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A critical review and future directions**

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# 1 **Building Information Modeling (BIM) for Green Buildings: A** 2 **Critical Review and Future Directions**

3 **Abstract:** Although a large number of studies on Building Information Modeling (BIM) have been  
4 conducted in the past decade, a lack of consensus remains among researchers and practitioners regarding  
5 the applications of BIM for the development of green buildings, the activity of making buildings in a way  
6 that protects the natural environment. As the usefulness of BIM has been widely recognized in the building  
7 and construction industry, there is an urgent need to establish an up-to-date synthesis on the nexus between  
8 BIM and green buildings. After an in-depth review of hundreds of journal articles published from 1999 to  
9 2016 and 12 widely used types of BIM software, this study provides a holistic understanding and critical  
10 reflection on the nexus between BIM and green buildings, which is systematically illustrated by a “Green  
11 BIM Triangle” taxonomy. The proposed taxonomy indicates that the nexus between BIM and green  
12 buildings needs to be understood based on three dimensions, namely project phases, green attributes and  
13 BIM attributes. Following the proposed taxonomy, this paper systematically illustrated 1) the applications  
14 of BIM in supporting the design, construction, operation, and retrofitting processes of green buildings; 2)  
15 the various functions of BIM for green building analyses such as energy, emissions, and ventilation analysis;  
16 3) the applications of BIM in supporting green building assessments (GBA); and 4) research gaps and future  
17 research directions in this area. Through critical review and synthesis of BIM and green buildings based on  
18 evidence from both academic research and industrial practices, this paper provides important guidance for  
19 building researchers and practitioners to better align BIM development with green building development in  
20 the future.

21 **Keywords:** Building Information Modeling (BIM); BIM software; Green buildings; Sustainability; Life  
22 cycle; Review.

## 23 **1. Introduction**

24 The building and construction industry has been driven to adopt green building strategies in light of  
25 increasing sustainability concerns such as reducing CO<sub>2</sub> emission and energy dependency on fossil fuels  
26 [1,123,124]. As a revolutionary technology and process, Building Information Modeling (BIM) has been  
27 regarded by many as a significant opportunity in the architecture, engineering and construction (AEC)  
28 industry. BIM emerged as a solution to facilitate the integration and management of information  
29 throughout the building life cycle [11], thereby providing an opportunity for making the best use of the  
30 available design data for sustainable design and performance analysis [122]. As BIM and green building  
31 both continuously gain momentum, growing AEC firms are embarking on green BIM practices [121]. An  
32 online survey conducted by McGraw-Hill Construction investigated a wide range of industry professionals  
33 who use BIM tools for delivering green buildings, showing that BIM could significantly facilitate green  
34 construction and it is expected to be extensively used in the future if relevant challenges could be identified  
35 and effectively tackled. Since 1999, when the concepts and technologies related to BIM application were  
36 first discussed [1], continuous efforts have been made in exploring the possibility of BIM in facilitating  
37 the development of green buildings. Various functions of BIM have been studied, such as energy  
38 performance simulation, lighting analysis, and construction and demolition waste analysis. Different  
39 management aspects associated with BIM adoption have been highlighted, such as its economic benefits  
40 and organizational challenges [2-8]. A number of BIM applications have been proposed and developed to  
41 seamlessly integrate sustainability analysis into traditional design, construction, and operation processes.

42 Although BIM has been advocated for its potential to support green building development in the past  
43 decades, few systematic literature review was conducted to delineate the state-of-the-art development of  
44 the connections between BIM and sustainable building development based on both academic research and  
45 industrial practices [9-10]. Wong and Zhou [11], for instance, presented an important review of the  
46 academic research efforts in BIM and green buildings, but paid less attention to systemically comparing  
47 the various BIM applications for green buildings in the industry. A number of important research questions  
48 concerning the BIM-supported green building development remain unexplored, such as (1) the benefit  
49 and additional value of using BIM in green buildings throughout the project lifecycle; (2) the functions  
50 that BIM software provides for a specific type of sustainability analysis; (3) the potential of BIM  
51 applications to support Green Building Assessments (GBA) frameworks; and (4) the gaps between  
52 industry development and academic research in the application of BIM for green buildings.

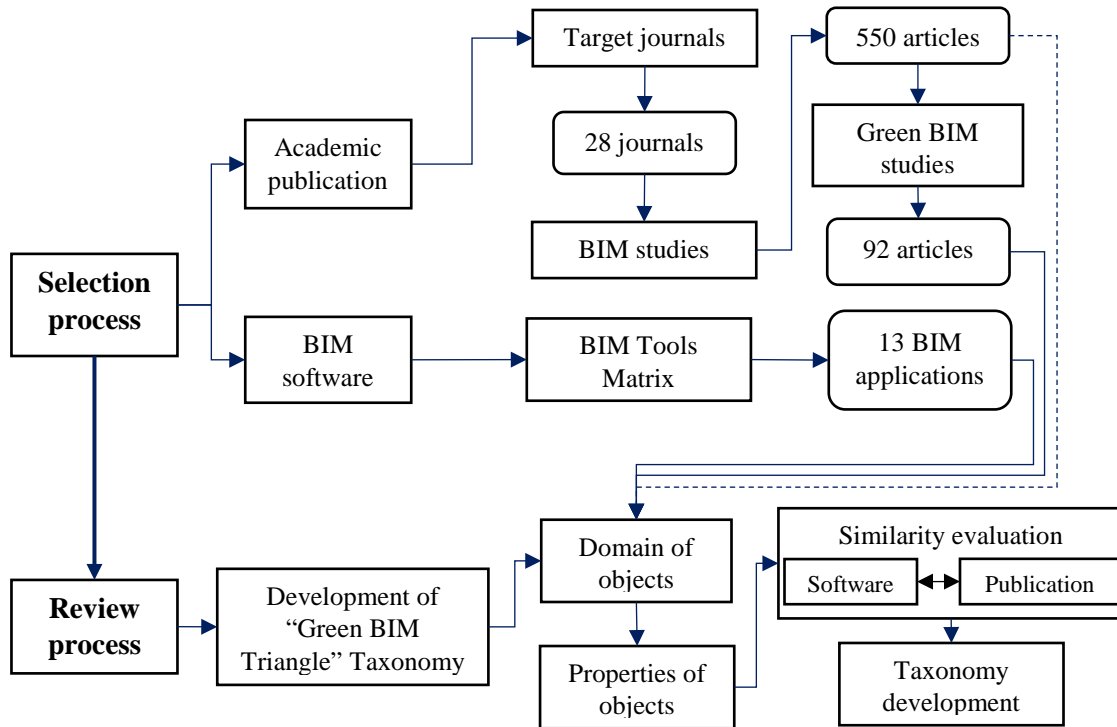
53 In order to address the above-mentioned research questions, this study conducts a critical review on  
54 the nexus between BIM and green buildings based on both academic research and industrial practices.  
55 Specifically, over 500 journal articles from 28 key AEC journals published (1999–2016), as well as 12

