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A review and outlook for integrated BIM application in green building assessment

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Abstract

In the past decade, there has been a momentous increase in the utilization of Green building assessment schemes (GBAS). Also, the recognition of the useful of BIM for evaluating GBAS criteria has driven the need for research on the application of BIM for calculating and evaluating GBAS credits. Although many green BIM literature have been published in the past decade, there is a lack of studies which synthesize comprehensively the application of BIM for calculating and evaluating GBAS credits. The need to provide an in-depth review on the development of BIM tools for calculating and evaluating GBAS credits remains unaddressed. This study presents a thorough systematic review of literature to provide a comprehensive view on the breadth of evaluation matrixes covered by literature. In addition, the study also evaluated practical tools developed by software vendors for evaluation of GBAS criteria. The results of this study is a thorough review covering the entire scope of assessment achieved with BIM, generation and managing of database for 3D model, data exchange modules and criteria assessment modules. This paper present relevant guidelines and future directions for researchers and practitioners interested in the calculation and evaluation of green building assessment criteria from a BIM model.

Key words: GBAS; BIM; Integration; Data exchange; Assessment criteria

Nomenclatures

Abbreviations

GBA	Green Building Assessment
GBAS	Green Building Assessment Schemes
BIM	Building Information Modelling
AEC	Architecture, Engineering and Construction Industry
LEED	Leadership in Energy and Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
BEAM PLUS	Building Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment Efficiency

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COBie	Construction Operations Building Information Exchange
GBL-ASGB	Green Building Labelling-Assessment Standard for Green Building
IES-VE	Integrated Environmental Solutions, Virtual Environment
gbXML	Green Building XML schema
XML	Extensible markup language
IFC	Industry Foundation Classes
USGBC	United States Green Building Council
BCA	Building and Construction Authority
API	Application Programming Interface
HVAC	Heating, ventilation, and air conditioning
RFA	Revit family files
RVT	Revit files
GIS	Geographical information system
ODBC	Open Data Base Connectivity
FM	Facility management
Revit MEP	Revit Mechanical Engineering and Plumbing
CUI	Concrete user index
SA	Site Aspect
MA	Materials Aspects
EU	Energy Use
IEQ	Indoor Environment Quality
NRNC	Non-Residential New Construction
RNC	Residential New Construction
INC	Industrial New Construction
NREB	Non-Residential Existing Building
IEB	Industrial Existing Building
ID	Interior
T	Township
UI	User Interface

1. Introduction

In the last decades, interactions between increasing demands for buildings, higher quality of life and environmental sustainability has revolutionized the Architectural, Engineering and Construction (AEC) industry. In response these concerns, green buildings practices have been deployed globally. Other than building codes, an effective tool with a solid connection to green building practices is Green Building Assessment Schemes (GBAS). GBAS such as LEED, BREAM, BEAM Plus and CASBEE have come about as a comprehensive measure of the sustainability levels of a building which can be used from the inception of design to the commissioning of buildings. Thus, the benefits of GBAS extend beyond mere certification.

Criteria of GBAS can provide building practitioners with a dependable forecast of the sustainability levels of alternative designs [1]. However, the practitioners are faced with a major challenge utilizing these criteria especially at the design stages of buildings [2]. Conventional green building assessment are less accurate, inconsistent and resource demanding with regards to time and cost.

Building Information Modelling emerged as a technology and process which allows 3D modelling and information management through the life cycle of buildings [3]. It is well agreed that the outcome of this technological process is a data-rich, intelligent, object oriented and parametric model of a building [4]. Various categories of information can be inserted into a 3D model and managed to suit the needs of users. In the past years, innovative development of BIM has provided opportunities to support green building practices and has been classified as Green BIM. At the heart of many definitions of green BIM is "a model-based process of generating and managing coordinated and consistent building data that facilitate the accomplishment of established sustainability goals" [5]. By this definition, green BIM facilitates various performance analysis and evaluations such as operational energy use, water use, construction and demolition waste management, acoustic analysis, carbon emission and lighting analysis. These very sustainable analysis forms the core of GBAS. Since BIM can contain multidisciplinary data for various analysis, it implies sustainability metrics can be superimposed on a 3D model to support the evaluation of credits in line some GBAS [1]. Storing and managing GBAS rating data within BIM tools help to make useful design decisions with real project data at the early stages of the project.

Over the last two decades, a large amount of scholarly works on green BIM literature has been published. Many scholars have mapped the potential application of BIM for green buildings. Gao et al. [4] presented a review on BIM-based Building Energy Modelling (BEM) for the development of energy efficient building design. Pezeshki and Darabi [6] for instance, presented a valuable review on green BIM literature within the years of 2015 and 2018 with focus on the use of BIM database in BEM. Sanhudo et al. [7] presented a review on the technological capabilities of BIM for energy retrofitting. Kamel and Memari [8] reviewed the challenges and solutions to interoperability between BIM and BEM modelling process. Wong and Zhou also [5] presented a review on green BIM literature from the perspective of a building's life cycle. While these studies have made remarkable contribution to mapping green BIM literature, none of these studies addressed literature on the use BIM for evaluating GBAS criteria and credits. Lu et al. [3] present a comprehensive review of green BIM literature. The authors addressed the application of BIM through the life cycle of a project, various function of BIM for sustainable analysis but paid less attention to BIM for green building assessment (GBA). The authors did not address the breadth of criteria evaluation achieved with BIM. Furthermore, none of these studies considered commercial applications for the evaluation of GBAS criteria and credits. Other studies such as Akcay and Arditi [9] have addressed the application of BIM evaluating GBA criteria and addressed criteria such as public transportation access, rapidly renewable materials, and material reuse as not achievable with BIM. However, these criteria have been addressed with BIM in [10–12].

Clearly, there have been advances yet a lack of a systematic review on the application of BIM for evaluating GBA criteria. There are number of research question which remain unaddressed such as (1) the breadth of assessment criteria than can be achieved from the extensive use of BIM and (2) the developments of practical BIM tools by software vendors for the evaluating GBAS criteria in BIM. This study therefore reviews BIM and GBAS literature in order to address the research questions identified. The present study provides a synthesis on application BIM for calculating GBAS credit from the perspective of research literature and commercial BIM tool. The following sections are organized in the following manner. Section 2 presents the research methodology. Section 3 addresses the breadth of assessment achieved with different green building assessment schemes. Section 4 address the application of tools to calculate credits. Section 6 address the data exchange modules. Section 7 addresses the criteria assessment modules. Section 8 present identified research gaps and recommendation. Finally, section 9 concludes the study. Figure 1 summarizes the entire scope of the review.

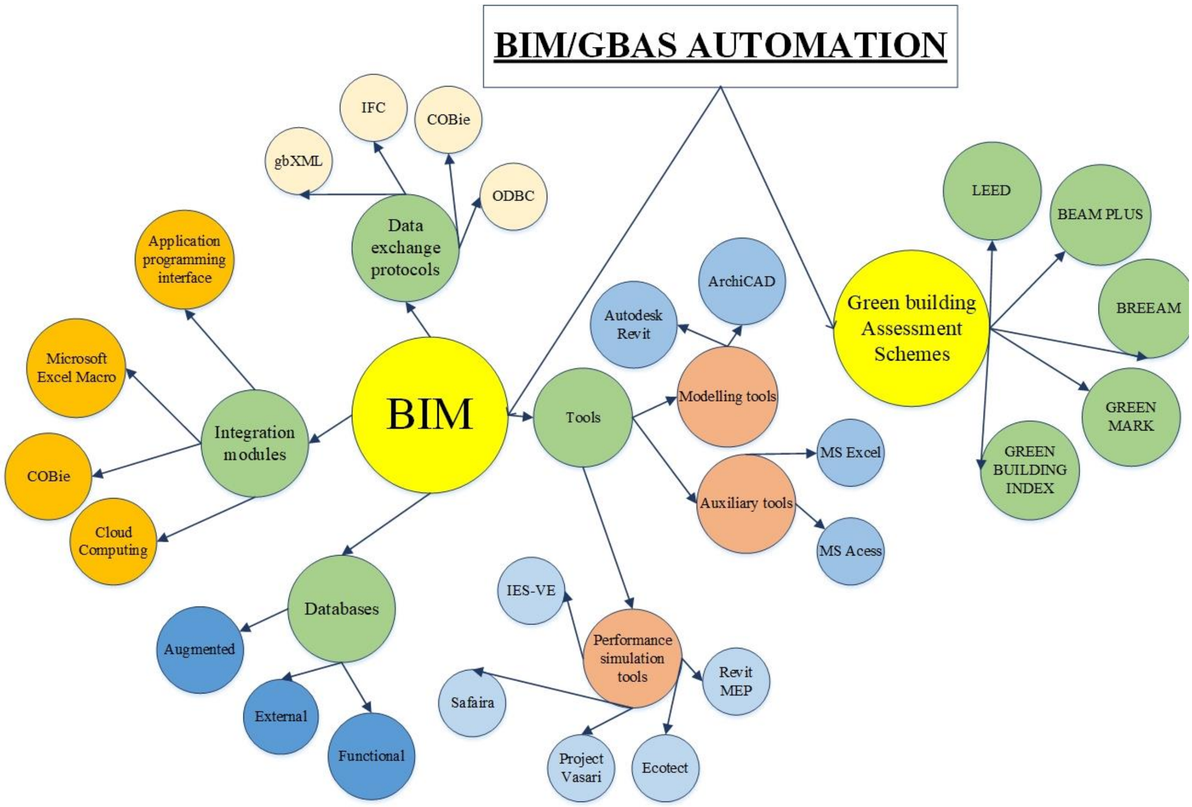


Figure 1 Scope of review for BIM/GBAS automation

2. Methodology

The concept of green BIM has been previously mapped by other studies such as [3,5,13]. These are valuable inputs to understanding the whole concept of BIM and green buildings and therefore provide a good foundation to further green BIM research. The present study is therefore not a repetition of already extant literature but rather an addition to further delineate the point of convergence of BIM and automated evaluation of GBAS criteria. This study does not address managerial issues associated with questionnaires and interviews nor sustainable assessment such as energy performance analysis, water usage, solar radiation and lighting analysis, acoustic performance and thermal comfort analysis. Such issues are well delineated in similar review such as [4,6,8,13,14]. Rather, the presented study defines its scope within technological and system extensions employed to facilitate automated evaluation of green building assessment criteria within BIM environment. Therefore, the breadth and depth of incorporating assessment rubrics into BIM model and supportive technical advances are of interest to the present study. In other to provide a comprehensive review, the review has two components, research publications and BIM software. The following subsection describes the research methods in detail.

