

# 1 A review of BIM integration with building performance analysis in the project life-cycle

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## 8 Abstract

9 Adopting Building Information Modelling (BIM) in Building Performance Analysis (BPA)  
10 is becoming an emerging research area in the application of information technology in the  
11 Architecture, Engineering, and Construction (AEC) industry. To investigate the current state of  
12 research in the adoption of BIM in BPA, this study performed a holistic review consisting of a  
13 bibliometric analysis of existing literature, content analysis of selected studies, as well as  
14 follow-up qualitative discussion in BIM integration with BPA. The bibliometric analysis  
15 identified 60 relevant studies; the content analysis of these studies revealed the research  
16 focuses of BIM-enabled BPA, including interoperability, semantics, and sustainability rating  
17 systems; the qualitative discussion further highlighted the learning process throughout project  
18 delivery stages and addressed the potential gap between ‘as-designed’ building performance  
19 and ‘as-built’ performance. Overall, this study contributes to existing research by identifying  
20 key input attributes and workflow in BPA, reviewing the state-of-the-art research on BIM  
21 integration with BPA, and investigating the major research areas, namely, interoperability  
22 issues in BIM-enabled BPA within the context of life-cycle BPA.

23 **Keywords:** Building information modelling; Building performance analysis;  
24 Interoperability; Level of details; Energy performance.

## 25 1 Introduction

26 The building sector accounts for 20% to 40% of the overall energy consumption [74,79,97]  
27 and one-third of the greenhouse gas emission worldwide[76]. It is vital to evaluate the energy  
28 performance of a building in the design stage to ensure minimum building energy consumption  
29 and maximum building performance before it is built because any changes to be made later are  
30 subject to excessive cost and resource waste. The building performance analysis (BPA)  
31 provides feedback on building design and facilitates the design optimisation. BPA in existing  
32 studies has been primarily focused on building energy assessment[19,62,88]. However,  
33 researchers in this study believe that BPA should cover a more comprehensive list of building  
34 performance indicators besides energy performance, such as daylighting [24], carbon footprint  
35 [9],and overall sustainability performance [7].

36 Traditionally, engineers who build the building energy models act as assistants to  
37 architects and use professional tools in their domain. Recently, the integration of design tools  
38 and building energy modelling tools have changed the way the two types of professional work  
39 together. The emerging Building Information Modelling (BIM) technology is becoming part of

40 the design practice. BIM provides more accurate and interoperability capabilities than  
41 traditional computer-aided design[65]. Traditionally, the indoor work of information input in  
42 translating a geometric model to the simulation model is accomplished by an energy modeller.  
43 This progress is complicated and time-consuming. Also, manual input work may lead to low  
44 efficiency and limitation of data integration. BIM integrated multidisciplinary information in a  
45 model which facilitates the BPA in preliminary design phases. BIM authoring tools not only  
46 create geometric models but also can store non-graphical information such as material  
47 properties. It could be used as a repository of the information for a building energy analysis,  
48 such as the identity, geometry, material and other alphanumeric data of building components  
49 [36].

50 Although BIM-enabled BPA has become an interactive and intuitive process such that a  
51 designer without any simulation skill can perform the calculation which leads to analysis  
52 reports including charts and diagrams, the reliability of the calculation depends on the richness  
53 and accuracy of the information defined in the model. Multiple studies [16,67,75,100] have  
54 emphasised that integration of BIM and BPA can optimise the building performance in early  
55 design stages. It is also imperative that the designer establishes the knowledge base of the types  
56 of BPAs required corresponding to different design stages with different Levels of  
57 Development (LoDs). However, it remains a challenge of how to couple building information  
58 and building performance models in the design lifecycle [67].It should be noticed that the  
59 building information herein does not only include geometric models, but also non-geometric or  
60 semantic information as demonstrated in existing studies focusing on transporting information  
61 from BIM to BPA.

62 Although there have been a few studies [42,80,85] providing a review of studies on  
63 integration of BIM and BPA, these existing studies were either limited to the review of  
64 technological development (e.g., laser scanning) or data acquisition and analytics. For example,  
65 the study of Gerrish et al. [32] demonstrated a method to link the data from BIM to building  
66 operation through a case study of building design and operation. The feedback on user based  
67 issues implementing BIM as a performance management tool [32] was collected through  
68 follow-up interviews to stakeholders. So far limited review work has been done to consider  
69 different project stages and their significance when applying BIM for BPA. This study aims to  
70 investigate the contemporary research focuses and issues in BIM-enabled BPA based on a  
71 thorough literature review. Section 2 provides the background of project design stages by  
72 illustrating design details related to different building design stages; Section 3 describes the  
73 literature review methodology; Section 4 illustrates the details of review-based analysis and  
74 findings related to BIM integration with BPA; Section 5 summarises the content analysis of  
75 BIM integration with BPA; Section 6 investigates the major research area (i.e., interoperability)  
76 identified in the content analysis of the literature; Section 7 provides a further qualitative  
77 discussion by incorporating project life cycle into the integrated BIM&BPA; and finally  
78 Section 8 concludes the review-based study.

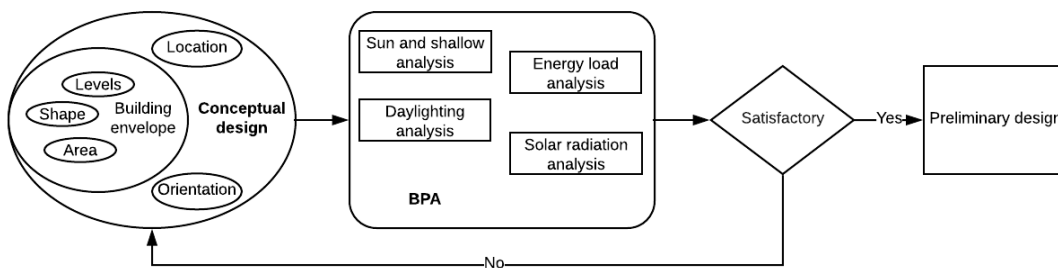
## 79 **2 Background**

80 The Royal Institute of British Architects (RIBA) divided a project lifecycle into eight  
81 stages which serve as milestones for determining the activities of the project stakeholders and

82 agreeing on information deliverables[45]. Based on RIBA’s definitions, the activities of the  
 83 conceptual design, preliminary design, and the detailed design stages are summarised herein.  
 84 The deliverables at each stage include BPA at different LoDs, i.e., LoD100, LoD200, and  
 85 LoD300. These are shown in Figure 1, Figure 2, and Figure 3.

