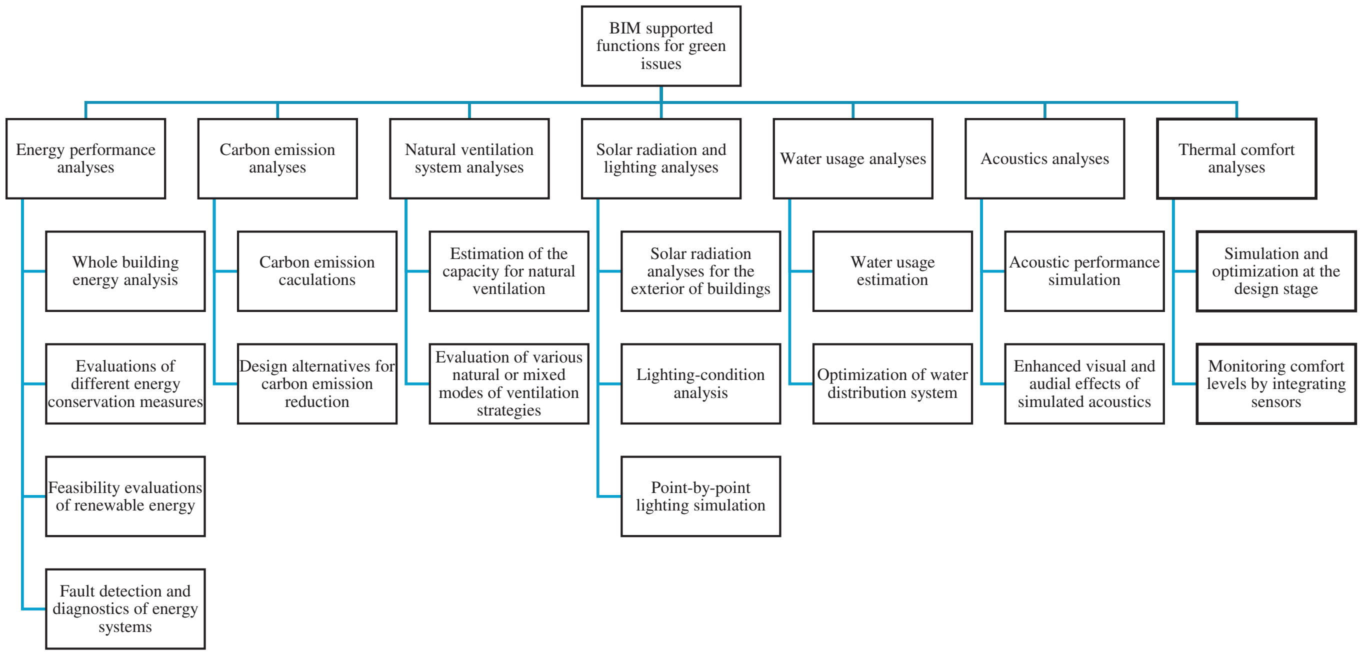

Fig. 4. Main BIM functions for sustainability analyses.

paid more attention to.

Moreover, since BIM serves as an open and collaborative database-exchange platform, a foreseeable trend is the combination of green BIM with other emerging technologies such as geographic information systems [90], cloud computing [50,90–92], laser scanning [21,63], and nanotechnology [69]. For instance, in order to effectively reduce radical pollution and waste in the AEC industry, a new building paradigm, i.e. using BIM and biotechnology, has been proposed [69]. According to this new paradigm, bio-nan robots produce building materials by using carbon extracted from CO_2 in the air and thus “buildings build themselves” [69]. New research initiatives can also enhance BIM by providing new analyses or more reliable solutions through various approaches, such as using social media, big data, and human behaviors to engage stakeholders and increase the accuracy of simulations. Similar studies are foreseeable to advance sustainability research in the built environment to the next level.