56 commonly used types of available BIM software were critically reviewed. By examining the reviewed  
57 articles and BIM software based on a stringent four-step taxonomy process, this study proposes a “Green  
58 BIM Triangle” taxonomy to categorize current efforts connecting BIM and green buildings through three  
59 dimensions, namely project phases, green attributes and BIM attributes [12]. The taxonomy provides a  
60 useful tool for researchers and practitioners to understand the current body of knowledge and helps to  
61 stimulate future research.

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

## 67 **2. Research Methodology**

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



78  
79 **Fig. 1.** Research methods and procedure of this study

80 **2.1 Selection of Academic Publications**

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

92 Step 1: Select target journals. In order to acquire all possible papers pertaining to BIM and green  
 93 buildings, this study adopted three criteria to select the journals for academic review. (1) The journal is  
 94 included in the Science Citation Index (SCI)-Expanded database or Engineering Index (EI) Compendex  
 95 database. (2) The journal is recognized or encouraged by two world-recognized international associations  
 96 for civil engineering and built environment, namely the American Society of Civil Engineers (ASCE) that

97 is dominated by American researchers, and the International Council for Research and Innovation in  
98 Building and Construction (CIB) dominated by European scholars. And (3) the journal has an important  
99 impact and prominent position in the research community of either BIM and sustainability or building and  
100 construction industry. Based on the above criteria, 28 widely acknowledged peer-reviewed journals were  
101 identified as target journals for paper selection, as shown in Table 1.

102 Step 2: Perform a search on BIM-related studies. This step aimed to screen all BIM-related articles  
103 by using the search keywords of “Building Information Modeling” or “Building Information Model” or  
104 “BIM”. To determine the eligibility and level of relevance of the article, all articles published in the above  
105 28 journals from 1999 to 2016 were searched for the keywords via specific domains, such as “title”,  
106 “keywords” or “abstract”. By manually selecting articles specifically related to BIM, a total of 550 BIM-  
107 related articles were identified in this step.

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

114

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

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

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

## 118 2.2 Selection of BIM Software Used in AEC Industry

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

125 It is important to note that there is no single satisfactory definition of BIM [125]. An extensively  
 126 referred definition is provided by Succar, B. [128], who defined BIM as “a set of interacting policies,

127 processes and technologies producing a methodology to manage the essential building design and project  
128 data in digital format throughout the building's life-cycle.” This definition reveals that BIM is a  
129 methodology comprised of interacting processes and technologies, serving for the entire life cycle of  
130 buildings from architectural design to facility management, demolition and refurbishment of buildings.  
131 Various BIM applications exist, with some emphasizing the aspect of architectural design while others  
132 may focus on sustainability analysis. Based on a systematic review of the literature, a structured  
133 questionnaire survey, action learning, focus group discussions and email surveys, Abanda et al [126]  
134 provide one of the most holistic reviews of BIM applications, listing 122 BIM software systems including  
135 BIM systems for architecture such as Vectorworks, for structural engineering such as Tekla Structures  
136 and Robot Structural Analysis; for building service such as Revit MEP and MagiCAD, for project  
137 management such as Synchro, Vico and BIMMeasure, for facilities management such as Bentley Facilities  
138 and ArtrA, and for sustainability analysis such as Green Building Studio and DesignBuilder. Similarly,  
139 Kassem et al [127] propose protocols for BIM collaborative design that can be utilized at project level to  
140 increase the consistency of information flow and BIM deliverables, by using several BIM systems  
141 including Revit, Integrated Environmental Solutions Virtual Environment (IES-VE) and Navisworks as  
142 an example. These studies indicate that the family of BIM software systems should holistically cover the  
143 various aspects of buildings, and tools for sustainability analysis such as IES-VE are part of the BIM  
144 family. This is further illustrated in Azhar and Brown [129] and Azhar et al [95], which found that there  
145 are three commonly used BIM-based sustainability analyses software, namely Autodesk Ecotect™ (which  
146 has been ended since 2015), Autodesk Green Building Studio (GBS)™, and IES-VE. Similarly, these  
147 sustainability analysis tools are named as “BIM analysis tools” in the *BIM Tools Matrix*, compiled by BIM  
148 Forum. In accordance with the above studies, this study selects and review 12 BIM analysis tools from  
149 *the BIM Tools Matrix*.