86 2.1 Conceptual design (LoD100)

87 In the conceptual design stage, descriptions of internal environmental conditions and  
 88 seasonal control strategies and systems should be prepared. At this stage, BPA requires the  
 89 identification of design objectives, desired rooms or spaces, room sizes, relationships between  
 90 spaces and relationships to the site. The content of BPA and information required in the  
 91 conceptual design stage are shown in Figure 1.



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Figure 1 BPA at the conceptual design stage – LoD100

94 BPA at the conceptual design stage includes:

- 95 • Sun and shadows analysis, which is to simulate the sun moves through the sky and analyse  
 96 the shade on site;
- 97 • Energy loads analysis, which is to identify the area requires heating and cooling;
- 98 • Solar radiation analysis, which is to quantify the amount of the solar energy that can be  
 99 used for energy generation on site;
- 100 • Daylighting analysis of conceptual design, which is to quantify the sunlight in the project  
 101 that can be used to reduce light loads and cooling loads.

102 Generally, the energy consumption of a building can be affected by several factors, such as  
 103 daylight harvesting, natural ventilation and thermal mass. There are some significant factors  
 104 which are essential to energy consumption optimisation, such as the shape and size of a  
 105 building [12], building orientation [1] and building topology [48]. A BIM model that includes  
 106 all the information is referred as LoD100.

107 2.2 Preliminary design (LoD200)

108 The preliminary design starts with sketches, floor plan studies, and 3D or physical models.  
 109 The BPA at this stage requires floor plans, elevations, sections, area analysis, rendering and  
 110 preliminary cost (Figure 2). A BIM model that includes all the information is referred as  
 111 LoD200.

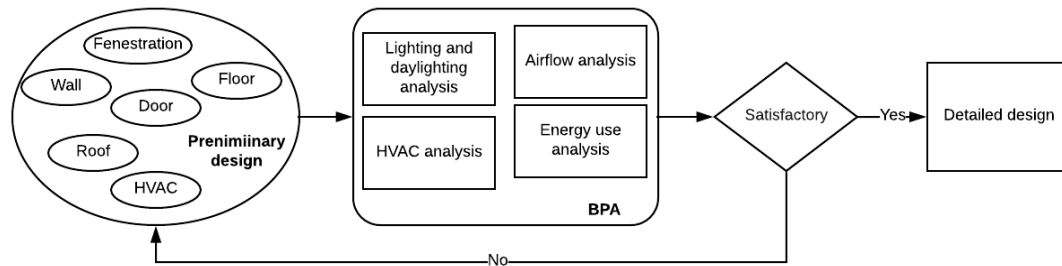


Figure 2. BPA at the preliminary design stage – LoD200

According to Figure 2, Building elements should be defined as general geometric primitives with approximate dimensions, shapes, location, and orientation. BPA at the preliminary design stage includes:

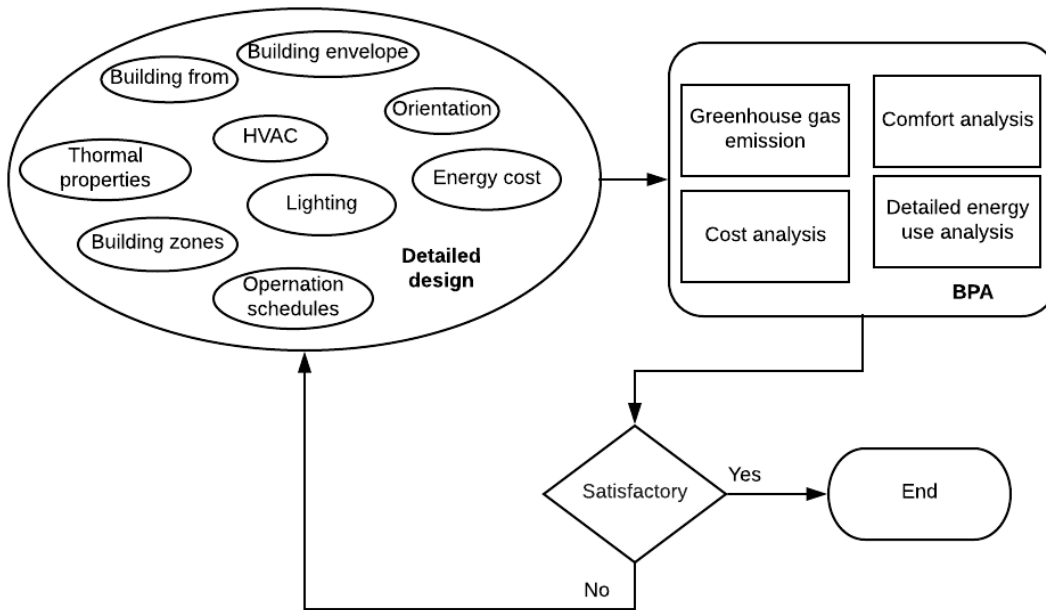
- Lighting and daylighting analysis, which is to test interior visual comfort with the help of computer simulation and lighting consultants;
- HVAC analysis, which is to adjust building systems, and compare results to determine the optimal configuration;
- Airflow analysis, which is to improve the air quality and natural ventilation;
- Energy use analysis, which is to calculate normal energy use (i.e., fuel and electricity) based on the building's geometry, climate, building type, envelope properties, and active systems (HVAC & Lighting).

Building design at this stage should be associated with a more accurate BPA. It is essential to take into account a comprehensive list of building information to assess building performance at the preliminary stage, including geometric, semantic and topological information [82]. Factors influencing building energy consumption would include building orientation, building layout and form, geometry, building fabrics, building envelope and passive strategies such as solar gain and shading strategies and natural ventilation strategies. Design optimisation could be assisted by building performance simulation through understanding and weighing the critical influence factors (e.g., building fabrics). Decision making during preliminary design stages would have an enormous effect on building energy performance.

