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Review

Building Information Modeling (BIM) Capabilities in the Operation and Maintenance Phase of Green Buildings: A Systematic Review

Yu Cao , Syahrul Nizam Kamaruzzaman * and Nur Mardhiyah Aziz *

Faculty of Built Environment, Universiti Malaya, Kuala Lumpur 50603, Malaysia; s2035978@siswa.um.edu.my
* Correspondence: syahrulnizam@um.edu.my (S.N.K.); nurmardhiyah@um.edu.my (N.M.A.)

Abstract: In recent years, green buildings have gradually become a worldwide trend. Compared with traditional buildings, green buildings have advanced requirements and standards in their operation and maintenance phase. In such a context, some studies proposed that building information modeling (BIM) is an effective method to improve green buildings' operation and maintenance quality. The aim of this study is to perform a comprehensive review of the BIM capabilities in the operation and maintenance phase of green buildings through a systematic literature review. To achieve this aim, the PRISMA protocol was used to perform this systematic review. The whole systematic review was conducted between January 2022 and April 2022: 128 articles were included. In the process of study, Web of Science (WoS) and Scopus were adopted as bibliographic repositories. Through this study, it can be determined that BIM capabilities can be utilized in the facility management of the green building in the following aspects: safety and emergency management, maintenance and repair, energy management, security, retrofit and renovation, space management, and asset management. Secondly, these BIM capabilities were discussed, and the challenges and shortcomings of BIM capabilities in the operation and maintenance phase of green buildings were reviewed. Finally, a comprehensive overview of BIM capabilities in the facility management of green buildings was developed, and suggestions for future study were provided.

Keywords: building information modeling (BIM); green building; operation and maintenance; facility management

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1. Introduction

In the 21st century, due to the worldwide emphasis on environmental protection and energy efficiency, green buildings have gradually become a trend in many developed countries. Green building is also known as sustainable building. Green building is defined as "The practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout." [1]. Compared with traditional buildings, there are several significant advantages to green buildings, including high comfort, energy efficiency, low pollution, low toxic emissions, and environmentally benign [2]. According to Y. Lin et al. [3], green buildings should maintain the efficient utilization of resources and the harmonious symbiosis between people and the environment. These mentioned contexts dictate that green buildings are required to reduce energy consumption and greenhouse gas emissions, reduce environmental pollution, and provide a comfortable environment for occupants during their operation and maintenance phase.

As a multi-function method, BIM can facilitate management organizations to achieve these objectives during the operation and maintenance phase of green buildings [4,5]. BuildingSMART Alliance [6] formulated the definition and contribution of BIM in the following three aspects: BIM is a business process that allows all stakeholders to generate and utilize assets' data throughout the lifecycle of building to design, construct, and operate the building. BIM is the digital presentation of the physical and functional characteristics of facilities. It can provide shared knowledge resources about facility information and a reliable basis for decision-making. BIM is the organization and control of the business process, which can support stakeholders to effectively manage the projects and share information in the lifecycle of projects based on the information in the digital prototype. Due to the significant advantages of BIM application, BIM was deemed an effective method to be utilized in operation and maintenance phase of green buildings. Lu et al. [4] reviewed that BIM has indispensable contributions to the sustainability performance of green buildings in the operation phase. Kehily et al. [7] and Park and Cai [8] proposed that the BIM application has vast potential in the maintenance activities management in the post-construction stage. Liao et al. [9] also emphasized that BIM can effectively overcome obstacles and emergencies, sustain operation efficiency, and improve service quality in the operation and maintenance stage of green buildings. In addition to these, BIM utilization was recognized to have benefits throughout the lifecycle of green buildings, from the initial conceptual design phase to the operation and maintenance phase [10].

In such a context, the BIM application in the operation and maintenance phase of green buildings was discussed extensively in the AEC (architecture, engineering, and construction) industry. Al Ka'bi [11] pointed out that BIM can be utilized to simulate and analyze energy-consumption conditions for management personnel in the operation and maintenance phase of green buildings. For instance, BIM can be performed to analyze heating and cooling requirements to automatically adjust lighting and air conditioning through daylight identification and analysis [12]. Lim et al. [13] suggested that BIM can facilitate operational personnel to make decisions and support the maintenance and repair activities in green buildings. In addition to these, sustainable performance monitoring, clash detection, data storage, and integration can also be achieved by BIM application in the operation and maintenance phase of green buildings. Besides these, BIM can also be utilized to conduct schedule management, cost estimation, and budget control in the operation and management phase of green buildings [14].

Despite multiple studies about the BIM application in the facility management of the green building, research is still insufficient in this area. Given the insufficient awareness of the benefits of BIM utilization to green buildings' operation and maintenance phases, the studies about BIM application in facility management of green buildings are deficient [4]. Wong and Zhou [12] emphasized that the green BIM studies about environmental performance at the building maintenance and retrofitting stage were still limited. Compared with facility management of green buildings, users preferred to perform BIM in their design and construction process [9,14,15]. Only 16% of green buildings have databases or information-management tools [16]. In a critical literature review about BIM application in the lifecycle of green buildings, 30 articles on BIM application in design were screened. However, just five articles were about BIM application in the operation and maintenance phase. This also confirms that studies in this area are still insufficient [4]. In addition, there are rarely systematic literature reviews concentrated on the BIM application in the operation and maintenance of green buildings [5,17].

To promote the BIM utilization in the operation and maintenance of green buildings and fill the research gap of insufficient articles and systematic literature reviews on the application of BIM in the facility management of green buildings, this study is developed with the aim to perform a systematic literature review on the BIM capabilities in the operation and maintenance phase of green buildings. To achieve the abovementioned aim, this systematic literature review is performed with the following objectives:

1. Identify the BIM capabilities that can be utilized in the operation and maintenance phase of green buildings.
2. Determine which aspects of facility management for green buildings these BIM capabilities can be utilized for.
3. Discuss BIM capabilities and how these BIM capabilities are utilized throughout the operation and maintenance phase of green buildings.

4. Summarize the advantages and challenges of BIM capabilities in green buildings' operation and maintenance phase and provide suggestions for future research directions for prospective studies.

In addition to these, given that information technology is renewed or upgraded on average every three years, it is necessary to conduct this systematic literature review to summarize and update the latest research findings on the BIM capabilities in the operation and maintenance phase of green buildings. Through this systematic literature review, the BIM capabilities that can be utilized in the O&M phase of green buildings were summarized, categorized, and demonstrated. This study could facilitate other researchers and green building facility management personnel to comprehensively understand the BIM capabilities in the O&M phase of green buildings, thus boosting the promotion, development, and optimization of BIM application in the O&M phase of green buildings.

The structure of this article is demonstrated as follows: Section 1 is the introduction. Section 2 demonstrates the research methodology of this paper. In Section 3, the research results are reviewed and categorized through the systematic literature review; this section is divided into several subsections, including Safety/Emergency Management, Maintenance and Repair, Energy Management, Security, Retrofit and Renovation, Space Management, and Asset Management. In Section 4, the research results are discussed. Moreover, in Section 5, the conclusions are drawn.

2. Methodology

This study adopted PRISMA-2020 (Preferred Reporting Items for Systematic reviews and Meta-Analyses 2020) as the primary research method to perform this systematic literature review. According to Page et al. [18] and Fargnoli and Lombardi [19], PRISMA should include the following steps: define the information source (e.g., electronic databases, contact with study authors, trial registers, and so on); determine eligibility criteria (study characteristics and report characteristics); define the search strategy (formulate the draft of the search strategy utilized in the electronic database); specify data-management method (determine the record data management mechanisms); determine selection process (confirm the study screening and qualification process); develop data-collection process; confirm data items (make a list of all variables for which data will be requested and define them); perform classification and categorization; identify the risk of bias in individual studies; conduct result analysis and discussion.

In this study, a similar three-phase methodological approach [20,21] was adopted by following PRISMA.