2.1 Selection of academic journals

To identify and examine extensive output within the scope established, the methods used by [3,14] were adapted for this study. The adopted literature review methods in these studies include a preliminary literature search with different databases, a filtration process and a content analysis. Thus, a three-stage process selection of academic journals, selection of relevant publications and systematic content analysis.

Stage One: Relevant Paper search

The initial search for literature was conducted using Scopus, a power search engine. The rationale behind selecting Scopus was that Scopus covers an extensive range academic publication [15,16]. Also unlike Web of Science, Google Scholar and ProQuest, Scopus has higher accuracy and a faster indexing process and therefore most likely to archive recent publications [17]. In addition, Scopus has been widely used in similar review such as [5,18]. A desktop search was conducted using Scopus to identify relevant literature on the point of convergence between BIM and green building assessment. Thus, a comprehensive search was done under the title/abstract/keyword field of Scopus with keywords of "Building information modelling" or "Building information modeling" or "building information model" or "virtual design and construction" or "as-built model", which are limited by any of the following terminologies: "LEED", "Leadership in Energy and Environmental Design", "BEAM Plus", "Building Environmental Assessment Method", "BREAM", "Building Research Establishment Environmental Assessment Method", "CASBEE", "Comprehensive Assessment System for Built Environment Efficiency", "Green Star", "Green Mark", "Green Building Index", "GBI", "Green globes", "SBtool", "Green Building Labelling-Assessment Standard for Green Building", "GBL_ASGB", "HK BEAM", "HK-BEAM". To avoid the omission of any relevant paper, the date range was set to "all years till present". Also, the query was not limited to specific journals as this may limit the number of identified publications. The document type was also set to article or review as they represent the most certified, reputable and influential source of knowledge [19,20].

A total of 85 publications were retrieved from this search query. Given the limited number of publications retrieved from Scopus, Web of Science, ScienceDirect, ProQuest and Google Scholar were selected for a further search. This was to ensure that adequate amount of research outputs on BIM for evaluating GBAS credits were retrieved for the review. After removing duplicates, a total of 92 publications including journal and conference articles were retrieved. A preliminary screening was conducted to remove publications that covered subjects not related to construction or just happened to contain some of the search keywords within their title/abstract/keywords section. The results of this exercise revealed that Automation in Construction, Sustainable Cities and Society, Building and Environment, Building Simulation, Engineering Construction and Architectural Management, Journal of Civil Engineering and Management, Journal of Cleaner Production and Journal of Management in Engineering had at least three papers. These eight journals are included in the Science Citation Index Expanded database. The total number of publications after this stage was 43 from 23 journals and conference proceedings.

Stage Two: Targeted Paper Search

After completing stage one, a more critical and comprehensive examination of the 43 publications was carried out to identify those papers that are highly relevant to solve the identified research gap. Given the existence of green BIM reviews, a delamination of research boundaries was critical in other to address the research gap identified. As such, the criteria for selection was based on its research objectives, methods and the major findings. The main criteria for the selection process was technical development of BIM to support, contain and process various criteria of green building assessments. In this regard, the study is inclined towards issues such as storing, recognising, capturing, processing data related to the evaluation of GBAS criteria within the BIM environment. Therefore, other issues related to managerial issues, such as adoption and implementation in addressed in [14] are not the focus of this paper. Also building energy modelling and green BIM related to functions such as Energy performance analyses, Carbon emissions analyses and evaluations and Carbon emissions analyses and evaluations in [3,4,6,8] were not the focus of the present study. However rather than excluding such papers, the present study referred to them when necessary. The number of selected publications and relevant papers are shown in Table 1.

Table 1 Overview of selected publication and publications relevant to the study

Journal	**No. of selected publications**	**No. of relevant papers for the study**
Automation in Construction	6	5
Sustainable Cities and Society	4	1
Building and Environment	3	0
Building Simulation	3	1
Engineering Construction and Architectural Management	3	0
Journal of Civil Engineering and Management	3	0

Journal of Cleaner Production	3	0
Journal of Management in Engineering	3	0
Journal of Construction Engineering	1	1
Journal of Architectural Engineering	1	1
Arpn Journal of Engineering and Applied Sciences	1	1
International Journal of Architectural Computing	1	0
International Journal of Architectural Computing	1	1
Electronic Journal of Information Technology in Construction	1	1
Open Construction and Building Technology Journal	1	1
Congress on Computing in Civil Engineering Proceedings	1	1
Proceedings of The AEI Conference 2015	1	1
Built Environment Project and Asset Management	1	0
Construction Innovation	1	1
Energy Procedia	1	0
Ework And Ebusiness In Architecture Engineering And Construction Proceedings Of The 11th European Conference On Product And Process Modelling ECPPM 2016	1	1
Proceedings of The 2009 ASCE International Workshop On Computing In Civil Engineering	1	1
Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia	1	1
	43	19

2.2 Review method of Selected Publications

It is important to iterate the present study builds upon previous contributions in green BIM. This study therefore furthers "BIM supported analysis and assessment of green projects" scope of Green BIM Triangle taxonomy [3]. Consequently, the present study adapted the methodology used by [3] in other to review the relevant papers identified.

Step one: The first step was to specify the domain of objects to be classified. The main goal of this stage was to classify the outputs of the relevant publications in other to allow examination of items in a context. The domain of objects for this present study are the relevant literature identified.

Step two: The second was to define and measure essential properties. The selection of essential properties for this study was based on the keywords, themes and major components of the frameworks underlying the relevant studies. For the themes and framework, four essential properties identified included integration modules, data exchange protocol, BIM tools and databases. The major properties that evolved from the keywords was the green building assessment schemes and the various criteria addressed.

Step three: The main task for this stage was to evaluate the differences and similarities for the relevant papers in other to permit classification and assignment of their output to a scope of essential properties. For instance, the various databases or integration and assessment modules identified.

Step four: The final step was to assess the point of convergence and divergence in the reviewed papers. Thus, after identifying the essential groups, the present paper critically reviews the output of the papers other to synthesize relevant contributions to the current body of knowledge. Also, to identify research gaps in line with automated evaluation of GBAS from BIM environment. As indicated, the present study synthesizes the output of relevant studies based on the essential properties identified within the papers. It may happen that not all papers contain the essential properties identified. Tables 3 and 4 provides a summary of essential properties extracted from the relevant publications.

2.3 Selection of BIM tools

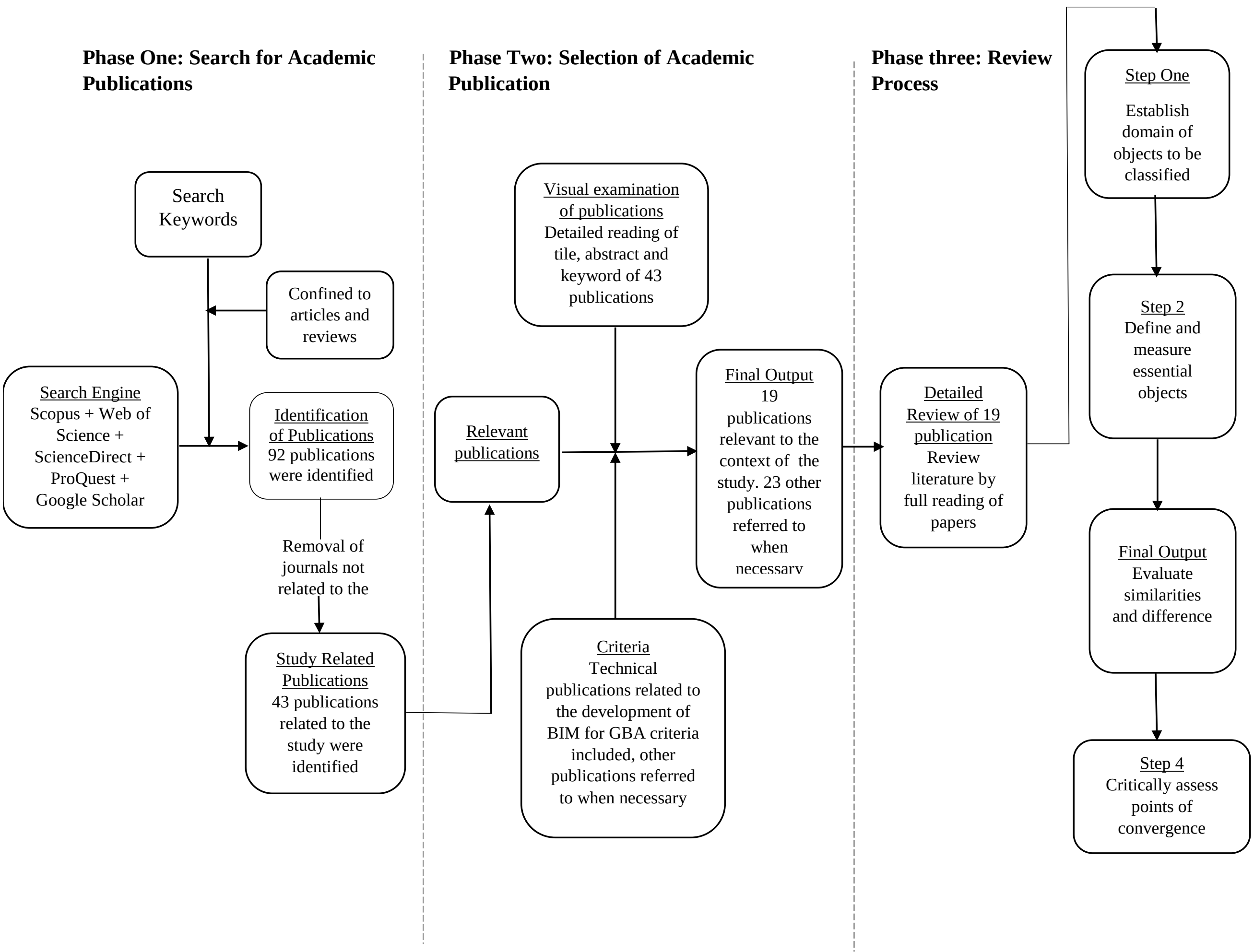
Besides the relevant literature identified, it was necessary to identify the development by software vendors in other to grasp the evaluation of GBAS criteria from BIM in its entirety. The selection BIM software was done based on twelve popular BIM software identified by [3] for use in green BIM issues. Besides these tool, others relevant tools identified from a search on evaluating GBAS criteria were included. Table 2 presents a summary of the tools selected. In the following sections, the details of development of BIM for green building assessments are presented in line with the essential properties identified in Table 3 and 4.