150 Most software programs are specially developed for the design phase and used by architects, designers  
151 or engineers. Few can be used at the construction or operation phase. In regard to the functionality, these  
152 12 types of software programs can contribute to the sustainability analysis of green buildings in six aspects,  
153 including energy consumption, carbon emissions, natural ventilation, solar radiation and lighting,  
154 acoustics, and water usage. The first four aspects can be addressed by around ten types of software, while  
155 the last two aspects are only supported by certain types. The details of these 12 types of BIM software  
156 programs will be discussed in Section 3.2.

### 157 **2.3 Review Method and the Development of “Green BIM Triangle” Taxonomy**

158 The review of the academic research and 12 types of BIM software identified above follows a stringent  
159 four-step process proposed by Fleishman and Mumford [12]. The outcome of this rigorous review process



160 is the development of a “Green BIM Triangle” taxonomy, which synthesizes the connections between  
161 BIM and green buildings into an overarching framework. The details of the four-step process developing  
162 the “Green BIM Triangle” taxonomy is as follows.

163 Step 1: Specify the domain of objects to be classified. A classification system describes the structure  
164 and relationships among a set of objects drawn from a certain domain, in which similar objects can be  
165 assigned to a smaller number of categories [12]. In this study, the domain of objects is the previously  
166 identified research articles and BIM software.

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

176 Step 3: Appraise the similarity and differences of the reviewed papers and BIM software respectively  
177 based on the “project phases” and “green attributes” identified above. For the research articles, according  
178 to their research topics and aims, they were categorized into different groups based on their level of  
179 similarity in the dimensions. For instance, Schlueter and Thesseling [18] as well as Shrivastava and Chini  
180 [19] focused on the application of BIM for energy analysis in the design phase, and thus were classified  
181 into the same category, i.e. “energy-design group”. Likewise, other groups of articles could be generated  
182 such as “carbon emission-design group” and “energy-construction group”. For the 12 types of BIM  
183 software, they were similarly examined and compared according to their features in the “project phases”  
184 and “green attributes” dimensions. For instance, both types of BIM applications, i.e. DOE2 and TRNSYS,  
185 could conduct energy analysis and natural ventilation analysis for the design phase.

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

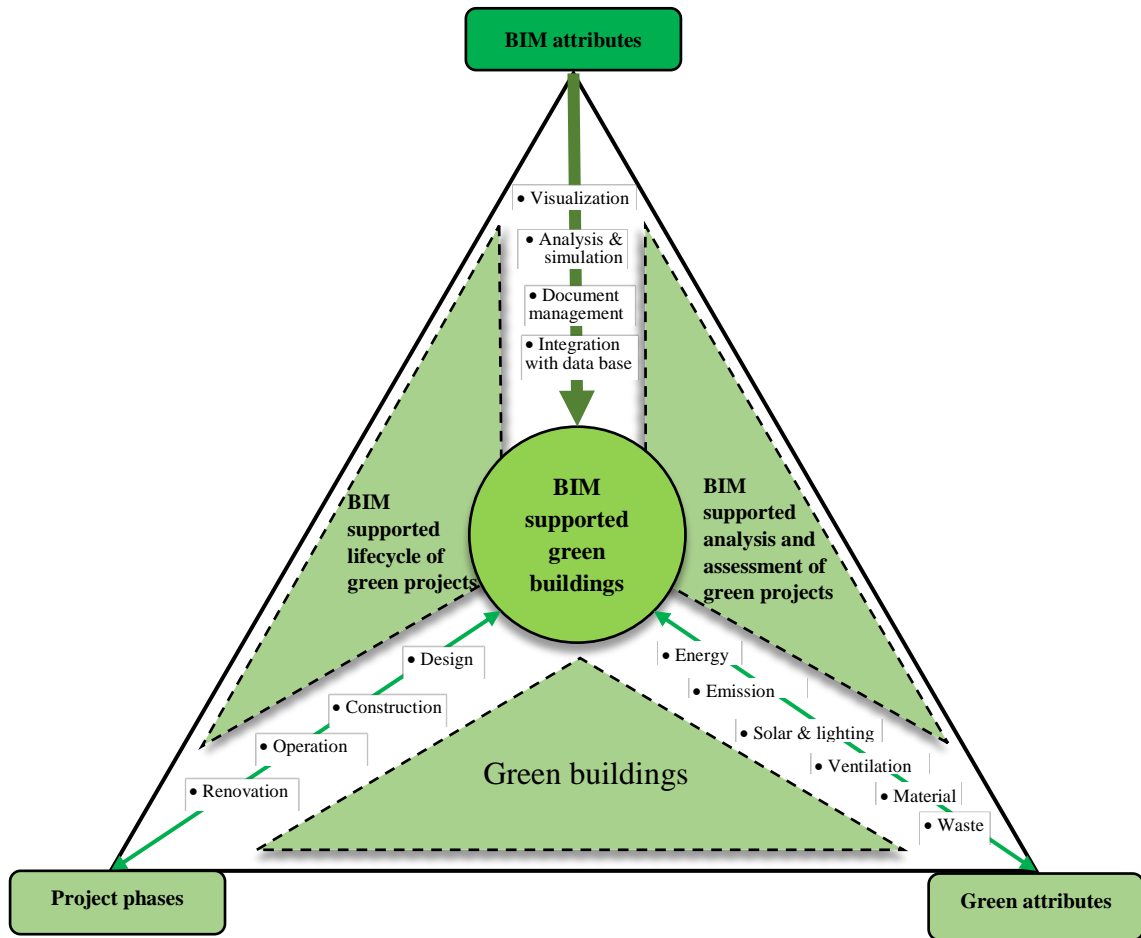
### 192 **3. The Nexus between BIM and Green Buildings**