The first phase is planning. In this phase, the research objective, keywords, and inclusion and exclusion criteria were determined by the researcher. This study is performed to identify the BIM capabilities that can be utilized in the operation and maintenance of green buildings. The papers adopted in this study were journal articles that can be searched by Web of Science (WoS) and Scopus. Articles that had not been peer-reviewed were excluded by the researchers. In addition to these, the inclusion criteria also include the articles edited in English and with relevance to the research objectives.

In this study, the following keywords were adopted as the initial search criterion: "Building Information Modeling", "BIM", "Green Building", "Sustainable Building", "Operation & maintenance", and "Facility Management". These keywords were utilized to conduct the search within the articles' titles, abstracts, and keywords. Through the initial literature search and review, the overview of BIM utilization in the operation and maintenance phase of green buildings was developed.

The search was conducted between Jan 2022 and April 2022. In this study, the publication date of selected studies was not restricted. The detailed search strings and keywords were demonstrated in Table 1. In this step, there were 1026 articles retrieved in databases (899 in WoS, 127 in Scopus).

Table 1. The search string and results of the Scopus and WoS databases.

Search Engine	Search String	Results
WoS	TS = ((building AND information AND modeling OR building AND information AND modeling OR BIM) AND (green building OR sustainable building) AND (operation OR maintenance OR O&M))	899
	Document Types: Articles or Proceedings Papers or Review Articles	895
	AND LANGUAGES: (ENGLISH)	891
Scopus	"TITLE-ABS-KEY ((building AND information AND modeling OR building AND information AND modeling OR BIM) AND (green building OR sustainable building) AND (operation OR maintenance OR O&M))	127
	AND (LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re"))	102
	AND (LIMIT-TO (LANGUAGE, "English"))	102
Search Keywords	"Building Information Modeling", "BIM", "Green Building", "Sustainable Building", "Operation & maintenance", "O & M", "Facility Management"	
Sum of the papers = 993 **Duplicates and invalid** paper = 118 **Remaining = 875** **After titles and key words screening** = 317 **After abstract screening** = 189 **After full paper screening = 128** **Total = 128**		

The second phase is to perform a review of these articles. The exclusion and inclusion criteria are shown in Table 2. In this step, 33 articles were removed because they did not meet the inclusionary criteria in the primary data. After excluding 43 duplicate articles and 75 invalid papers (the papers that cannot provide full text online), there were 875 papers in total.

Table 2. Inclusion criteria and exclusion criteria.

Primary Data		Secondary Data	
Inclusionary	**Exclusionary**	**Inclusionary**	**Exclusionary**
Journal articles which can be searched in Web of Science (WoS) or Scopus.	Duplicate.	BIM utilization in operation and maintenance of green buildings.	Not related to BIM utilization in operation and maintenance of green buildings.
Conference paper that are searchable through WoS or Scopus.	Invalid articles or paper.	Relevant to the research objective.	Irrelevant research objectives.
Review articles that are searchable through WoS or Scopus.			
Published in English	Non-English-edited articles or paper.		

After that, the remaining articles, conference papers, and review studies were screened according to secondary data. In the first step, the titles and keywords of these remaining articles were screened manually to exclude the articles that were not relevant to BIM utilization in operation and maintenance of green buildings. After this step, 317 articles remained, and 558 articles were excluded. Then, the abstracts of the remaining papers were reviewed; 189 papers remained in this step. Finally, the researchers reviewed the full text of these 189 articles; the number of articles was reduced to 128. Through the full-text review, it can be summarized and categorized that BIM capabilities can be utilized in the operation and maintenance phase of green buildings in seven main aspects, including safety/emergency management, maintenance and repair, energy management, security, retrofit and renovation, space management, and asset management. The process of classification follows the criteria in Table 3.

Table 3. Selection criteria for developing categories [20].

Selection Criteria
Identify the articles that are relevant to BIM utilization in the operation and maintenance phase of green buildings.
Determine BIM capabilities in the facility management of green building by performing qualitative data collection and analysis.
Categorize similar BIM capabilities.
Group BIM capabilities according to their application in the different areas of the facilities management phase and formulate category.
Check the consistence by referring to other literature.
Verify and determine the final category.

The third phase is reporting. These 128 articles were reviewed and analyzed, and the results of analysis were critically documented and presented to support the research in the Results section and the Discussion section. The whole process of paper selection is shown in Figure 1.

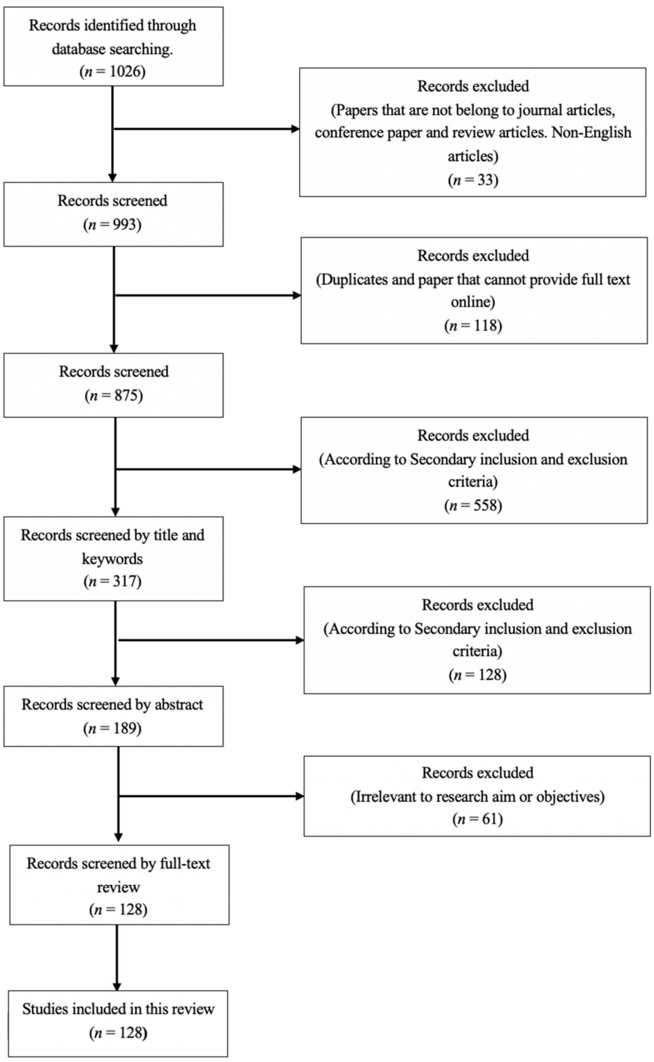

Figure 1. Flowchart of articles screened in this study.

In this flowchart, the n in the left-hand box represents the number of articles remaining after screening in this process.

To sum up, 993 articles were retrieved from the databases (891 in WoS, 102 in Scopus). After excluding 118 duplicate articles and invalid papers (papers that cannot provide full text online), 875 papers were initially extracted in total. After that, the remaining papers were brought into the second step to conduct further screening (through title and keyword analysis, abstract analysis, and full-text analysis). Finally, there were 128 papers included in this systematic literature-review study.

3. Results

3.1. Descriptive Analysis

In this section, the distribution of the included papers is demonstrated. The included papers were classified and categorized through their publication year, country of first authorship, and journal.

The distribution of the selected studies is demonstrated through these figures. According to Figure 2, of the reviewed articles, the earliest was published in 2005. Figure 2 demonstrates that the research in BIM application in the operation and maintenance phase of green buildings has become a trend since 2015. Between 2015 to 2021, the number of articles reviewed remains constantly within the range of 13 to 18. In this study, the number of reviewed articles published in 2022 is 10. Given that the article searching in this study was performed between January 2022 and April 2022, the articles published between May 2022 and December 2022 were not retrieved. Therefore, the number of included articles in 2022 does not indicate a decrease in the number of studies in this direction. Nevertheless, there are 10 articles published in the first four months of 2022 that were reviewed by this study. This phenomenon also indicates that the studies on BIM application in the operation and maintenance of green buildings are still prevalent in 2022.