Table 2 Selected BIM tools and functions for evaluating GBAS criteria

Software Tool	Criteria	Not applicable
Autodesk Revit Light Analysis Revit	LEED (IEQc8.1 2009) and LEED v4 (EQc7 opt2)	
Autodesk Green Building Studio		x

Integrated Environmental Solutions® Virtual Environment Navigator	LEED (Thermal comfort, daylight and quality views of indoor environment quality), BREEAM (management, health and wellbeing and energy credits)	
Bentley Hevacomp		x
AECOsim		x
EnergyPlus		x
HEED		x
DesignBuilder Simulation		x
eQUEST		x
DOE2		x
FloVENT		x
ODEON Room Acoustics Software		x
TRNSYS		x
Navisworks		x
ArchiCAD		x
One Click LCA	LEED V4 (Building Life Cycle Impact Reduction of (MRc1)) and BREEAM (Life Cycle Impact of (Mat 1))	

Figure 2 Research Methodology


Phase One: Search for Academic Publications
Phase Two: Selection of Academic Publication
Phase three: Review Process
Search Keywords
Confined to articles and reviews
Search Engine
Scopus + Web of Science + ScienceDirect + ProQuest + Google Scholar
Identification of Publications
92 publications were identified
Removal of journals not related to the
Study Related Publications
43 publications related to the study were identified
Visual examination of publications
Detailed reading of tile, abstract and keyword of 43 publications
Relevant publications
Criteria
Technical publications related to the development of BIM for GBA criteria included, other publications referred to when necessary
Final Output
19 publications relevant to the context of the study. 23 other publications referred to when necessary
Detailed Review of 19 publication
Review literature by full reading of papers
Step One
Establish domain of objects to be classified
Step 2
Define and measure essential objects
Final Output
Evaluate similarities and difference
Step 4
Critically assess points of convergence

sTable 3 Summary of established BIM frameworks

Authors	BIM Tools	BIM-Based performance analysis and Auxiliary tools	Database	Integration and data exchange model	Output
Akcay and Arditi, 2017 [9]	Autodesk Revit Architecture	Safaira/Excel	External (RSMeans Database)	Microsoft Excel Macro	Excel
Alwan et al., 2015 [21]	Autodesk Revit Architecture	Integrated Environmental Solutions-Virtual Environment (IES-VE), Project Vasari	NR	gbXML	NR
Azhar et al., 2011 [22]	Autodesk Revit Architecture	Integrated Environmental Solutions-Virtual Environment (IES-VE)	NR	gbXML	Integrated Environmental Solutions (IES)
Barnes and Castro-Lacouture, 2009 [23]	Autodesk Revit Architecture	NR	Augmented database	NR	NR
Bergonzoni et al., 2016 [24]	Autodesk Revit Architecture	Excel	NR	Dynamo visual scripting tool	Excel
Biswas and Krishnamurti, 2012 [25]	Autodesk Revit Architecture	NR	Augmented database (Evaluation rules)	COBie/IFC model	LEED submittals in XML format
Chandra and Zhou, 2014 [11]	Autodesk Revit Architecture	NR	NR	Revit Application Programming Interface (API).	XML format Report
Chen and Nguyen, 2017 [10]	Autodesk Revit Architecture	Google Maps Web Map Service	External (Web Map Service)	Revit Application Programming Interface (API).	Excel Sheets and Map Images
Ilhan and Yaman, 2016 [12]	ArchiCAD	Green building rating tool	External database (Green materials library)	IFC to green building rating tool	Spreadsheets

Authors	BIM Tools	BIM-Based performance analysis and Auxiliary tools	Database	Integration and data exchange model	Output
Jalaei and Jrade, 2014 [26]	Autodesk Revit Architecture	Autodesk Ecotect Analysis/ Integrated Environmental Solutions (IESVE), Microsoft Excel	Green families stored in external database	Eco scorecard plugin	Ecoscorecard plugin interface
Jalaei and Jrade, 2015 [27]	Autodesk Revit Architecture	Microsoft Access	External database	Revit Application Programming Interface (API).	Microsoft Access
Jrade and Jalaei, 2013 [28]	Autodesk Revit Architecture	Microsoft Excel	External sustainable database	Open Database Connectivity (ODBC)	NR
Nguyen et al., 2010 [29]	Autodesk Revit Architecture	Microsoft Access	Augmented database (Sustainability indicators)	Revit Application Programming Interface (API).	API interface
Nguyen et al., 2016 [30]	Autodesk Revit Architecture	LEED EVALUATOR	Augmented database (Shared parameters in BIM model)	Revit Application Programming Interface (API).	LEED EVALUATOR
Raffee et al., 2016 [31]	Autodesk Revit Architecture	Sustainable Assessment Building Information Green Building Index (SABIG)	Augmented and External databases	IFC	Sustainable Assessment Building Information Green Building Index (SABIG)
Wong and Kuan, 2014 [32]	Autodesk Revit Architecture	NR	Augmented database	NR	Schedules
Wu and Issa, 2011 [33]	Autodesk Revit Architecture	Integrated Environmental Solutions (IES)	NR	Revit Application Programming Interface (API)/Open Database Connectivity (ODBC) and IFC	NR

Authors	BIM Tools	BIM-Based performance analysis and Auxiliary tools	Database	Integration and data exchange model	Output
Wu and Issa, 2012 [34]	Autodesk Revit Architecture	Leed authoring server, LEED analysis server, Field cloud, LEED automation cloud	Augmented and Functional databases	Cloud-based approach	Leed automation cloud; PDF
Zhang and Chen, 2015 [35]	Autodesk Revit Architecture	Revit API interface	Augmented database	Revit Application Programming Interface (API).	API Interface developed with sub-interfaces
Note: NR - Not Reported					

Table 4 Investigated green building assessment schemes and categories

Authors	GBAS	Category	Validation
Akcay and Arditi, 2017 [9]	LEED	Energy and Atmosphere	Case study on Office building, Chicago Midway, Illinois
Alwan et al., 2015 [21]	LEED	Sustainable sites, Water efficiency, Energy & atmosphere and Indoor environment quality	Sample Revit model of Museum of Architecture, Doha.
Azhar et al., 2011 [22]	LEED	Energy and Atmosphere, Water Efficiency, and Indoor Environmental Quality	Case study on Perdue School of Business, Salisbury University
Barnes and Castro-Lacouture, 2009 [23]	LEED	Sustainable sites and Materials & Resource	Sample Revit project
Bergonzoni et al., 2016 [24]	LEED, Italy	Indoor Environment Quality	Sample case sstudy; Jewellery Manufacturing Plant
Biswas and Krishnamurti, 2012 [25]	LEED	NR	Case study on LEED NC 2.1 silver-certified building
Chandra and Zhou, 2014 [11]	Green Mark	Materials category	Sample BIM Project
Chen and Nguyen, 2017 [10]	LEED	Location and Transportation	LEED Gold certified wafer factory project (based on LEED v3)
Ilhan and Yaman, 2016 [12]	BREEAM	Materials category	Sample Project

Authors	GBAS	Category	Validation
Jalaei and Jrade, 2014 [26]	LEED Canada	Energy and Atmosphere, Materials, Resources, Indoor Environment Quality	Sample Project
Jalaei and Jrade, 2015 [27]	LEED Canada	Energy and Atmosphere, Material and Resources	Sample residential building
Jrade and Jalaei, 2013 [28]	LEED Canada	Sustainable site, Energy and atmosphere, Indoor environment quality, Materials and Resources, Innovation in Design, Regional Priority	Six floor apartment building at the design stage in the city of Ottawa.
Nguyen et al., 2010 [29]	LEED	Energy and Atmosphere	Sample Revit project
Nguyen et al., 2016 [30]	LEED	Sustainable Site	Sample 4 storey project
Raffee et al., 2016 [31]	GBI	NR	NR
Wong and Kuan, 2014 [32]	BEAM PLUS;	Materials and Resources	Sample BIM Project
Wu and Issa, 2011 [33]	LEED	NR	NR
Wu and Issa, 2012 [34]	LEED	NR	NR
Zhang and Chen, 2015 [35]	LEED	Materials and Resources	NR

3. Breadth of Assessment Achieved with Green s

In this section, five GBAS are presented. LEED and BREEAM were selected as these two GBAS are commonly used and appeared in the literature for BIM-GBAS. Moreover, most other GBAS were developed based on LEED or BREEAM and therefore share similar criteria. BEAM plus, Green Mark and Green Building Index are also presented because they appeared in relevant literature. The focus of this section is to delineate the breadth of assessment accomplished in literature. The following subsections provide details on the criteria of GBAS that has been addressed and opportunities for further studies.