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

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

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

216



217  
218

Fig. 2. Green BIM Triangle taxonomy

### 219 3.1 BIM-Supported Lifecycles of Green Buildings

#### 220 3.1.1. BIM-Supported Designs of Green Buildings

221 Sustainability of buildings has become a critical consideration for building design as decisions made  
 222 in the early design stages has a significant influence on the actual environmental impacts of buildings [28-  
 223 29]. Traditional design methods are limited in term of continually analyzing sustainability during the  
 224 design process due to fragmented information [1]. A BIM model can be used as a database for data  
 225 exchange and integration based on the industry foundation classes (IFC) [23]. Regarding the design phase,  
 226 BIM allows for multi-disciplinary information to be superimposed on one model, which creates an  
 227 opportunity for sustainability measures to be incorporated throughout the design process [20]. With the  
 228 aid of these BIM applications, architects and engineers can more effectively share information related to  
 229 sustainability, such as daylighting and energy consumption, and thus the sustainability analysis can be  
 230 seamlessly integrated into the design process. BIM can also help designers utilize the existing building

231 data sets to optimize the default configuration for building performance simulations during early phases  
232 of new building design [33].

233 To be specific, various BIM applications have been developed to address sustainability issues in the  
234 design process. The majority of green BIM applications are designed for building performance analyses  
235 and simulations, such as energy performance analyses [8, 18-19, 34-37], CO<sub>2</sub> emission analyses [28,38],  
236 lighting simulations [39] and some integrated building performance optimization [40]. These BIM  
237 applications help designers by providing more integrated and visualized views of building performance in  
238 the early design phase. For instance, Schlueter and Thesseling [18] presented a prototypical tool, the  
239 Design Performance Viewer (DPV), which enables instantaneous energy calculations and graphical  
240 visualization of the resulting performance indices, thereby assisting designers to make energy  
241 conservation decisions. Another example illustrated the use of BIM to provide a powerful visualized  
242 workflow in control systems [24]. BIM also has great potential in helping to minimize construction waste  
243 during project design phases, especially at the concept and design development stages [42-44]. For  
244 example, various BIM-based estimation systems of construction waste, which extract and process the  
245 component information of each building element in a BIM model, have significantly improved waste  
246 estimation and planning [45-47]. Similarly, BIM-based material analysis tools have also been proposed to  
247 enable designers in simulating architectural and structural design requirements and making necessary  
248 design adjustments to reduce material waste, such as rebar waste [48].

249 Based on the above-detailed sustainability analyses, BIM can be used to assess the impacts of various  
250 design alternatives on the building performance so that designers can make more rational decisions  
251 environmentally. For instance, Jrade and Nassiri [30] integrated BIM with a decision-making approach  
252 (Entropy-TOPSIS), which can efficiently optimize the selection of sustainable building materials at the  
253 conceptual design stage of building projects. Inyim et al. [31] introduced a design optimization tool  
254 integrating BIM with Simulation of Environmental Impact of Construction, to help designers fulfill  
255 multiple sustainable objectives in their decision-making process, such as objectives related to construction  
256 time, initial construction cost, and CO<sub>2</sub> emissions. Similarly, Oti and Tizani [41] provided a BIM  
257 integrated system combining three green indicators, i.e. life cycle costing, ecological footprint and carbon  
258 footprint, to aid structural engineers in the sustainability assessment of alternative design solutions.

### 259 ***3.1.2. BIM-Supported Construction of Green Buildings***

260 It is widely acknowledged that construction process has a major impact on the environment in terms  
261 of many aspects, such as carbon emission [49], noise pollution, resource consumption and waste  
262 generation [42, 146]. BIM software provides various efficient solutions to mitigate these environmental  
263 impacts of the construction process. For instance, a 3-D BIM model was proposed to measure the CO<sub>2</sub>  
264 footprint in a house construction process and to provide recommendations for improving construction

265 activity schedule and to reduce associated emissions [49].

266 Existing studies highlighted that BIM technology could contribute to waste reduction which is an  
267 important aspect of sustainable construction. [51-52]. For instance, Shanghai Center, the tallest building  
268 in China, has benefited from a new BIM-based lifecycle data management approach that has helped the  
269 project to achieve a material waste rate of 4%, compared with the average level of 10% in China [50].  
270 Similarly, a BIM-based system was developed to provide early alerts of construction waste to contractors  
271 [48], and likewise, a real-time BIM and System Dynamics based methods was proposed to minimize  
272 construction waste generated due to rework, lack of coordination, and poor integration of building  
273 subsystems during the construction process [53].

### 274 ***3.1.3. BIM-Supported Operations of Green Buildings***

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

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

### 290 ***3.1.4. BIM-Supported Renovations and Retrofit of Green Buildings***

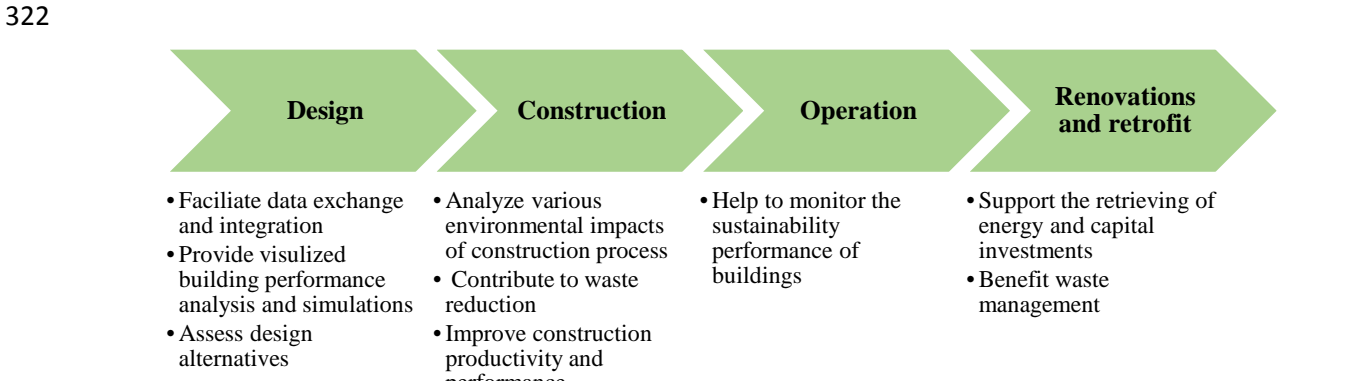
291 Practitioners believe BIM applications provide feasible solutions to address sustainability issues on  
292 project renovations [58]. Researchers have also demonstrated examples of using BIM on retrofitting  
293 /renovation projects. For example, Akbarnezhad et al. [62] proposed a sustainable deconstruction strategy  
294 which use the information provided by BIM to enable the retrieving of energy and capital invested in  
295 building components. Similarly, Lagüela et al. [63] presented a hybrid method based on BIM and other  
296 information technologies to support energy rehabilitation processes ranged from energy usage diagnoses  
297 to retrofitting decision-making. Woo and Menassa [64] provided the Virtual Retrofit Model (VRM), an

