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Sustainable Cities and Society

Building Information Modelling and Green Building Certification Systems: A Systematic Literature Review and Gap Spotting

--Manuscript Draft--

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Abstract:	There has been an increasing focus on using Building Information Modelling (BIM) for sustainability assessment. Especially in the aspect of applying BIM-based tools to provide documentation for Green Building Certification Systems (GBCS) credits in sustainability assessment. Despite the huge potential of BIM for GBCS, there is limited literature that has established this link. Hence, the purpose of this paper is to explore the synergies between BIM and GBCS to achieve a deeper understanding of the GBCS currently BIM-enabled, level of BIM implementation in GBCS sustainability areas, challenges and gaps in integrating BIM and GBCS, BIM and GB tools currently in use and areas for further research in the BIM-GBCS domain. The research methodology includes a combination of systematic literature review (SLR) and gap spotting. The SLR includes a total of 84 papers from highly ranked journals between 2009 and 2020. In terms of sustainability areas, energy (71%) has the highest amount of literature in the environmental sustainability dimension while social and economic dimensions had a representation of 15% and 11% respectively. The knowledge gaps and areas for proposed future research directions are critical to developing work in the BIM-GBCS domain.
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HIGHLIGHTS

- The number of BIM-GBCS papers increased significantly between 2019 and 2020.
- Energy and LEED are the most researched sustainability area and GBCS respectively.
- Ontology, BIM, IoT and Blockchain can enhance GBCS assessment process.
- Areas of confusion, neglect, and application in BIM-GBCS domain is established.
- A conceptual mapping for BIM-GB software and GBCS integration is proposed.

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Building Information Modelling and Green Building Certification Systems: A Systematic Literature Review and Gap Spotting

ABSTRACT

There has been an increasing focus on using Building Information Modelling (BIM) for sustainability assessment. Especially in the aspect of applying BIM-based tools to provide documentation for Green Building Certification Systems (GBCS) credits in sustainability assessment. Despite the huge potential of BIM for GBCS, there is limited literature that has established this link. Hence, the purpose of this paper is to explore the synergies between BIM and GBCS to achieve a deeper understanding of the GBCS currently BIM-enabled, level of BIM implementation in GBCS sustainability areas, challenges and gaps in integrating BIM and GBCS, BIM and GB tools currently in use and areas for further research in the BIM-GBCS domain. The research methodology includes a combination of systematic literature review (SLR) and gap spotting. The SLR includes a total of 84 papers from highly ranked journals between 2009 and 2020. In terms of sustainability areas, energy (71%) has the highest amount of literature in the environmental sustainability dimension while social and economic dimensions had a representation of 15% and 11% respectively. The knowledge gaps and areas for proposed future research directions are critical to developing work in the BIM-GBCS domain.

Keywords: Building information modelling, green building certification system, systematic literature review, and sustainability

1. INTRODUCTION

The high rate of global resource utilisation in such forms as excessive water, energy, and forest use and raw materials has encouraged the concept of sustainable development to meet the current needs without adverse effects on the future [1, 2]. Buildings are one of the most dominant sources of resource usage and environmental emissions, using about 50% of raw materials, consuming 71% of electricity and 16% of water usage, and producing 40% waste disposed of in landfills [3]. Buildings need adequate monitoring throughout their life cycle, and the concept of building sustainability assessment is central to reducing global warming.

The global Architecture, Engineering and Construction (AEC) industry is currently undergoing a dynamic transformation with the introduction of green building (GB) and BIM [4]. The shift to GB has led to the development of several GB certification systems (GBCS) such as Green Star (Australia, New Zealand, and South Africa), Leadership in Energy and Environmental Design [LEED] (the United States of America and Canada), Building Research Establishment Environmental Assessment Method [BREEAM] (United Kingdom), SBTool (Portugal and the Czech Republic), Chinese evaluation standard of green building [ESGB] (China), Building Environmental Assessment Method [BEAM] Plus (Hong Kong), Green Mark (Singapore), Green Building Index [GBI] (Malaysia), Simple Versatile Affordable Green Rating for Integrated Habitat Assessment [SVAGRIHA] (India), Deutsche Gesellschaft für Nachhaltiges Bauen [DGNB] (Germany), Living Building Challenge (LBC), among others.

In addition, researchers have also developed GBCS for developing countries by adapting existing GBCS due to the limitations of the existing GBCS. Some prominent examples of newly developed GBCS by researchers are as follows: BSAM - Sub-Saharan Africa [5, 6], SABA - Jordan [7], and

GB tool for existing buildings [8]. The first and second generations of GBCS such as LEED, BREEAM, among others have geographical limitations which hamper its use in other locations outside their jurisdiction. Furthermore, the third generation (e.g. WELL, LBC) included the social dimension of sustainability as a critical element of indoor evaluation. The focus on indoor comfort emphasized a user-centred methodology of GB assessment. However, researchers still have mixed opinions regarding this approach [9, 10]. Nonetheless, many of the existing GBCS suffered poor automation, making GB assessment time consuming and expensive because many of the assessment processes are done manually [11-13]. Therefore, there is a need to apply innovative technologies to enhance the GB assessment process.

The AEC industry has been more focused on applying emerging technologies to improve environmental sustainability [14]. Technologies such as artificial intelligence (AI), prefabrication, BIM, business process reengineering (BPR), and total quality management (TQM) have been deployed to facilitate the integration of construction processes and achieve value for money [15]. Existing studies have shown that BIM is a valuable technology that can transform the building sustainability assessment process [11, 16-18]. BIM surfaced as a solution to facilitate the integration and management of information throughout the building life cycle [13], thus, enabling effective use of design data for sustainability evaluations [19]. The successful integration of BIM and GB assessment requires a lot of data. Quantitative and qualitative data are the backbone of sustainability assessment [17, 20]. However, Zhao *et al.* [21] noted that one of the fundamental gaps in green building is information technology applications. Lu *et al.* [13] revealed that contemporary BIM software packages are still inadequate in delivering a unified analytical solution for a distinct green building assessment. It cannot simultaneously analyse all green aspects of buildings.

Furthermore, Gandhi and Jupp [22] findings revealed one of the problems of BIM and green integration as lack of alignment between the activities, processes, and tasks that encourage modelling and analysis and those that encourage the realisation of green building certification criteria. Also, Ansah *et al.* [17] identified interoperability issues as a major setback in implementing BIM for green building assessment due to the loss of quality information. Xu *et al.* [14] further acknowledged that one of the major challenges with the green construction process is an inaccurate assessment.

In recent years, there have been several studies on integrating BIM and GBCS [11, 12, 16, 23-27]. Examples include LEED [12, 24, 28, 29], SBTool [11, 30, 31], and ESGB [32]. Jalaei and Mohammadi [12] developed a BIM-LEED Revit plugin using data mining method (K-Nearest Neighbour). The plugin included location and transportation, sustainable sites, energy and atmosphere, materials and resources, indoor environmental quality, innovation in design, and regional priority, accounting for 6 of 8 credits in LEED v4. Similarly, Kang [29] created a rule-based LEED evaluation method with BIM to facilitate the sustainability assessment and save time. Although many BIM applications have been proposed and developed to seamlessly integrate BIM and GBCS into the traditional design, construction, and operation processes. Nevertheless, there is still a need for comprehensive integration of BIM and GBCS throughout the project lifecycle [13] and provide researchers in the industry with a clear pathway for future research in the BIM-GBCS domain. In addition, most of the existing SLR on BIM and GBCS, as shown in Table 1, are not detailed in describing the knowledge gaps and future research direction in the BIM-GBCS domain. This is a critical gap that needs to be filled to advance the field. Hence, this current study combines SLR and gap spotting techniques to address the shortcomings of the previous SLR.

Different approaches are currently being used to integrate BIM and GBCS with no clear standard.

This lack of uniformity makes it difficult to ascertain the level of BIM integration in sustainability assessment. This paper explores the relationship between BIM and GBCS to determine the GBCS currently BIM-enabled, level of BIM implementation in GBCS sustainability areas, challenges and gaps in integrating BIM and GBCS, the BIM and GB tools currently in use and areas for further research in the BIM-GBCS domain. In order to achieve the research aim, SLR and gap spotting were carried out. Relevant publications between 2009 and 2020 were identified and synthesized accordingly. The year range was based on literature search output after excluding papers not relevant to the study. This research will provide a roadmap and future directions for BIM and GBCS integration. Thus, making BIM-based assessment adaptable for new and existing GBCS. The structure of this paper is as follows: First, the following section will summarize and present the research methods, followed by analysis, review, and discussion of selected articles. Then, a detailed gap spotting of the selected papers was carried out. The concluding section addresses future research directions, implications and conclusions based on the review.

Table 1: Previous SLR and Current Study

S/N	Author	GBCS	Country	Year range	Initial Search	No of articles	Database	Gaps
1	Ghaffarian Hoseini *et al.* [18]	Green Star	New Zealand	2007-2015	418	20	Elsevier, Emerald, Wiley, American Society of Civil Engineers, Taylor & Francis.	The paper lacks clear areas for future research, and it is limited to only Green Star. The gaps in the BIM-GBCS domain is not well established.
2	Ansah *et al.* [17]	LEED, BEAM Plus, BREEAM, Green Mark, Green Building Index	Spain		92	19	Scopus, Web of Science, ScienceDirect, ProQuest and Google Scholar	The applicability of BIM in GB sustainability areas was not investigated. The gaps in the BIM-GBCS domain is not well established.
3	Muller *et al.* [33]	LEED	Brazil	2006-2018	511	115	Scopus, Engineering Village and Proquest	Only considered LEED GBCS. The gaps in the BIM-GBCS domain is not well established.

4	Carvalho *et al.* [30]	LEED	Portugal	2011-2019	248	26	Web of Science	The paper did not include a detailed review of the existing BIM tools that can aid in building sustainability assessment. The gaps in the BIM-GBCS domain is not well established.
5	**Current Study**	**All notable GBCS**	**New Zealand**	**2009-2020**	**400**	**84**	**Scopus**	-

2. RESEARCH METHODS

Figure 1 shows the entire overview of the paper's research methods. The research method is divided into four stages which includes 1) SLR, 2) gap spotting, 3) BlackBox, and 4) research outputs. The "*BlackBox*" is where the SLR and gap spotting results are processed to summarize the current state of knowledge in the BIM-GBCS domain and future research directions.

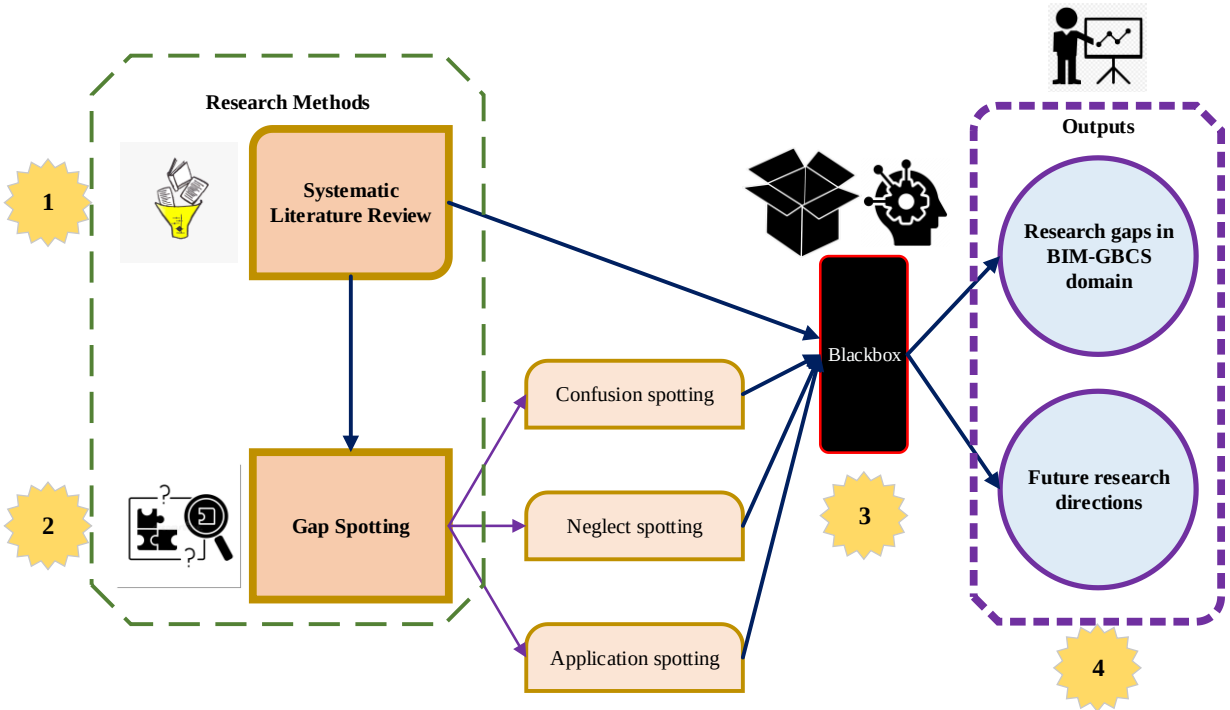


Figure 1: Research process

2.1. Systematic Literature Review

The main focus of this SLR is to provide research topics or areas for future research. The review process is divided into two steps: SLR protocol development (Step I) and SLR execution (Step II), as shown in Figure 2. The SLR protocol development has four sub-steps (purpose definition, research question formulation, keywords and database selection), while the second step has six sub-steps (search strings refinement and article search, inclusion and exclusion criteria, title and abstract scanning, quality assessment, coding, and data extraction pattern). Carvalho *et al.* [30] highlighted the need for a more elaborate SLR to include more keywords and green building rating tools such as Green Star, DGNB, BEAM Plus, among others. The SLR steps are discussed elaborately in sections 2.1.1-2.1.6.