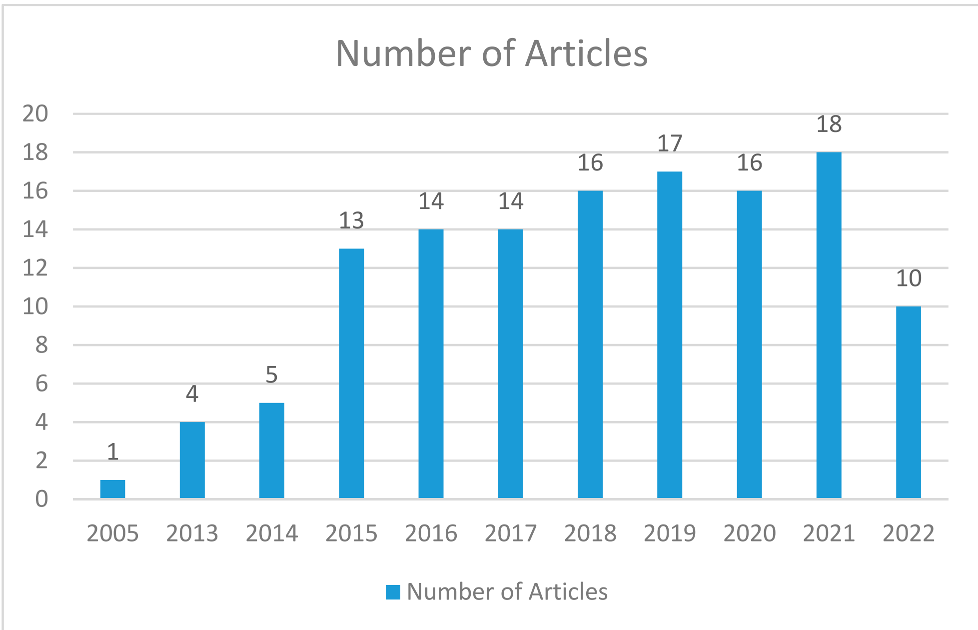

Figure 2. Number of articles published per year.

Moreover, according to Figure 3, in this study, the reviewed articles that contributed were mostly from the People's Republic of China (22) and the USA (20). In addition to these, researchers from UK (9), Taiwan (9), Singapore (7), Canada (6), Malaysia (6), South Korea (5), and Belgium (4) also paid significant attention to this topic.

3.2. Result Analysis

According to the systematic review of the included papers, the BIM capabilities in the operation and maintenance of green buildings can be classified into eight categories, including safety/emergency management, maintenance and repair, energy management, security, retrofit and renovation, space management, and asset management.

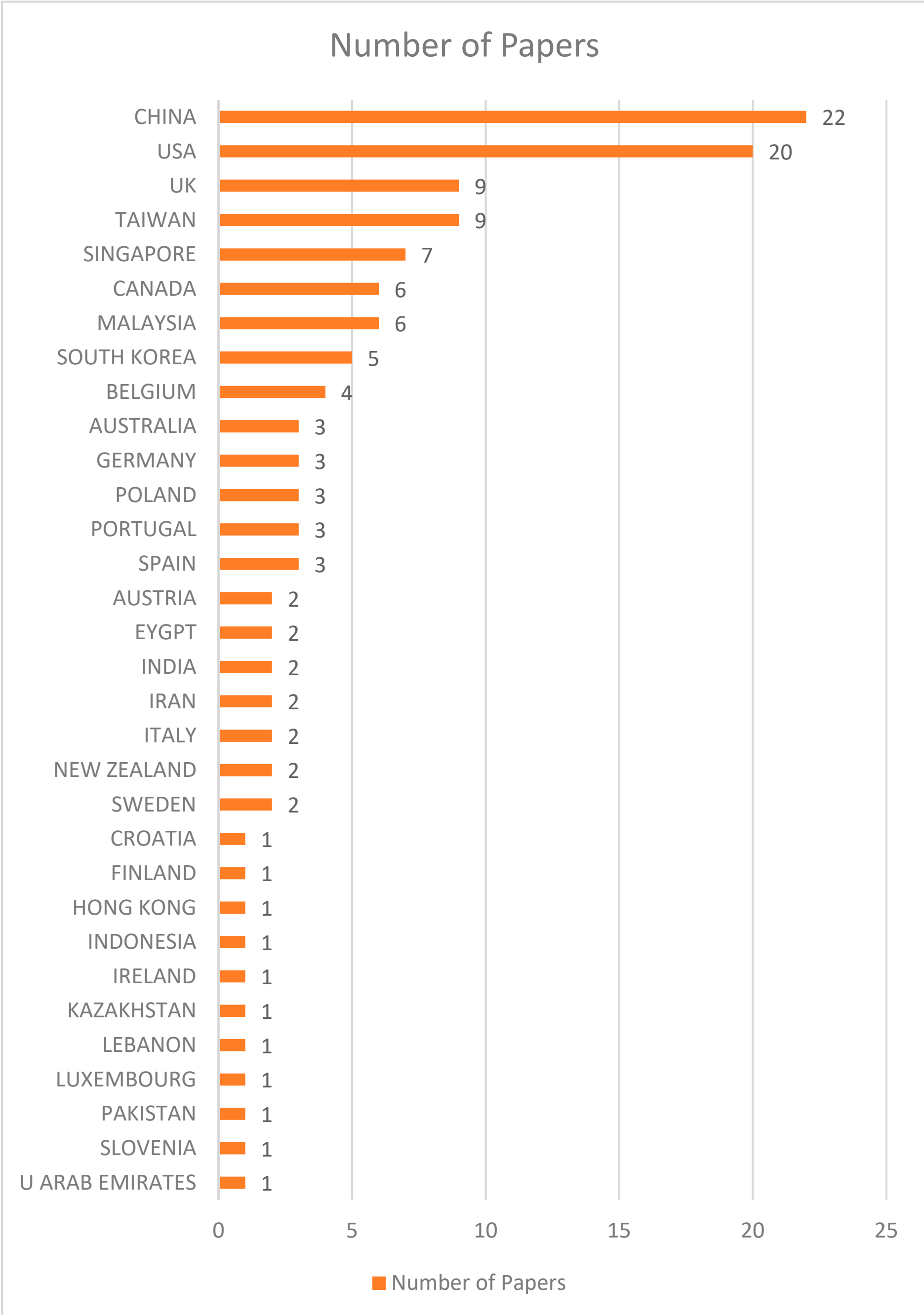

Figure 3. Number of publications per country or region (the country/region of first author).

3.2.1. Safety/Emergency Management

There are various safety risks and hazards in the operation and maintenance phase of green buildings. Classified by the type of hazard, the safety risks and hazards can be categorized as force majeure (the unpredictable events, including war, riot, and disasters such as hurricanes, tornados, earthquakes, tsunamis, mudslides, floods, etc.), equipment breakdown (insufficient productivity or effect of equipment in the process of operation and maintenance phase due to inaccurate utilization method), inappropriate solid or gas waste production (the waste which is unlawfully disposed or controlled), and injuries and accidents (labor, residents or other personnel injured due to overexertion, exposure to hazardous materials, equipment failure, or electrocution), and some environmental issues (air, water, or soil contamination) [22,23].

The growing implementation of BIM revision is continually revising the safety management methods and approaches in the facility management of green buildings. By applying BIM in the operation and maintenance of green buildings, safety hazards can be automatically identified. As summed up by Zhang et al. [24], the corresponding risk control or elimination approaches can be automatically conducted. In addition, BIM can identify the corresponding potential risks in different areas or tasks and provide a collaborative platform for the facility management team to conduct cooperation tasks to resolve targeted risks [25]. Besides these, BIM can support management personnel to perform safety training and education, safety scheduling (operation, maintenance and renovation activities, hazard analysis, and pre-task planning), and accident investigation during the facility operation and maintenance phases [26]. Through the above BIM capabilities in the aspect of safety management of green building facility management, the manual workload of facility management personnel can be mitigated, and the risk identification and hazard elimination become more precise and effective.