298 affordable computational platform integrating BIM, energy simulation and other technologies to support  
 299 streamlined decision making of building retrofit projects. Likewise, Larsen et al. [21] proposed a new  
 300 approach for analyzing energy performance of retrofit projects using BIM and 3D laser scanning.

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

306 **3.1.5. Summary of BIM-supported Project Lifecycles**

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



323  
 324 **Fig. 3. BIM-supported lifecycles of green projects**

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

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

### 344 **3.2. BIM Functions for Major Green Issues**

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

348 The selected 12 types of software are highly diverse in their own features, end users, and applicable  
349 stages, which are listed in Table 2. For instance, ODEON Room Acoustics Software is designed for  
350 acoustic analyses for special professionals. Other BIM software provides broad and comprehensive  
351 sustainability analyses, such as Green Building Studio (GBS). GBS is mainly used in the design phase,  
352 but it also serves various end users, including architects, designers and engineers, as well as other project  
353 participants whose work can benefit from using BIM applications, such as consultants, owners, and  
354 contractors [70]. Another example is Integrated Environmental Solutions® Virtual Environment (VE),  
355 which visualizes sustainability issues in project delivery and helps owners determine the most optimized  
356 green-design solutions [71].

357

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

BIM software	Green analyses*						Users**	Stage***	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

358 Note:

359 \*E for energy, CE for carbon emissions, NV for natural ventilation, SD for solar and day lighting, A for acoustic, W for water

360 \*\*A for architects, D for designers, E for engineers, O for owner, C for consultants, U for utility companies, G for government

361 \*\*\* De for design, C for construction, OM for operation and maintenance

362



### 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

397 it may impact building energy consumption, few studies have explored how IBE impacts the  
398 potential of utilizing renewable energy in buildings.

399 4) Fourth, BIM software can support an online real-time fault detection and diagnostics (FDD) of  
400 building energy to achieve more effective energy performance maintenance over the lifecycle of  
401 buildings. Such BIM-supported FDD approach provides a scalable and adaptable information  
402 infrastructure that can integrate other energy performance analysis and simulation technologies to  
403 streamline the information exchange process, thereby closing the information gap between facility  
404 managers and designers [61].

405 Although BIM software can contribute to energy performance analysis in various areas, as discussed  
406 above, the direct application of BIM with preloaded energy performance properties in existing buildings  
407 is still challenging because heat transfer condition of building elements gradually degrades during the  
408 operational phase [74]. In order to address this limitation, both semi-automated and automated methods  
409 for BIM reconstruction are proposed, such as automatic as-is 3D modeling methods from point clouds  
410 [75-78] and image-based thermal BIM reconstruction methods [79-80]. By using as-is BIM as an input of  
411 BIM-supported energy analysis, the gap between the energy performance information in the as-designed  
412 BIM and as-is building conditions can be significantly shortened [80], and designers can model the current  
413 energy performance of existing buildings in a more reliable way.

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

### 421 **3.2.2. Carbon Emissions Analyses and Evaluations**

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

429 Besides carbon emissions analyses, current BIM software also provides alternative designs for carbon  
430 emission reduction, thereby helping designers and engineers optimize their original designs towards

431 carbon neutrality. For instance, GBS can provide suggestions in selecting local utility providers who  
432 discharge fewer emissions by using renewable energy [70]. Liu et al. [82] developed a BIM-based multi-  
433 objective optimization model, which aids designers to identify and choose the optimal design scheme  
434 balancing carbon emission and cost for their clients. Similarly, BIM software can simultaneously estimate  
435 embodied and operational carbon over the life span of buildings, so designers can make better decisions  
436 on material selection [81].

### 437 **3.2.3. Natural Ventilation System Analyses and Optimization**

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

### 445 **3.2.4. Solar Radiation and Lighting Analyses**

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

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

463 Despite the benefits discussed above, one major issue has been identified in the integration of green

464 BIM with lighting and solar radiation simulation, i.e. the lack of information for simulations. Most  
465 researchers argue that BIM does not have all the information that is necessary for creating the input files  
466 for lighting simulation tools, such as Radiance and DAYSIM. To solve this issue, a new methodology,  
467 ThermalOpt, was proposed as an automated BIM-based simulation method intended for use in  
468 multidisciplinary design optimization environments [84]. Meanwhile, Landry and Breton [85] presented  
469 a detailed workflow of doing daylighting analysis using 3ds Max Design from BIM software. Kota et al.  
470 [86] provided a new method to enable direct integration of BIM with Radiance and DAYSIM. However,  
471 all the above efforts focus on the integration of BIM with specific types of lighting and solar radiation  
472 simulation tools. Therefore, future studies could develop a general method applicable for the majority of  
473 existing simulation tools.