2.1.1. Purpose definition and research question formulation

The review aims to uncover the research gaps in BIM and green building assessment tools and suggest areas for future research directions. The research questions were developed according to the gap spotting guidelines specified in Sandberg and Alvesson [34]. The RQ1 and RQ2 were formed based on the confusion among researchers and practitioners regarding the level of BIM implementation in GBCS sustainability areas. The RQ3 seeks to identify the neglected areas in the BIM-GBCS domain. The RQ4 seeks to evaluate the BIM and GB tools in the BIM-GBCS domain to have an overview of their function and conceptual relationship with GBCS. Lastly, the RQ5 aims to uncover possible areas for future research. As such, the research questions for this SLR include the following:

RQ1. What are the GBCS currently BIM-enabled?

RQ2. What is the level of BIM implementation in GBCS sustainability areas?

RQ3. What are the challenges and gaps in integrating BIM and GBCS?

RQ4. What are the BIM and GB tools/applications currently in use and their function?

RQ5. What are the future research directions in the BIM-GBCS domain?

2.1.2. Keywords selection, Search strings refinement and article search

A search string was developed and implemented on the Scopus search engine based on the identified keywords. The search strings were based on three main keywords (BIM, Green building and assessment tools and method) divided into three groups from which several other keywords related to the main keywords were generated. These three groups are then connected using "AND" while the intra-group keywords are connected using "OR" before final implementation on Scopus. Several construction-related studies like Wuni *et al.* [35] have implemented a search string on Scopus. The keywords for the SLR were formulated based on the initial check of existing literature and presented in Table 2.

Table 2: Keywords for systematic literature review

BIM	**Green building and assessment tools**	**Method**
BIM OR "Building information modeling" OR "Building Information Modeling (BIM)" OR "Building information model" OR "Building an information-model" OR "BIM (building information modeling)" OR "Building Information Modelling"	"green building" OR "green construction" OR "sustainable building" OR "high performance building" OR "building environmental performance" OR "ecological building" OR sustaina* OR "Green building concept" OR LEED OR CASBEE OR GBI OR DGNB OR BREEAM OR "Green Star" OR "Green Mark" OR "Green Globes" OR ESGB OR GBL OR ECOEFFECT OR ECOPROFILE OR ESCALE OR HK-BEAM OR "BEAM Plus" OR "GB Tool" OR "SB Tool" OR "Home Star" OR HQE OR "Energy Star"	"Assessment Method" OR "Assessment Rating Method" OR Certification OR "Green Building Certification" OR Evaluation OR "Labeling Method or System" OR Guideline OR Benchmark OR "Assessment Standard" OR "Green Building Rating Tools"

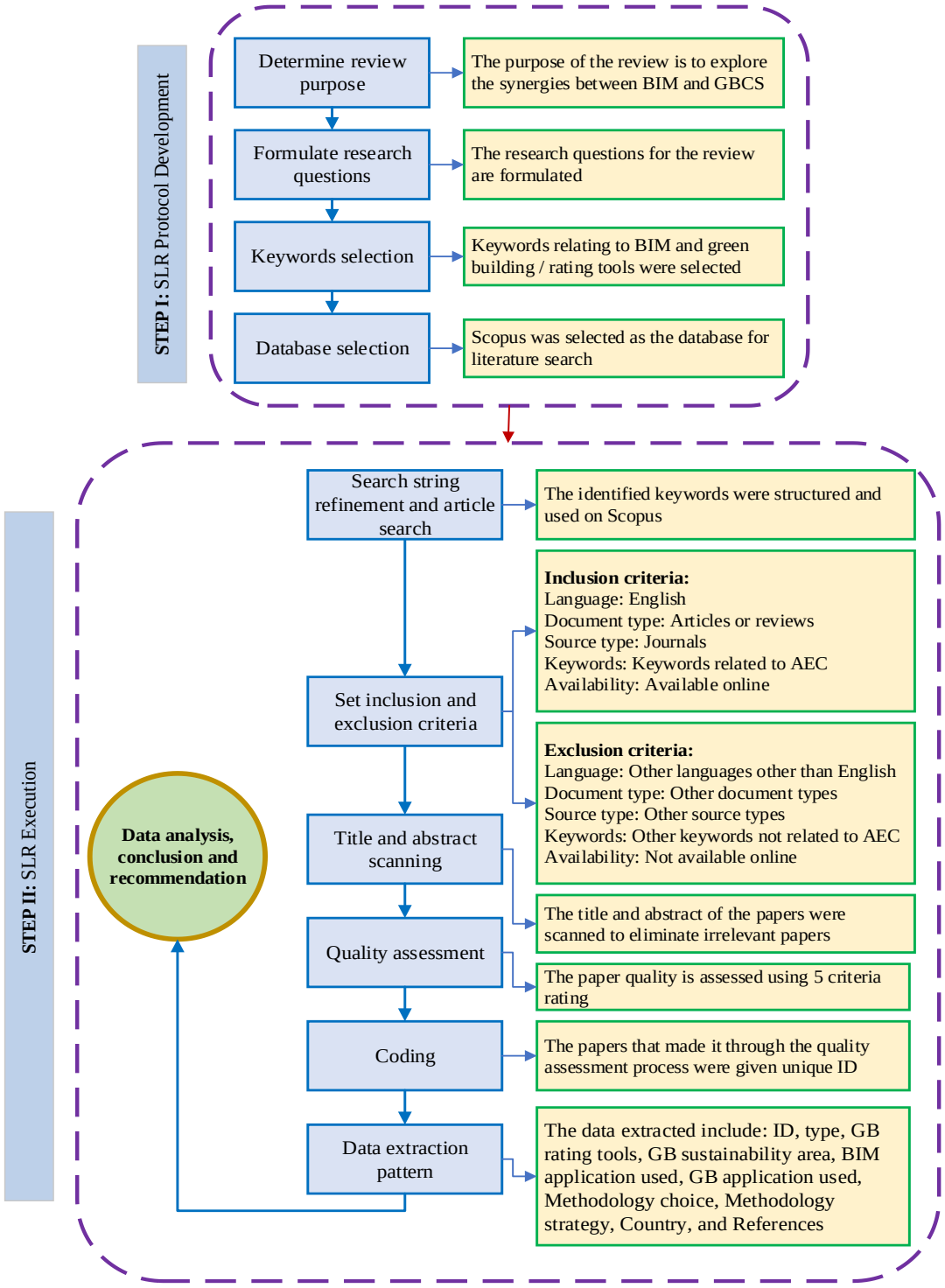


Figure 2: Systematic literature review process

2.1.3. Database selection

The database selected for the SLR was Scopus. Hong & Chan (2014) noted that Scopus is one of the widely used databases cutting across major fields, including engineering, medicine, management, business, etc. Wuni *et al.* [35] acknowledged that Scopus has more coverage area and is widely used than Web of Science and Google Scholar. However, Google Scholar has no scalable and reliable data extraction algorithm. This limitation makes Google Scholar inadequate for large-scale citation analyses and good for manual data collection or small-scale analyses [36].

2.1.4. Title and abstract scanning

The title and abstract of the articles in the Scopus search output were checked to determine relevant articles and those not relevant. Furthermore, the articles not relevant to the SLR purpose were removed. Articles from 2021 were excluded from the literature search on Scopus because the search was done in April 2021. Hence, 2021 cannot be added as part of the year under review. Nevertheless, relevant articles deemed necessary in 2021 were included in the SLR. A similar approach was made in Wuni *et al.* [35].

2.1.5. Quality Assessment

Quality assessment (QA) is often used to critically decide the selected articles in an SLR [37]. For this study, QA was used to determine the strengths and weaknesses of the included studies as done by Nidhra *et al.* [37]. The QA criteria used for this SLR include the following:

1. Are the topics addressed in the article related to BIM and green building criteria?
2. Are the GB and BIM tools used or reviewed clearly stated?
3. Does the article clearly state the GBCS considered?
4. Is the methodology of research clearly explained in the article?
5. Is the data collection and analysis method explained in the article?

The five criteria stated above were utilised to evaluate the quality of 84 chosen articles to ascertain the confidence and credibility of the identified articles. The schema was structured to include three ratings (high, medium or low). Consequently, the articles' quality was assessed based on the sum of the five questions rating score (0 – criterion not achieved, 1 – criterion partially achieved and 2 – criterion fully achieved). It is illustrated mathematically below:

$$Rating\ score\ = \sum QA\ criteria$$

Where;

High: $\sum QA\ criteria\ > 6$

Medium: $\sum QA\ criteria\ = 5$

Low: $\sum QA\ criteria\ =$ below 5

Only articles with a QA value higher than five were chosen for the next stage to ensure the quality of articles used in this review. Figure 3 shows the overall elimination process of the articles.

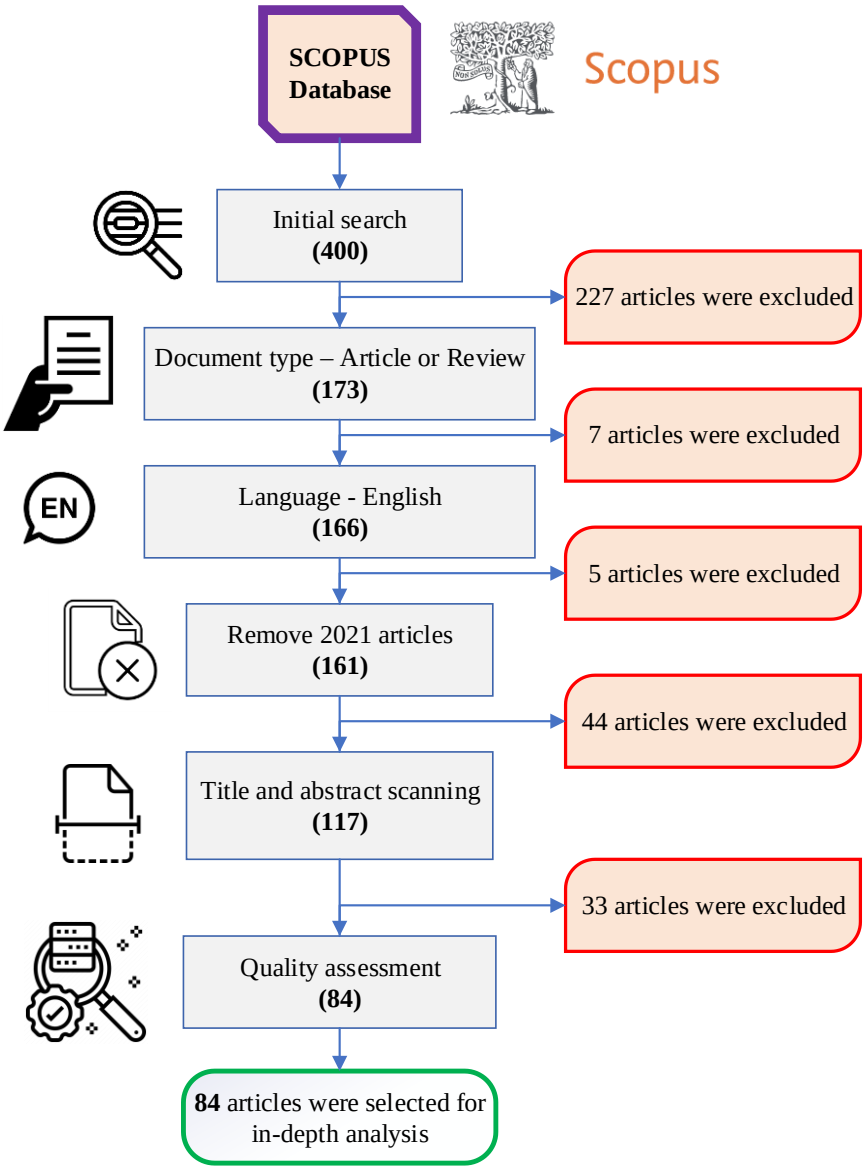


Figure 3: Article elimination process

2.1.6. Coding

The papers after QA were assigned to a unique ID for easy identification, data extraction and analysis. The coding system used was "P", followed by the number of the paper. On the other side, additional papers were coded using "AP".