### 2.3 Detailed design (LoD300)

The detailed design phase includes finalising the size of the rooms and spaces, refining the appearance, selecting materials, determining the systems, and deciding on the door and window types and locations. A full formal sustainability assessment should be carried out. A design stage carbon/energy declaration need to be undertaken.

At the end of the design development phase, the documents from the preliminary design phase need to be updated in further detail to support BPA. It is common to also have documents including specification outline, key details, interior schedules, and revised cost estimate, as shown in Figure 3. A BIM model that includes all the information is referred as LoD300.



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Figure 3 BIM-enabled BPA at the detailed design stage – LoD300

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The information specified at this stage should be able to support the generation of construction documents and shop drawings. The geometry of the building elements should be defined using more accurate quantity, size, shape, location, and orientation. Physical characteristics of the building elements should be defined as alphanumeric properties.

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Building energy analysis in the detailed design stage includes:

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- 151 • Detailed building energy use analysis of the final design and other performance-based analysis in support of detailed information, such as lighting and daylighting analysis, sun and shadow analysis, airflow and ventilation analysis;
- 152 • Greenhouse gas emission and carbon footprint analysis;
- 153 • Living comfort analysis;
- 154 • Cost analysis

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### 3 The literature review method

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The literature review of BIM-enabled BPA followed three steps:

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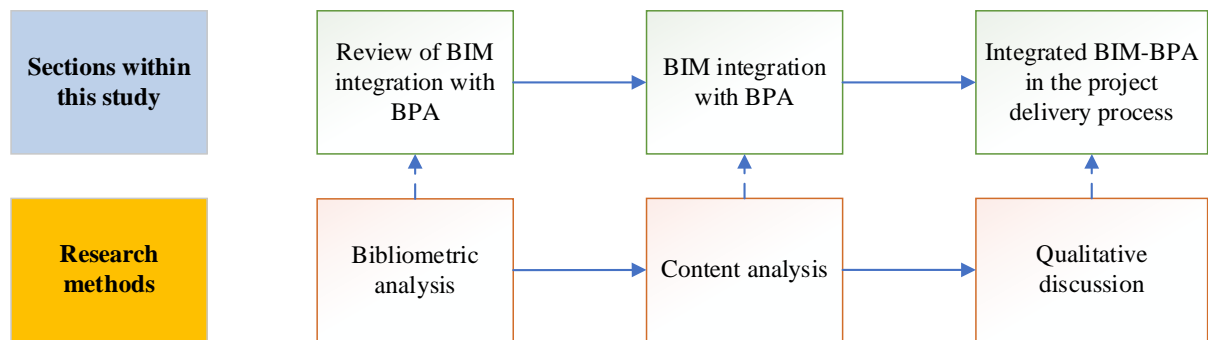
- 158 • A bibliometric search and review of *Scopus*-indexed journal articles followed by categorising keywords focusing on BPA integrated with BIM;
- 159 • content analysis of existing studies linking BIM to BPA;
- 160 • qualitative discussion for applying LoDs into BIM-assisted BPA following the study of GhaffarianHoseini et al [35].

161

These research methods used in this paper are illustrated in Figure 4.

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168 *Figure 4 Description of the study sections and corresponding research methods*

169 3.1 Initial review of BIM integration with BPA

170 The bibliometric analysis of the literature was carried out using VOSViewer [93].  
171 VOSViewer supports the analysis of clustering solutions with visualisations[92]. Scopus was  
172 chosen as the source to search the key published literature on BIM-enabled BPA, as it was  
173 identified by Aghaei Chadegani et al. [14] that Scopus has broader coverage of journals in the  
174 area of construction IT than other search engines including Web of Science with more recent  
175 publications. The following query was used to retrieve recent publications on BIM-enabled  
176 BPA.

177 TITLE-ABS-KEY ("BIM" OR "building information modelling" OR "building  
178 information modelling") AND TITLE-ABS-KEY ("building performance" OR "energy  
179 analysis" OR "energy performance")

180 The query limited the years of publication to recent ten years (from 2009 to 2018), only  
181 Articles or Article in Press in Journals were included, and finally it restricted the language to be  
182 English.

183 3.2 Content analysis of key studies linking BIM to BPA

184 Following the bibliometric review assisted by VOSViewer, content analysis, which is the  
185 research method that has been adopted in multiple studies [28,91] in the field of engineering  
186 and management, was adopted to summarise the research contents within the selected sample  
187 of journal articles. Content analysis is a tool to examine trends and patterns in documents, and  
188 it allows researchers to sift through a large amount of data with relative ease in a systematic  
189 approach. The detailed steps of performing content analysis can be found in several existing  
190 studies such as Bogus et al. [10].