#### 474 **3.2.5. Water Usage Analyses**

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

#### 485 **3.2.6. Acoustics Analyses**

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

492 BIM-based acoustic simulation software provides multiple types of outputs. For instance, visualized  
493 maps could be generated based on simulation results to show various acoustic effects of the building.  
494 Furthermore, some BIM software, such as ODEON Room Acoustics Software, can present simulated  
495 acoustics in 3D audio effects and vividly broadcast over headphones or loudspeakers according to users'  
496 customized requests [89]. Future BIM-based acoustic simulation software could further integrate with

497 emerging technologies, such as virtual reality, to provide visual and audial experience in a more vivid way.

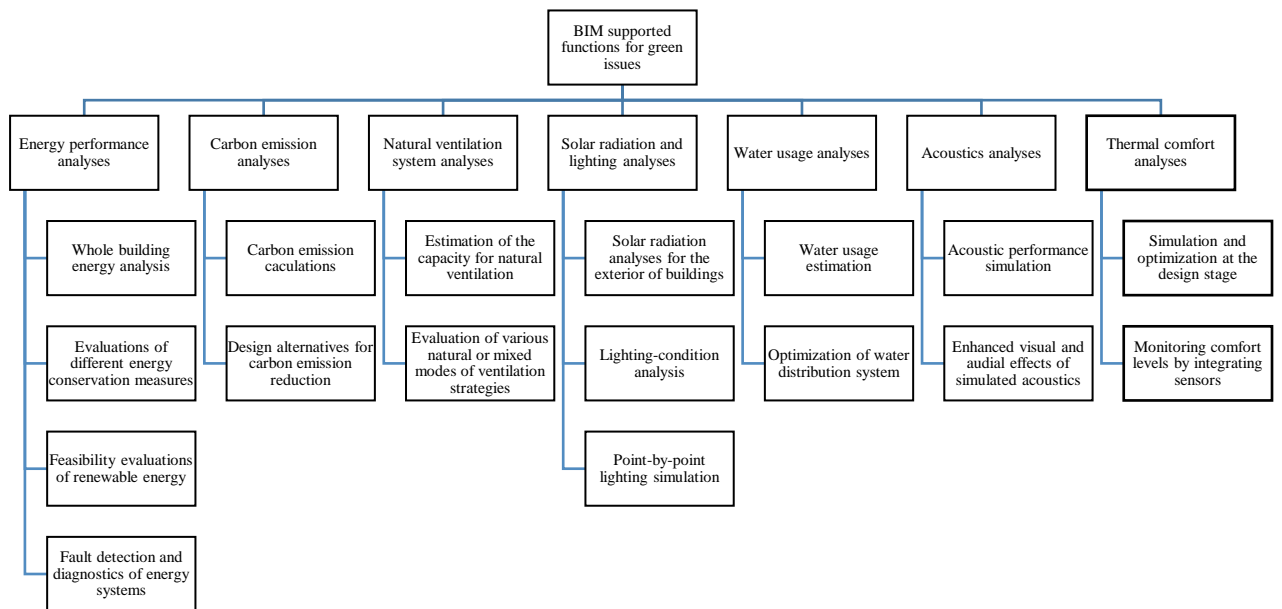
### 498 **3.2.7. Thermal Comfort Analyses**

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

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

### 520 **3.2.8. Summary of BIM Functions for Green Issues**

521 The above-mentioned BIM applications are designed and developed for various sustainability analyses,  
522 such as energy performance, CO<sub>2</sub> emissions and lighting analyses. A few BIM applications have also  
523 proposed solutions for water conservation and indoor air improvement. Fig. 4 has summarized the main  
524 functions of BIM for green analyses. However, most of these applications are designed specifically for  
525 one type of analysis and cannot address others. As a result, industry practitioners may underutilize their  
526 capabilities in using these BIM applications [67]. In the future, a generic and integrated green BIM  
527 application is needed that would allow a systematic analysis of a building’s whole environmental  
528 sustainability.



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**Fig. 4.** Main BIM functions for sustainability analyses

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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 paid more attention to.

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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<sub>2</sub> 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

549 sustainability research in the built environment to the next level.

### 550 **3.3. BIM-Supported Green Building Assessment (GBA)**

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

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

Name of GBA	LEED-NC 2009*	BREEAM 2011 New Construction**	Green Star 2008***	BEAM Plus 2010****
<b>Country/region of practices</b>	USA	UK	Australia	Hong Kong
<b>Total credits and points</b>	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
<b>Minimal required credits</b>	3/7 credits (SSp1, WEp1, EA p2)	2/3 credits (Man 01, Man 04)	N.a.	4/9 credits (SA P1, MA P4, EU P1, WU P2)
<b>BIM-supported management related credits</b>	N.a.	10.4% points (Man 01, Man 02, Man 03, Man 04)	no supported credits	N.a.
<b>BIM-supported site and transportation related credits</b>	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
<b>BIM-supported energy and atmosphere/emissions related credits</b>	1 credit (EA c1) 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
<b>BIM-supported water related credits</b>	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
<b>BIM-supported materials and waste related credits</b>	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
<b>BIM-supported indoor environment quality related credits</b>	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
<b>BIM-supported innovation related credits</b>	1/2 credits (IDc2)	all credits	no supported credits	IA 2 applicable, IA 1 and IA 3 not applicable,
<b>BIM-supported other credits</b>	regional priority credit (3.6% of total points)	N.a.	N.a.	N.a.
<b>Examples of available BIM software</b>	GBS	Revit, GBS	GBS	Revit, VE

560 Note:

561 \*Cited references are [117] [118] [94] [95].