2.2. Gap Spotting

Gap spotting is one of the fundamental ways of developing research questions [34]. It is seldom applied in construction-related research, and it is regarded as the most effective way of acquiring research questions in pragmatic studies. This can be attributed to insufficient awareness of the gap problematisation structure [38]. Furthermore, Sandberg and Alvesson [34] noted that gap spotting questions do not often lead to the development of theories due totheir inability to question foundational assumptions of existing theories. The process of gap spotting is carried out in three modes: confusion, neglect, and application spots, as indicated by Sandberg and Alvesson [34]. The application modes are discussed briefly below based on Sandberg and Alvesson [34] framework:

- *Confusion spotting* is concerned with identifying confusions in the BIM-GBCS body of knowledge. This mode of gap spotting entails pointing research questions towards areas of disagreement or competing explanations among researchers. It is intended to identify the gaps in the literature and resolve them [39].
- *Neglect spotting*is the most common approach to gap identification. This mode of gap spotting identifies BIM-GBCS areas that have been neglected in existing studies. It aims to decipher areas that are unexplored and critical for researchers to fill the knowledge gaps and thus advance the body of knowledge. The mode also has three sub-categories: an overlooked area, an under-researched area, and a lack of empirical support [34].
- *Application spotting* isthe third mode of gap spotting is concerned with areas in existing literature where a shortage is spotted in terms of theory or perspectives. This mode focuses on existing literature, including case studies and their applications [34].

3. SYSTEMATIC LITERATURE REVIEW RESULTS

3.1. Descriptive Analysis

This section of the paper presents a descriptive analysis of the articles considered in this SLR. The presentation was based on the frequency of articles, GB sustainability area, sustainability rating tools, and country of origin.

3.1.1. Frequency of Articles between 2009 and 2020

The frequency of publications between 2009 and 2020 is presented in Figure 4. It is seen that the year 2020 has the highest number of publications accounting for 29% of the total articles used in this study, while no publication was recorded in 2012. Overall, it can be deduced that annual publications have grown continuously over the years. The increasing interest in GB is due to government policies and the coronavirus pandemic [40-42]. For instance, an executive order was signed in 2007 that requires federal agencies in the United States of America to adhere to green building standards [43]. Similarly, China introduced the GB 50189 standard in 2015, a design standard for the energy efficiency of public buildings to improve energy efficiency in public building throughout life cycle [44]. Furthermore, researchers in the construction domain have also shown increased interest in the impact of the coronavirus pandemic on green buildings [45-47].

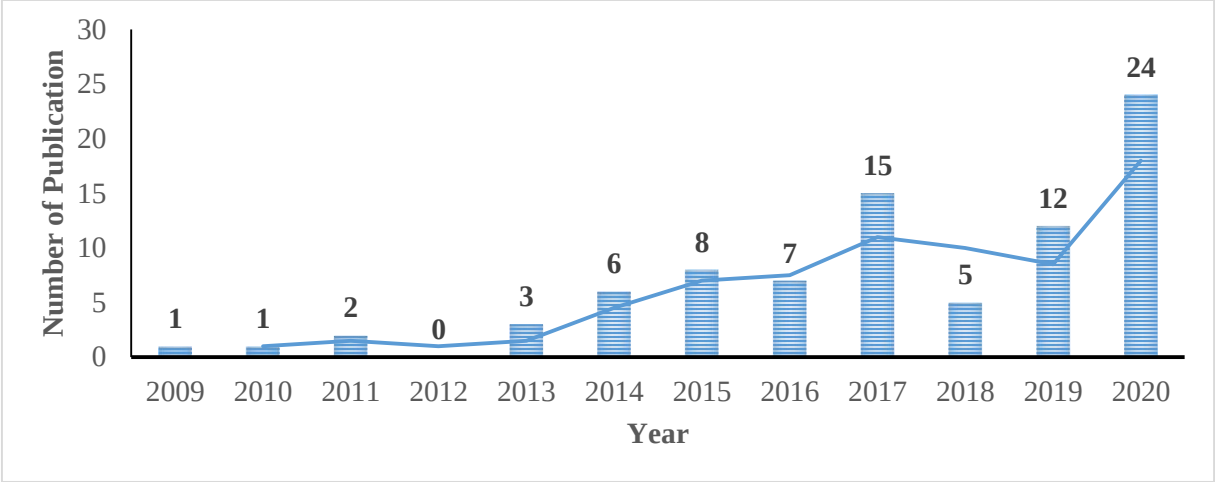


Figure 4: Frequency of Publication

3.1.2 Journal of Selected Articles

Table 3 shows the top fifteen (15) journals in which the selected articles were published. The table contains highly ranked journal articles that guarantee data reliability in the SLR. Nearly 40% were published in Sustainability [Switzerland] (15.48%), Automation in Construction (9.52%), Sustainable Cities and Society (7.14%), Journal of Green Building (4.76%), and Applied Sciences [Switzerland] (2.38%).

Table 3: Top 15 Journals of Selected Articles

S/N	Journal	Frequency	*Percentage (%)
1	Sustainability (Switzerland)	13	15.48%
2	Automation in Construction	8	9.52%
3	Sustainable Cities and Society	6	7.14%
4	Journal of Green Building	4	4.76%
5	Applied Sciences (Switzerland)	2	2.38%
6	Architectural Engineering and Design Management	2	2.38%
7	ARPN Journal of Engineering and Applied Sciences	2	2.38%
8	Buildings	2	2.38%
9	Energy and Buildings	2	2.38%
10	International Journal of Sustainable Building Technology and Urban Development	2	2.38%
11	International Journal of Sustainable Development and Planning	2	2.38%

12	Journal of Building Engineering	2	2.38%
13	Journal of Cleaner Production	2	2.38%
14	Journal of Information Technology in Construction	2	2.38%
15	Advances in Materials Science and Engineering	1	1.19%

*Percentage is based on the overall contribution of the journal based on the 84 articles

3.1.3 Green Building Sustainability Area

Figure 5 shows the classification of the articles based on the GB sustainability area. Using the Green Star NZ as a yardstick, a large portion of the articles focused on the environmental aspect of sustainability which includes; management (4%), indoor environment quality (35%), energy (71%), transport (20%), water (26%), materials (54%), land use and ecology (35%), emissions (23%), and innovation (18%). On the other side, the social (11%) and economic (15%) aspects of sustainability were not often researched. These findings connote that the management, innovation, water, and transport areas under the environmental dimension of sustainability need more research.

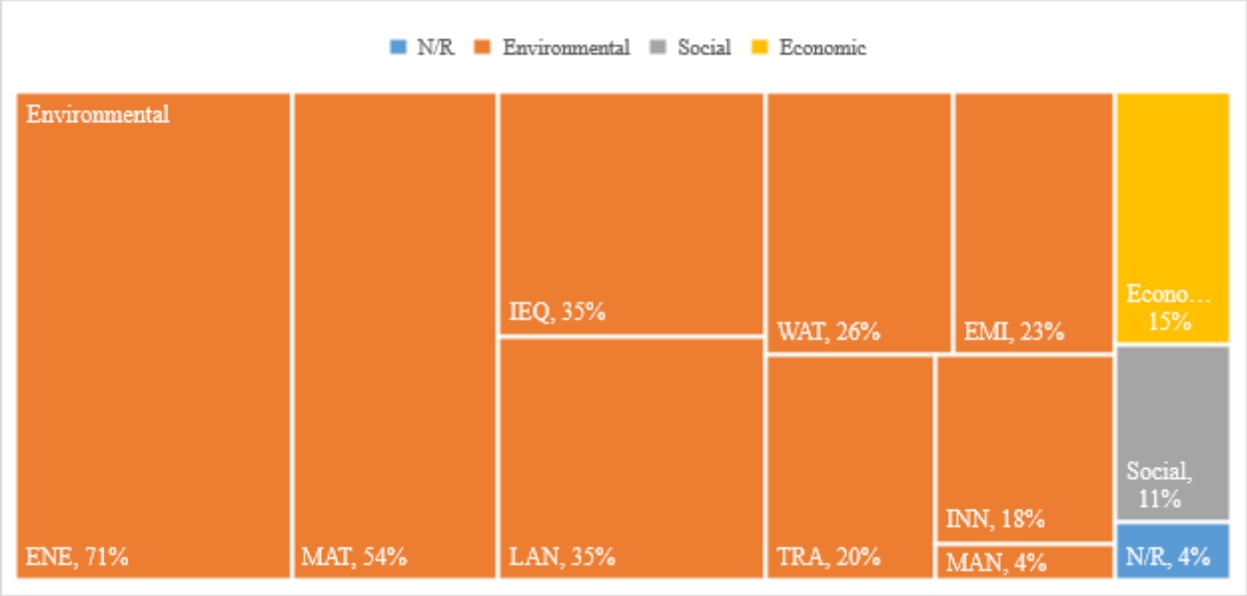


Figure 5: Classification of Articles based on GB Sustainability Area

Note: N/R = not reported; MAN= management; IEQ = indoor environment quality; ENE = energy; TRA = transport; WAT = water; MAT = materials; LAN = land use and ecology; EMI = emissions; and INN = innovation

3.1.4 Classification of Articles by Sustainability Rating Tools

Table 4 shows the classification of the articles based on the sustainability rating tools (SRT) considered in the study. It is important to note that many studies are mainly focused on the multi-criteria tool. At the same time, only one paper by Acampa *et al.* [20] mentioned some of the existing lifecycle-based assessment tools (Building for Environmental and Economic Sustainability [BEES], Building Environmental Assessment Tool [BEAT], and EcoQuantum). Forty percent (40%) of the studies did not report any GBCS, 35% mentioned LEED as a basis for their research, and 10% mentioned BREEAM. Other GBCS such as Green Star (7%), SBTool/SBToolCZ / SBToolPT-H (5%), GBI (5%), among others. has been seldom considered in the existing literature. Furthermore, some of the existing studies by Khoshdelnezamiha *et al.* [48], Olawumi and Chan [49], Mahmoud *et al.* [8], and Ahmad and Thaheem [50] have developed new rating tools (5%) to complement the shortcomings of the existing GBCS.

Table 4: Classification of Articles by SRT

Category	GBCS	Percentage (%)*
Multi-criteria	BREEAM	10%
	LEED	35%
	Green Star	7%
	DGNB	4%
	SBTool/SBToolCZ / SBToolPT-H	5%
	GBI	5%
	Green Mark	1%
	BEAM Plus	4%
	ESGB	2%

	CASBEE	4%
	SVAGRIHA	1%
	G-SEED	2%
	New Tool	5%
	ARCA	1%
	Green Globes	1%
Lifecycle Based	BEES	1%
	BEAT	1%
	EcoQuantum	1%
Not Reported		40%

*Percentage is based on the number of papers with the GBCS per 84 papers

3.1.5 Classification of Articles by Country of Origin

Table 5 shows the number of selected articles from twenty-six (26) countries and specific demographics (CO_2 *emissions, Electric power consumption [EPC], Area, Population, and Rank by country population [R]*) based on the SLR results. Considering the top five countries, almost 15% of the articles were from the United States of America, followed by South Korea (9.52%), Malaysia (7.14%), China (7.14%), and Hong Kong (5.95%). Furthermore, the relationship between the number of articles and certain demographics was explored. It can be deduced that there is a moderate link between the country population and research outputs. This cannot be generalized due to differences in governance and culture system. For instance, India has the highest population, but only one article can be attributed to the country. However, it is essential to note that there may be other articles not covered by Scopus due to their quality and journal reputation. The United States of America ranked second in CO_2 emissions, land area and EPC, which justifies its first position as the country with the leading number of articles. On the other side, South Korea maintained its second position and ranked 12th in population.