The BIM capabilities in the safety management in facility management of green buildings can be started in the early stage to prevent hazards. Zulkifli et al. [27] developed a framework that integrated automated safety rule checking (ASRC) with BIM in hazard prevention, eliminating dangers by preventing them. Besides that, BIM can simulate and demonstrate the movement of people in and around constructions to automatically identify potential safety hazards and formulate prevention schemes through computational algorithms [28]. Riaz et al. [29] developed the "Confined Space Monitoring System" to improve health and safety by integrating real-time monitoring of sensors and BIM. In this system, sensors collect information such as temperature and oxygen levels in real time and summarize them to the central database. With sensor data exceeding the threshold limit, the alarm would be activated, and the warning notifications could be delivered to the mobile phones of the occupants and manager [29]. With the integration of BIM and Internet-linked open datasets, the information on weather conditions, flood risks, population density, and road congestion can be performed using real-time monitoring [30].

With the emergency happening, BIM has functional capabilities in pathfinding, indoor localization, and fire and safety management. In the emergency, the pathfinding function in BIM aims to locate trapped persons immediately and evacuate them to safety positions to avoid potential dangers (e.g., fire, explosion, ceiling or wall collapse, smoke) [31]. In the BIM-based Intelligent Fire Prevention and Disaster Relief System developed by Cheng et al. [32], the visualization function in BIM was integrated with Bluetooth-based sensor networks, location-aided designs, optimal evacuation/rescue route planning, and real-time mobile APP. With the contribution of the above functions, not only can the evacuation guidance be effectively achieved, but also the evacuees' assistance and the prompt initial detection and response in fire disaster can be conducted to assist firefighters and facility managers [32,33]. For spacious and complex green building communities, Chen and Chu [34] developed a time-dependent vehicle routing problem (TDVRP) model for rescue route planning. It was cooperated by BIM and network analysis. The medial axis transform (MAT) is utilized to establish building geometry in specific green communities. The hazards of various building materials and footfall at different periods were also considered in this model. Based on IFC, the 3D Indoor Emergency Spatial Model (IESM) can provide digital indoor environment demonstration [35].

In the rescue and evacuation, indoor and outdoor environment information is vital for victims and rescue personnel [36]. To overcome the barriers in the operability aspect between indoor and outdoor information systems, Teo and Cho developed the

Multi-purposed Geometric Network Model (MGNM), which was integrated with BIM and GIS [37]. With indoor information in BIM and outdoor information in GIS, indoor and outdoor networks can be connected to establish a detailed indoor network model (considering all opening elements, such as doors and windows) by creating a route-planning process from general to detailed [37]. Based on these, Tang et al. [38] proposed a complete level of detail (LoD) definition for 3D building models that includes both interior and outdoor scenarios to compensate for the defects of narrow definition in interior-space LoD.

In indoor localization, with emergencies happening, it is vital to achieve the real-time location of victims to optimize the rescue efficiency and reduce fatalities and injuries. The indoor localization function is the basic module in various evacuation or rescue systems [31]. With the support of third-party technologies or tools, BIM can facilitate stakeholders to achieve precise location. Li et al. [39] proposed the BIM-based indoor centric localization algorithm that provides an optimized beacon-deployment scheme to locate trapped residents in disasters by locating their carry-on mobile phones and RF devices. To facilitate firefighters to arrive at critical targets quickly (e.g., location of evacuees) and reduce the response period for disasters, Bluetooth-based sensors and BIM were integrated to be utilized to detect/transmit environmental data and human activity data and achieve mutual guidance [32]. In the test conducted by Fang et al. [40], to overcome the defects of traditional localization methods that cannot conduct unobstructed information spreading, the researchers achieved the visualization of personal localization through a passive RFID positioning system, BIM, and cloud computing, which covered entire constructions. This framework allows the location of people to be displayed visually in BIM and users to access location data in real time on various remote platforms via cloud computing systems [40].

From the perspective of fire and life safety management, fire emergency is deemed the most common emergency in buildings, and most BIM-based emergency management applications are suitable for fire safety management [31]. Given the destruction and mortal danger caused by fire disasters, it is essential for management teams to conduct fire-prevention measures. A BIM-based and augmented reality (AR)-based cloud database was established to update real-time building information to provide essential information for fire safety equipment inspection and management [41]. In this process, Construction Operations Building Information Exchange (COBie) was utilized to organize the information and contents of the framework in the BIM–AR-based system. In building fire emergency operations, situational awareness is essential for supporting escape and rescue actions; immersive virtual reality (VR) simulation training for rescuers can reduce casualties and improve the rescuing performance [42]. To achieve the above objectives, the novel framework with the combination of BIM, IoT, and VR/AR technologies was developed to improve the situational awareness of trained firefighters [43]. Beata et al. [44] developed a BIM-based fire-monitoring framework that can provide dynamic fire position demonstration. To mitigate the hazard of hazardous gas accumulation, a real-time construction safety monitoring system was organized by Cheung et al. [45]. With the contribution of the wireless sensor network and building information modeling, ventilation and associated safety devices can be automatically activated by this system when abnormal conditions are detected to restrain potential explosions and injuries to persons [45].

3.2.2. Maintenance and Repair

According to Roper and Payant [46], facility maintenance refers to "the process to maintain the specified performance of an asset over its expected useful life". The primary purpose of facility maintenance is to prevent the loss or partial loss of performance of the facilities. The definition of facility repair is "the work necessary to restore damaged or worn-out property to a normal operating condition". They are curative and reactive measures utilized after partial or total loss of performance of facilities, as commented by Gao and Pishdad-Bozorgi [31].

- Understanding the Current Practice and Information Source

In the operation and maintenance phase of green buildings, various BIM-based building management systems were developed and utilized to collect, manage, and analyze the information related to maintenance and repair. According to the review from Shalabi and Turkan [47], the facility management information systems such as building energy management systems (BEMS) and building automation systems (BAS) are the aggregation of microcomputer systems that are formed by direct digital controllers (DDC) and their control devices and equipment. Through BEMS and BAS, the supervision of device operation and software run situation can be automatically conducted. Furthermore, these systems can share and extract data with the single controller for coordination and optimization [47].

In addition to these, computerized aided facility management systems (CAFM) and computerized maintenance management systems (CMMS) were deemed to be effectively valuable information-capturing systems [48]. With the assistance of other plugins and tools, BIM can collect and manage the data related to maintenance and repair effectively. In the BIM/RFID (radio-frequency identification) facility management system developed by Kameli et al. [49], the maintenance and repair record of each component can be automatically recorded and demonstrated. When the routine maintenance or repair date for specific components is approaching, the system will automatically send notifications to the corresponding maintenance personnel [49]. Suprabhas and Dib [50] developed the information-collection system combining BIM and sensors by detecting the indoor temperature in each zone through sensors to confirm the operation condition of the heating, ventilation, and air conditioning (HVAC) system in each zone.

To extract and input data conveniently in the maintenance and repair process, barcodes were utilized in the BIM-based information system. In the BIM/2D Barcode-Based Automated Facility Management System developed by Lin et al. [51], maintenance staff can utilize their mobile phones to scan the QR code on the components to obtain corresponding background information, performance, maintenance records, maintenance problems, and link to the corresponding BIM model of the facility.

According to Peng et al. [52], the information related to maintenance and repair activities is mainly retrieved from the following sources: manually input/retrieve from standard component libraries [53]; transformed through algorithms from outside the BIM environment by utilizing building-management instruments; documents transformed from the design or construction phase to the maintenance and repair process; collected by sensors [54].

- Case-Based Reasoning (CBR) Modules

Case-based reasoning (CBR) is the problem-resolution technology that utilizes the principles of artificial intelligence. It originated from the cognitive science field and required previous data and knowledge from similar cases in the past [55]. The definition of case-based reasoning is "To solve a new problem by remembering a previous similar situation and by reusing the information and knowledge of that situation." [56]. The CBR process usually has five standard processes: retrieval, reuse, revision, review, and retention [57]. There are various benefits to case-based reasoning (CBR): the costs associated with maintenance and repair are calculated based on specific previous cases instead of utilizing generalized relationships so that the forecasts that CBR develops are trusted [55]. Moreover, CBR can also help facility managers to estimate the maintenance and repair expenditure in the lifecycle of the green building project.