3.3. BIM-supported green building assessment (GBA)

Following the six aspects of green analyses mentioned above, this section discusses how BIM can holistically facilitate the green building assessment (GBA) processes. GBA aims to provide comprehensive and quantitative assessments on building performance that is influenced by buildings' site selection, energy performance, carbon emissions, water efficiency, indoor environment quality, and material consumption. Recently, several efforts have been made to integrate BIM software with various GBAs, but there is still no systematic review of the connections between BIM software and popular GBAs. This study develops a matrix (shown in Table 3) to compare various GBA accreditation requirements and BIM-supported analyses for these requirements.

A total of four global GBA standards have been examined in this study, which include LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Methodology), Green Star, and BEAM Plus (Building Environmental Assessment Method). For each one, related studies were reviewed and analyzed to extract essential information in regard to the usefulness of BIM. This study highlights the unique value provided by BIM software for the GBA process, as well as the improved efficiency of GBA process after using BIM. Subsequently, this study presents the use of BIM for the LEED certification process and the associated challenges as an illustrative case.

3.3.1. The value of BIM for end users in the GBA process

The value of BIM in facilitating the GBA process could be summarized into three aspects. First, BIM software can help users choose effective strategies to achieve green building certification. For instance, to achieve LEED certification, BIM software can help users determine the number of LEED points targeted and the level of LEED certification they are pursuing [93]. Second, BIM software can interpret and estimate credits for different GBA standards. With the aid of BIM software, project participants can better understand the requirements of the credits and ensure that the building design, construction, and operation follow such certification requirements. Third, BIM software can facilitate documentation management needed to apply for and maintain GBA certificates. As a result, the management efficiency and success rate of applications could be improved, and the upfront management costs of GBA applications could be reduced [92,94,95].

LEED, as one of the most popular GBAs in the world, was developed to provide building owners and operators a concise framework for implementing practical and measurable green building design, construction, and operation solutions [98]. Environmental sustainability analysis is compulsory for all projects that pursue LEED certification. Previously, the LEED certification process and BIM model application were two separate processes and performed by two teams. Recent studies have proposed to streamline the LEED certification process by using BIM models that can store multi-disciplinary information used for certification. Compared to traditional methods, BIM-supported GBA methods could save substantial time and resources. For instance, 25 credits, or 75% of elective points in LEED-NC 2009, can be examined using BIM software.

3.3.2. Challenges for integrating BIM with GBA

While the majority of green practitioners recognize the value of BIM-LEED calculating tools for sustainable design and construction, several challenges exist for popularizing these tools. The current BIM software is still insufficient in providing an integrated analytical solution for an individual GBA, as it does not have the capacity to simultaneously analyze all green aspects of buildings. Most types of BIM

Table 3
BIM-supported green building assessments (GBAs).

Name of GBA	LEED-NC 2009[a]	BREEAM 2011 New Construction[b]	Green Star 2008[c]	BEAM Plus 2010[d]
Country/region of practices	USA	UK	Australia	Hong Kong
Total credits and points	42 credits (7 required credits), 110 points	49 credits (3 required credits), 100–110 points	64 credits (2 required credits), 100–110 points	80 credits (9 required credits), 100–103 points
Minimal required credits	3/7 credits (SSp1, WEp1, EAp2)	2/3 credits (Man 01, Man 04)	N.a.	4/9 credits (SA P1, MA P4, EU P1, WU P2)
BIM-supported management related credits	N.a.	10.4% points (Man 01, Man 02, Man 03, Man 04)	No supported credits	N.a.
BIM-supported site and transportation related credits	8 credits in sustainable site	2/5 credits (LE 01, LE 03) with 86.4% points in Land use and Ecology category. No supported credits in transport category	25% points in Land use and Ecology, and 45.5% points in transport	2/15 credits (SA 7, SA 15) with 18.2% points
BIM-supported energy and atmosphere/ emissions related credits	1 credit (EAc1) with 54.3% points; 5 other credits with limited support	4/9 credits with 2/3 points	51.7% points in energy efficiency	5/22 credits with 61.9%–64.3% points
BIM-supported water related credits	All 3 water credits	2/4 credits (Wat 01, Wat 04) with 2/3 points	91.7% points in water efficiency	2/5 credits with 44.4% points
BIM-supported materials and waste related credits	All 7 credits in material and resource	2/5 material credits (Mat04, Mat05) with 2/3 points applicable; no supported waste credits	95.2% points in material resource	7/16 credits with 59.1%–63.6% points
BIM-supported indoor environment quality related credits	7/10 credits with 2/3 points in indoor environment quality	4/6 credits (Hea 01, Hea 02, Hea 03, Hea 05) with 78.6% points in health and wellbeing	70.4% points	4/23 credits with 18.8%–21.9% points
BIM-supported innovation related credits	1/2 credits (IDc2)	All credits	No supported credits	IA 2 applicable, IA 1 and IA 3 not applicable,
BIM-supported other credits	Regional priority credit (3.6% of total points)	N.a.	N.a.	N.a.
Examples of available BIM software	GBS	Revit, GBS	GBS	Revit, VE