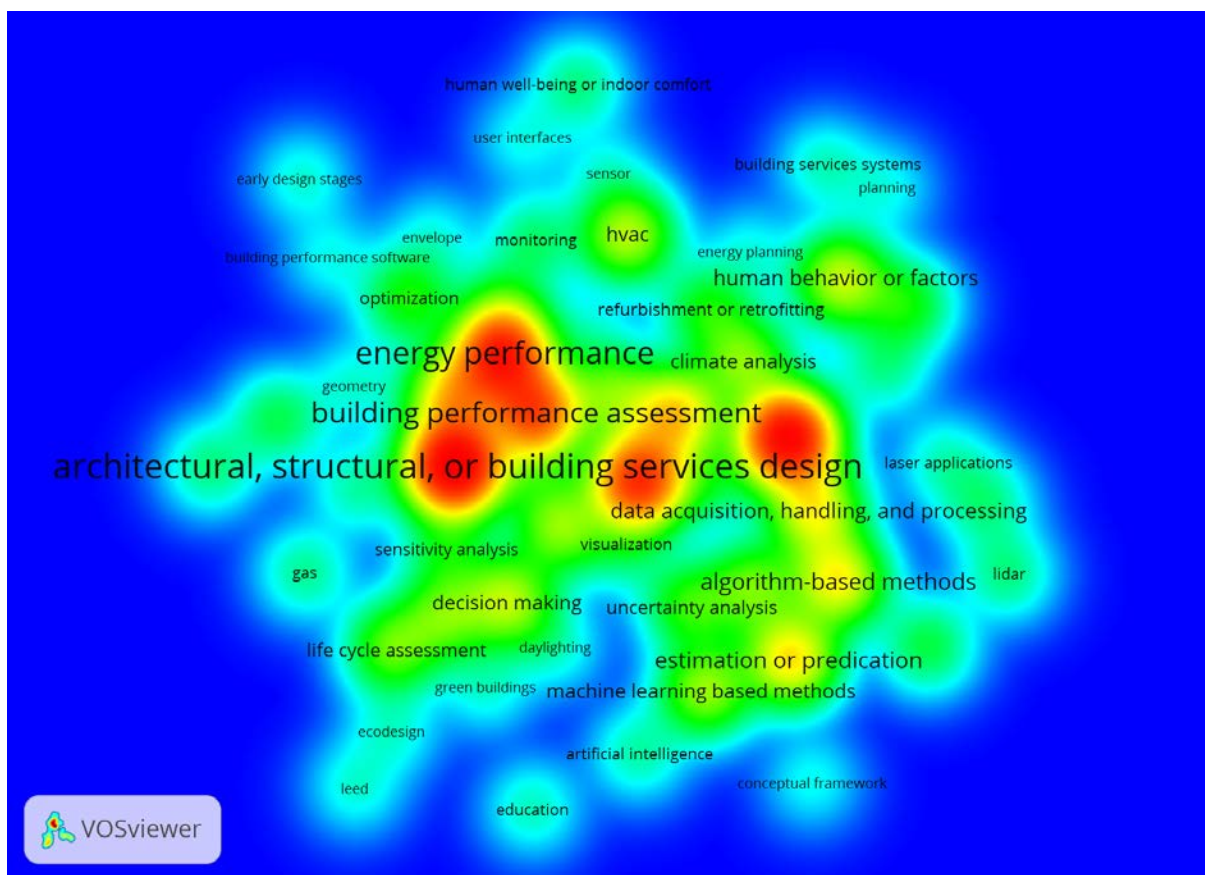
191 3.3 Incorporating different project stages into the integrated BIM&BPA

192 Based on the design stage descriptions illustrated in Figures 1-3, bibliometric review,  
193 content analysis, as well as existing studies stressing LoD and project life cycle[2], a follow-up  
194 discussion targeting on the integrated BIM and BPA in the context of project stages was  
195 initiated and discussed in a qualitative approach. The workflow was demonstrated,  
196 highlighting the input of building parameters and outputs within different LoDs.

197 **4 The bibliometric analysis**

198 Following the bibliometric search in Scopus, manual searching and screening was also  
199 conducted to weed out studies that did not fall into the scope of BIM-enabled BPA. For

200 example, the study of Jalaei et al. [46], although adopting BIM in the building conceptual  
 201 design for decision making of material selection, did not focus on integrating BIM and BPA.  
 202 Finally, 546 research papers in total were selected from Scopus. These papers have 6,264  
 203 keywords; 299 of them, including both Author and Index keywords, were used in at least five  
 204 papers. Some of the irrelevant or apparent keywords (e.g., BIM or building) were manually  
 205 removed from the list. Then, some keywords with semantically similar meanings were  
 206 categorised into the same terminology. For example, *air conditioning, heating, and ventilation*  
 207 were categorised as *HVAC*; *Bayesian networks, decision trees, and artificial neural network*  
 208 were all categorised as *Machine learning based methods*. After removing the irrelevant  
 209 keywords and categorizing the remaining keywords with semantic similarities, 57 keywords  
 210 are selected, as shown in Figure 5. These keywords were categorized and visualised to  
 211 highlight the research focuses in recent years.



212  
 213 *Figure 5 The identified 57 major keywords (not all the 57 keywords are visible)*

214 The font size of keywords indicates the frequency of them in the sample journal articles.  
 215 The distance between two keywords could infer their closeness. For example, the *architectural,*  
 216 *structural or building services design* is highly relevant to decision making and life-cycle  
 217 assessment. It can be found that *architectural, structural or building services design, energy*  
 218 *performance, and building performance assessment* are the most frequently studied as the  
 219 research focuses. These frequently keywords can be found closely connected to the rest  
 220 keywords (e.g., data acquisition, handling, and processing). The relationships among these  
 221 keywords can be summarized as below:

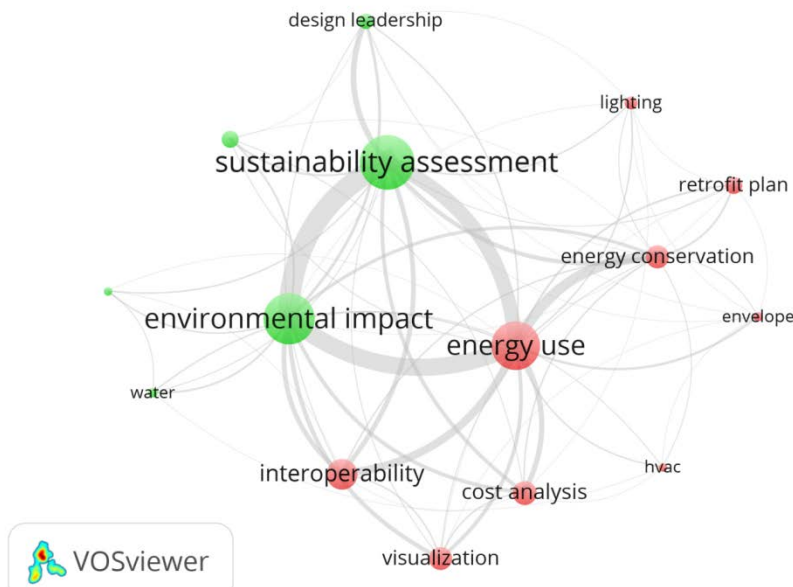
- 222 • Energy performance of building is one of the widely studied building performance assisted  
223 by BPA software, especially in the early design stages [56]. Other building performance  
224 studied included, but were not limited to daylighting [24], and thermal comfort;
- 225 • Sustainability rating systems (e.g., LEED or Leadership in Energy and Environmental  
226 Design) have been embedded in BIM-driven green building design [68];
- 227 • Influence factors to BPA that should be considered, for example, the real behaviour of  
228 building users [26];
- 229 • The linkage between BIM and BPA could be achieved or showcased with certain hardware  
230 and software, such as wireless sensor network to monitor thermal conditions in built  
231 environment [64]
- 232 • Data shared between BIM and BPA need the further handling, processing, and analytics,  
233 such as sensitivity analysis as showcased in Ahn et al. [3]. Multiple data analytics  
234 approaches have been adopted in the assisting BIM-driven BPA, such as algorithms [37]  
235 and programming [48]. These approaches have been applied in achieving optimization  
236 [52]in building performance design;
- 237 • Interoperability-related data format (e.g., IFC or *Industry Foundation Class*) would be  
238 needed to allow information exchange between BIM and BPA. The information would  
239 include both geometric information [44]and semantic data [59].
- 240 • Other research focuses, such as utilising integrated BIM and BPA for engineering  
241 education purpose [39], have not been widely studied.