The BIM-based CBR process has significant advantages in the quality improvement of maintenance and repair. In the process of conducting CBR, with the contribution of structured and graphical data in IFC, the CBR model can facilitate the FM (facility management) personnel to conduct an accurate cost estimate based on the best available match case [58]. FM stakeholders can select the specific component from the BIM, obtain the attributes associated with the corresponding component, utilize these data in the CBR model, and retrieve the most approximate case match [57]. Motawa and Almarshad [59] proposed a methodology that integrated CBR modules and BIM; BIM capabilities can retain knowledge cases for asset maintenance and repair and identify corresponding cases.

This system can facilitate related personnel to record and consult maintenance and repair records for the corresponding components and develop a comprehensive understanding to provide adequate support for the decision-making process in new maintenance and repair cases [59]. In addition to these, as an incremental and sustained improvement method, the storage function in BIM can retain the experience of resolution after the problems are solved. These experiences can be utilized as the knowledge database for future problems in maintenance and repair activities in green buildings [12,60]. In the BIM–CBR integration system, information about the individual building elements of the stored cases can be retrieved through the BIM module to facilitate the identification of shared attributes of the cases, simplify case descriptions, and enable the retrieval of the most appropriate cases [59].

- Fault Detection and Diagnosis

In addition to information management and case-based reasoning modules, BIM can also facilitate stakeholders to conduct fault detection and diagnosis (FDD). Through the system fault detection and location, failure cause–effect pattern identification, and information analysis capability in BIM, maintenance and repair procedures in green buildings can be efficiently optimized [31].

Fault detection and diagnosis (FDD) is the process of revealing errors in a physical system and recognizing the source of errors. There is various research about the BIM-based FDD method in maintenance and repair. With the support of automated decision-making in BIM, Golabchi et al. [61] utilized the FDD algorithm to improve the process of HVAC system repair. This BIM plug-in has been proven to obtain the ability to guide the HVAC maintenance operations, which significantly reduces the duration and effort spent by property managers manually completing the corresponding process based on their judgement and experience [61]. To optimize the FDD performance, Yang and Ergan [62] utilized BIM to demonstrate HVAC-error-elimination-related information, identify suitable causes, and match causes to facility-specific instances to solve problems. It contributes to maintenance and repair personnel not wasting their time in component localization and tracking and reduces the search space of applicable causes by 68% on average.

With the integration of BIM, BEPS (building energy performance simulation) and FDD, Andriamamonjy et al. [63] proposed a BIM-based strategy to automate the implementation and deployment of model-based FDD in the air handling unit (AHU), to reduce the manual operation of related personnel in FDD implementation and deployment. In addition to these, Cao et al. [64] provided a scheduling framework to arrange the maintenance activities according to their corresponding priority and evaluate the occupants' satisfaction with maintenance activities. Given that the expenditure of reactive-repair activities is an average of four times the same predictive repair activities, Motamedi et al. [65] developed the fault-originated detection patterns based on the visual analytic and knowledge-assisted visualization that BIM conducted. In these patterns, facility management personnel can utilize BIM to retrieve existing lifecycle knowledge and relationships between building elements in BIM to visualize the possible causes of defections. Besides these, BIM was utilized to demonstrate the spatial and temporal distribution of the problems, infer patterns and trends in failure generation, and visually analyze the potential causes of problems [65].

3.2.3. Energy Management

The utilization of BIM in energy management was started before the operation and maintenance. After the completion acceptance, the energy-related information in BIM can be transferred from design organization and construction organization to the facility management corporate [10]. For green buildings in which BIM is not adopted in their design and construction phase, the energy-related information is input manually or collected by sensors, passive RFID tags, 3D laser scanning, and photogrammetry [66]. Energy-related data can contain asset geometry, material properties, the utilization ratio, location, climatic condition, sun path, thermal radiation, and weather [66–69]. Based on this information, BIM can be utilized to record and simulate the energy-consumption situation. In the process of energy-consumption simulation, the digital twin in BIM has a significant contribution;

it can map the diverse properties of physical devices into virtual cyberspace to form an identical model that can be used as the basis for energy consumption simulations [70]. Based on the abovementioned technologies, the facility management personnel can utilize computational fluid dynamics, thermal radiation analysis, and illumination analysis to conduct energy consumption simulation and energy performance optimization [70]. With the integration of BIM and the Internet of Things (IoT), it can automatically control and optimize energy utilization according to the light environment around the building and in conjunction with historical movement data [71].

- Collecting and Managing Energy-related Information

As an information-management platform, BIM relies on its storage and information instructing capabilities; the modeling of objects and data collected and generated during the design and construction phase have been proven to enable the formation of datasets leveraged in the management of assets post-construction [72].

The light, heat, ventilation, temperature, and humidity of the buildings are both influenced by the location, geometry, and materials of green buildings; therefore, it is necessary for facility management personnel to be familiar with the geometry and material information in the process of energy management. As a comprehensive information management tool, BIM can achieve the precise and interoperable delivery of required information (such as location, climate, geometry, and material) from the design and construction phase to the operation and maintenance phase [73].

Del Giudice et al. [74] proposed a BIM–GIS integrated distinct model that can demonstrate the information about buildings and their surrounding environment to support energy management. To fully consider the climate and weather factors in the energy management process in green buildings, C.-J. Chen et al. [75] developed virtual weather station technology utilizing BIM cloud tools; it facilitated green building to obtain and retrieve simulated weather-related data from the nearest weather stations. Subsequently, the collected data were transmitted to DOE-2 Engine in gbXML format to support energy performance analysis. In the Web3D graphics-enabled sensor network developed by Hamza-Lup and Maghiar [76], energy consultants can communicate embedded messages to the design party. Moreover, it can achieve the integration of energy-management-related construction materials and corresponding specifications in the design process.

In addition to the information about the elements related to energy management (such as climate, geometry, location, and materials), BIM can also be utilized to conduct the statistics on energy consumption. Lee et al. [77] formulated a BIM-supported method to implement real-time building energy consumption monitoring; BIM can provide a visual demonstration of the building environment and energy consumption record. In the facility management optimization framework established by Oti et al. [78], BIM was leveraged as an information integration platform to manage predicted and actual energy consumption data. The integration of related geometry, materials, and the energy-consumption information can provide practical support to energy-management systems. In the spatiotemporal analysis system of power consumption data, BIM was responsible for counting the solar photovoltaic appliances and managing the electricity consumption data, which effectively reduces the manual workload and increases the accuracy of the statistics [79]. To improve the effectiveness and quality of energy management in large comprehensive buildings, a BIM-based energy management support system (BIM-EMSS) was developed by Tu and Vernatha [80]. The function of BIM-EMSS can include (a) sensors installed for every occupant and equipment, (b) corresponding electricity record for sub-parts (record the corresponding electric consumption of each lighting, HVAC system, and socket in different areas), (c) energy-related data repository, and (d) multi-function building energy management system and energy simulation tools.

- Evaluating and Simulating Energy Performance

Given the comprehensive energy-related data storage, visualization demonstration and simulation function in BIM, green BIM can effectively perform energy performance prediction and simulation to facilitate FM personnel to conduct energy management in green buildings. From this perspective, the BIM capabilities include the following: performing energy consumption simulations and forecasts, simulating indoor thermal conditions, and conducting the comparative analysis between predicted energy performance and actual energy performance [31].

The energy consumption conditions are influenced by their location, surrounding environment and climate, ventilation, and thermal and radiation conditions. With the support of third-party tools, BIM can model the surrounding environment of buildings to provide the necessary information for energy simulation or prediction [81]. Considering the deterioration of green building materials over time, Ham and Golparvar-Fard [82] developed a BIM-based 3D thermal model to minimize the error between architectural information in BIM and the actual data for energy performance. In the green BIM approach developed by S. Chen [83], BIM was leveraged into building energy performance assessment (BPA). In this study, BIM can simulate the expected energy consumption of different energy optimization scenarios and predict the corresponding energy consumption of different zones and components under different scenarios [83].