[a] Cited references are [117,118,94,95].
[b] Cited references are [12,96]. The results are based on new construction projects of commercial office buildings; required credits are based on the level of passing; 110 points cover innovation credits.
[c] Cited references are [97,119]. The results are based on commercial office buildings; 110 points cover innovation credits.
[d] Cited references are [120,121]. The results considered bonus credits; 103 points cover innovation credits.

software are designed to focus on one feature such as carbon emission analysis or lighting analysis. These analytical features are optimized individually due to limited interoperability among BIM functions. Thus, currently BIM is still limited in holistically assessing both the environmental and social sustainability of buildings. Credits that currently are not supported by BIM software mainly focus on four areas, namely management (e.g. in Green Star), ecological issues (e.g. in BREEAM), innovative techniques and performance (e.g. in BEAM Plus, Green Star, LEED) and transportation conditions (e.g. in BREEAM). For instance, it was discovered that the impact of buildings on biodiversity is difficult to be addressed by BIM [96].

The reasons for the unsupported GBA in BIM could be a lack of tangible evaluation rubrics. These unsupported credits usually have no definitive evaluation approaches and are highly dependent on expert experience and knowledge. For instance, innovation credits in LEED require that the proposed project design present exceptional performance above LEED requirements, or show innovative performance that has not been previously addressed by LEED. A LEED panel committee evaluates the innovativeness of the proposed design based on contextual documents and oral discussion, which is difficult to be automated using BIM software. An Australian case showed that 12% of GBA credits, such as management issues, are almost impossible to be addressed by BIM software [97]. Future research of BIM software could focus on the development of new functions which provide flexible and qualitative-based evaluation for these currently unsupported credits, as well as the integration of different types of existing BIM-based green analytical tools, thereby providing an integrated BIM-based platform that supports various analytical functions covering all GBA aspects. Several recent studies have demonstrated possibilities in this area of research. For instance, Kensek et al. [147] have used the visual programming language Dynamo with the BIM software Revit, to automate the formula calculation for compliance for LEED Pilot Credit 55: Avoiding Bird Collisions specifically for the bird collision threat rating.

Another challenge is the complexity of traditional tools and users' lack of appropriate BIM knowledge [58]. Alwan et al. [99], for instance, demonstrated the feasibility of integrating LEED into BIM, but highlighted that high software complexity could be an issue if users do not have sufficient knowledge about BIM. It was discovered that due to users' irregular and inaccurate update of BIM models, credits in LEED certification are difficult to be documented by green BIM software [95]. Similarly, studies revealed that there are discrepancies between BIM-supported and manual GBA results due to an inadequately developed BIM model [95,99]. Even though Wu and Issa [92] proposed a new paradigm in which project teams can leverage cloud-based BIM to automate and simplify LEED accreditation, there are no applicable case studies to assess its performance and efficacy. Future research can further simplify the operations of BIM tools thereby facilitating the transition from traditional GBAs to BIM-based GBAs. Furthermore, there is a lack of well-defined business goals and processes of using BIM in LEED projects. Researchers have identified that current green BIM practices are heavily technology-driven instead of process-driven. Wu and Issa [2] proposed an integrated green BIM process map to more clearly define business processes and execution planning in LEED project. Future research could further examine the industrial players' business processes and goals of BIM application in LEED projects.