Table 5: Country of Publication and Demographics

Country	No.	%	CO_2	EPC	Area	Population	R
United States of America	12	14.29%	5,006,302	12,994	9,833,517	328,239,523	3
South Korea	8	9.52%	620,302	10,497	99,720	51,709,098	12
Malaysia	6	7.14%	248,289	4,652	329,847	31,949,777	16
China	6	7.14%	9,893,038	3,927	9,596,960	1,397,715,000	1
Hong Kong	5	5.95%	43,645	6,083	1,108	7,507,400	23
Portugal	5	5.95%	48,742	4,663	92,090	10,269,417	20
Taiwan	5	5.95%	-	-	35,980	23,340,136	18
Canada	4	4.76%	544,894	15,588	9,984,670	37,589,262	14
Spain	4	4.76%	244,002	5,356	505,370	47,076,781	13
Italy	4	4.76%	320,411	5,002	301,340	60,297,396	11
New Zealand	3	3.57%	34,382	9,026	268,838	4,841,000	24
United Kingdom	3	3.57%	379,025	5,130	243,610	66,834,405	10
Israel	2	2.38%	65,166	6,601	20,770	9,053,300	21
Australia	2	2.38%	375,908	10,071	7,741,220	25,364,307	17
Turkey	2	2.38%	372,725	2,847	783,562	83,429,615	8
Egypt	2	2.38%	238,560	1,683	1,001,450	100,388,073	7
Brazil	2	2.38%	462,299	2,620	8,515,770	212,559,417	6
Slovenia	1	1.19%	12,633	6,728	20,273	2,087,946	26
Lithuania	1	1.19%	12,963	3,821	65,300	2,786,844	25
Switzerland	1	1.19%	34,477	7,520	41,277	8,574,832	22
Czech Republic	1	1.19%	102,218	6,259	78,867	10,669,709	19
Saudi Arabia	1	1.19%	563,449	9,401	2,149,690	34,268,528	15
Germany	1	1.19%	727,973	7,035	357,022	83,132,799	9
Pakistan	1	1.19%	201,150	448	796,095	216,565,318	5
Indonesia	1	1.19%	563,325	812	1,904,569	270,625,568	4
India	1	1.19%	2,407,672	805	3,287,263	1,366,417,754	2
Total	**84**	**100%**					

Note: EPC = Electric power consumption; R = Country rank by population;

3.2. Thematic Analysis

Lu *et al.* [13] emphasized that BIM is still not capable of assessing buildings' environmental and social sustainability in a holistic manner. Furthermore, Zanni *et al.* [51] and Lu *et al.* [13] indicated four sustainability areas not supported by BIM software packages: management, ecological issues, innovative techniques and performance, and transportation conditions. The discussion in this part of the paper is structured based on Green Star Design and As-Built New Zealand v1.0 (Green Star NZ) certification system. It includes nine credit categories: management, indoor environment quality, energy, transport, water, materials, land use and ecology, emissions, and innovation [52]. Due to limited management and innovation credits literature, both were merged as "*Management*

and innovation". Also, there was no discussion for the land use and ecology category. This is because of the unavailability of paper in the SLR that can account for the land use and ecology category. In addition to the credit categories of Green Star NZ, the social and economic dimension of sustainability that is lacking in the GBCS [6] will also be discussed concerning BIM integration. Therefore, the total categories for the discussion based on Green Star credits were reduced to eight categories in this paper.

3.2.1. Management and innovation

The management and innovation criteria are often given less attention in most of the existing GBCS despite its presence in many sustainability research [53, 54]. This is evident in Green Mark GBCS, where less than 2% of the entire credits is allocated to "*Management*" [6]. Gandhi and Jupp [22] mentioned that assessing management and innovation components of green building assessment tools is almost unfeasible with BIM. Hence, future studies could concentrate on developing a qualitative oriented and adaptable approach for credits not achievable with BIM [55].

3.2.2. Indoor environment quality

The AEC industry is responsible for 40% of the total energy use, 32% of CO_2 emissions, and 25% of the generated waste [11, 56]. GB was introduced to mitigate the impacts of buildings on the environment and create better indoor environmental quality (IEQ) with minimal resource utilisation [57]. Furthermore, a building IEQ is crucial to the comfort and wellbeing of occupants [58]. IEQ consist of indoor air quality, acoustic comfort, lighting comfort, visual comfort, indoor pollutants, and thermal comfort based on Green Star.

There have been few studies on integrating BIM and IEQ components in GBCS. Al-Sulaihi *et al.*

[59] developed a framework to integrate IEQ data into the BIM model to detect and track IEQ problems. Marzouk and Abdelaty [60] integrated BIM and wireless sensor network (WSN) for effective monitoring of thermal comfort in subways, an essential ingredient of IEQ. The study revealed that BIM better visualises the building components and IEQ metrics. It also enables efficient control of HVAC systems in an energy-efficient manner. Furthermore, HSE [61] revealed the six factors that influence the thermal comfort of occupants as 1) air temperature, 2) radiant temperature, 3) air velocity, 4) humidity, 5) clothing insulation, and 6) metabolic heat.

Owing to the unavailability of mixed adaptive comfort models in ASHRAE 55 2007 and EN 15251 2007. Studies have included active and passive cooling and heating methods in building simulation modelling. This limitation has led to the introduction of hybrid adaptive comfort models. With the help of Ladybug, the comfort thresholds are adjusted automatically for active cooling and heating systems present in the adaptive model [62]. Amoruso *et al.* [62] measured the indoor comfort based on the adaptive comfort model (EN 15251 comfort class II) using Seoul's Energy Plus simulation and climate data. Lim *et al.* [63] also integrated BIM and Genetic algorithms to compute Overall Thermal Transfer Value (OTTV), which is affected by building envelope materials. Liu and Chen [64] studied indoor lighting and the thermo-environment of a building using Autodesk Ecotect and varying the height of balcony shades. A shade type balcony depth of 2.5m for a window with a 50% opening rate and 3m for 75-100% opening rate windows was recommended. This finding by Liu and Chen [64] connotes that the higher the balcony shade, the more energy-efficient the building becomes.

Acoustic comfort is another critical component of IEQ [65]. Minimal work has been done in this aspect, but there are several software packages for acoustic analysis [66-69]. The findings concurred with that of Azhar and Brown [70] where a negligible number of the respondents

indicated that they use BIM-based software packages for sustainability analyses. Wu and Clayton [71] developed a plugin with auralization and visualisation features using the Revit application programming interface (API). The plugin is designed to extract geometric and component information from BIM models and use it for acoustic calculations (reverberation and sound intensity level).

3.2.3. Energy

The AEC industry contributes significantly to greenhouse gas generation and global warming due to the enormous primary energy consumption [33]. In most green rating systems used in many countries, energy-related credits account for a large percentage of the overall certification score [27]. Montiel-Santiago *et al.* [72] revealed that BIM application for energy analysis of existing buildings has great potential in reducing energy use and CO_2 emissions.

Pučko *et al.* [73] introduced a systematic approach for energy and cost analysis of building envelop using ArchiCAD, DesignBuilder and Vico Office. Venkatraj *et al.* [74] used Kieran Timberlake's Tally and Autodesk Green Building Studio (GBS) to compute embodied and operating energy. The study quantitatively revealed that altering the amount of insulation, glazing type, window to wall ratio and depth of external shades to reduce operating energy may lead to the use of energy-consuming. Rodrigues *et al.* [75] compared the performance of GBS and ECO.AP for energy analysis. It was revealed that GBS is suitable at the early design stage of a building with poor performance Galiano-Garrigós *et al.* [25] evaluated existing BIM-enabled tools for assessing energy performance and CO_2 emissions. The study showed that GBS, Herramienta Unificada Lider-Calener (HULC), Sefaira and DesignBuilder perform better than other energy supply tools because their values were close to the actual values. Galiano-Garrigós *et al.* [25] suggested that

incorporating crossed ventilation or thermal energy inertia could help minimise the differences in values between simulations and actual energy and CO2 emissions values.

Jalaei and Jrade [76] developed a plugin integrated into the Autodesk Revit environment to act as a decision support system to improve building material and components selection during the conceptual stage to achieve high energy efficiency. It was also revealed that gbXML contains more data for energy analysis at the conceptual stage of building. Furthermore, the discrepancies were observed in the results of Autodesk Revit, Integrated Environmental Solutions Virtual Environment (IES-VE), and Ecotect owing to different calculation methods and engines, including material types variation associated with the tools. This signifies that location has an impact on energy consumption. Ryu and Park [27] proposed a methodology to improve the reliability and productivity of energy simulation with a focus on model verification using the check function on Revit, gbXML viewer, and FZKViewer. The finding suggests that an effective model check reduces errors in simulation results. Hence, this purports that model verification should be included in the framework for BIM-based sustainability assessment in future studies. Andreani *et al.* [77] explored the impacts of building components on sustainability by using Autodesk Revit and IES-VE to evaluate the performance of the components. The BIM-based sustainability assessment revealed a wide range of benefits if properly integrated. Wei and Chen [78] explored energy consumption analysis using Ecotect from a value engineering perspective to optimise building costs. Akcay and Arditi [79] developed a simple tool aimed at automating the "*Energy Performance*" criteria under "*Energy and Atmosphere*" in LEED V4 using Autodesk Revit, Sefaira, MS Excel and RSMeans. Macro was developed in MS Excel to automate the entire process. Chen *et al.* [80] also developed a model to enhance energy performance assessment in building using Autodesk Revit, Vasari and GBS. It was revealed that building components could

be adjusted appropriately to achieve the desired energy use intensity (EUI).

Bahar *et al.* [81] indicated that condensation performance impacts building energy savings and living environments. As a result, Hong *et al.* [82] developed a methodology to evaluate the condensation performance of a building at the design stage using Autodesk Revit and Physibel Trisco to address the shortcomings of the traditional method, which reduces productivity and is time-consuming. Furthermore, Reeves *et al.* [83] developed a guideline for selecting appropriate software for building energy modelling after evaluating 12 software packages using a set of criteria (interoperability, usability, available inputs, and available outputs). The guideline is critical as it guides users while selecting software packages that will match a building energy assessment.

3.2.4. Transport

Within the last few years, efforts have been made by researchers to integrate web map service (WMS) and BIM tools for sustainability rating enhancement. The primary function of WMS is to help users extract map data from geographical information systems (GIS), execute route planning, generate documentation including proof map images with special mark information where necessary and other location-related data [12]. With the aid of application programming interface (API) keys, the WMS provides the HyperText Transfer Protocol (HTTP) port for developers, giving them access to a wide range of map information. A web-compatible open-standard data format called JavaScript Object Notation (JSON) is returned [84]. The two languages that can be used to receive information from a web server are JSON and eXtensible Markup Language (XML). However, Wang [84] indicated that JSON has high efficiency compared to XML. The architecture of WMS is shown in Figure 6. The previous studies that have integrated BIM and WMS are discussed below.

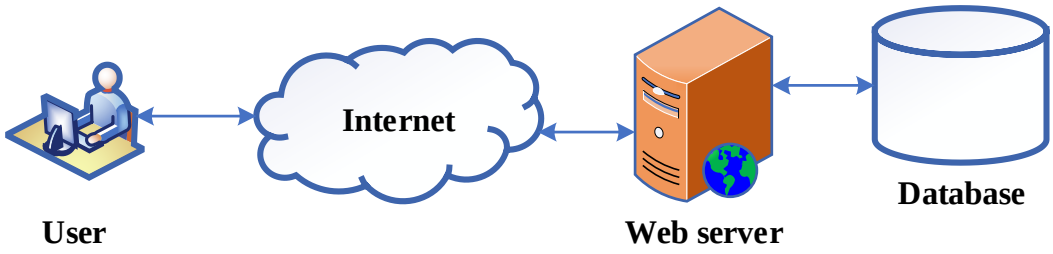


Figure 6: Architecture of Web Map Service (WMS)

Chen and Nguyen [85] developed a plugin to achieve a part of sustainable cities criteria (location and transport analysis) of the LEED rating system using Autodesk Revit and Web Map Service (WMS). The WMS used was Google Map API integrated as a plugin in Autodesk Revit. The developed plugin simplified calculating credit points for the two significant credits under the Sustainable Sites category (Credit 2 and 4.1). Similarly, Chen and Nguyen [4] developed an integrated BIM and Web Map Service (WMS) decision support system to enhance supply chain management processes of building materials using Google Map API. Li *et al.* [86] explored the possibility of integrating Dynamo BIM and WMS using Python and Dynamo core. An integrated tool that can be used to achieve the "*Access to Quality Transit and Diverse Uses*" criteria in LEED *v*4 was developed based on "Amap", a prominent WMS in China only. The tool could be used for the evaluations of publicly available diverse uses and transportations. More recently, Jalaei and Mohammadi [12] developed a LEED assessment plugin in Autodesk Revit with a transportation module that utilises Google Map API to count the number of public services regarding the project site and give a rating based on the results.