- Energy Optimization

In ESGB (Evaluation Standard of Green Buildings), green buildings are required to reduce nonrenewable energy consumption, decrease greenhouse gas, hazardous gas, and pollutant emission, and provide a comfortable service environment for occupants [2]. To keep the balance between environment protection and suitable environment, the facility management personnel must conduct energy optimization. BIM is deemed to be the required method to achieve waste and greenhouse gas emissions, minimize performance gaps in green buildings, and improve energy utilization efficiency and total lifecycle assessment [84]. Given that green buildings need to meet the corresponding green building assessment standard during their operation and maintenance phases, BIM can assess the green building index based on their operation and maintenance performance, thus ensuring the quality and efficiency of operation and maintenance [85,86]. According to the review from Gao and Pishdad-Bozorgi [31], from the perspective of energy management optimization, the contribution of BIM tools can include the ability to monitor the energy consumption situation and analyze their performance, to propose energy conservation methods and suggestions for FM personnel or occupants, to conduct fault detection and diagnosis and to evaluate the sustainability of green buildings.

Through data integration and intelligent automated energy control, the BIM-based building management system can automatically conduct energy-consumption control for electricity, gas, water, oil, and solid fuel [87]. In the study of Pazhoohesh et al. [88] and Guo et al. [89], the energy management system detected the ambient conditions in each room via sensors to automatically control the HVAC systems and heating systems in the different zones. Wong and Zhou [12] reviewed a semantic web-based approach to narrow the performance gap between the design intent and the real-time energy performance of buildings, which can smooth and facilitate the integration of data in the energy management process. In the agent-based model proposed by Cao et al. [64], EnergyPlus was utilized to qualify the negative influence on energy expenditure caused by various defects in the HVAC system. In addition to the positive performance in energy management optimization, BIM also makes an effective contribution to the energy conservation retrofit in green buildings [84]. The BIM database should collect the lifecycle energy information in standard format for each material, facilitating the account of energy lifecycle consumption of different materials in the energy-sustainable retrofit process [90]. Yuan et al. [91] proposed a BIM-VE-based optimization method to verify which green building envelopes conform to the requirements of green building standards and compare the expenditure (lifecycle cost) of different green building optimization plans. In addition to these, with the combination of BIM and photovoltaics, it can automatically adjust the power supplied by the PV panels with monitoring in real time of the energy usage and energy surplus, thus reducing energy costs and improving the occupants' comfort [71].

3.2.4. Security

From the perspective of human and property security enhancement, the contributions of BIM can include the following: design security system, such as determining the type and location of security device, especially incursion detection, access control, CCTV; retrieve, manage, analyze, and store security information, especially digital video images; track and locate equipment and materials; expenditure analysis—estimating the cost of security personnel and security facilities (the expenditure of purchase and operation); conduct the review of security standards and guidelines automatically; arrange and optimize the security facilities' maintenance program and the guards' patrol scheme [92].

Given the unstable data transmission and random system errors in traditional underground space safety monitoring, BIM was utilized to develop an online monitoring system for structural safety to facilitate the conduction of all-weather real-time monitoring capabilities that are realized with early warning capabilities [93]. Moreover, to prevent information from stealing and leaking, Das et al. [94] proposed two BIM-utilized frameworks: The first framework was recommended to help with data confidentiality and data-sharing security, and the second framework was offered to protect selected information from unauthorized data revision. In the study of Ding and Xu [95], researchers assigned different levels of confidentiality for information in the operations and maintenance phases and assigned access authorization levels to various stakeholders to prevent important information from unnecessary leaking in the process of information sharing.

3.2.5. Retrofit and Renovation

To ensure that the green buildings conform to the above requirements in the whole operation and maintenance phase, it is necessary for the facility managers to conduct retrofits and renovations to sustain their sustainable abilities. BIM was deemed to be an efficient tool in green building retrofit and renovation. It can support stakeholders to successfully accomplish the retrofit for buildings in a limited time and with limited cost [96].

The functions of BIM in the retrofit and renovation procedure of green buildings can include the following: to identify what rating level of green building assessment criteria the refurbished building can achieve; to analyze the geometry of buildings (such as orientation, massing, and envelope); to evaluate green building functions (such as HVAC) [97]. Given the fragmentation and decentralization of retrofit- and renovation-related information in the green building lifecycle, BIM can collect, store, and integrate multi-disciplinary information about buildings effectively [98]. In the case study of the West-Twelfth building at Huazhong University of Science and Technology (HUST) refurbishment, BIM was utilized to simulate the corresponding performance and impact of different renovation scenarios, and comparison was conducted between various renovation scenarios to facilitate stakeholders to choose the most suitable renovation schemes [89].

BIM can be utilized for retrofit decision-making, streamlining the decision-making procedure in retrofit projects, and evaluating energy performance in renovation projects by integrating BIM with laser scanning [4]. In addition to these, BIM effectively contributes to the estimation of waste production (amounts and types) in the retrofit and renovation of existing green building projects and identifies the recycled and renewable materials in the produced waste [99]. Moreover, based on the above information, the energy consumption and expenditure in the retrofit and renovation procedure can be accounted for, and the cost–benefit analysis (such as return on investment) of retrofit and renovation activities can be performed. BIM can also facilitate all stakeholders to be familiar with the retrofit and renovation situation and progress. A progressive BIM methodology was formulated by Stegnar and Cerovšek [100] to improve the quality of design, reduce the refurbishment and renovation expenditure, and prevent errors and delays.

3.2.6. Space Management

Space is a valuable and manageable asset; it should be treated as a significant tangible asset. In the operation and maintenance phase of green buildings, space can be rented or reassigned and utilized to locate other items such as equipment, furniture, components, personnel, HVAC, etc. [101].

According to Loeh et al. [102], BIM can conduct space-related information collection and visualization demonstration of the space area, utilization status, and other relevant information for each functional area and floor. Based on this information, BIM can reflect the average expenditure per unit area, detailed analysis of costs, area occupied per person, and space utilization to achieve optimal space allocation and planning. In addition to these, it is vital for asset managers to be familiar with the condition of space utilization; BIM can help facility managers to streamline the move process and forecast space requirements [103].

In the process of facility management, due to the application of BIM, the space-related information which originated from the design and construction phase can be delivered to the operation and maintenance phase comprehensively and precisely, including BIM visualization models, 2D drawings, assets (such as furniture, furnishings, and equipment), maintenance handbooks, specifications, regulation, and other information customarily required at the completion stage [101].

In addition to these, BIM can be integrated with closed-circuit television (CCTV). This integration can help the management team conduct a better three-dimension visual demonstration, facilitating collaboration and information transmission between occupants, facility management personnel, and other contractors [104]. Three-dimensional BIM can provide detailed information and characteristics of each space area and component and can perform intelligent space allocation management and indoor path navigation; this not only reduces the difficulty of space management but also reduces the manual workload [105]. In the case study of Syed Mustorpha and Wan Mohd [106], when the utilization conditions of space were changed, the BIM–GIS model was utilized to automatically update spatial information and develop the schedules, elevations, and 3D visuals. Moreover, the BIM–GIS model can also generate instant profiles and drawing sheets required by the space usage and computational optimization procedure [106].