4. Research gaps and suggestions

To systematically conceptualize the nexus between BIM and green buildings, this study constructed a taxonomy composed of three dimensions, namely BIM attributes, project phases and green attributes. The taxonomy can be used as a framework to systematically consolidate the existing studies and to better align the future research areas to the existing ones. Based on the taxonomy, this study reviewed BIM-supported project lifecycle and BIM-supported green functions. This study highlighted the differences between industrial norms and academic research, and between ideal situation and current capacities of green BIM research. Followed by this comprehensive review, research gaps in green BIM have been identified and summarized as follows.

1) The first research gap is the weak interoperability among various BIM applications. For instance, massive BIM data is difficult to be directly adopted for a specific sustainability analysis [100–103]. To support the required green analyses, BIM data requires many modifications which weakens the design benefits. Data extraction and data exchange are two key processes associated with the interoperability among BIM applications. In terms of optimizing the data extraction process, Cemesova et al. [104] improved the IFC schema, enabling the compilation between building fabric data from BIM authoring tools and energy related information from specific low energy design tools, such as Passive House Planning Package. Similarly, Ladenhauf et al. [105] developed new algorithm that enabled automatic extraction of specific types of data from the BIM model. Ahn et al. [106] developed IFC–IDF interface to automatically convert the building information of IFC into IDF, an input file format for EnergyPlus. To improve the data exchange process among BIM applications, a new framework was proposed based on an open standard of BIM files [100]. Similarly, a physical BIM library was also developed for building thermal energy simulation from an Object-Oriented Physical Modeling (OOPM) approach [107]. Geyer [101] provided a semantic material-name matching system to enable automatic data exchange between BIM and other systems. These solutions are mainly designed to address the interoperability of file exchange or syntax commands, e.g. exchanging files between two BIM applications. However, a large amount of BIM applications, such as BIM-based energy analysis software, are suffering from the low visualization interoperability that enables the visualization of models being exchanged between two tools [23], and the weak semantic interoperability that interprets the meaning of models being exchanged. Thus, the visualization and semantic interoperability worth to be further studied in the future.
2) The second gap arises from the limited capability of BIM applications supporting the construction and operation phases of green projects. Currently, the development of green BIM applications heavily skewed towards the project design phase where important decisions concerning building sustainability are normally made [18,58,108]. However, emerging green construction practices, such as prefabricated buildings and lean construction, could be all linked to green BIM applications, but few studies have focused on the application of BIM in these topics. Future research could examine the applicability of using BIM to address these green construction practices. Meanwhile, in the building operation phase, facility managers have gradually realized the benefits brought by BIM-based facility management (FM) applications [58]. An increasing number of BIM vendors has also started to recognize the benefits of BIM to FM, and therefore has shifted their focus from the design phase to the operation and maintenance stage [22]. This trend calls for more research to develop BIM-enabled green FM.
3) Another research gap is the lack of clear industry standards or codes for the various aspects of green BIM applications. Integrating multidisciplinary information in a single BIM model requires the access to the BIM model by multiple users. However, there is lack of BIM standards for model integration and management by multidisciplinary teams [26]. This is further supported by Kassem et al. [127], who studied various BIM protocols such as AEC (UK) BIM Protocol specific to Revit and Bently Building and Singapore BIM Guide, and revealed that these protocols do not concurrently consider enabling technologies and the variables affecting its deployment on projects such as interoperability required for different BIM work-streams. Similarly, Chong et al. [140] examined 36 standards and guidelines of BIM, revealing that even though the standards stipulate the methodologies of BIM adoption to foster a

collaborative working environment, the standards paid little attention to the refurbishment and demolition of green buildings, and the incorporation of GBA criteria into the standards. Meanwhile, few studies on the best practices of green BIM have been presented for the AEC industry [109], even though many studies have provided valuable recommendations for implementing BIM in green projects. In fact, appropriate guidance on the efficient execution of green BIM applications is equally if not more important than the technological development of green BIM applications. To this end, the industry best practices should be researched and developed to guide BIM implementation in the green built environment.