562 \*\* 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

563 \*\*\* Cited references are [97] [119]. The results are based on commercial office buildings; 110 points cover innovation credits

564 \*\*\*\* Cited references are [120] [121]. The results considered bonus credits; 103 points cover innovation credits

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567 A total of four global GBA standards have been examined in this study, which include LEED  
568 (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment  
569 Environmental Assessment Methodology), Green Star, and BEAM Plus (Building Environmental  
570 Assessment Method). For each one, related studies were reviewed and analyzed to extract essential  
571 information in regard to the usefulness of BIM. This study highlights the unique value provided by BIM



572 software for the GBA process, as well as the improved efficiency of GBA process after using BIM.  
573 Subsequently, this study presents the use of BIM for the LEED certification process and the associated  
574 challenges as an illustrative case.

### 575 ***3.3.1. The Value of BIM for end users in the GBA process***

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

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

### 595 ***3.3.2 Challenges for integrating BIM with GBA***

596 While the majority of green practitioners recognize the value of BIM-LEED calculating tools for  
597 sustainable design and construction, several challenges exist for popularizing these tools. The current BIM  
598 software is still insufficient in providing an integrated analytical solution for an individual GBA, as it does  
599 not have the capacity to simultaneously analyze all green aspects of buildings. Most types of BIM software  
600 are designed to focus on one feature such as carbon emission analysis or lighting analysis. These analytical  
601 features are optimized individually due to limited interoperability among BIM functions. Thus, currently  
602 BIM is still limited in holistically assessing both the environmental and social sustainability of buildings.  
603 Credits that currently are not supported by BIM software mainly focus on four areas, namely management  
604 (e.g. in Green Star), ecological issues (e.g. in BREEAM), innovative techniques and performance (e.g. in

605 BEAM Plus, Green Star, LEED) and transportation conditions (e.g. in BREEAM). For instance, it was  
606 discovered that the impact of buildings on biodiversity is difficult to be addressed by BIM [96].

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

622 Another challenge is the complexity of traditional tools and users' lack of appropriate BIM knowledge  
623 [58]. Alwan et al. [99], for instance, demonstrated the feasibility of integrating LEED into BIM, but  
624 highlighted that high software complexity could be an issue if users do not have sufficient knowledge  
625 about BIM. For instance, it was discovered that due to users' irregular and inaccurate update of BIM  
626 models, credits in LEED certification are difficult to be documented by green BIM software [95]. Similarly,  
627 studies revealed that there are discrepancies between BIM-supported and manual GBA results due to an  
628 inadequately developed BIM model [95, 99]. Even though Wu and Issa [92] proposed a new paradigm in  
629 which project teams can leverage cloud-based BIM to automate and simplify LEED accreditation, there  
630 are no applicable case studies to assess its performance and efficacy. Future research can further simplify  
631 the operations of BIM tools thereby facilitating the transition from traditional GBAs to BIM-based GBAs.  
632 Furthermore, there is a lack of well-defined business goals and processes of using BIM in LEED projects.  
633 Researchers have identified that current green BIM practices are heavily technology-driven instead of  
634 process-driven. Wu and Issa [2] proposed an integrated green BIM process map to more clearly define  
635 business processes and execution planning in LEED project. Future research could further examine the  
636 industrial players' business processes and goals of BIM application in LEED projects.

#### 637 **4. Research gaps and suggestions**

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

- 646 1) The first research gap is the weak interoperability among various BIM applications. For instance,  
647 massive BIM data is difficult to be directly adopted for a specific sustainability analysis [100-103].  
648 To support the required green analyses, BIM data requires many modifications which weakens the  
649 design benefits. Data extraction and data exchange are two key processes associated with the  
650 interoperability among BIM applications. In terms of optimizing the data extraction process,  
651 Cemesova et al. [104] improved the IFC schema, enabling the compilation between building fabric  
652 data from BIM authoring tools and energy related information from specific low energy design  
653 tools, such as Passive House Planning Package. Similarly, Ladenhauf et al. [105] developed new  
654 algorithm that enabled automatic extraction of specific types of data from the BIM model. Ahn et  
655 al. [106] developed IFC-IDF interface to automatically convert the building information of IFC  
656 into IDF, an input file format for EnergyPlus. To improve the data exchange process among BIM  
657 applications, a new framework was proposed based on an open standard of BIM files [100].  
658 Similarly, a physical BIM library was also developed for building thermal energy simulation from  
659 an Object-Oriented Physical Modeling (OOPM) approach [107]. Geyer [101] provided a semantic  
660 material-name matching system to enable automatic data exchange between BIM and other systems.  
661 These solutions are mainly designed to address the interoperability of file exchange or syntax  
662 commands, e.g. exchanging files between two BIM applications. However, a large amount of BIM  
663 applications, such as BIM-based energy analysis software, are suffering from the low visualization  
664 interoperability that enables the visualization of models being exchanged between two tools [23],  
665 and the weak semantic interoperability that interprets the meaning of models being exchanged.  
666 Thus, the visualization and semantic interoperability worth to be further studied in the future.
- 667 2) The second gap arises from the limited capability of BIM applications supporting the construction  
668 and operation phases of green projects. Currently, the development of green BIM applications  
669 heavily skewed towards the project design phase where important decisions concerning building  
670 sustainability are normally made [18, 58, 108]. However, emerging green construction practices,  
671 such as prefabricated buildings and lean construction, could be all linked to green BIM applications,

672 but few studies have focused on the application of BIM in these topics. Future research could  
673 examine the applicability of using BIM to address these green construction practices. Meanwhile,  
674 in the building operation phase, facility managers have gradually realized the benefits brought by  
675 a BIM-based facility management (FM) applications [58]. An increasing number of BIM vendors  
676 has also started to recognize the benefits of BIM to FM, and therefore has shifted their focus from  
677 the design phase to the operation and maintenance stage [22]. This trend calls for more research to  
678 develop BIM-enabled green FM.