3.2.7. Asset Management

- Handover

From the perspective of asset management, it is necessary to deliver the required asset-related information from the predesign, design, and construction phase to the operation and maintenance phase. As a data repository and information management tool, BIM can overcome the deficiencies of poor information fidelity and insufficient interoperability in project delivery to support the lifecycle of their assets' information. In the design and construction phase, information is stored as structured digital data within a project information model (PIM); this information is transferred from PIM into an asset information model (AIM) once the project passed completion acceptance [107]. Compared with the enormous files in the traditional handover process, the handover activities in BIM are convenient and concise, and various aspects of the information in the project can be integrated into a single BIM file [108]. In the case study of Cavka et al. [73], the information which was required by the asset management process was identified, and a BIM-based relationship framework was formulated to facilitate the handover of the project-required information (including space allocation; access adjacency and circulation requirements; constructions regulation and specification; mechanical, structural, civil, and electrical systems descriptions and requirements) and personnel required information (including preventive maintenance schedule, preventive maintenance inspection report, backflow prevention assembly test report, systems list, equipment lists, required database attributes, cost information related to replacing and maintaining equipment/system, maintenance history, and installation manuals) in the aspect of asset management. In the green building projects that have utilized BIM in their design and construction, the information can be stored as structured digital datasets within the project information model (PIM) [107]. This information would be transmitted to the asset information model (AIM) to support the asset management in the operation and maintenance phase of green buildings, as reviewed by Hull and Ewart [107].

- Asset Management Optimization

The multi-dimension modeling in BIM provides the 3D or 4D visual demonstration of assets. In the case study of Neuville et al. [109], the visual presentation of BIM was utilized to conduct the visual counting of negative condition assets based on the BIM model in facility management. Spilling [110] summarized the benefits which can be implemented through the BIM-AM (asset management) database in the process of asset management, including enhancing ROI (return on investment), reducing asset management expenditure, optimizing decision-making, enhancing customer satisfaction and confidence, and enhancing health and safety management. Moreover, BIM can establish asset hierarchy classification for the information stored in the BIM database according to their asset class, asset group, asset type, and asset parameters. It can also develop the asset hierarchy systems by utilizing the corresponding asset number, equipment number, location, type, function, and process to enable the efficient and rapid retrieval of asset-related information in asset management [111].

4. Discussion

The literature review and literature analysis in Section 3 provided an overview of BIM capabilities in the operation and maintenance phase of green buildings. Since 2013, there has been a dramatic increase in the papers involved in the BIM application in the operation and maintenance of green buildings. This area has gained wide attention from the AEC industry since 2016. From the perspective of countries, authors from the USA, China, and the UK contributed the most articles, but research in this area from Western Europe was also significant. In addition to these, despite numerous papers in this field, compared to the BIM application in the design and construction phase, BIM capability utilization in practice is still minimal in the operation and maintenance of green buildings.

To explore the BIM capabilities in the operation and maintenance phase of green buildings, the research objectives are developed as follows: (1) identify the BIM capabilities which can be utilized in the operation and maintenance phase of green buildings; (2) determine which aspects of facilities management for green buildings these BIM capabilities can be utilized to; (3) discuss BIM capabilities and how these BIM capabilities are utilized throughout the operation and maintenance phase of green buildings; (4) summarize the advantages and challenges of BIM capabilities in green buildings' operation and maintenance phase and provide suggestions for future research directions for prospective studies.

After the article-screening process was completed, there were 128 articles remaining in this study. Then, the full texts of these remaining articles were reviewed to identify which BIM capabilities can be utilized in the operation and maintenance phase of green buildings and to explore how these BIM capabilities work. After that, these identified BIM capabilities were summarized and categorized according to the areas in which they can be applied to green buildings. In this step, these BIM capabilities can be identified to be utilize in seven aspects of green buildings' facility management, including safety/emergency management, maintenance and repair, energy management, security, retrofit and renovation, space management, and asset management. Then, these BIM capabilities were further discussed to explore how these BIM capabilities work to facilitate and improve the facility management of green buildings. In this step, it can be determined that BIM's utilization is conducted through the following four characteristics: knowledge storage and management, visualization and demonstration, simulation, and machine learning. Moreover, through the further review and discussion of the retrieved articles, the trend, research gaps, and future opportunities of BIM application in the operation and maintenance of green buildings are revealed and discussed below.

4.1. Knowledge Storage and Management

From the perspective of safety and emergency management, energy management, maintenance and repair, and asset and space management, various papers emphasize the BIM capabilities in information storage and management. BIM can deliver data generated during the green buildings' design and construction phases to their operation and maintenance phase and receive feedback and opinion from facility management personnel [53,72,73,76,101]. In addition to these, BIM has the ability to store, categorize, and manage the data generated in the process of operation and maintenance [28,31,38,47,62,90,92,98,101,111]. Through BIM utilization, stakeholders can conveniently retrieve and utilize necessary information [111]. From the perspective of asset management, energy management, maintenance, and repair, with the integration of plugin and third-party equipment (RFID, barcode, and sensor), BIM can collect the necessary data (including material and energy consumption and inventory information, and the operational status of equipment) automatically and modify the corresponding bill of quantities [49–51,53,77,78,92,93,102,106].

For the knowledge conducted in green buildings' design and construction phase, this information can be stored in the project information model (PIM) as structured digital data, then transferred to facility management organizations of green buildings through integrated project delivery (IPD) [107,112,113]. In the integrated project delivery (IPD) process, various information from multiple stakeholders can be integrated into a single BIM file [108,112,114]. In BIM, this information is stored in unified IFC (Industry Foundation Classes) format or gbXML (Green Building XML Schema) format to facilitate data exchange between stakeholders by utilizing Information Delivery Manual (IDM) and International Framework for Dictionary (IFD) through BIM [76,77,115–121]. This information can be categorized and retrieved according to the location, attributes (column, wall, beam, etc.), or functions [116,118,119].

In the operation and maintenance phase of green buildings, with the integration of the BIM and building management system, the produced information (including daily facility management activities, energy consumption information, maintenance and repair records, renovation and refurbishment activities, safety management information, security records, space and asset utilization situation, etc.) can be retrieved, stored, and categorized automatically [47–50,73,98,102,122]. Besides these, with the integration of BIM and GIS (Geographic Information System), environmental information (including topography, terrain, hydrology, vegetation, road, utility, infrastructure, etc.) around green buildings can also be captured [74,123,124]. BIM can also be connected to the Internet of Things (IoT) to search for and retrieve weather-related information [75].

However, there are still some challenges in BIM utilization in the operation and maintenance phase of green buildings. Given that some green building projects did not utilize BIM in their design and construction process, these projects had to enter information manually during the application of BIM, thus increasing the workload of the stakeholders. The challenge in integrating BIM and facility management includes incompatible file formats between BIM and other FM devices, a lack of necessary operation and maintenance data, and uncertainty in existing building data [125,126].

In the case study of Gerrish et al. [72], there were various challenges in the BIM-based knowledge management, including redundancy in the database, lack of indexing in recorded logs, and system downtime due to incorrect information commissioning of the building management system. Ghaffarianhoseini et al. [10] pointed out that the main challenges were the intellectual property issue and information security in the BIM utilization process. In addition to these, the BIM operation requires staff to perform the appropriate training; this issue makes it difficult for some operations staff to operate BIM to conduct knowledge and information management [127].

Considering the abovementioned issues, it is necessary for BIM developers and BIM vendors to enhance the interoperability to promote BIM's compatibility. In addition to these, BIM software is necessary to stick to simplicity and accessibility, thus facilitating most operation and maintenance personnel to utilize BIM.

4.2. Visualization and Demonstration through BIM

Through the analysis of the results, it can be determined that visualization and demonstration are the trends in the facility management of green buildings. From the perspective of safety and emergency management, BIM has the potential to be utilized in risk identification, emergency localization and navigation, disaster scene simulation and demonstration, and escape and rescue training [24–26,28,31–35,42–45]. From the perspective of maintenance and repair, BIM was deemed an effective method to monitor the operation condition of devices and demonstrate the equipment condition to be repaired [31,47,49–51,65]. From the perspective of security and space management, with the contribution of sensors, the conditions of different areas and components can be visualized through BIM [92,93].