A summary of the studies on BIM-enabled transportation analysis for GBCS criteria is given in Table 6. It is observed that most of the studies were aimed at developing a plugin (as an end product) while only Li *et al.* [86] developed a methodology by integrating Dynamo and "Amap"

WMS. Furthermore, LEED GBCS is the only one considered in all the four studies that have attempted the automation location analysis credits. Over 70% of existing studies use Google Map API due to its versatility and flexibility. Conversely, there is a need to explore other WMS strengths and weaknesses. It has been established that the "*Amap*" WMS has geographical and language limitations which will influence its adoption in other locations.

Table 6: Matrix for previous research on transport-related credits

S/N	Author	Country	GBA Tool	Programming Language					Map API		Support Tool		End Product
				Python	C#	HTML	JSON	XML	Google Map	Amap	Dynamo	Autodesk Revit	
1	Chen & Nguyen (2017)	Taiwan	LEED		✓	✓	✓		✓			✓	Plugin
2	Chen and Nguyen (2019)	Taiwan	LEED NC 3.0		✓	✓	✓		✓			✓	Plugin
3	Li *et al*. (2019a)	China	LEED v4	✓						✓	✓		Methodology
4	Jalaei & Mohammadi (2020)	Canada	LEED v4		✓	✓	✓		✓			✓	Plugin

3.2.5. Water

Water is an essential part of GB, which account for a significant portion of most existing GBCS. There is a lack of research regarding automating BIM for water efficiency analysis [65], although some existing BIM-GB applications such as EnergyPlus, EcoDesigner and Ecotect offer metrics on water usage analysis. Recently, Liu *et al.* [87] developed a water efficiency framework for sustainable building design and construction management, which is yet to be validated. The framework would act as a road map for potential software development in future. However, there is a need to develop an adaptable plugin or framework for GBCS based analysis.

3.2.6. Materials

The material production stage, including the operation stage, accounts for many embodied emissions in buildings [88]. Adopting green-certified materials reduces energy consumption and emissions, including reducing lifecycle costs [89]. Thus, there is a need for careful selection of material at the design stage of buildings, considering proximity and sustainability. Cheng *et al.* [90] categorised the lifecycle of greenhouse gases (GHG) emissions into three stages based on lifecycle assessment (LCA) theory. These stages include the materialisation stage (GHG from material production, transportation, and construction process on-site), operation and maintenance stage (GHG from electrical and mechanical components) and demolition stage (GHG from material waste disposal and demolition activities).

Similarly, Najjar *et al.* [91] classified LCA methodology into three levels for easy computation. These levels include LCA of construction materials, LCA of the entire building, and LCA of construction stage hinged on the three pillars of sustainability. Different tools are used to analyse each level to estimate the actual environmental impacts. For instance, GaBi (Germany), SimaPro, LCE, OpenLCA, Umberto, TEAM (France), BEES, TAKE-LCA, among others are applied in LCA of construction materials. Prominent tools like LEED, Green Star, BREEAM, GBTool, and SBTool are used to analyse LCA at the construction stage [91]. At the same time, tools like BRI LCA (energy and CO_2), Athena Environmental Impact Estimator (Canada), Green Building Studio, EcoQuantum, LISA, Envest, Energy Plus, IES-VE, Autodesk Ecotect, among others are used to analyse the LCA of the entire building.

Al-Ghamdi and Bilec [92] conducted a comparative assessment of three common LCA tools (SimaPro, Athena Environmental Impact Estimator, and Kieran Timberlake's Tally). The study

revealed discrepancies in the selected LCA tools due to different methodologies and databases used for calculations. As a result, there is variation by 10% and 17% in embedded and operational impacts, respectively. Similarly, Schultz *et al.* [93] conducted a comparative analysis between Athena Impact Estimator and Kieran Timberlake's Tally. It was reported that there is a disconnection between design and sustainability assessment at the early stage of buildings. Furthermore, it was revealed that there is a lack of an elaborate database for the LCA of materials. Also, there is a need for existing and new sustainability tools to incorporate the concept of transparency and benchmarking in LCA evaluation.

Najjar *et al.* [91] integrated BIM and LCA using Autodesk Revit, GBS, and Kieran Timberlake's Tally to assess designs at the early design stages to minimise the environmental impacts of building materials. Renewable energy systems were suggested to mitigate excessive energy consumption in buildings. Thus, it was concluded that integrating BIM and LCA benefits sustainable development, decision-making, and environmental protection. Long *et al.* [94] used BIM-enabled LCA tools to assess the sustainability of building to be printed. Chowdary and Gunarani [89] set alternative construction materials that offer more energy savings using BIM and Integrated Environment Systems Virtual Environment (IES-VE). Ansah *et al.* [88] created an integrated life cycle assessment framework to assess the type of façade that is more sustainable using BIM, IES-VE and ICE v2.0 database. The study revealed that stabilised earth block façade performs better than other façades (shotcrete insulated composite, steel insulated composite, and concrete block and mortar façade) in terms of cumulative energy demand, global warming potential and cost. Ilhan and Yaman [95] developed a tool to facilitate the assessment of the material criteria in BREEAM using ArchiCAD and Visual studio.

3.2.7. Emissions

Chowdary and Gunarani [89] demonstrated that green-certified products reduce CO_2 emissions and electricity consumption by combining Autodesk Revit and IES-VE for sustainability analyses. Furthermore, Galiano-Garrigós *et al.* [25] revealed that Autodesk Revit and HULC perform better for CO_2 emissions assessment at the early and advanced design stages.

3.2.8. Social and economic aspects of sustainability

It has established that sustainability's economic and social dimensions are of great importance [50]. Social sustainability guarantees a safe and healthy environment for all project stakeholders, including end-users, while economic sustainability is more concerned about project efficiency and viability. Little attention has been paid to sustainability's social and economic dimension in most of the existing GBCS [6, 96]. Furthermore, most of the GBCS that have been developed over the years concentrated on the environmental aspects of sustainability, neglecting the social and economic aspects [6, 54, 97, 98]. In the same vein, Illankoon *et al.* [53] acknowledged that almost 75% of LEED credits are related to the environmental aspect of sustainability, 20% can be attributed to the social aspect. In contrast, the economic aspect is seldom represented in LEED.

Ahmad and Thaheem [50] stressed that BIM still has a long way to integrate the social dimension of sustainability into BIM. Also, the economic aspect of sustainability is not left out of this trend. Incorporating corporate social responsibility (CSR) and BIM into GBCS gives it the ability to act as a "*social integrative system*" [96]. Reychav *et al.* [96] established that existing BIM guidelines only focused on stakeholder management, teamwork, and participation. It was revealed that tenants are not involved in a project's design and construction stage, negating the equity aspect of social

sustainability. The research also presented CSR as a basis for BIM and sociocultural sustainability integration.

Additionally, Zanni *et al.* [99] argued that a clear line of communication aid an effective, sustainable building design process. This emphasizes the need to keep project stakeholders, including end-users (tenants), alongside up-to-date information regarding the project. Similarly, Kim *et al.* [100] used the number of workers needed to represent the social aspect of a large-scale development master plan. Yung and Wang [98] utilised employment and housing to describe the social components of sustainability. Subsequently, Ahmad and Thaheem [50] developed a conceptual framework for social sustainability assessment BIM plugin applicable to residential buildings.

On the other side, studies have attempted to account for the economic dimension of sustainability in evaluation systems. For instance, Pavlovskis *et al.* [101] represented the economic criteria with sub-criteria such as: investments, net present value, payback period, profitability index, the average rate of return, and internal rate of return while developing an evaluation system for asset redevelopment using multi-criteria decision making (MCDM) tool and BIM. Kim *et al.* [100] used cement demand, building construction cost, and infrastructure construction cost as economic metrics while developing a decision support system for master plan sustainability assessment.

4. DISCUSSION OF RESULTS

This section of the paper contains an elaborate discussion of the results. For better comprehension, the section is divided into five key areas, which include: 1) trends in the BIM-GBCS domain, 2) GBCS sustainability areas, 3) BIM-GB software in the AEC industry, 4) internet of things (IoT), Blockchain, BDA and Ontology Applications in BIM-GBCS, and 5) gap spotting.

4.1. Trends in the BIM-GBCS Domain

There has been increasing interest in BIM and GBCS between 2019 and 2020; this can be attributed to the various government policies that have been introduced to combat climate and other sustainability issues. For instance, in the United States of America, the City of Sunnyvale amended their green building standards in 2019 to include non-residential buildings above 5,000 sq. ft [42]. Similarly, the City of Alexandria also introduced a green building policy based on LEED in 2019 [41]. Also, the coronavirus pandemic led to the increasing interest among researchers and key stakeholders of the construction industry to develop a sustainable building that can minimize the spread of the virus [40, 45, 47].

Figure 7 shows the GBCS and BIM integration considered in the selected articles and their respective percentage contribution. LEED (35%) is the most researched GBCS in terms of BIM automation of credits. Followed by other GBCS such as Green Star, GBI, BREEAM, DGNB, SBTool/SBToolCZ/SBToolPT-H, Green Mark, BEAM Plus, ESGB, CASBEE, SVAGRIHA, Green Standard for Energy and Environmental Design (G-SEED), ARCA, Green Globes, BEES, BEAT, and EcoQuantum. Olawumi and Chan [49] and Mahmoud *et al.* [8] have also integrated BIM with the new GBCS they developed.

Table 7 shows the GBCS and their life cycle coverage based on the BS EN 15978 standard. It is observed that all the GBCS covers the product and construction phase (A1-A5). Almost all GBCS cover B1, B6 and B7, while the other sub-phases are lowly represented. This highlight the need for an elaborate LCA framework in the GBCS. These findings agree with Politi *et al.* [102], which emphasized the lack of information and transparency in the LCA framework of GBCS. Solving

this issue would require effective collaboration between AEC industry stakeholders in the construction supply chain.