3.1 Leadership in Energy and Environmental Design (LEED)

Over 70% of the relevant publications demonstrate various evaluation procedures for LEED criteria. [9,10,21–26,28,33,35]. The high occurrence of LEED may be associated with its global adoption. LEED has the widest geographical coverage with applications in over 165 territories around the world [36]. Since its establishment by the United States Green Building

Council (USGBC) in 1998, LEED has been improved to evaluate a wide range of building typologies. Currently, over 2.4 million square feet of buildings and 94,000 projects are LEED certified. Many countries have adopted and modified LEED US to suit their local conditions, for instance LEED Canada and LEED Italy [24,26–28]. The current version of LEED was launched in 2014. In this version there are nine categories of criteria which include Integrative Process, Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Material and Resources, Indoor Environmental Quality, Innovation and Regional Priority. Each of these categories are made up of different assessment criteria. For LEED version 4, there are four levels of certification namely; Certified (40-49 points), Silver (50-59 points), Gold (60-79 points) and Platinum (≥80 points). The level of certification achieved is determined by the sum of credits gained within the nine categories and the satisfied minimum program requirements and prerequisites [37]. Recently, LEED v4 beta for existing buildings has been launched as grounds for LEED v4.1 [36]. Version 4.1 is not a full version change but rather an improvement to assess the environmental and social impact of buildings.

LEED provides two platforms: LEED online and LEED automation. These two can streamline and expedite LEED assessments with robust services like manufacturer-certified component databases, modelling and documentation processes from USGBC's partners. A survey of the official webpage of USGBC council did not indicate any direct association of LEED assessment with BIM. However, a few records of BIM to satisfy "innovation" criteria were identified. These included BIM as a useful tool for meeting detailed framing documents, waste reduction, accurate quantity take-off and integrated project management.

However, LEED assessment criteria have been widely addressed in literature. The extent to which LEED criteria can be evaluated within a BIM environment is subject to the quantitative or qualitative nature of the criterion. In [25], quantitative criteria refer to those with numeric values such as annual energy and water consumption while qualitative criteria refer to those requiring subjective judgement such as commissioning of building systems. Azhar et al. [22] discovered that 17 credits and 2 prerequisites forming a total of 38 points can be achieved and documented within a BIM environment. Assessment criteria in public transportation access, development density, community connectivity and indoor air quality performance criteria have been demonstrated recently in [10,24]. It has also been extensively demonstrated that the following criteria can be evaluated with BIM: Optimise energy performance, Site Selection, Light Pollution Reduction, Minimum Energy Performance, On-Site Renewable Energy, Thermal Comfort (design, verification), Daylight and Views, Materials and Resources, Innovative Wastewater Technologies, Water Use Reduction, Heat

Island Effect, Storage and Collection of Recyclables, Materials Reuse, Recycled Content, Regional Materials, Rapidly Renewable Materials, Minimum Indoor Environment Performance and Increased Ventilation and Low-emitting materials [9,10,21–24,26–29].

At the current levels of development of BIM software and databases, it is easier to incorporate and manage data relevant to evaluate of quantitative credits. This is evident from a visual inspection of criteria addressed in the relevant literature. An typical example is renewable energy. Currently BIM software such as Autodesk Revit and Virtual Environment can model renewable energy systems such as photovoltaic. These two also have Application Programming Interfaces (API) with which data and computations can be manipulates to evaluate “renewable energy” criteria in the BIM software. A previous report by [22] indicates enhanced commissioning of LEED cannot be earned using BIM. Such criteria indeed require a review of building operations several months after substantial completion or verification after seasonal testing. Therefore, the level of development of BIM at the time of the study may have permitted such a conclusion. However, recent development of BIM tools can accommodate operational data in a BIM software. ERGON module of Integrated Environment Solutions Virtual Environment (IESVE) can model real operational data. Such data driven modelling can further evaluations of BREEAM “Energy Prediction and Verification” and LEED monitoring-based building commissioning. These are valuable opportunities to explore new dimensions of BIM-based GBAS. Unlike quantitative criteria, qualitative criteria such as “innovation” may require the subjective judgement of an assessor. Accordingly, they are more complex to incorporate within the BIM environment. Nevertheless, external applications which form a part of multi-faceted cloud BIM can be explored to incorporate, handle, process and deliver qualitative data requirements. Incorporating such information in BIM environment may be contributing to justifying “innovation” criteria introduced in the building.

3.2 Building Research Establishment Environmental Assessment Method (BREEAM)

Building Research Establishment Environmental Assessment Method, BREEAM, is the earliest established green building assessment scheme launched in 1993, United Kingdom. Currently the Building Research Establishment BRE has recorded 565,900 and 2,275,290 certified and registered buildings across 79 countries. BREEAM offers five standards for Community (Master Planning), Infrastructure (Civil Engineering and Public Realm), New Construction (Homes and Commercial Buildings), In-Use (Commercial buildings), Refurbishment and Fit-out (Home and Commercial buildings) [38].

BREEAM has ten main categories of assessment criteria with unique goals and benchmarks. The ten main categories are Energy, Health and Wellbeing, Innovation, Land use, Materials, Management, Pollution, Transportation, Waste and Water. Based on the improved performance of a design relative to a benchmark, credits are awarded and summed to a total score, which is then labelled as Pass (≥30), Good (≥45), Very Good (≥55), Excellent (≥70) and Outstanding (≥85). Like LEED, BREEAM requires satisfaction of minimum performance standards in 6 out of the ten categories [37]. Regarding BIM-based assessments, only one study is conducted by Ilhan and Yaman [12], which proposed and validated a novel framework for the material category of BREEAM. Although BREEAM shares similar assessment criteria with other GBAS such as LEED, the requirements to attain credits for these criteria may vary. In additions, there are a limited number of studies which demonstrate criteria evaluation for these GBAS. This present an opportunity to explore how BREEAM credits can be evaluated within a BIM environment.

3.3 Building Environmental Assessment Method (BEAM PLUS)

Building Environmental Assessment Method (BEAM PLUS), formerly known as HK-BEAM, was launched in 1996 as a joint effort between Hong Kong Green Building Council and the BEAM society. BEAM Plus provides four folds of assessments which are New Buildings, Existing Buildings, Building Interiors and Neighbourhoods. Also, BEAM Plus has six main categories namely "Site Aspect, Materials Aspects, Energy Use, Water Use, Indoor Environment Quality and Innovation and Auditions". Unlike BREEAM and LEED, the final grade is determined by the percentage of credits acquired in four key categories, satisfied minimum prerequisites and the weighted sum of acquired percentage in all categories. The four key categories are Site Aspect, Energy Use, Indoor Environment Quality and Innovation and Audition. The final grades are classified as Platinum (Overall ≥ 75%, SA & EU & IEQ ≥ 70%, IA ≥ 3%), Gold (Overall ≥ 65%, SA & EU & IEQ ≥ 60, IA ≥ 2%), Silver (Overall ≥ 55%, SA & EU & IEQ ≥ 50, IA ≥ 1%), and Bronze (Overall ≥ 40%, SA & EU & IEQ ≥ 40) [37,39].

Like BREEAM, only one study was found which evaluated BEAM Plus criteria in a BIM software [32]. The study reported that twenty-six criteria of BEAM Plus can be attained through documentations produced by BIM. Out of these, fifteen can be attained through scheduling with the BIM software, while the eleven others require simulations with a BIM-based performance assessment tool. The fifteen criteria attainable through scheduling included Minimum Landscape Area/Landscaping and Planters, Microclimate Around Building, Waste Recycle Facilities, Building Reuse, Modular and Standardised Design, Predication, Rapidly Renewable Materials, Rapidly Renewable Materials, Rapidly Renewable Materials, Regionally Manufactured Materials, Minimum Water Saving Performance/Annual Water Use/Effluent Discharge to Foul Sewers and Embodied Energy Building in Structural Elements.

Unfortunately, criteria evaluated so has been limited to the case study present as part of the work. The study predominantly focused on evaluating "Materials Aspects" of BEAM Plus. There is therefore the need to explore new methodologies to evaluate unaddressed criteria.

3.4 Green Building Index (GBI)

Green Building Index (GBI) is Malaysia's industrially recognised green rating tool to promote sustainable buildings. GBI has different folds of assessments for seven building and neighbourhood developments. They are Non-Residential New Construction (NRNC), Residential New Construction (RNC), Industrial New Construction (INC), Non-Residential Existing Building (NREB), Industrial Existing Building (IEB), Interior (ID) and Township (T) [40]. The most updated versions of GBI for buildings have 6 main categories as Energy and Efficiency, Indoor Environment Quality, Sustainable Site Planning and Management, Materials and Resources, Water Efficiency and Innovation, each of which has unique criteria to be satisfied. By October 2018, GBI recorded 854 registered projects with 463 certified, amounting to 217,545,835 square foot Gross Floor Area. NRNC, RNC, INC, NREB, IEB, ID and T accounted for 51%, 40%, 2%, 3%, 1%, 1% and 2% of the projects respectively [41]. For GBI, a certified building is rated as Platinum (86-100 points), Gold (76-85 points), Silver (66-75 points) or Certified (50-65 points) [42]. A study proposed a model BIM-based method to evaluate GBI criteria [31]. However, the model failed to provide a replicable approach to assessments, because of the lack of focus on specific criteria and practical demonstration.

3.5 Green Mark

Building and Construction Authority (BCA) of Singapore launched the Green Mark Scheme as a step to create an environmentally friendly built environment. BCA provides twenty-four unique Green Mark Schemes addressing different building typologies [40]. The latest version of Green Mark for residential and non-residential buildings has been restructured into 5 categories as Smart and Healthy Buildings, Climatic Responsive Buildings, Building Energy Performance, Advanced Green Efforts and Resources Stewardship. The total number of sustainable criteria within each category varies with each scheme, but the maximum achievable points for all schemes is 140. All building typologies are rated Platinum (≥70), Gold Plus (≥60) or Gold (≥50). Recently Liu et al. [43] explored the potential of applying BIM technology to aid the certification process of Green Mark for Non-Residential buildings. The authors indicated that 31 Green Mark assessment criteria could be attained through a combined input of the BIM software (Revit) and other BIM-based performance analysis software. This study did not make any contribution to practical demonstration of BIM-based evaluation.