679 3) Another research gap is the lack of clear industry standards or codes for the various aspects of green  
680 BIM applications. Integrating multidisciplinary information in a single BIM model requires the  
681 access to the BIM model by multiple users. However, there is lack of BIM standards for model  
682 integration and management by multidisciplinary teams [26]. This is further supported by Kassem  
683 et al [127], who studied various BIM protocols such as AEC (UK) BIM Protocol specific to Revit  
684 and Bentley Building and Singapore BIM Guide, and revealed that these protocols do not  
685 concurrently consider the enabling technology and the variables affecting its deployment on  
686 projects such as interoperability required for different BIM work-streams. Similarly, Chong et al  
687 [140] examined 36 standards and guidelines of BIM, revealing that even though the standards  
688 stipulate the methodologies of BIM adoption to foster a collaborative working environment, the  
689 standards paid little attention to the refurbishment and demolition of green buildings, and the  
690 incorporation of GBA criteria into the standards. Meanwhile, few studies on the best practices of  
691 green BIM have been presented for the AEC industry [109], even though many studies have  
692 provided valuable recommendations for implementing BIM in green projects. In fact, appropriate  
693 guidance on the efficient execution of green BIM applications is equally if not more important than  
694 the technological development of green BIM applications. To this end, the industry best practices  
695 should be researched and developed to guide BIM implementation in the green built environment.

696 4) The fourth gap is the low industrial acceptance of green BIM applications, despite a large number  
697 of BIM studies have been conducted. Issa and Anumba [110] have shown that research findings  
698 have hardly been adopted in AEC industrial practices. Complex barriers exist hindering the wide  
699 application of BIM, which include but not limited to lack of holistic industry codes, the lack of  
700 clear ownership of the BIM data through copyright laws, the blurred responsibility for ensuring the  
701 accuracy of the BIM data due to the integrated approach of BIM, and the industry's reluctance to  
702 change existing work practices and habits [26]. Similarly, Ghaffarianhoseini et al [141] suggested  
703 that the lack of widespread uptake of BIM is linked to various risks and challenges including cyber  
704 security of BIM tools, the unclear intellectual property and responsibility, the incremental cost  
705 needed to input and review BIM data, and the reluctance from small construction enterprises.

706 Education and training is one way to bridge the above gap. However, Becerik-Gerber et al. [111]  
707 discussed problems on the integration of BIM and sustainability from the perspective of AEC  
708 educational programs in the America. Project stakeholders may not be willing to adopt green BIM  
709 because of the various interests involved in the supply chain of AEC projects [91]. The future  
710 research should not only focus on developing and evaluating the prototype of new green BIM  
711 software, but also aim to investigate the actual needs from practitioners, and raise their interests in  
712 green BIM.

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

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

736 The "Green BIM Triangle" taxonomy proposed in this paper maps the nexus between BIM and green  
737 buildings. As a conceptual framework, the nature of which is similar to other BIM frameworks such as  
738 [142, 143], the taxonomy aims to provide synthesized understandings and knowledge of green BIM, which  
739 has not been explored by previous studies. The taxonomy, together with its supporting information such

740 as Fig 4, could be used to guide practitioners in green BIM implementation. For instance, through  
741 comparing the applied green analyses of BIM in real-world projects and the various analyses summarized  
742 in Fig 4, the maturity level of green BIM implementation in the real-world projects could be preliminarily  
743 evaluated. The “Green BIM Triangle” taxonomy could also be tailored for different types of green  
744 buildings in various countries through specific empirical studies and reviews in the future. It is important  
745 to note that similar to other BIM frameworks such as those proposed by Chen et al [143], the “Green BIM  
746 Triangle” taxonomy in this study is a grand framework which was not tailored for specific buildings.  
747 Rather, it serves as a foundation in green BIM, and specific frameworks could be developed based on this  
748 foundation. For instance, based on this taxonomy, future studies could investigate the potential of BIM in  
749 facilitating the Three Star Rating System for green building certification in China and identify the green  
750 analyses of BIM that are commonly or seldom used in China, thereby formulating tailored frameworks  
751 that could guide green BIM development specifically in China. Furthermore, the taxonomy should be  
752 regarded as a continuously updated framework provided that the emerging studies can be incorporated  
753 into thereby enriching the taxonomy. For instance, if a new BIM plug-in is developed to address the  
754 impacts of buildings on biodiversity, such as bird collision, the aspect of biodiversity may need to be  
755 included in the dimension of “green attributes”. This expandable feature ensures the flexibility of the  
756 taxonomy that can accommodate both current and future studies for green BIM.

## 757 **5. Conclusions**

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

767 First, the applicability of using BIM in each project phase and the whole project lifecycle of green  
768 buildings was analyzed. It was discovered that while BIM is mainly perceived as a vital tool for the design  
769 stage of green buildings, its potential value for the construction, facility and operation management phases  
770 has been increasingly recognized. BIM could facilitate data exchange and integration, provide visualized  
771 building performance analyses, and enhance the communication and collaboration of various stakeholders

772 during the lifecycle of green buildings. Second, the advantages and challenges of BIM functions for  
773 environmental sustainability analyses of buildings were discussed. 7 major BIM functions for green  
774 analyses were identified and critically reviewed, including energy performance analyses and evaluations,  
775 carbon emission analyses, natural ventilation system analyses, solar radiation and lighting analyses, water  
776 usage analyses, acoustics analyses and thermal comfort analyses. Third, the potential of applying BIM to  
777 support the GBA process was explored and reviewed. This study reveals that green BIM applications  
778 could bring various benefits for GBA, such as estimating GBA scores, managing application documents,  
779 and improving the efficiency of GBA process.

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

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

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