4) The fourth gap is the low industrial acceptance of green BIM applications, despite a large number of BIM studies have been conducted. Issa and Anumba [110] have shown that research findings have hardly been adopted in AEC industrial practices. Complex barriers exist hindering the wide application of BIM, which include but not limited to lack of holistic industry codes, the lack of clear ownership of the BIM data through copyright laws, the blurred responsibility for ensuring the accuracy of the BIM data due to the integrated approach of BIM, and the industry's reluctance to change existing work practices and habits [26]. Similarly, Ghaffarianhoseini et al. [141] suggested that the lack of widespread uptake of BIM is linked to various risks and challenges including cyber security of BIM tools, the unclear intellectual property and responsibility, the incremental cost needed to input and review BIM data, and the reluctance from small construction enterprises. Education and training is one way to bridge the above gap. However, Becerik-Gerber et al. [111] discussed problems on the integration of BIM and sustainability from the perspective of AEC educational programs in the America. Project stakeholders may not be willing to adopt green BIM because of the various interests involved in the supply chain of AEC projects [91]. The future research should not only focus on developing and evaluating the prototype of new green BIM software, but also aim to investigate the actual needs from practitioners, and raise their interests in green BIM.

5) The low accuracy of BIM-based prediction models is the fifth research gap. Current research has recognized the shortcomings of the predicted approach to achieve high sustainability performance of buildings. For instance, most green building certificates, such as LEED, are based on predicted rather than actual performance [112]. However, complaints about the energy performance of LEED buildings have been raised. An investigation of the LEED buildings' energy performance revealed that 28–35% of LEED buildings were found to use more energy per floor area than the "conventional counterparts" [113], which challenges the validity and legitimacy of the LEED certificate. Therefore, a recent trend is to require all LEED projects to track and report actual energy performance to benchmark their energy efficiency [114]. The future development of green BIM applications also needs to align with actual rather than predicted performance. Governments are advised to establish policies that select green buildings based on a building's actual performance, such as the UK Government BIM Task Force policy [115].

6) The last gap lies in the lack of appropriate project delivery methods to leverage green BIM applications. The current BIM applications provide an integrated design model which allows for synchronous multi-disciplinary analysis, such as structural analysis, building performance analysis, MEP (Mechanical, Electrical and Plumbing) analysis, and material usage analysis [8]. This integrated design approach enables and encourages a more effective project delivery. For instance, many experienced construction professionals responded that BIM applications are essential conditions to adopt the integrated project delivery methods [116]. Similarly, Bynum et al. [67] argued that integrated project delivery approaches, e.g. Design-Build, are the optimal project delivery methods to integrate BIM with green buildings. Yet these preliminary results need to be further investigated to explore the relationships between the adoption of integrated project delivery approaches and green BIM applications.