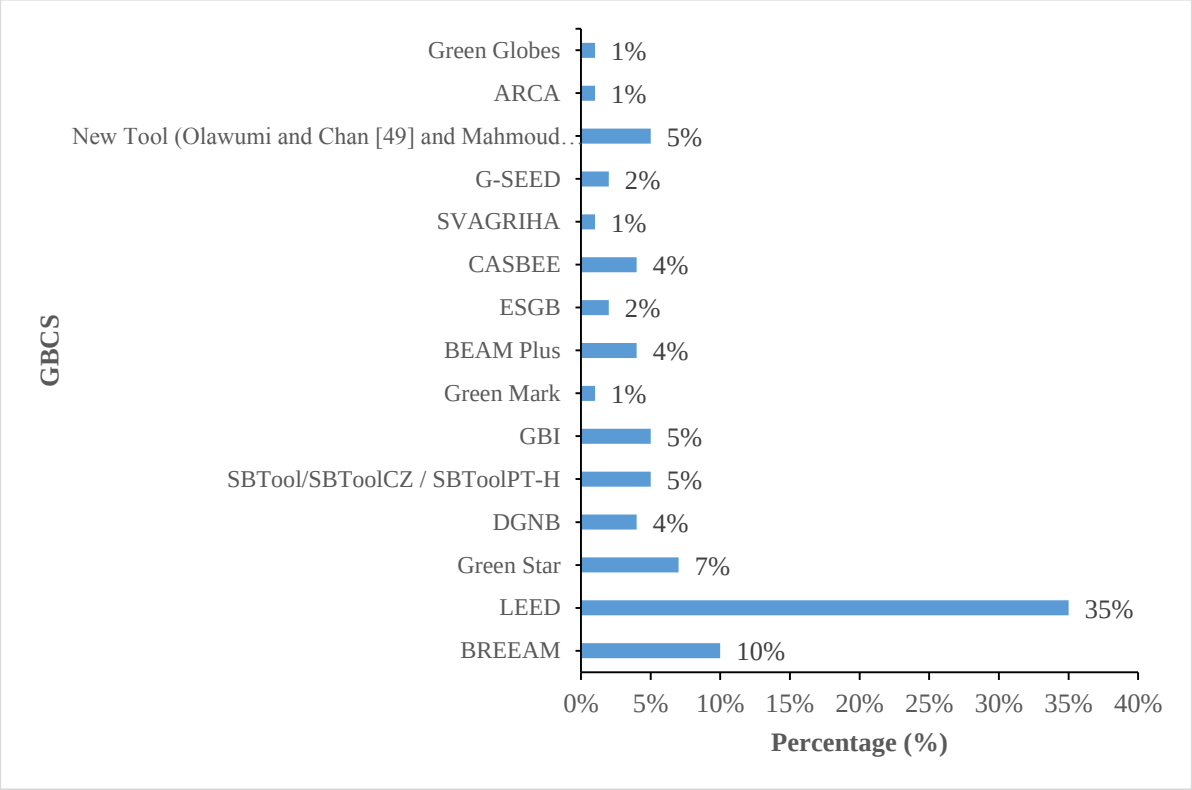


Figure 7: GBCS and BIM Integration in the Selected Papers

Table 7: GBCS and Building Lifecycle Coverage

GBCS	Product			Constr		Use							End of Life			
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
BREEAM	✓	✓	✓	✓	✓	✓					✓	✓		✓		✓
LEED	✓	✓	✓	✓	✓	✓					✓	✓		✓		✓
Green Star	✓	✓	✓	✓	✓	✓					✓	✓		✓		✓
DGNB	✓	✓	✓	✓	✓						✓					
SBTool/SBToolCZ / SBToolPT-H	✓	✓	✓	✓	✓						✓					
GBI	✓	✓	✓	✓	✓						✓					
Green Mark	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
BEAM Plus	✓	✓	✓	✓	✓	✓					✓	✓				
ESGB	✓	✓	✓	✓	✓	✓					✓	✓				
CASBEE	✓	✓	✓	✓	✓	✓					✓	✓				
SVAGRIHA	✓	✓	✓	✓	✓	✓					✓	✓		✓		✓
G-SEED	✓	✓	✓	✓	✓	✓										

New Tool (Olawumi and Chan [49] and Mahmoud et al. [8])	✓	✓	✓	✓	✓	✓					✓	✓				
ARCA	✓	✓	✓	✓	✓	✓					✓	✓				
Green Globes	✓	✓	✓	✓	✓	✓					✓	✓				
Total	**15**	**15**	**15**	**15**	**15**	**12**	**1**	**1**	**1**	**1**	**14**	**10**	**1**	**5**	**1**	**5**

4.2. GB Sustainability Areas

The environmental dimension of sustainability is the most researched area compared to the social and economic dimensions. Based on Green Star criteria, energy is the most researched area. Few papers in other areas such as management, innovation, water, land use and ecology, and transport that are under-researched. Particularly, the management area is poorly researched in the BIM-GBCS domain. This is because many of the points available in the management criteria do not need automation. However, this management credit information could be built as part of the BIM model.

4.3. BIM-GB software in the AEC industry

The foundation of BIM-based GB assessments is the availability of accurate qualitative and quantitative data. Furthermore, these data are being affected by interoperability issues, resulting in data loss and excessive manual efforts [17, 103]. Interoperability is one of the key setbacks in integrating BIM and GBCS. Barreca *et al.* [104] observed a lack of integration between BIM and laser scanning software tools. Chong *et al.* [105] emphasised a need to improve the interoperability between existing BIM and simulation tools, including laser/point to cloud tools.

Venkatraj *et al.* [74] observed some bottlenecks in the interoperability between Autodesk Revit and GBS which caused incorrect replication of U-values in GBS. The pre-populated lists of construction assembly data were used, and GBS results were verified with e-Quest. Regarding

energy-related BIM-GB application, studies have shown discrepancies between GBS results and actual energy use across different geographical locations [75]. Similarly, Reeves *et al.* [83] revealed IES VE, Autodesk Ecotect, and GBS as reliable building energy modelling software packages. Furthermore, it is essential to note that lifecycle assessment tools (LCA) calculations are based on different lifecycle inventory techniques, including process-based, input/output-based and hybrid with varying sources of data and system boundaries [74]. Chong *et al.* [105] highlighted the need for new BIM tools that will cover the entire building lifecycle because most existing tools are limited to the design stage.

The SLR revealed eighty-five (85) software packages that have been used in the existing literature. After that, they were grouped into sixteen (16) categories (BIM authoring, BIM model viewer, LCA, energy analysis, cost analysis/quantity take-off, point/scanning to the cloud, ventilation analysis, spreadsheet/database, GIS/Map, thermal analysis, computational/programming, scheduling, document management, collaboration support, acoustic analysis, and ontology) based on their functions. Figure 8 shows the conceptual mapping for BIM-GB software and GBCS integration. Various software tools can be applied to the different dimensions of sustainability in a GBCS. However, it is essential to note that not all the software packages used in the conceptual mapping are still relevant. Some of the software packages (such as Autodesk Ecotect, Autodesk Vasari, among others) are outdated and not available for use anymore.

Also, Tagliabue *et al.* [106] reported that the current data schema (IFC) widely used could not accommodate all the data required for GB sustainability rating using GBCS. Furthermore, research has indicated the lack of social and economic indicators in many existing GBCS [6]. This shortcoming calls for more research into potential software packages that can be applied to these

dimensions of sustainability. Additionally, tools could be developed after incorporating the social and economic indicators substantially into the existing GBCS.

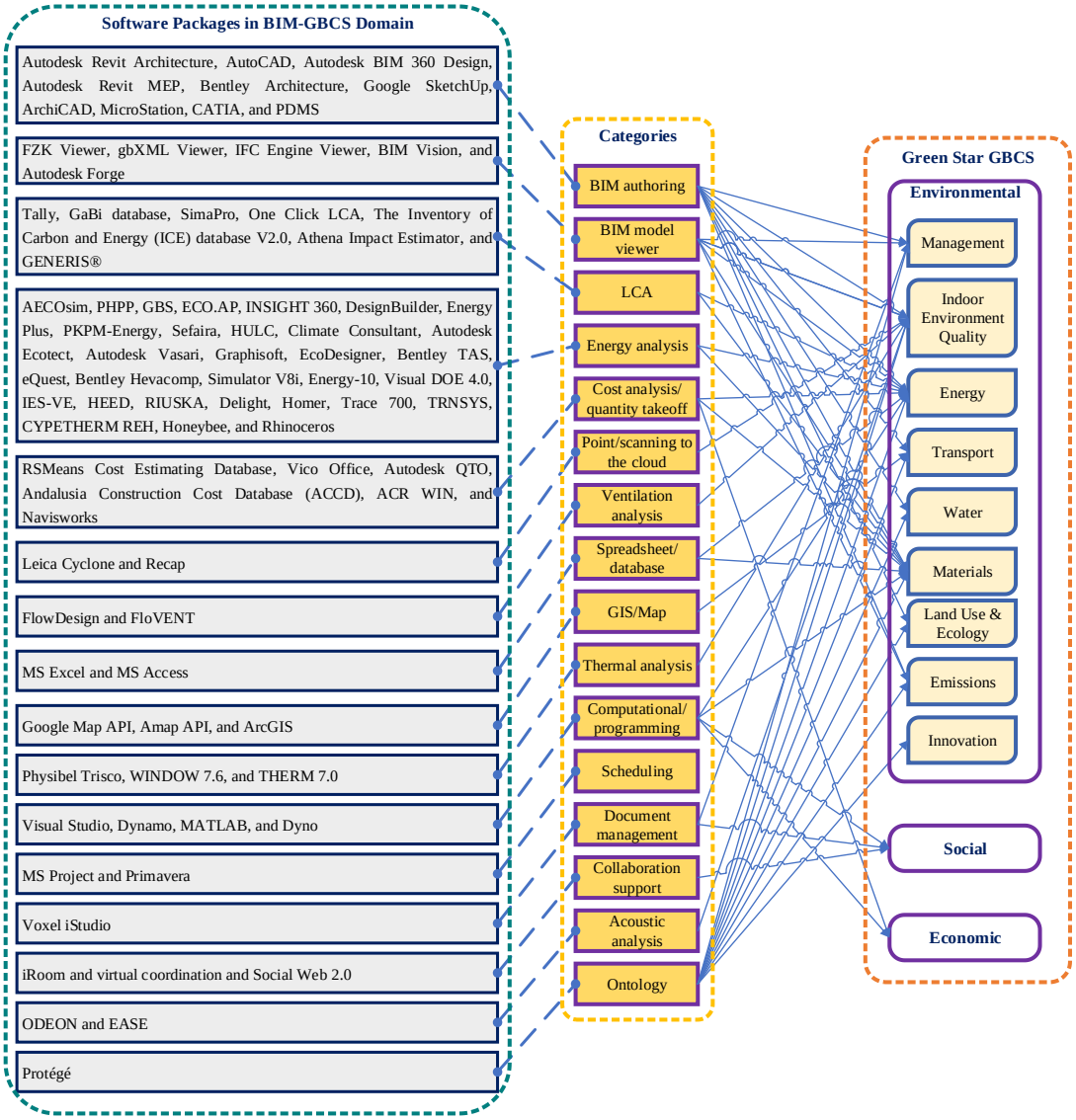


Figure 8: Conceptual Mapping for BIM-GB Software and GBCS Integration

4.4. IoT, Blockchain, BDA and Ontology Applications in BIM-GBCS

The combination of IoT and BDA with GB is in its embryonic stage but is already creating rekindled curiosity in several areas [107]. The prominent BDA techniques include statistics (such

as correlation and regression), machine learning (such as neural networks and support vector machine), data mining (such as classification, simulation, visualisation, and clustering), and optimisation (such as genetic algorithm, simulated annealing, and tabu search) [108]. Recently, Jalaei and Mohammadi [12] applied the K Nearest Neighbour (KNN) algorithm to predict missing credits based on previously-rated buildings data. Similarly, Cheng and Ma [109] used machine learning techniques (Artificial Neural Network, KNN, regression and correlation) to select related previously rated green buildings based on set targets. The study revealed that machine learning could be applied to develop interactive recommender systems for GBCS evaluations. Lim *et al.* [63] used the genetic algorithm (GA) to predict building envelop OTTV. The study demonstrated that GA helps to improve the accuracy of predictions and reliability. In the same vein, Yu *et al.* [110] utilised GA to optimise the accuracy of artificial neural networks (ANN) predictions for energy efficiency and thermal comfort in building design. The literature presents a use case of BDA techniques in enhancing the assessment process of green building. BDA techniques could be used to develop a predictive model that can shorten the assessment time of GB.

Furthermore, Geng *et al.* [57] stressed the importance and benefits of IoT in revolutionising data collection for GB assessment variants. Bapat *et al.* [111] integrated BIM and IoT for energy management of rail stations using Arduino board and sensor. The study revealed that implementing the proposed BIM-IoT framework for energy management will result in a 25% reduction in operational cooling load. Similarly, Li *et al.* [112] integrated BIM with blockchain, IoT, and cyber-physical systems to enhance the management and connectivity of prefabricated building construction processes. This helps increase the resilience and sustainability of prefabrication building construction.

Nonetheless, the GBCS could also benefit from integrating these technologies with the certification process. For instance, Tagliabue *et al.* [106] integrated BIM and IoT to facilitate real-time sustainability rating using LEED at the building operation stage. The research majorly covered the "*materials and resources*" and "*indoor environmental quality*" of GBCS. IEQ variables such as CO_2, temperature, humidity, and volatile organic compound) were measured through IoT-enabled sensors while building comfort data was collected through a specialised application. Hence, more research is needed to extend the sustainability areas that can be assessed in real-time using emerging technologies.

Recently, integrating ontology and BIM-GBCS is beginning to attract the attention of researchers in the AEC industry [32, 113]. Ontology has been adapted to the BIM domain, leading to the development of BIM ontology. BIM ontology has four crucial objects: concepts, attributes, relations, and knowledge Sets [114]. Noy and McGuinness [115] supported the adaptation of existing ontologies into new ones. Gruber [116] emphasized clarity, coherence, extensibility, minimal encoding bias and minimum ontological commitment as the criteria for shared ontologies. The BIM ontology stemmed from three major ontologies, namely, *existing ontologies* [114], the *general technological ontology* [116] and the *general process ontology* [117]. BIM ontology can be described as a colloquial, flexible, hypothetical domain-based ontology employed for knowledge gathering and effective communication between stakeholders or BIM players in a construction project. It portrays knowledge transfer between project BIM players, expectations, and standards. It also promotes the validation of conceptual models [114]. Figure 9 shows the transition from BIM ontology to BIM-GBCS ontology.