In general, many of the identified studies has been limited to LEED. While it may be possible to evaluate many criteria in a BIM software, many of the methods used focus on individual projects and fail to produce a replicable approach. Furthermore, the comprehensiveness of these evaluations remains questionable as many details on incorporating assessment criteria within BIM tools are not reported. Furthermore, some studies indicate the potential for evaluating criteria from a BIM model without substantial practical demonstration. With regards to criteria which were previously reported as not achievable, recent improvement to BIM applications shows that opportunities exist to address criterion such as building commissioning, parking capacity, materials reuse and waste management. There is therefore the need to research improvement to methods of evaluation and secondly evaluate unaddressed criteria.

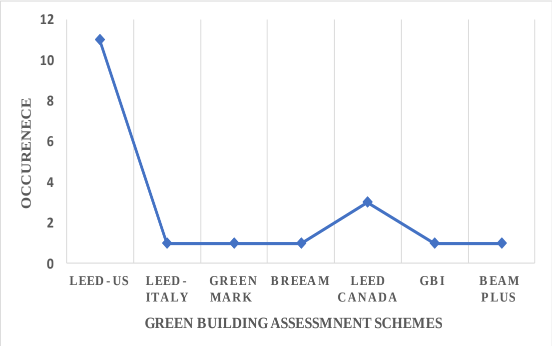


Figure 3 Green building assessment tools identified

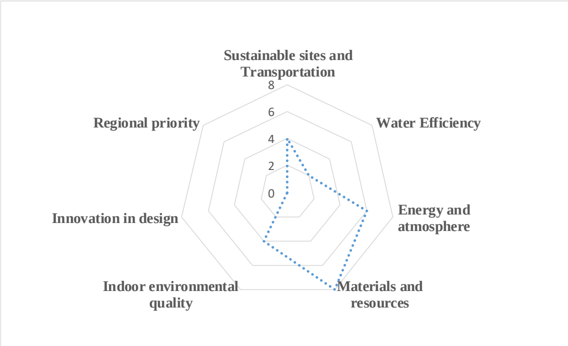


Figure 4 Assessment criteria addressed

4. Application of Software tools in Evaluating Assessment Criteria

Several tools were identified to evaluate different criteria with a BIM model. For the present study, they are categorized as BIM modelling tools, BIM-based performance assessment tools and auxiliary tools. The focus of this section is to provide an up to date synthesis on the capacities of the tools to support GBAS criteria evaluation. First, the application of these software in the relevant literature is present followed by the practical developments by software vendors to evaluate different criteria of GBAS.

Autodesk Revit Architecture and ArchiCAD were the two main authoring tools identified for this study. Autodesk Revit Architecture is built on a parametric modelling technology which allows users to create designs from a combination of graphical and non-graphical data [29]. Like Revit, ArchiCAD combines the power of the parametric design with profile editing to create a 3D model from intelligent building elements. 3D BIM models can be developed based on real construction elements such as walls, columns, beams, floors and windows. Once the 3D model is built, users can automatically generate views like plans, sections and elevations linked to the model so that any change in one view will be simultaneously propagated to other corresponding views. Revit and ArchiCAD were used for either modelling or scheduling in the reviewed literature. Typically, schedules are extracted directly from models (for materials and resource category) or exported to the performance analysis software (for categories such as energy and atmosphere). Irrespective of these tasks, designing the BIM model is primary and was mostly conducted with Revit [9,21,26,30,32] except for [12] in which ArchiCAD was used. Although, both tools have their API, ArchiCAD's API has not been explored in any of the reviewed literature.

The second group of software (BIM-based performance tools) includes IESVE, Sefaira, Ecotect analysis, Project Vasari. These tools have been associated with simulation-based quantitative criteria such as building energy use, water use or indoor environment quality [9,21,26]. To evaluate these criteria, the BIM model must be imported into these software tools either manually or through automated queries. An appropriate data exchange platform is therefore required to reduce data losses as per discussions in Section 6. IESVE was identified as the most commonly used tool for simulation. IESVE has different modules. They include Solar Shading, Heating Ventilation and Air Conditioning (HVAC) System Sizing and Optimization and Renewable Energy Design and Optimization. Although most of its functions centre on performance assessment, it can accomplish model authoring as well. In [21], IES-VE was incorporated in a framework for design performance assessments such as the lighting scheme. Azhar et al. [22] also exported a Revit BIM model into IES-VE to carry out sustainability analyses on the energy and atmosphere, water efficiency and indoor environment quality category of LEED. Wu and Issa's [33] framework captured IES-VE as the BIM-based sustainability analysis tool.

Other tools such as Microsoft Office and Access were also identified for the purpose of data generation, manipulation, storage and presentation of assessment results [9,24,27–29]. Web Map Service was used to generate map data for transportation and location criteria [26]. Ilman and Yaman [12] proposed a software, green building assessment tool (GBAT), for criteria in the material category of BREEAM. With a BIM model from ArchiCAD for input, GBAT can assess, calculate and document credits gained for criteria within the material category of BREEAM for any given project.

Aside the literature reviewed, a survey was conducted to evaluate the technical developments by selected BIM software vendors to support the evaluation of GBAS criteria.

The results of the survey IES, One Click LCA and Revit had developed tools for evaluating and generating submittals for some LEED and BREEAM.

VE-Navigator is a module developed by IES for automated assessment of certain credit of LEED version 4. From a BIM model, this tool can evaluate, and award credits related to thermal comfort, daylight and quality views of indoor environment quality. Also, the tool can address four credits and prerequisites of energy and atmosphere. Some credits under location and transportation such as green vehicles and reduced parking footprint are supported as well. Finally, credits such as rainwater management and heat island reduction. This tool provides the platform to input, manage and produce results fitted for use with LEED templates. Besides, this tool is fully compatible with IES Tap For LEED. IES Tap for LEED is a cloud-based project management tool which allows direction submission of evidence uploads to LEED online. Besides LEED, IES provides analysis capability to for some management, health and wellbeing and energy credits of BREEAM.

Autodesk Revit developed Revit Credit manager which was compatible with Revit 2014 2015 to automate the assessment and generation of LEED submittals. The tool was able to evaluate four LEED 2009 credits. They were daylight (option 1: simulation and option 2: prescriptive), views (IEQ 8.2), water use reduction and recycled content of materials. Presently, Autodesk has ended the technology. The preview version released is no more available. However, Autodesk continues to run Light Analysis Revit (LA/R) which is a plug-in used to evaluate LEED IEQc8.1 2009 and LEED v4 EQc7 opt2. Light Analysis Revit (LA/R) uses Autodesk Rendering Cloud service to evaluate and generate LEED submittals. The results generated show all rooms meeting LEED requirements and the number of credits gained.

One Click Life Cycle Assessment tool was found to be found useful in evaluating credits such Building Life Cycle Impact Reduction of LEED V4 (MRc1) and Life Cycle Impact of BREEAM (Mat 1). This tool operates both as a standalone or together with Revit or IESVE. Thus, BIM models can transferred between software in the IFC or gbXML format. These data transfer protocols are present in section 7 below.

5. Database infrastructure

The use of BIM for effective green building assessment requires a minimal variation between the BIM model and the constructed building. In this regard, it is necessary to develop the BIM model using materials and elements with same properties as those used for construction. As such, the development of a quality database is critical to the evaluation process. Different forms of databases were ideintified in the literature reviewed. As proposed in [25], these databases can be classified as augmented, external and functional. BIM software such as Autodesk Revit, ArchiCAD and IES-VE have an embedded library of building elements [27] from which users can construct a building envelope. In this study, they are classified as augmented databases. In Revit building elements are classified under three levels. These are categories, families and types. Categories form the first level. They are general group of elements such as columns, beams, doors, roof, windows and walls. Families narrowed down as subgroups for example concrete walls, brick walls and timber floors. Types have more defined characteristics. For example, dimensions and glazing type. Figure 5 shows a typical Revit single flush door family and some associated parameters.

Properties of materials in the form of texts, integers or computations can be inputted into definitive fields called parameters [27]. Parameters can be further classified as family, project or shared parameters. Family parameters are specific to families and control values such as the length, width and material. Project parameters can be added at the category level. It is important to note that a family or project parameter can only be shared in a single project. In contrast, shared parameters added at family or category level can be used across multiple projects and must be stored in a separate file for this nature. For instance, a shared parameter can be used for the heat transfer coefficient of the same glass component contained in windows and doors. Different from family parameters, project and shared parameters are very useful in scheduling elements and materials [44]. For instance, concrete of the same grade (i.e. same strength) in different components can be scheduled through a shared parameter added at the family level of columns and beams. Regardless of the type, parameter in Revit may be created and assigned to one of six disciplines: Common, Structural, HVAC, Electrical, Piping and Energy depending on the desired functionality [44]. While some parameters are completely customizable, others are limited to some form of computations and values. The "text parameter" of the common discipline for instance is completely customizable while "mass density" and "URL" accept only specific values [44].

Besides these parameters, extensible parameters can be created and assigned to Revit elements using programming languages (e.g. C#) with Revit API [30]. Extendible parameters are particularly useful for automating the assessment process. Unlike family, project and shared parameters, the level of access to extensible parameter depends on access granted by the supplier. With the use of extensible parameters, building objects can be tagged with characteristics such as "reused or renewable" so that API can automatically retrieve details to assess criteria within Revit [21,32]. This is particularly useful for materials and resources related criteria. For others such as energy and water use related criteria, API can retrieve model information to be fed into performance assessment tools. In such scenarios, retaining as much information as possible after the transfer is essential. This remains a major hurdle due to interoperability among software which will be addressed in section 6.