The "Green BIM Triangle" taxonomy proposed in this paper maps the nexus between BIM and green buildings. As a conceptual framework, the nature of which is similar to other BIM frameworks such as [142,143], the taxonomy aims to provide synthesized understandings and knowledge of green BIM, which has not been explored by previous studies. The taxonomy, together with its supporting information such as Fig. 4, could be used to guide practitioners in green BIM implementation. For instance, through comparing the applied green analyses of BIM in real-world projects and the various analyses summarized in Fig. 4, the maturity level of green BIM implementation in the real-world projects could be preliminarily evaluated. The "Green BIM Triangle" taxonomy could also be tailored for different types of green buildings in various countries through specific empirical studies and reviews in the future. It is important to note that similar to other BIM frameworks such as those proposed by Chen et al. [143], the "Green BIM Triangle" taxonomy in this study is a grand framework which was not tailored for specific buildings. Rather, it serves as a foundation in green BIM, and specific frameworks could be developed based on this foundation. For instance, based on this taxonomy, future studies could investigate the potential of BIM in facilitating the Three Star Rating System for green building certification in China and identify the green analyses of BIM that are commonly or seldom used in China, thereby formulating tailored frameworks that could guide green BIM development specifically in China. Furthermore, the taxonomy should be regarded as a continuously updated framework provided that the emerging studies can be incorporated into thereby enriching the taxonomy. For instance, if a new BIM plug-in is developed to address the impacts of buildings on biodiversity, such as bird collision, the aspect of biodiversity may need to be included in the dimension of "green attributes". This expandable feature ensures the flexibility of the taxonomy that can accommodate both current and future studies for green BIM.

5. Conclusions

With recent developments, BIM has gained increasing importance in the AEC industry. Using BIM applications to facilitate green built environment has received growing attention in both academia and the industry. This study presents a critical review of the nexus between BIM and green buildings. Based on the review of journal articles and 13 types of BIM applications, this study proposes a "Green BIM Triangle" taxonomy to conceptualize the interactions between BIM and green buildings, and provides insights on the advantages and challenges of implementing green BIM. Three main facets of green BIM are critically examined, namely the contributions and applications of BIM in the lifecycle of green buildings, the various functions of environmental sustainability analyses provided by BIM programs, and the integration of green building assessment (GBA) with BIM. The main research findings are as follows.

First, the applicability of using BIM in each project phase and the whole project lifecycle of green buildings was analyzed. It was discovered that while BIM is mainly perceived as a vital tool for the design stage of green buildings, its potential value for the construction, facility and operation management phases has been increasingly recognized. BIM could facilitate data exchange and integration, provide visualized building performance analyses, and enhance the communication and collaboration of various stakeholders during the lifecycle of green buildings. Second, the advantages and challenges of BIM functions for environmental sustainability analyses of buildings were discussed. 7 major BIM functions for green analyses were identified and critically reviewed, including energy performance analyses and evaluations, carbon emission analyses, natural ventilation system analyses, solar radiation and lighting analyses, water usage analyses, acoustics analyses and thermal comfort analyses. Third, the potential of applying

BIM to support the GBA process was explored and reviewed. This study reveals that green BIM applications could bring various benefits for GBA, such as estimating GBA scores, managing application documents, and improving the efficiency of GBA process.

Even though BIM could add values to green building development, the empowerment of green BIM is not without challenges. This study identifies 6 major gaps of knowledge that need to be responded by future studies, including (1) the weak interoperability among various green BIM applications; (2) lack of supports for the construction and operation phases of green buildings; (3) lack of industry standards holistically covering the various application areas of green BIM and studies on the best practices of green BIM projects; (4) low industrial acceptance of green BIM applications; (5) low accuracy of BIM-based prediction models; and (6) the lack of appropriate project delivery methods. Future research opportunities exist in these areas to further promote green BIM.

This study provides an important reference for both researchers and practitioners studying BIM or green buildings. The proposed “Green BIM Triangle” taxonomy provides a systematic approach to understanding the current body of knowledge on green BIM. Researchers could use it as a guiding framework to find research opportunities in green BIM. Similarly, this study helps practitioners understand the various functions of BIM software for green buildings. Future research could respond to the identified gaps of knowledge in this study, thereby extending and enriching the “Green BIM Triangle” taxonomy.

Acknowledgement

This study is financially supported by the National University of Singapore (Grant Number: R-296-000-151-133) and the National Natural Science Foundation of China (Grant Numbers: 71390523 and 71471136). The views represented in this article are those of the individual authors only.

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