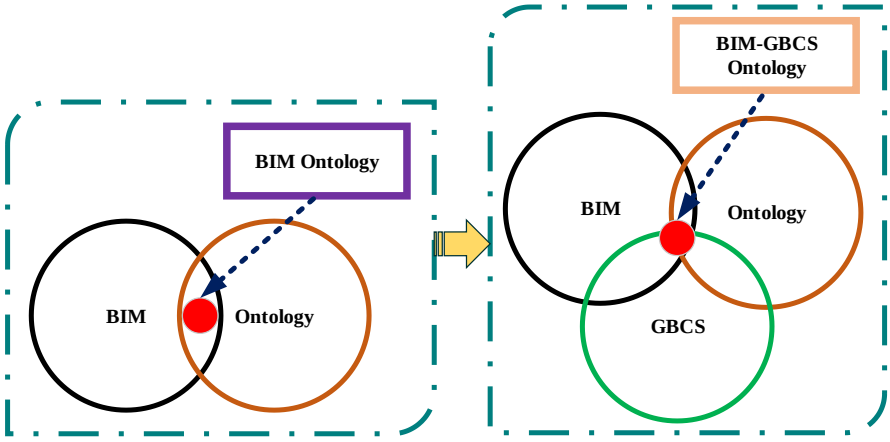


Figure 9: Transition from BIM ontology to BIM-GBCS ontology

Jiang *et al.* [113] revealed that integrating BIM and ontology for GB evaluation offers potential energy reduction, time efficiency, and accuracy. Zhang *et al.* [32] developed an intelligent green building rating framework for calculating GB rating scores using semantics and a social approach. The framework also incorporates social, and BIM aspects, including the use of the social web and Autodesk Forge for effective communication. Similarly, Jiang *et al.* [113] combined BIM and ontology to aid GB evaluation. Jess rule engine with semantic web rule language (SWRL) rules and ontology web language (OWL) was integrated, while Autodesk Revit was used to extract quantities for the evaluation. Table 8 shows a summary of previous research on ontology-based BIM-GBCS evaluation. It is evident that most of the existing studies only focused on the Chinese GBCS (ESGB), and there is limited application of ontology-based evaluation using BIM and ontology authoring software to other existing GBCS. Also, it is noted that SPARQL, which is one of the flexible and powerful query languages, is rarely used. SPARQL allows the Resource Description Framework (RDF), including its benefits over traditional databases [118].

Table 8: Previous Studies on Ontology-based BIM-GBCS Evaluation

S/N	Authors	GBCS	Credit Criteria	BIM Software		Ontology Language				Software
				Autodesk Revit	Autodesk Forge	Jess rule engine	OWL	SWRL	SPARQL	Protégé
1	Jiang, Wang, & Wu (2018)	ESGB	Land saving and outdoor environment (Clauses 4.2.1, 4.2.2, and 4.2.3)	✓	×	✓	✓	✓	×	✓
2	Zhang, Zhang, Guo & Xiong (2019)	ESGB	95 articles identified from the ESGBC	✓	✓	✓	✓	✓	×	✓

4.5. Gap Spotting

Gap spotting is achieved by critically synthesizing the available literature on the subject matter with the view to identify gaps based on the following gap-spotting modes: 1) *confusion* (competing explanations), *neglect* (overlooked area, under-researched, and lack of empirical support) and *application spotting* (extending and complementing existing literature) [34]. This synthesis gave a rationale for the areas of future research directions.

4.5.1. Confusion spotting

The main purpose of this spotting is to uncover confusion in BIM-GBCS existing literature [34]. Carvalho *et al.* [30] noted the UK BREEAM 2014 has a low level of BIM integration with 24% of its criteria assessable. TheLEED v3 criteria without Pilot Credits have 67% of its criteria assessable with BIM. Alwan *et al.* [16] findings also revealed that BIM could help estimate 14 credits of LEED. The SBToolPT-H, one of Portugal's prominent sustainability assessment tools, has 68% of its criteria practically assessable with BIM. However, it was indicated that it is possible to theoretically assess 96% of SBToolPT-H [11]. In contrast, Carvalho *et al.* [119] demonstrated that 52% of SBToolPT-H criteria could be achieved with Autodesk Revit.

Despite the level of development in the BIM domain, it has not been fully utilised for sustainability evaluations [120]. This drawback can be attributed to a lack of research in other sustainability areas, constant concentration on energy-related credits, and differences in the credit structure of GBCSs. Hence, there is a need for new strategies to minimise gaps between BIM technologies and GBCS [22]. The strategies will foster sustainable development and improve the sustainability decision-making [121]. There is also confusion around discrepancies among existing BIM-GB analysis software packages. Most BIM-GB tools give different results even when tested with a baseline project [92]. This raises severe problems regarding the number of variations expected from actual values. Schultz *et al.* [93] have called for transparency in BIM-GB calculations. It is believed that this will help the users make necessary additions and subtractions when necessary when the entire processes are understandable.

This section maximised the potential of confusion spotting. Firstly, it is evident that there is still disagreement among authors regarding the GBCS credits assessable with BIM, leading to gaps between BIM technologies and GBCS. Although different GBCS used in various countries have their differences, one of the major reasons for this disagreement. Nonetheless, it was observed that most of the studies that stated certain percentages have not thoroughly validated their speculations. This will help automate GBCS processes, which are mostly manual at the moment and reduce waiting time for GBCS certificates.

Consequently, a study is required to validate the speculations in previous research regarding the number of credits assessable with BIM. Secondly, several authors have revealed different percentage differences between the results of BIM-GB software packages with no guideline in benchmarking the outputs for these software packages. Furthermore, the lack of transparency

between the computation processes of different software packages has also fuelled the differences in their outputs.

4.5.2. Neglect spotting

This aspect seeks to spot areas of BIM-GBCS that have been neglected in the existing literature. It is regarded as the most common method of establishing research questions [34]. Many studies have concentrated on an aspect of GB, thereby making assessing GBCS ambiguous and complex [122]. Also, these studies are mostly centred on energy [12, 72], materials [122, 123], and location and transportation [4, 12, 85, 86]. Among these sustainability areas, the energy-related credits are commonly researched, while credits/sustainability areas are potentially overlooked [33]. The SLR revealed that the water, land use and ecology, socio-economic, and emissions sustainability areas are underrepresented in the BIM-GBCS domain. This finding concurred with Al Hattab [124], where it was reported that land protection, public transport, heritage, community, acoustics, and fire emergency are underexplored.

Also, only one study has embraced the concept of biodiversity criterion assessment in a BIM environment [125]. These necessitate the need for future research to focus on any of the neglected areas to develop a comprehensive BIM-based framework or tool for holistic GBCSs assessments. Furthermore, the LEED rating system has the highest number of researches in the BIM-GBCS. Thus, most researchers tend to neglect other GBCSs and focus solely on LEED because it cuts across many territories worldwide [17]. It is important to explore other GBCSs to have a more generalised BIM implementation for GB evaluations due to differences in GBCSs across territories.

The acoustic component of IEQ is currently under-researched, and there are very few papers available. This can be a result of numerous software packages available for acoustic analysis. However, no study has compared the performance of these software packages. This comparison will uncover the discrepancies in their outputs. Thus, the acoustic part of IEQ needs more research regarding integrating it with BIM. BIM offers numerous benefits, including visualisation, which will enhance acoustic evaluations.

Furthermore, it is reflected in the literature that studies have concentrated on developing guidelines or frameworks for evaluating the software packages to be used in building energy modelling [83]. Other sustainability areas are being neglected, and this calls for the development of a comprehensive framework or guideline that will consider software packages for all aspects of sustainability in a GBCS. More recently, ontology-based evaluation of credits criteria in GBCS using BIM has gained the attention of a few researchers, but most of them concentrated on the Chinese GBCS (ESGB) [14, 32, 113]. This focus on ESGB portends that other certification systems are being neglected. It calls for more research in adapting the same process for other GBCS and expanding the coverage to include more sustainability criteria in the existing GBCS.

Sustainability consists of three critical pillars, which include social, economic, and environmental dimensions. The social and economic dimensions of sustainability have little or no points in most existing GBCS. Although, studies have attempted to design new GBCS that will include more social and economic dimensions [6-8, 126]. However, most of these new GBCSs are still yet to encompass the social and economic dimensions satisfactorily. Studies by Ahmad and Thaheem [50] and Atanda [127] have explored the concept of social sustainability in the BIM-GBCS domain without integrating the developed indicators and frameworks into any of the existing GBCS. Furthermore, a framework to satisfy the economic evaluation of buildings in GBCS and

the need to integrate these social and economic indicator frameworks into the existing GBCS is required.

4.5.3. Application spotting

This helps spot new BIM applications for GBCS in existing literature [34]. BDA and IoT are beginning to gain relevance in the GB and BIM-GBCS domains. Currently, BDA techniques are used to predict energy-related and thermal-related criteria [63, 110]. It has also been used to develop a recommender system that can suggest closely related previously rated LEED GB based on certain input parameters [109]. BDA and IoT can be integrated in future to enhance data management, analysis and the GBCS evaluation process. BDA will be used to analyse data generated by the IoT devices to provide tools for process automation.

Furthermore, Blockchain is another emerging technology that can improve the GB certification process. It has been applied in decentralizing energy production and consumption [128] andcarbon credit acquisition [129]. Blockchain will decentralize the GBCS certification process and make it more transparent and time-efficient. In addition, blockchain could help solve the issues of data falsification, transparency and integrity in building LCA [130]. Blockchain can also verify the certificates issued after the GBCS assessment process and reduce human efforts. The verification and traceability potential of blockchain can be maximized to verify Green Star NZ certificates using the hash function of blockchain. A hash would be assigned to every Green Star NZ certificate issued by New Zealand Green Building Council (NZGBC), which can be verified easily on the blockchain network. This would help reduce the risk of Green Star NZ certificate falsification.

A considerable amount of manpower is expended in assessing a building using GBCS, and it is always time-consuming. Yadav and Singh [131] reported that less manpower is required when blockchain technology is well implemented. However, the required manpower needs to be highly

skilled. Sadia *et al.* [132] stated that blockchain technology helps reduce the amount of manpower required during an election process. Doan *et al.* [133] acknowledged that the current assessment process takes time (See Figure 10). Using the current assessment process flow adopted by NZGBC to assess the sustainability of buildings, it takes almost two months to complete the first round of the assessment. The second round takes nearly four months.

Consequently, around six months is used to assess a building and manpower are heavily invested to achieve the desired outcome. Certain aspects of the assessment process can be automated using *Smart Contract* powered by blockchain. This will help reduce the amount of time and manpower utilized. For instance, there may be a significant reduction in the number of administrative tasks performed if the process is made autonomous with blockchain technology. The proposed conceptual improvement to the Green Star NZ assessment process by integrating blockchain is illustrated graphically in Figure 10.