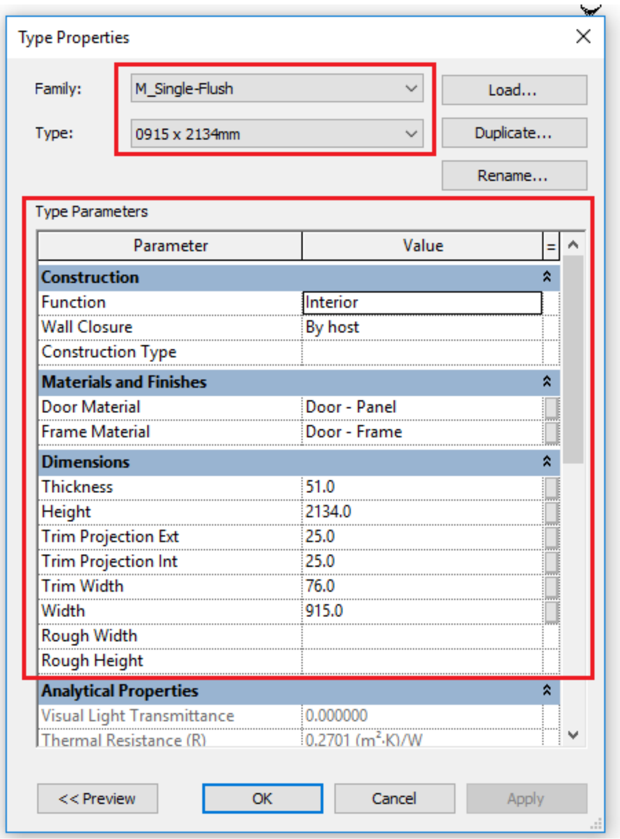


Figure 5 Sample Revit Family, Type and Parameter window of a typical door assembly

While augmented databases are intrinsic to the BIM authoring software, other forms of databases can be external to the BIM application. These are classified as external databases. External databases identified range across online platforms to study-specifically designed platforms. With regards to the former, organisations such as SMARTBIM Technologies provides platforms for manufacturer certified BIM objects. Objects are categorised based on manufacturers and can be downloaded in the form of Autodesk Revit files or XML files compatible with Revit or other widely used database management systems. SMARTBIM Technologies provides over 20,000 manufacturer-certified BIM objects which can be downloaded Revit families or types [45]. Manufacturer specific green labels pre-programmed as parameters into these BIM objects. EcoScorecard (as shown in Figure 6 is another platform which provides users with sustainable information of manufacturer-certified elements or components. This sustainable information includes sound transmission value, solar heat gain, recyclable content and manufacturer location. Currently, the data provided is limited to a few assessment schemes including LEED [46]. Nonetheless, it can be adequately streamlined for use with others such as BEAM Plus. Another platform which provided sustainable data is GreenWizard, a partner of USGBC [47]. While developing a database of building elements and materials may be easily achieved the major challenges lie in regular updates to reflect changes and improvement to these products. Such updates when done manually are tedious. Sign-in requirement associated with most of these databases like Green Guide to Specification make automated updates even more challenging [12]. Extensible parameters and API can provide opportunities to automate a substantial part of this process. It is therefore necessary to develop tools that can identify and manage parameters of sources of sustainable information, database management software or BIM software.

1600 SS Curtain Wall System 3185

Where Faster Installation and Performance Meet

- 2-1/2" (63.5mm) sightlines
- 6" (152.4mm) or 7-1/2" (190.5mm) depth
- Thermal performance
- Structural silicone glazed (SSG) options
- Blast mitigation

U-Factor, SHGC, VT and STC values are calculated using commercially available high performance glass. Please consult the glass manufacturer for actual values for your project.

Recycled content used is an average. Recycled content may range from 25-100%.

Product category :	Curtain Wall
Product type :	Unitized
MasterFormat Number :	08 44 13
Manufacturing Locations	Bloomsburg, PA 17815 Lethbridge, AB T1H 5S8 Springdale, AR 72764

Environmental Characteristics

Post-Consumer Recycled Content :	0.0%
Pre-Consumer Recycled Content :	50.0%
Recyclable :	Yes
Sound Tranmission Class :	31.0
Reduces Solar Heat Gain :	Yes
Product contributes to daylight factors :	Yes
U-Value :	0.36
Solar Heat Gain Coefficient :	0.28
Visible Transmittance :	0.63
Product contributes to acoustic factors :	Yes

Environmental Certifications

Global Reporting Initiative (GRI) Sustainability Report :	Yes
Multi-Attribute Assessment of Products: EPD product specific Type III EPD :	Yes
EPD Documentation :	Yes

Figure 6 Sample manufacturer-certified curtain wall in EcoScoreCard database

Apart from using online databases, a few studies established databases from collating information in research papers, assessment schemes' website and online data platforms including EcoScorecard mentioned above. In [12], the authors developed a green material database divided into elemental categories based on BREEAM's Green Guide to Specification. A recommendable feature of this database is the linkage between specific building elements and building types since a particular building element may be rated differently depending on the particular building within which it is used [12]. Similarly, [26] organize over 3000 green building design families into a web breakdown structure of sixteen master formats. The main sources of data were literature, US and Canadian Green building Council websites, publish data and supplier's information. Objects in the established database were saved as Revit family files (RFA) or Revit files (RVT), linked to Autodesk Revit and loaded whenever the application was launched. Also, commercially available database management tools such as Microsoft Access and Office can be designed with cells to correlate with various parameters of objects or family files directly imported in RFA or RVT formats. In Jalaei and Jrade's research [27], the first phase of the proposed framework is a Microsoft Access-based database with information on sustainable components and their associated LEED credits. Burdensome manual updates required remain a challenge to these databases.

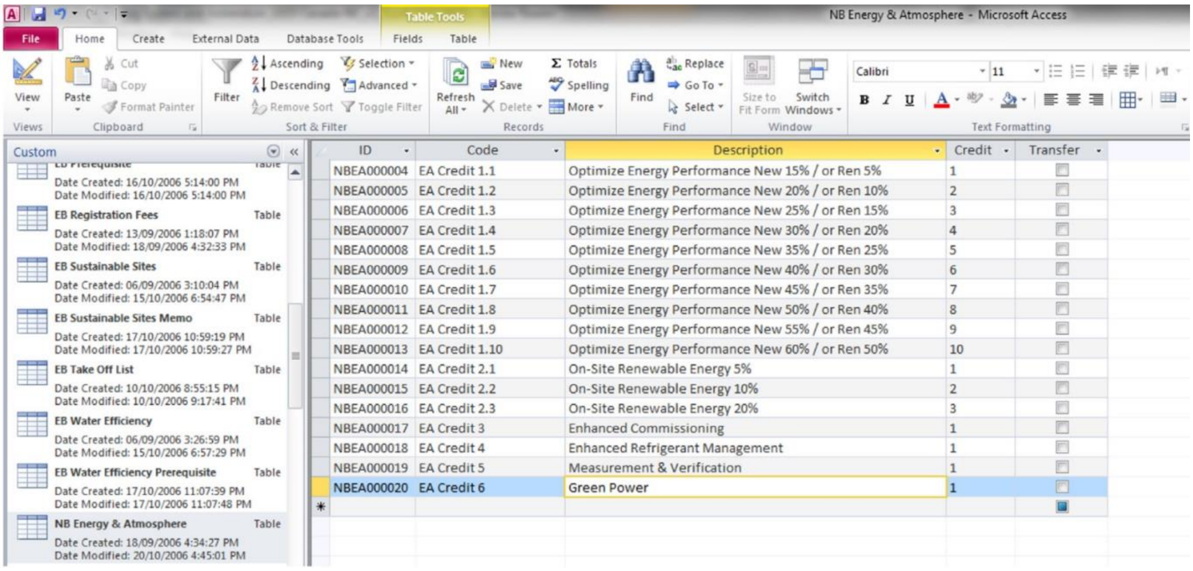


Figure 7 Sample external database in Microsoft Access [27]

Augment databases and external database explore BIM tools and database management software functionalities to facilitate BIM-based designs and sustainable assessments. Some studies [25,34] however identify information pertinent to BIM-based green building assessments but beyond those described above and proposed the third category - functional databases. In this category, the desired functionality significantly influences the used tool. Chen and Nguyen [10] combined web map services from various providers such as Bing, Google, Nokia, OpenStreetMap and Yahoo to provide map information for assessing the location and transportation criteria of LEED. Unlike the rather static material databases identified earlier, users can be automatically fed with the most updated and suited map data once API is loaded.

Finally, the cloud-based approach in [34] extends functionalities beyond design levels by providing for field and inventory data. Later during the construction stage, the project team can garner information as the work progress to validate the design model. This information is referred to as field data. Similar information on materials and equipment used may be collected and categorised as inventory data. Instead of sophisticated methods of collecting as-built information through BIM demonstrated in [48–50], [34] proposed a much simpler approach, a Velka cloud-based computing software which allows real-time validation and acquisition of data model even without physically accessing the model.

6. Data exchange module

Due to the requirement of transferring BIM models between authoring software and BIM performance assessment tools, 3D models must be easily interpreted and used by different applications. First, manipulation of data between the BIM related software involves interoperability issues which may result in substantial data loss. Furthermore, new development of tools should focus on immediate reflection in credits when changes are made to BIM model. Such developments require a shift in operation between tools from a sequential approach to a concurrently interactive approach [34]. Hence, the ability to exchange data between BIM and BIM-based performance assessment tools is crucial to an effective evaluation process. To overcome this setback, BIM authoring tools provide proprietary information exchange protocols as well as other formats generally agreed upon by different BIM software developers. Another dimension of the file exchange is the ability to transfer assessment to populate GBAS templates. Exchange protocols identified from BIM/GBAS literatures include Green Building XML schema (gbXML) in [11,21,22], Industry Foundation Class (IFC) in [12,25], Open Database Connectivity (ODBC) in [26,27,31,33,34] and Construction Operations Building Information Exchange (COBie) in [33]. The level of performance attained with each of these exchange protocols vary depending on the type of data [7].