242 These 57 keywords were categorised into six clusters which could be defined as:

- 243 • BPA measurements (e.g., *energy performance*);
- 244 • Design-related (e.g., *ecodesign*);
- 245 • Influence factors to BPA ;
- 246 • Equipment or hardware needed in BIM or BPA (e.g., *laser application*);
- 247 • Methodologies adopted (e.g., *machine learning-based methods*);
- 248 • Interoperability-related (e.g., *IFC*).

249 Not all the initially identified 57 keywords were all related to BIM-enabled BPA,  
250 especially discussing the input (e.g., building envelope) and output variables (e.g., energy use)  
251 in BPA. Therefore, these 57 keywords were further reduced to 15 according to their relevance  
252 to this research. A total of 60 out of the 546 papers which used these 15 keywords were  
253 identified for further content analysis. Figure 6 illustrates these 15 main keywords.





254  
255 *Figure 6 Categorized keywords related to BIM integration with BPA*

256 According to Figure 6, BPA can be divided into these few major categories:

- 257
- Building energy performance (e.g., energy conservation)
  - 258 • Environmental sustainability
  - 259 • Indoor comfort including illumination and daylighting
  - 260 • Resources (e.g., water and carbon footprint)

261 Several main input factors in building design that would affect BPA include:

- 262
- Thermal characteristics of building elements (insulation, roofs, windows);
  - 263 • Building envelope including position and orientation information;
  - 264 • Heating, ventilation and air conditioning (HVAC) system

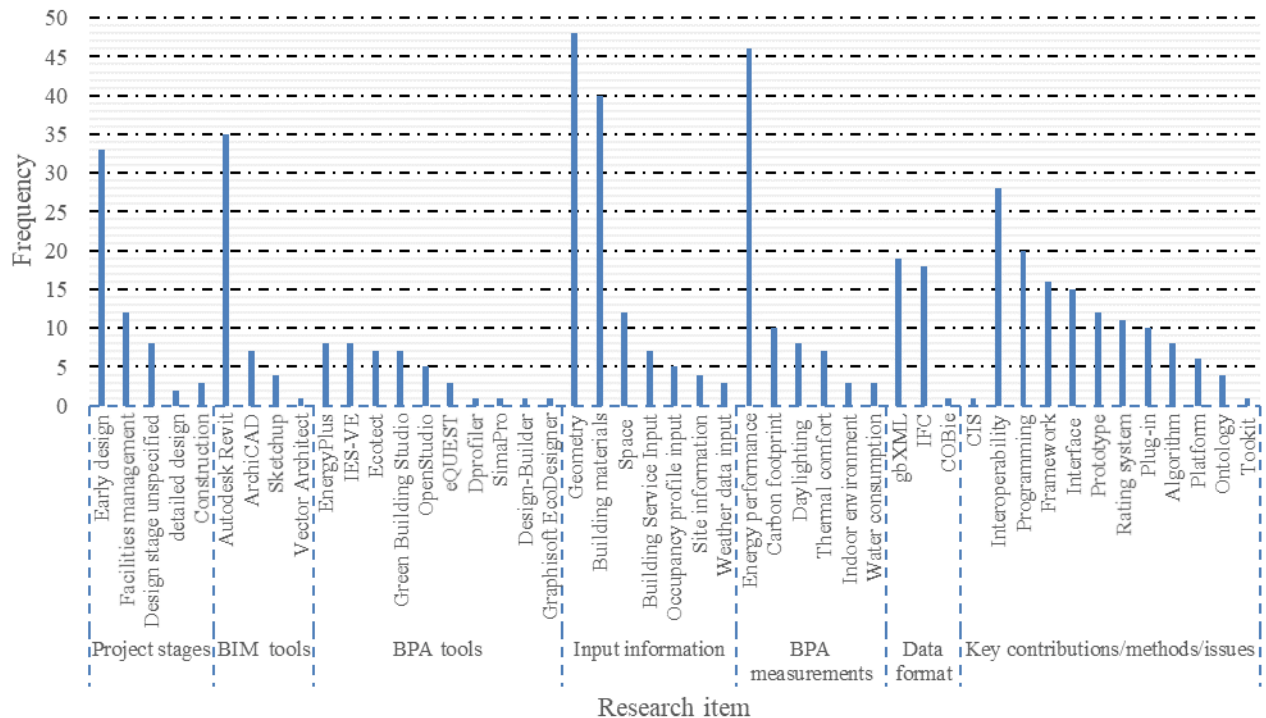
265 Besides these BPA categories, Figure 6 also indicates that sustainability assessment (e.g.,  
266 LEED rating system[86]) is one of the key research areas[51]. It was suggested by Chong et al.  
267 [22] that new BIM standards and guidelines should include requirements on BIM tools'  
268 compliance with specific sustainability assessment. Interoperability is a crucial issue when  
269 linking BIM into BPA. BIM offers interoperability opportunities and integration among  
270 different players. Although BIM can provide accurate material quantities and building  
271 components [34], insufficient interoperability between BIM and BPA raises barriers to reliable  
272 BIM-based BPA such as energy assessment [21].