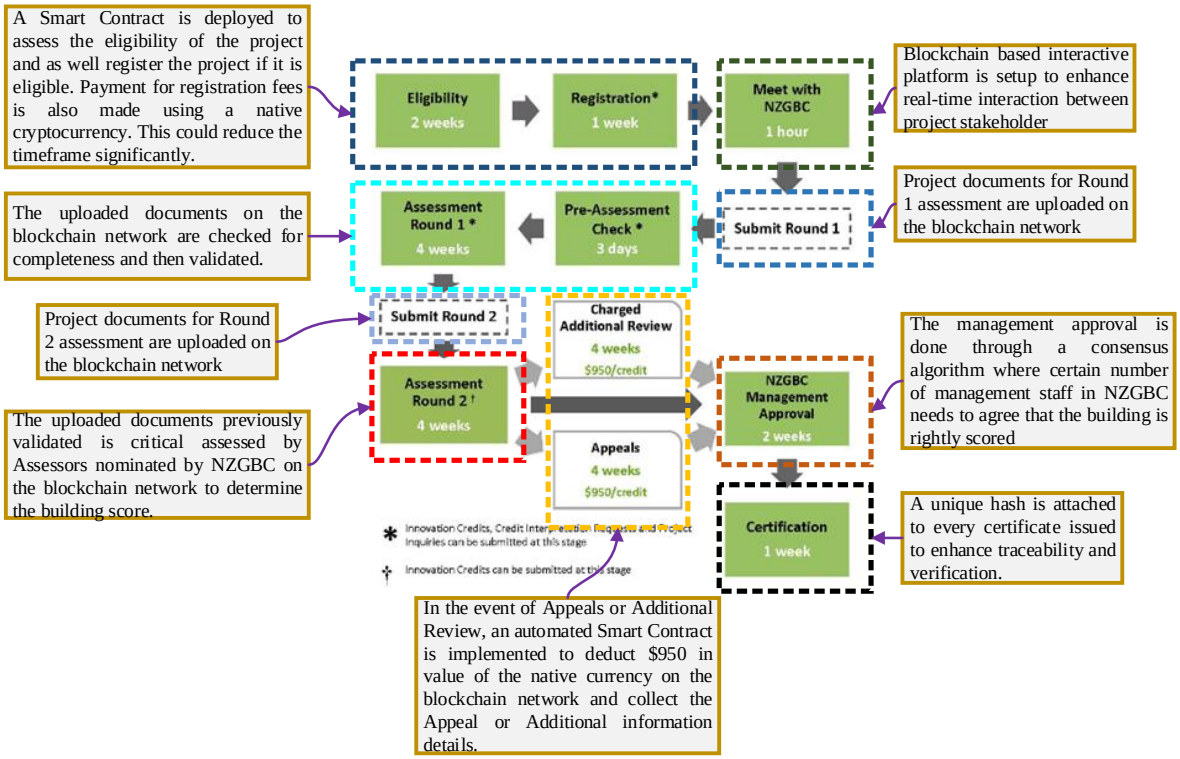


Figure 10: Conceptual Blockchain and Green Star NZ Process Integration

5. PROPOSED FUTURE RESEARCH DIRECTIONS AND CONCLUSIONS

5.1. Proposed future research directions

The proposed future research directions which answer RQ5 is based on the extensive literature review, gap-spotting and consideration of different perspectives outlined; the following nine key areas are essential for future research in the BIM-GBCS domain as presented in Figure 11 and summarised below:

1. ***Development of a holistic framework for BIM-GBCS integration***: there is scanty literature on the holistic application of BIM for GBCS. Different GBCS have unique credit categories as a result of geographical differences. Nevertheless, there are still some credit criteria that are common among GBCS. Some of these can be fully integrated into the BIM-GBCS framework. Lu *et al.* [13] reported a lack of a holistic system/framework for GBCS as one of the major setbacks in implementing BIM for sustainability analyses.
2. ***Inclusion of other WMS in location/transportation-related credits integration with BIM***: although the integration saves time and physical assessment, there is a need to include other WMS such as Autodesk's Infrastructure Map Server, ArcGIS Server, Bing Map, Mapbox, and Open Street Map (OSM). to have a wide range of quality images to include in the report [4].
3. ***Development of plugins and database containing acoustic properties of the materials***: future research in the BIM-GBCS could develop a database with acoustic properties which will facilitate the evaluation of acoustic comfort in the GB.
4. ***Development of framework or guideline for evaluating software packages to be used for GBCS evaluations***: different GBCS have embraced the use of different software packages to support the evaluation process of GB. Hence, there is a need to develop a framework or

guideline that will assist GB professionals in selecting the best software packages for the building evaluation.

5. ***Minimising gap between simulation outputs from GB analysis tools and actual values***: It is observed that there are still differences between GB analysis tools and actual values [25]. In some scenarios, these differences are significant, questioning the integrity of data in the existing GB analysis tools. More research is required to minimise the gap between simulation outputs and actual values. Al-Ghamdi and Bilec [92] stressed a need to create a robust database for various components of a building across diverse locations to help reduce the discrepancies in results during computations. Blockchain and BDA can be implemented to improve data integrity.
6. ***Development of adaptable plugins or frameworks for GB water efficiency analysis***: The body of knowledge regarding BIM and water efficiency analysis is limited due to the few papers available in the area[65]. Developing an adaptable framework or plugin that will help green professionals assess GB accurately is needed. Also, BDA can be introduced in this aspect by training a system to predict water efficiency based on certain parameters.
7. ***Integrating BIM and ontology for GBCS credits evaluation***: Currently, few pieces of literature on ontology in the BIM-GBCS domain despite the benefit ontology offers reported in previous studies [113]. Future research should consider developing a holistic BIM ontology mapping for all GBCS credit criteria in different countries. This will support BIM-GBCS ontology development.
8. ***Incorporating the social and economic dimension of sustainability into existing GBCS***: Studies have shown that most of the existing GBCS lack sustainability's social and economic aspects and focus majorly on the environmental aspect [5, 6, 134]. Including

some of the developed frameworks in previous studies [50, 127] after thorough validation or developing new ones will be crucial in expanding the current scope of the existing GBCSs, which is largely limited to environmental aspects.

9. ***Integrating BDA, blockchain and IoT for BIM-based GBCS evaluation***: Combining the potentials of big data analytics and the internet of things for BIM-based GBCS evaluation will enhance the GB evaluation process and reduce manpower requirements and process costs [135]. BDA methods can be used to predict the score a GB is likely to receive based on certain features of the proposed building. It could also enhance GB assessment data storage and gathering process, as demonstrated in Marzouk and Abdelaty [60]. Exploring the synergies between Blockchain, IoT and GBCS will be valuable in reducing the costs associated with GBCS processes.

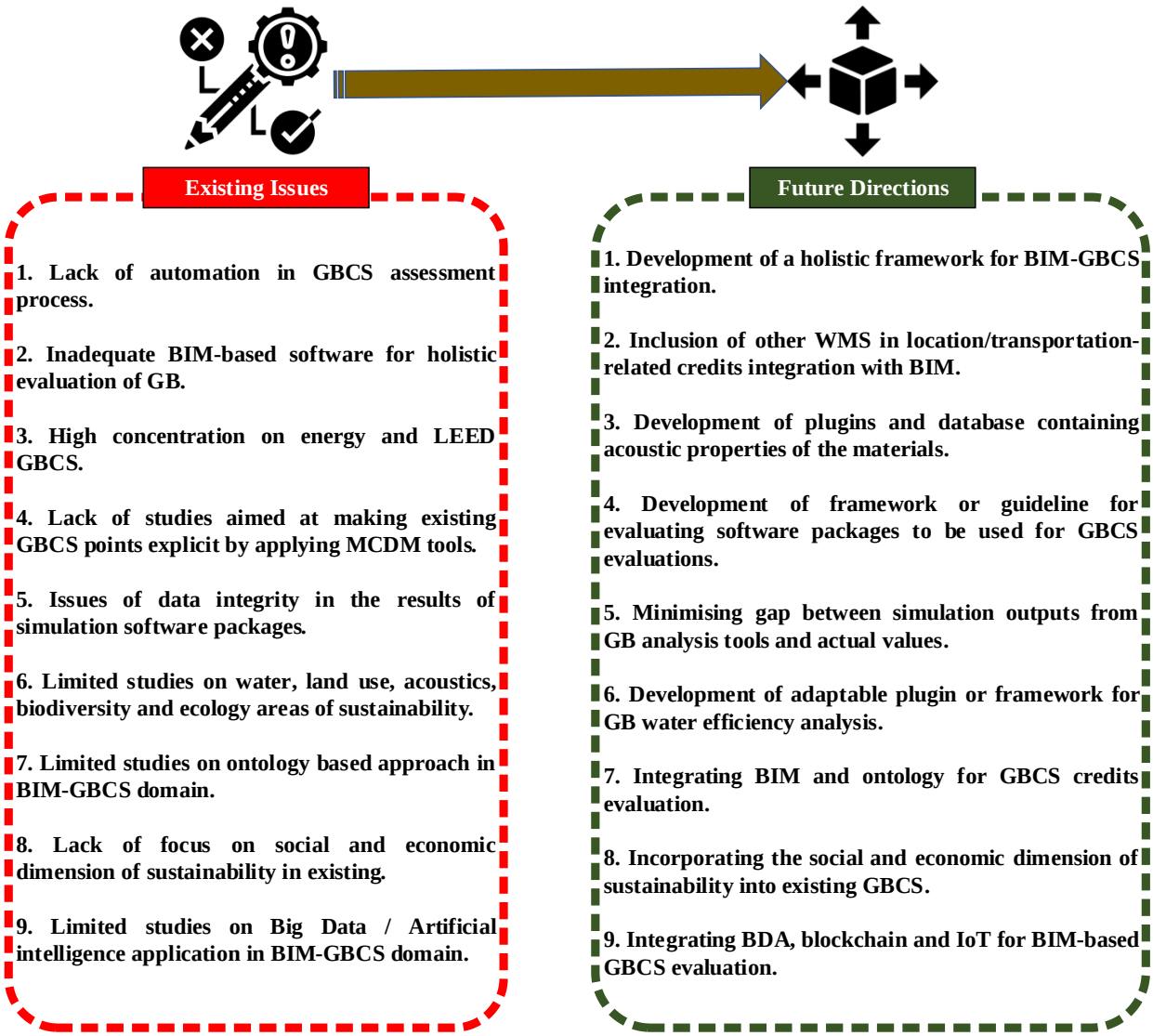


Figure 11: Future Research Directions in the BIM-GBCS domain

5.2. Conclusions

BIM has grown to be a useful tool in the AEC industry. The use of BIM to support GBCS has received huge attention from researchers. Particularly, between 2019 and 2020, the number of published works increased significantly by 50%. This can be attributed to government policies, discoveries by researchers and the coronavirus pandemic. This study presents a systemic literature review of the relationship between BIM and GBCS. Based on the review of journal articles (n = 84) between 2009 and 2020, this study summarized the: (1) GBCS currently BIM-enabled, (2)

level of BIM implementation in GBCS sustainability areas, (3) challenges and gaps in integrating BIM and GBCS, (4) BIM and GB tools currently in use and (5) areas for further research in the BIM-GBCS domain. The main findings of this study include the following; Firstly, the current body of research has solely concentrated on the environmental dimension of sustainability while the social and economic dimensions are neglected in the BIM-GBCS domain. There is a need to maintain a balance across the dimensions of sustainability. Secondly, the study revealed BIM as a valuable tool for GBCS, and stakeholders need to maximize the use of BIM technology to automate building sustainability assessment.

Furthermore, biodiversity, water, land use and ecology, socio-economic and acoustics have been potentially neglected in the BIM-GBCS. As a result, there is a need for thorough research to address these gaps. Based on SLR, 84 journal papers were identified and classified into eight credit categories: management and innovation, indoor environment quality, energy, transport, water, materials, emissions, and 'social and economic aspects of sustainability. The study also identified nine key areas for future research directions.

This current study contributed significantly to the body of knowledge in the BIM-GBCS domain. The first study in the BIM-GBCS domain that combines SLR and gap spotting techniques. This study revealed that the AEC industry still has a long way to go regarding implementing BIM for the GBCS process. With the increasing interest of researchers in this domain, the application of BIM for GBCS criteria will continue to improve as different innovative technology evolves. The lack of a unified approach for BIM and GBCS integration and interoperability issues are the major drawbacks in implementing the BIM-GBCS. To achieve substantial uptake in BIM and GBCS, the government needs to support this initiative with proper consultation of AEC industry stakeholders and invest in BIM-GBCS research to resolve the gap between BIM and the country-specific GBCS.

Other technologies such as blockchain, IoT and BDA can improve BIM-GBCS integration, but more work is required in this area. The research gaps and future research directions identified in this study are necessary to guide researchers and policymakers regarding the areas of BIM-GBCS that need more research.

The study can act as a reference for professionals and stakeholders in the construction industry while framing policies to enhance the GBCS assessment processes through emerging technologies such as BIM, IoT and Blockchain. Additionally, the study will serve as a background for future research works in the BIM-GBCS domain and provide a mapping for practitioners through which different software packages can be applied to the GB sustainability areas. Lastly, the conceptual mapping for BIM-GB software and GBCS integration can serve as a roadmap for building a unified application encompassing all the GBCS credits analysis. The AEC industry's top players in software development for sustainability assessment can explore the mapping of BIM-GB software packages and GBCS to identify the core functionalities of efficient software for the GBCS assessment process. It is recommended that future studies should critically evaluate the tools identified in this study to ascertain their level of contribution to building life cycle sustainability assessment across the building lifecycle.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.