Green building Extensible Markup language (gbXML) facilitates the transfer of data between databases, BIM authoring software and simulation tools. Since its establishment by the Green Building Scheme in 1999, this protocol positions itself as a standard to define information in BIM models by linking building geometries with descriptive data [51]. gbXML is developed based on the extensible markup language (XML), a non-proprietary protocol which allows customization of markup languages for exchanging information within various domains [52]. In [52], the authors provide a thorough comparison between gbXML and IFC protocols. Concerning geometry information, gbXML can capture the representation rather than the relationship between information. Primarily, “surface” represents all surfaces in the geometry and has two representations, a planar geometry and rectangular geometry. They complement each other for the purpose of checking the accuracy of model translation. For a model containing sensor information related to lighting or energy data, the authors indicate that gbXML includes a meter element which handles the information name, description and utility rate for each sensor. gbXML is renowned for its simplicity, as data can be extracted with an XML sheet from the gbXML file especially with sensor information. However, geometry information is only limited to rectangular shapes [26]. Since it is a non-proprietary protocol, further studies can modify gbXML to recognise and interpret sustainable information unique to BIM-based GBA.

Industry foundation classes (IFC), developed by BuildingSMART in 1995 was developed to facilitate data exchange primarily in the Architecture, Engineering, Construction and Facility Management industry (AEC/FM). With each released version, classes have been expanded to support information storage and enhanced interoperability among a broader range of software [7]. IFC data files can be exchanged between applications using any of the three formats: the IFC data file, IFC data file using the XML document structure, and IFC data file using the PKzip 2.04g compression algorithm [53]. The first is the default file exchange format. The second can be generated from the authoring software or converted based on ISO10303-28. The last format requires compressing any of the first two to a zip archive. In exchanging data between software, IFC protocols provide and interpret relational and organizational data in the form of geometry and topology [52]. Unlike gbXML which allows representing only rectangular geometry, IFC can represent multiple geometry shapes. Its placement function locates an object within a coordinate system by two attributes: the location and dim. The location is the geometric position of an item with regards to the reference point, and dim is the space dimension of the object [52].

The quality of data transferred between application is to a larger extent dependent on the user implementation, transferred data type and interaction between software [7]. For instance, in [21], the authors gave preference gbXML over IFC because of the support for a wider range of performance assessment tools. Jalaei and Jrade [26] also used the gbXML protocol for transferring material quantity take-off to the energy performance analysis tool. Dong et al. [52] advocated that storing and retrieval sensing information related to energy and lighting is relatively simpler with the gbXML protocol. With regards to user implementation, model checking is essential. Occurrence of gaps after transfer between tools may occur which can affect the evaluations especially for energy related criteria. In other instances, [11,25] adopted

XML protocols to populate LEED templates. For the materials category of BREEAM assessment, [12] adopted IFC files for the model transfer between ArchiCAD and the developed green building rating tool. Functionalities of IFC protocols were extended beyond simulation domains to areas such as building construction and commissioning in [52] and may be useful for output representation. Further research may be required to explore the limits of managing IFC to generate submittals.

Beside these two exchange protocols, [25,26,28,33] other protocols like COBie and ODBC were proposed to overcome issues connected with data loss during model transfer. In [25] COBie was proposed as a protocol to incorporate unique data such as commissioning data. Comparable to IFC, COBie’s cumulative data structure facilitates accumulating data in BIM models through the design, construction commissioning and handing over stages of project. It is necessary to explore the amount and quality of information that can be embedded in COBie to fill in LEED templates automatically. Primarily, ODBC could be used to augment BIM models by integrating information that cannot be done with conventional methods. Compared with COBie, ODBC’s application occurs about 3 more times in BIM/GBAS studies. In [26] the authors linked Life Cycle Assessment tools with BIM models through ODBC protocols. Jalaei and Jrade [27] mentioned the possibility of directly exporting BIM data through ODBC to a predefined database in other database management software like Microsoft Excel and Assess. Wu and Issa [34] proposed a model to populate LEED online template with information generated directly from BIM models. However, the author paid less attention to exploring ODBC to this end. Unlike the protocols mentioned above, ODBC works as an application programming interface (API) independent of any programming language or operating system to access databases. Its independent structure enables maximum interoperability, provides software developers with enough workspace, and transfers data without compromising the intended functionalities. Basically through ODBC, users can extract building information in tabular forms accessible through database management software such as Microsoft excel or Access [27]. Wu and Issa also highlighted challenges associated with ODBC including the loss of shared parameter information. These protocols are recommended for the final stage of BIM/GBAS automation to aggregate, evaluate and propagate information into LEED templates [25]. It may be handy in material extraction when parameters are not a significant concern. The extra information required for BIM-based green building assessments raise concerns on the capabilities of these exchange protocols. Therefore, their capacities to transfer model details should be further investigated.

7. Criteria assessment modules

Different assessment modules were identified because of the unique requirements of criteria in GBAS. Generally, credit assessment required the extension of BIM software in the form of plugins or integration with some other tool functions [27]. They included an Application Programming Interface (API), Microsoft Excel Macros, and Inbuilt extensions such as the Revit's Dynamo Visual Scripting, COBie and Cloud-Based Approach.

In the most basic form of assessment, users tag material with desired properties, extract a material take-off through take-off and evaluate credits attained. An application of scheduling to evaluate materials aspect of BEAM Plus is demonstrated in [32]. Scheduling function is especially handy for the following LEED criteria: building reuse (existing walls, floors, roof, and interior non-structural elements), materials reuse, recycled content, regional materials, rapidly renewable materials, certified wood low-emitting materials (adhesives and sealants), low-emitting materials (paints and coatings), low-emitting materials (carpet systems), low-emitting materials (composite wood and agri-fiber). Before extraction of the take-off, designers need to tag materials or elements used in model designs with the criteria mentioned above. In this way, the take-off extracted can be categorised by the tags used. The tagged materials in the take-off list can then be expressed as a percentage of total material used and an appropriate credit rewarded. There are some limitations such as extracting irrelevant information, double counting or ignoring difference such as floor levels or schedules [11,32]. Also, this approach still requires substantial expertise to extract the take-off.

The identified Application Programming Interfaces (APIs) were unique to Autodesk Revit and Google Maps. API based integration modules operate as add-ons/plug-ins of applications. They are not inherent to BIM applications but can usually be embedded within the BIM software as toolbars developed with programming languages. Revit's API is based on the .NET framework compatible with programming languages like C#, F# or visual basic to develop the plug-in [15]. The simplicity of C# makes it a commonly adopted programming language [12–15,19,24]. APIs allow users and application developers to extend the functionalities of BIM through integration with other applications [10]. For Revit, API can automate repetitive tasks, extract project data to automatically generate reports, import external data to create new elements and integrate with other applications [54].

Revit API has been frequently demonstrated in BIM/GBAS automation. Chen and Nguyen [10] used an API to extract BIM model information and building's location information from Revit and Google Maps. This included information such as the total floor area of the project, area of peripheral buildings and development density which was used to generate LEED submittals for location and transportation criteria. Nguyen et al. [29] developed an interface between Revit and Microsoft Access with API to retrieve sustainable indicators for computing maximum LEED credits. Likewise, Jalaei and Jrade [27] used Revit API to execute conditional queries between Revit and a designed database in assessing materials & resources and energy & atmosphere criteria of LEED. Upon execution, the User Interface (UI) generated a list of building materials and associated components based on LEED sustainable information stored within the external database. Besides generating information, the UI can classify materials as regional or not by calculating the distance between site and manufacturer's location. The UI can finally calculate total LEED points and prepare submittals with additional information provided by the user. Another study proposed an API with sub-interfaces to assess each criterion explicitly [35]. Jalaei and Jrade [26] used an API to develop a plug-in which automates energy analysis and daylight simulation in Ecotect and IES-VE with input from Revit. A distinctive feature of the developed plug-in is the model evaluation provided based on different green building rating systems. These studies rather center on the evaluations achieved and paid less attention to the process of methodological process developing these APIs and also evaluating credits. As such the evaluation process is less replicable.

With regards to concrete user index (CUI) under the sustainable construction of Green Mark, [11] identified the inability to different between floor levels (e.g. in continuous columns) as major challenge. To address this problem, [11] developed an add-on for Revit to automate the evaluation process of CUI. Although the results indicated a higher level of accuracy in addition to distinguishing different floor levels, the authors failed to present a replicable methodology for the study. Nguyen et al. [30] designed LEED Evaluator based on conditional queries with Revit API to retrieve information required for LEED assessments. Once the developed interface is launched, it searches and populates itself with sustainable information retrieved from the BIM model. Achieved LEED points are then calculated to generate reports which are presentable in Microsoft Excel or Word.

Wu and Issa [34] demonstrated a seamless cloud-based information flow for the minimum energy performance credit of LEED. From BIM and BIM-based assessment tools, energy simulation results are imported into Lorax Pro, a third-party cloud-based LEED automation management tool, and then to LEED online with API. Through LEED Automation, partners of USGBC can receive API authorization and hence develop a natural interface to populate LEED online templates. Autodesk and IES, for instance, are partners and have developed apps for

LEED automation. API can also be used to embed supplementary information like LEED documents and literature into the user interface to facilitate a more informed decision making.

Apart from API, Microsoft excel macro, Dynamo and COBie were used to integrate BIM software with criteria assessment module. To determine the optimum material combination for the energy performance, [9] developed a macro in Microsoft Excel which provides the material combination and associated costs. Users can visualize LEED points and total costs associated with different scenarios. The macro requires other inputs such as the Revit quantity take-off, cost details, LEED rules and energy simulation values. Also, the computation is dependent on the scenarios provided by the user. In [24], an open source graphical programming extension to Revit (Dynamo) was presented. Dynamo was used to demonstrate a bi-directional data flow to verify the compliance of the design airflow with LEED requirements. Model information was exported to spreadsheets where further details are added to compute the minimum flow. The data file are then sent back to Revit as a shared parameter to compare with the design flow. COBie once again served as an integration and criteria assessment module. In [25], LEED requirements are converted into executable rules to demonstrate the assessment of construction activity pollution prevention and development density & community connectivity criteria with COBie. Model information retrieved and other information such as assessors' names are used to augment and value the model based on conditions embedded into COBie. The output can then populate LEED submission templates in the XML format.