## 273 **5 Content analysis of the literature**

274 Content analysis was conducted to summarize the 60 papers selected in the previous  
275 section. BIM-enabled BPA is achieved through BIM authoring tools and BPA analysis tools.  
276 Some BIM authoring tools have integrated BPA to deliver lifecycle building performance  
277 simulations, including expected energy demand, the projected financial running costs of the  
278 energy demand and CO<sub>2</sub> emissions. BIM-enabled BPA allows a fast, accurate, and iterative  
279 workflow as the ability to import the building geometry and thermal data from BIM has  
280 significant potential to reduce the time and uncertainty in BPA [43]. The potential

281 interoperability between BIM and BPA was tested by Calquin et al. [11] to showcase how the  
 282 existing BIM authoring tools (e.g., Autodesk Revit) could support BPA.

283 More statistical details of the totally 60 similar studies listed in Table 1 are summarised in  
 284 Figure 7.



285  
 286 *Figure 7 Frequency of research keywords in totally 60 research papers linking BIM to*  
 287 *BPA*

288 As the showcases for demonstration purpose, Table 1 lists some typical examples of  
 289 studies in linking BIM authoring tools to BPA tools.

290 *Table 1 Studies in linking BIM authoring tool to BPA tool*

Case study	BIM authoring	BPA tools	Data exchange and format	Information shared from BIM to BPA	Contribution
Eight-floor residential apartment building in Canada[51]	Autodesk Revit incorporating early stage design (i.e., conceptual design) information	Ecotect and IES-VE for energy analysis and lighting simulation	IFC and gbXML in Ecotect, and gbXML in IES-VE	Building's 3D geometric information, building components, services, Place and location	Plug-ins were created to enhance interoperability; The workflow developed in linking BIM to BPA enabled users to compare the select different materials and components for design and performance analysis.
A five-story	ArchiCAD	Energy-	IFC providing	Geometry and	Both the pros and cons of

library building in Korea [3]		Plus	information delivery manual (IDM) and model view definition (MVD)	space boundary information	full and semi-automation from BIM to energy simulation were discussed.
A high-rise residential building in the U.S.[75]	Autodesk Revit	Dynamo; Autodesk Green Building Studio	gbXML open schema	Project location, building type, moreover, building operating schedule, construction and material properties	A BIM-based framework was proposed and tested for building performance optimisation in the design stage
Five test cases in Modelica-BIM Structure Example package[57]	Autodesk Revit	Modelica-BIM Structure Example package	Revit2Modelica consisting of Revit Application Programming Interface (API)	Geometry, materials properties, and location information	BIM-based energy simulation using an Object-Oriented Physical Modelling approach using ModelicaBIM library was developed and validated.
A residential building and an instructional facility in the U.S.[43]	Autodesk Revit	The BPA tool not specified	gbXML	Thermal properties, but the limited geometric information could be transported from BIM to BPA	As-is building thermal properties were tested and updated in gbXML-based BIM for energy analysis.
An office building and a university library building in Korea[21]	Autodesk Revit and ArchiCAD	Energy-Plus	IFC converted to Input Data Format (IDF)	Building materials with thermal properties, geometry, space type	The BIM-enabled energy performance assessment process, a materials library, and a decision-support the system was initiated to address the low interoperability issue between BIM and BPA.

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These few examples of previous studies are shown in Table 1 to demonstrate the existing research in addressing the gap of interoperability between BIM authoring tools and BPA tools through certain data format (e.g., IFC and gbXML). Although IFC and gbXML are the two major data formats studies on BIM-enabled BPA, researchers have also proposed alternative technical or managerial approaches, such as combination of design tools and visual programming language suggested by Negendahl [67] and Revit2Modelica consisting of Revit Application Programming Interface (API) developed by Kim et al. [57].

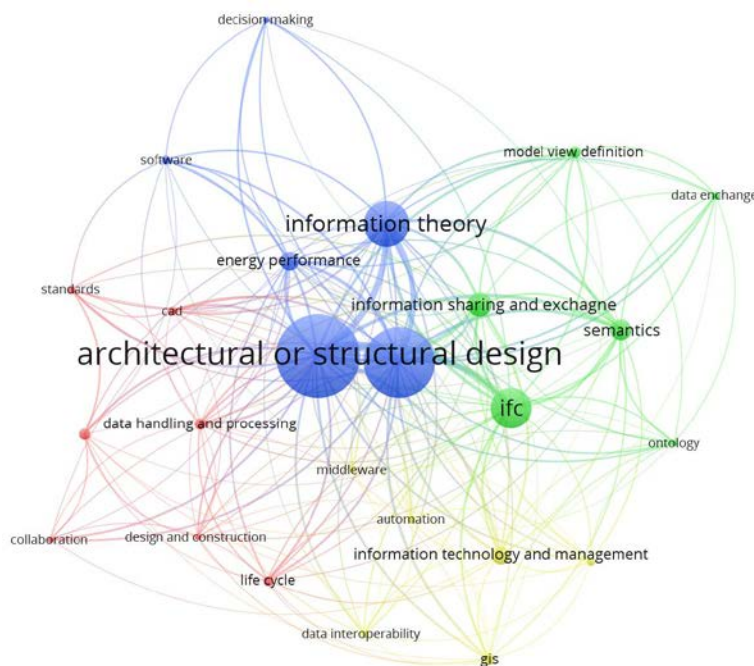
The research keywords in these 60 selected studies were divided into seven categories, namely project stages, BIM authoring tools, BPA tools adopted, input information in BIM, outputs in BPA, the data format, and key contributions & issues raised in the studies. Major findings are listed below:

- Interoperability[31,41,43,48,60,72] is one of the most frequently stressed issues in the integration of BIM and BPA. Multiple approaches have been proposed to address the interoperability issue, including algorithms [15,33,48], programming[9,25,55], and plug-ins [23,70,87]. Ontology and semantics[8,15,78]were addressed in some of these selected studies. These key terms, including framework [5,68,83], interface [58,69,77],prototype [13,18,40], and platform [21,27,46],have been frequently highlighted in these studies.
- Building energy performance is the most frequently studied BPA output, followed by carbon footprint, daylighting, thermal comfort, and indoor environmental quality.
- Various BIM authoring tools and BPA tools were adopted in these case studies. Compared to the BIM tools in which Autodesk Revit is the dominating software package, the use of BPA tools tended to vary widely.
- Most studies targeted at the building design stage, especially the early design stage as the phase where BIM can be coordinated with BPA. However, there has still been insufficient studies incorporating LoDs into the design stages. Gourlis and Kovacic [38] stressed the importance of incorporating LoDs in bridging BIM to building energy modelling (BEM) in order the reduce the uncertainties in integrated BIM and BEM, which are not solely an issue of software interoperability but also the redefinition of the design process.

The interoperability issue has been emphasised in the research of BIM integration to BPA. BPA for performance-based design is an area allowing the architects to create and explore different design alternatives [6]. There is a consensus on the need to achieve performance-based design via integrated use of BIM. Lack of integration and low levels of BIM use prevents applying BIM in the early design decisions to improve building energy performance. The issue of interoperability is widely present in many areas if collaboration and data exchange are needed [6]. An open data readable by any software package is considered vital to enhance the multi-party collaboration. Therefore, it is imperative to use an open standard that facilitates the collaborative work allowing any stakeholder to exchange data no matter what software where the data is created. The ISO-registered IFCdata standard can facilitate BIM interoperability by allowing information flow within the AEC industry [96]. IFC is a scheme widely accepted by the AEC industry to exchange BIM-based models [6]. It uses

334 four layers (i.e., resources, core, interoperability and domain) to describe the geometric  
 335 information, semantic information, and ontology in a BIM-based model. Besides IFC, gbXML  
 336 is another widely adopted scheme that facilitates the exchange of data between BIM and BPA  
 337 tools. Previous studies [90,95,98] summarized in Figure6 shared the similar methodology by  
 338 developing a framework, interface or platform with specific data schema (e.g., IFC or gbXML),  
 339 defining the scope of input information in BIM (e.g., geometric zones) and BPA output (e.g.,  
 340 energy performance), adopting a building case study for validation, and proposing  
 341 recommendation for further improvements. In the web service based framework linking BIM  
 342 to building energy simulation, Cheng and Das [20] highlighted code checking for automating  
 343 the building design evaluation process. Unfortunately, the full potential of BPA has not been  
 344 achieved due to lack of integration that prevents collaboration relationships throughout the  
 345 project life cycle. It could also be indicated from existing studies of linking BIM to BPA that  
 346 there is a further need of studying the interoperability between BIM and BPA tools when  
 347 building components are in a higher LoD or when the building is more complex.

348 The content analysis results showed two major research problems in BIM integration with  
 349 BPA: interoperability issues and BPA across the project life-cycle. To further address the  
 350 interoperability issues in BIM integration with BPA, a total of 129 journal articles from the  
 351 refined literature sample focusing on interoperability issues in BIM-enabled BPA were  
 352 reviewed. Figure 8 illustrates these keywords within of the 129 BIM-interoperability related  
 353 articles.



354  
 355 *Figure 8 Keywords within interoperability-related issues in BIM*

356 It can be found that the design stages, including architectural and structural of buildings,  
 357 are the keywords most frequently studied in the research. The connection lines convey the  
 358 information summarised and evaluated below:

- 359 • The interoperability issues encountered in BIM, highlighted in multiple studies  
 360 [4,71,83], have been more frequently studied in the area of energy performance

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361 compared to other areas such as life cycle or GIS (i.e., Geographic Information System).  
362 Currently, the interoperability in BIM is still low and limited to 3D coordination, and  
363 there have been limited standards guiding performance-based design in BIM [6]. An  
364 established standard to allow BIM in a multi-dimensional information transfer would be  
365 needed for enhanced multi-stakeholder information interaction. The information  
366 interaction should not be limited to design stages when utilizing BIM for BPA, but also  
367 construction stages and follow-up phases in the project life cycle. Currently the BPA in  
368 existing studies of BIM interoperability has been largely focusing on energy  
369 performance. It is expected that a comprehensive coverage of building sustainability be  
370 incorporated in an indicator system. This sustainability indicator system assisted by  
371 integrated BIM and BPA should not be limited to energy performance, thermal comfort,  
372 daylighting, but also resident health and wellbeing indoor;

- 373 • Data handling, storage, sharing, exchange in BIM interoperability is the key technical  
374 issue, with specific mainstream information flow formats, such as IFC. Interoperability,  
375 mainly related to IFC capacity to support information exchange among multiple BIM  
376 tools for different applications (e.g., energy simulation) is one of the main BIM-related  
377 research focuses according to Santos et al. [81]. Ugglá and Horemuz [89] tested the  
378 geographic capabilities of IFC and found that the open BIM standard IFC could be  
379 improved by adding a separate scale factor for the horizontal plane and support for  
380 object-specific map projections. Venugopal et al. [94] found the ambiguous nature of  
381 the current IFC definitions and suggested a semantically robust reform in order to  
382 extend IFC and to define subsets as model view definitions (MVD). Other work  
383 performed to improve the IFC schema can be found in various studies. For example, Sun  
384 et al. [29] applied a content-based compression algorithm to reduce the redundant  
385 information carried in the existing IFC files for information optimization. It could be  
386 envisaged that enhanced IFC scheme or other open data platform will be implemented in  
387 the future for seamless information flow in AEC projects;
- 388 • Non-graphic information defined by semantics and ontology is one of the researches  
389 focuses. The interoperability issue within BIM-BPA integration should include both  
390 graphics and semantic aspects. Semantic performance could enhance IFC  
391 interoperability to BPA [73] and improve the interoperability between BIM and its  
392 synergies [53]. Extending the BIM interoperability at the semantic level is important to  
393 link BIM with other geospatial data crossing construction project stages [54]. Karan and  
394 Irizarry [54] proposed a methodology to integrate BIM and GIS and applied the  
395 semantic web technology for construction site planning, and stated that future work was  
396 needed to develop an interoperable framework for linked data;
- 397 • Both technological aspects (e.g., data interoperability[47,78]) and managerial (e.g.,  
398 collaboration among project parties [49,50] and data management [31]) have been  
399 studied for the successful integration between BIM and BPA. The interface and  
400 BIM-based “green” building platform to enable the information sharing among AEC  
401 professionals, end-users and policymakers have been studied by El-Diraby et al. [27] to  
402 emphasise both technical and managerial aspects of BIM. Interoperability issues in BIM

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403 has not been the widely studied for AEC education and construction project  
404 management (e.g., interdisciplinary communication). More studies could be performed  
405 to verify how the improved interoperability would affect the AEC project performance,  
406 e.g., productivity, cost, and scheduling, etc. From the managerial perspective, case  
407 studies could be conducted to verify the effects of enhanced interoperability on project  
408 performance.

## 409 **6 Qualitative Discussion**

410 This paper finally discusses the integration of BIM and BPA to facilitate a more precise  
411 communication between architect/engineer and energy modeller/building performance analyst  
412 at different stages of a building project.

413 At the design stages, the BIM model is enriched continuously. Section 2 has illustrated the  
414 capabilities of BIM-enabled BPA with different model LoDs. The LoDs were defined (as  
415 shown in Figure 1, Figure 2, and Figure 3) based on the LoD matrix proposed by  
416 Abou-Ibrahim1 and Hamzeh[2]. Some research has taken into account the LoDs in  
417 BIM-enabled BPA[30].

418 BPA can be conducted across the project life cycle. As the project progresses, the  
419 building performance may not meet the original design requirement. As a result, building  
420 performance monitoring measures should be taken to identify the gap between the designed  
421 building performance and the actual performance, and potential causes of the gaps (e.g.,  
422 human behaviour related factors studied by Chen et al. [17], Li et al. [99], and Magalhães et  
423 al. [63]). The performance gap analysis strengthens the design review and knowledge base  
424 proposed in the BIM-ICKBMS framework by Ghaffarian et al. [35]. The comparison of  
425 building performance and design review form the loop in the framework, which enables the  
426 learning process in building design stages to address the gap between actual and designed  
427 building performance. The building performance simulation would then be updated adopting  
428 the developed deterministic or stochastic models by addressing the causes of performance  
429 gaps. One example of the prediction model for building performance is data mining approach  
430 studied by Singaravel et al.[84].

431 The proposed BIM-enabled BPA serve as the case by contributing to the knowledge base  
432 – a digital asset. The knowledge base would provide a collection of previous experience,  
433 history and operations for building components so that the building maintenance teams could  
434 adopt efficient implements in certain similar cases according to Motawa and Almarshad [66].  
435 As indicated by Singaravel et al. [84], deep-learning neural network approach could be one  
436 method to allow reliable prediction of BPA using the established cases from the knowledge  
437 base. The database could be further developed to apply Big Data for BPA by incorporating  
438 more input parameters, such as user profile and building sector, etc.

439 More future research directions can be proposed following the discussion of  
440 BIM-enabled BPA in the context of green buildings. For example, the performance analysis  
441 of green buildings adopting integrated photovoltaics in the research of Kuo et al. [61] can be  
442 extended by studying BIM-enabled BPA for buildings using renewable energy sources.  
443 BIM-enabled BPA for green buildings can also be extended from low energy-based design to

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444 other aspects of sustainability, such as low carbon, indoor comfort, and resource  
445 consumption.

## 446 **7 Conclusions**

447 This study adopted multiple research methods in identifying the major research topics in  
448 the area of BIM integration with BPA across the project life-cycle. A bibliometric review was  
449 conducted to identify most frequent keywords within BIM integration with BPA. Major  
450 categories within BPA (e.g., building energy performance) and corresponding influence  
451 factors (e.g., building envelope) were identified through literature review.

452 The raising issue of interoperability between BIM and BPA was highlighted as one of the  
453 main research areas. Through a further bibliometric analysis to narrow the scope of search  
454 focusing on interoperability within BIM, it was indicated that 1) most interoperability issues  
455 were related to application of BIM in building energy performance analysis; 2) both  
456 geographic and semantic information was involved in studying BIM interoperability issues; 3)  
457 both technical (e.g., data scheme) and managerial aspects should be considered critical in  
458 integrating BIM to BPA. The interoperability issue was further studied using content analysis to  
459 summarise 60 existing studies attempting linking BIM to BPA. Approaches to enhancing the  
460 interoperability issue between BIM and BPA could be found in these terminologies, including  
461 framework, interface, prototype, and platform, with critical methods proposed (e.g., algorithms,  
462 programming, and plug-ins). Ontology and semantics have become the research focuses. This  
463 research proposed the research directions to incorporate BIM to BPA crossing the building  
464 project delivery stages.

465 Both bibliometric analysis and content analysis also revealed the importance of integrating  
466 BIM and BPA in the project life-cycle. The LoDs at different project stages were highlighted  
467 which involve essential building information and building performance outcomes. The  
468 definition of LoDs enables information exchange and data sharing between BIM and BPA in  
469 different design stages. This paper proposed the research direction which allows a more precise  
470 communication between architect/engineer and energy modeller/building performance analyst  
471 at different stages of a building project. The performance gap analysis, development of  
472 knowledge base, and design review in the further discussion drive the ongoing learning process  
473 in transporting information in the building design model to the building performance model.  
474 Future case studies could be conducted to investigate the information exchange between BIM  
475 and BPA crossing different stages in the project life cycle. Future research can also extend the  
476 BIM-enabled BPA in a wider scope of green buildings by considering more sustainability  
477 measurements or scenarios, such as the adoption of renewable energy sources, indoor comfort,  
478 and resource consumptions, etc.

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