8. Research Gap and Recommendation for future work

This present has provided a comprehensive review of literature and software based on the need to identify current levels of developments concerned with automated evaluation of GBAS criteria from a BIM model. Based on reviewed literature and software identified, there is the need to further research into automated evaluation of GBAS criteria with BIM. A need to improve the nexus between BIM and evaluating criteria of green building assessments is identified, and possible research directions are summarized in Figure 8.

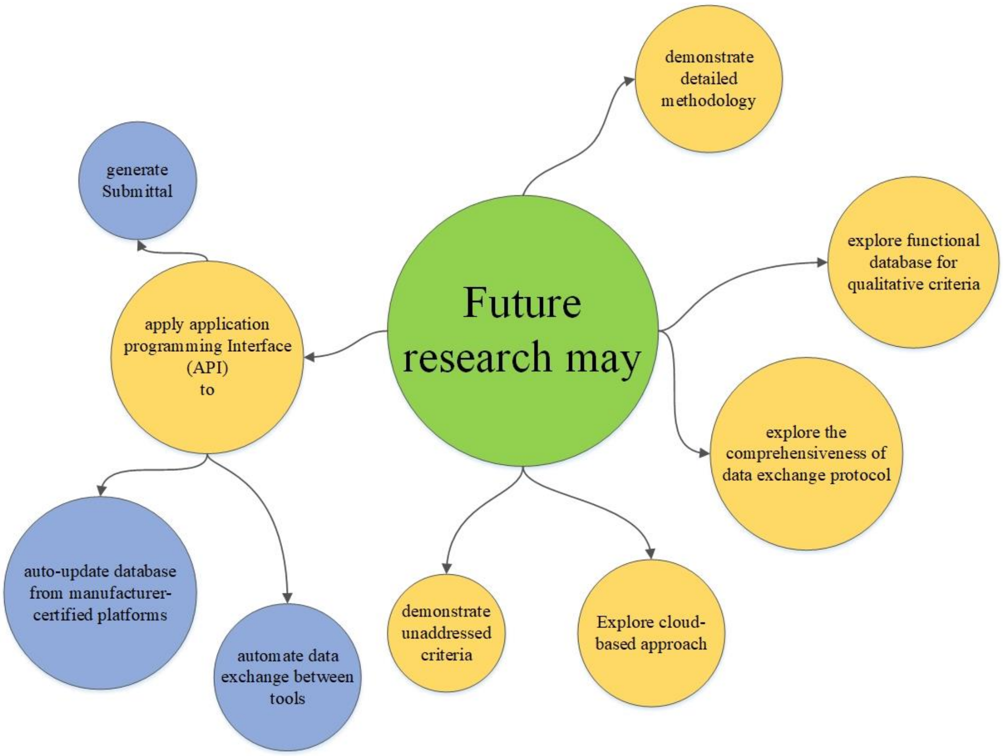


Figure 8 Summary of future research directions

The first research gap lies in the integrity of databases for the BIM model development. BIM-based green building assessments are highly dependent on comprehensive qualitative and quantitative data. Existing databases such as augmented data embedded into BIM Modelling software and external databases are primarily limited to quantitative data storage. With these databases, discrepancies in elements used for BIM models and as-built models raise questions about the robustness of BIM-based assessments. GBAS such as BREEAM and LEED can partner with other organizations providing sustainable manufacturer-certified product information, so that tremendous opportunities exist to create parametric components with such information. However, interoperability issues arise from the variance in the structure of augmented and external databases, resulting in the manual input and loss of quality information.

Furthermore, login requirements can limit possibilities of auto-updating databases. An important step to curb this issue is to use manufacturer-certified products at the design stage or development of databases. Future research can focus on the development of interfaces using API to facilitate automated data exchanges between BIM tools, databases and platforms providing manufacturer-certified BIM sustainable building components. Besides, provisions of qualitative data must be addressed in databases. Some authors have proposed functional databases through a platform like COBie. It is necessary that future studies explore the applicability of such tools in the qualitative data storage and retrieval.

The second gap is identified in the validity and robustness of studies reporting BIM-based green building assessments. Most of the studies reported lack rigorous validations of proposed models or are characterised by ad hoc nature. Some studies report frameworks assessing a wide range of criteria but have only demonstrated a few cases. Even with these few cases, reports centre on the final achieved criteria and seldom provide in-depth information on processes and procedures to them. Consequently, it is difficult to replicate the methods reported in these studies. Furthermore, most studies barely report the limitations of used methods, for instance, the impact of exchange module on data loss. Also, a generalised framework open to a range of categories without demonstrations is less meaningful. Therefore, future studies should centre on demonstrating a criterion with a greater focus on the replicability of methodologies. Some studies have indicated substantial differences between the reported and actual performance of GBAS certified projects. Hence, efforts should be made towards quantifying the difference between predicted and actual performance (i.e. the limitation of applied methods), when reporting the performance of green building based on BIM.

Another hurdle to the BIM-based sustainability assessment is the wide range of tools and varying information involved in assessments. This requires the transfer of BIM models among different tools. The key to interoperability is an appropriate model information exchange mechanism. Recent developments of IFC and gbXML facilitate the seamless bi-directional flow of standardised/conventional information between BIM, BIM-based performance analysis and other auxiliary tools. Nonetheless, BIM-based green building assessments rely on data-rich models, which require embedding more than standardised/conventional information into model design elements as highlighted earlier. In the case of the model transfer between tools, the model integrity after some iterations is questionable. Comprehensiveness of exchange protocols, as well as interoperability among software for BIM-based green building assessments, can be the next-step research. Also, future research should be extended beyond IFC and gbXML to explore the potential of COBIE and ODBC for transferring and managing various types of data required for GBAS.

Besides evaluations for design improvements, generating project submittals with the help of API and functional databases is also critical in BIM based green building assessments. The existing research pay less attention to the development process of API. Rather, many studies have focused on the results attained. Research and demonstration of the extraction of information through algorithms and functions of API and platforms should be brought to the future research agenda. A cloud-based BIM approach has been proposed to extend functionalities beyond normal single-desk BIM model developments. Facilitating green building assessments with cloud services is a potential research direction. Also, most GBAS have online platforms to coordinate the assessment process and provide API assess to partners. Future studies can also focus on exploring cloud-based BIM with a focus on automatically populating GBAS submittal templates.

With regards to criteria, although some criteria are assigned more weight in GBAS, the comprehensiveness of assessment is more valuable indicator of a building's sustainability. Most studies have extensively addressed criteria including materials and resources, innovative wastewater technologies, water use reduction, heat island effect, storage and collection of recyclables, materials reuse, recycled content, concrete usage index, regional materials, rapidly renewable materials, minimum indoor environment performance and increased ventilation, development density and community connectivity, alternative transportation – public transportation and low-emitting materials, modular and standardised design optimise energy performance and minimum energy performance especially for LEED. However, since assessment criteria are similar across different GBAS, future studies can focus on demonstrating the assessment of other design criteria such as Stormwater (quality and quantity control), Protect or restore habitat, Water use monitoring and reduction, Green power, Light pollution, Construction waste reduction and Security of other GBAS such as BREEAM. Despite that evaluating some of these criteria used to be impossible with BIM, it is now considered feasible with API and models developed by IES and One Click Lifecycle for instance. The recent development can be further explored in future studies.

9. Conclusions

BIM has evolved as an invaluable tool in the architectural, engineering and construction industry. With the recent increasing momentum in the green building assessment and certification, BIM can provide excellent opportunities to facilitate sustainable design while reducing the certification cost. This paper presents a comprehensive review of literature on the breadth of automated evaluaation of GBAS criteria. The study also addressed development by software vendors. Significant findings can be summarized as below:

(1) LEED criteria were identified as the most frequently addressed while BEAM plus, GBI, Green Mark and BREEAM were been seldom evaluated in literature. Concerning categories, energy & atmosphere, materials & resources have been extensively

demonstrated through Revit scheduling and API. The development density, community connectivity and alternative transportation, although seldom addressed, have been well demonstrated in literature.

(2) The databases identified within BIM/GBAS frameworks include augmented, external and functional databases. Augmented and external databases work best with quantitative criteria given the increased validity of assessments by reducing the deviation between BIM and as-built models. Functional databases, on the other hand, can facilitate the incorporation of unconventional data through the assessment process.

(3) Revit was identified to provide an API for extending functionalities. These API provide opportunities for future research in developing plug-ins to evaluate GBAS criteria. With a well-established developed database, materials and resources criteria can be assessed within the BIM model but assessing criteria in energy & performance, indoor environment quality, water use and site aspects requires other auxiliary tools such as Web Map Service providers (i.e. Google Maps, Yahoo maps), Safaira, Ecotect, Microsoft Excel and Word. IES-Navigator, Autodesk and One Click LCA were identified as tools provided by vendors for automated evaluation of criteria.

(4) IFC and gbXML are identified as the two most popular data exchange platforms across databases, BIM and BIM-based tools. IFC can store more geometrical forms than gbXML, while gbXML performs better with sensing information. Others exchange platforms like ODBC and COBie can be used to augment transferred models in case of data losses.

(5) For the integration and criteria assessment, the most frequently used method is the Application Programming Interface (API). The cloud-based approach, Microsoft Programming language and Dynamo (an inbuilt Revit extension) are also applicable for automating assessment process.

This study provides references for both researchers and practitioners. Practitioners can gain a more comprehensive knowledge in applying BIM to green building assessments, while researchers can obtain a substantial guide to broaden the scope of BIM-based green building assessments based on numerous addressed frameworks. Future research should fill the identified research gaps in Section 8 to promote a comprehensive evaluation of green building from a BIM model.

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