Visualization is one of the main features of BIM. There are some disadvantages to traditional 2D CAD, such as enormous and complex blueprints, inaccurate presentation, low accessibility, and non-intuitive expression [128]. However, three-dimensional and interactive models of specific projects can be provided in BIM, which familiarizes stakeholders (even amateurs) with the target projects [129]. In BIM, the 3D model can be automatically modified when the alteration is conducted by stakeholders, which supports users to have the ability to be familiar with the current situation and progress of projects in time [130]. In addition to these, with the development of BIM and information technology, online BIM visualization has become a potential direction in the AEC industry. Online BIM visualization is light-weighted, cross-platform, and open [131]. Light-weighted means the exchange's modeling data is light and in accordance with normative standards. Cross-platform and open represent the visualization model in BIM that can be shared between multiple platforms online to allow various stakeholders to utilize it.

The BIM visualization model can provide detailed geometrical and functional information about each component in assets [97,132]. In the manufacturing process of the visualization model, the sequence of design is the component, room, floor, building, and building layout; this sequence ensures that the user has the most detailed information about the building through the visual model [133]. The visualization model can be extended to the surrounding environment with the integration of BIM and GIS. It can visually demonstrate the surrounding environment in a 3D model [123,124]. Based on BIM and GIS, the legal boundaries and 3D cadaster are visually demonstrated by introducing the land administration domain model (LADM) into this integration [134]. Besides these, with the combination of BIM, surveillance, radio frequency identification (RFID), and sensor, the dynamic visualization model can be generated in operation and maintenance phase of green buildings [31]. With this contribution, the digital visualization can demonstrate that the accident scenes and automated LED escape route pointers can be achieved when accidents happen [135].

However, from the visualization perspective, there are still some challenges in the BIM application in the operation and maintenance of green buildings. The visualization function inevitably infringes on the privacy of some occupants, which may lead to resistance to BIM applications from some occupants [10,126]. In addition to these, the visualization of security and space-management aspects must be assisted with plentiful additional devices (such as sensors and RFID), thus increasing the expenditure during the operation and maintenance of the green building significantly. In addition to these, the deficient compatibility between BIM and sensors is also a challenge [126].

4.3. Simulation

According to the literature review of Section 3, the BIM simulation influences the aspects of safety and emergency management, energy management, retrofit and renovation, and space management. From the perspective of energy management, the light, heat, radiation, ventilation, temperature, humidity, and terrain of the indoor and surrounding environment can be simulated through BIM utilization, thus speculating the energy consumption based on this information [75,76,78,81–83,91]. In this process, by integrating the indoor and surrounding environment, building-related characteristics (location, material, orientation, etc.), building service systems (heating, ventilation, air conditioning etc.), and occupants' behavior, BIM can be utilized to simulate the energy demand of a green building [78,136,137]. Besides that, with the integration of BIM and building management system (BMS), BIM can count and analyze the energy utilization preference of different occupants and the energy consumption of green buildings in various periods and seasons [138]. Based on these, the energy utilization and consumption situations of green buildings can be simulated through BIM [78,136,139,140].

From the perspective of retrofit and renovation, the main contribution of BIM is to perform the simulation and comparison of the construction effects of different schemes, which can facilitate green building managers to select appropriate options [4,87,97,99]. In the process of green building retrofit, based on the location, layout, environment, materials, and terrain of the green buildings, BIM can simulate the thermal condition, ventilation condition, illumination intensity, and humidity of different refurbishment plans [141–143]. Then, the simulation results can be inputted into BIM to validate the compliance of these retrofitting solutions with the green building assessment standard and to screen the best retrofit scheme [142–144]. For the green building retrofit activities with potential uncertainty, BIM can simulate the impact that different retrofit activities can have, to perform the feasibility studies of the refurbishment scheme [145]. From the aspect of safety and emergency management, the main contribution of BIM is to conduct disaster situation simulation, to be utilized as the information foundation for the development of rescue plans and evacuation routes [42,43].

Despite various BIM simulation capabilities being developed by researchers, many BIM simulation capabilities are only feasible in the theoretical phase and cannot be, or are rarely, applied in practice [146].

4.4. Machine Learning

In the sample of papers selected in this study, there are only a few papers that involved machine learning. From the perspective of maintenance and repair, case-based reasoning (CBR) modules in BIM can store and learn maintenance and repair cases and automatically match solutions to similar cases when the maintenance and repair personnel are encountered [12,57–60,147]. Through the contribution of CBR, BIM can utilize this knowledge to competently assist personnel in conducting fault detection and diagnosis. In the situation where faults are detected by sensors or reported by personnel manually, the faults are mapped into the BIM visualization model and the potential impact of these provided faults is simulated. Then, the fault-related information is transferred to the fault detection and diagnostics (FDD) module. Monitoring data can be analyzed and checked based on the principles stipulated by BIM vendors or facility management personnel, then the FDD module develops problem descriptions and transmit to the CBR module. After the problem descriptions are received by the CBR module, the CBR module can automatically search previous items in the database for these problem descriptions and match a corresponding solution scheme. Finally, the process of fault solution is stored in the case repository [57,66,148].

In addition to these, BIM can be adopted to schedule preventive security maintenance and optimize guard positions, especially guard patrols, according to the security knowledge and instruction entered. In this process, BIM can be utilized to retrieve the security management experience in the repository. BIM can automatically match projects with similar profiles to those of assets, then formulate a security scheme based on the safety management experience in the retrieved project [92]. BIM safety management can also enrich their knowledge reserve through machine learning (ML) to simulate the potential risks and accidents in the operation and maintenance phase of green buildings [149].

5. Conclusions

In the operation and maintenance phase of green buildings, given their low energy consumption, low pollution, low expenditure, and high resident comfort requirements, green buildings require a higher quality facilities management process than traditional buildings. As a multi-function method, BIM is considered to have the ability to assist facility management personnel in fulfilling the operation and maintenance regulations of green buildings. Given the significant function of BIM, numerous papers were developed to study the BIM capabilities in the operation and maintenance phase of green buildings in recent years.

This study aimed to perform a systematic literature review of the BIM capabilities in the operation and maintenance phase of green buildings. In this study, there were 128 articles to be screened to perform a systematic literature review and analysis. Through the mentioned process, the capabilities and efficiency of BIM in the operations and maintenance phase of green buildings was reviewed. Besides that, the researchers also determined the defects and challenges of BIM application in the facility management through the review. Based on these processes, the research gap and future directions in this field were identified through results analysis. In this direction, the BIM capabilities in the facility management of green buildings were addressed for the following aspects: safety and emergency management, maintenance and repair, energy management, retrofit and renovation, security, space management, and asset management.

Through the results analysis, it can be identified that the BIM contributions in the facility management of green buildings relied on the following BIM characteristics: knowledge storage and management, visualization and demonstration, simulation, and machine learning. In addition to these, there are also some challenges in the integration of BIM and facility management, including high expenditure, difficulties in integrating with third-party devices and plug-ins, compatibility deficiencies, professional training requirements in BIM operation, and privacy violations.

The limitations of this study are as follows:

A. Some reviewed BIM capabilities can be utilized in the operation and maintenance phase of multiple types of buildings instead of specific to green buildings. However, these BIM capabilities were included and reviewed because they can assist green buildings either to improve their facility management's quality, or to reduce their costs, or to improve occupants' comfort during their operation and maintenance phases.
B. As an information technology, BIM technology is constantly changing and upgrading. Over time, some BIM capabilities' utilization methods might be changed in the facility management of green buildings.
C. Given that green building evaluation standards are not uniform across countries, some reviewed BIM capabilities might not be suitable in a specific country, or these BIM capabilities are required to be adapted to suit specific national green building evaluation standards.
D. To ensure research quality, this study only included the articles that can be searched in WoS or Scopus; some BIM capabilities might be omitted.

Given these limitations, other researchers are suggested to continue tracking the BIM application during the operation and maintenance of green buildings. Researchers could focus on exploring the functions of BIM utilization in the facility management of green buildings in specific countries. In the subsequent review of BIM capabilities in green buildings' operation and maintenance, documents that are searchable in repositories other than WoS and Scopus can also be included in the study to perform a more comprehensive systematic review. In addition to these, other researchers are encouraged to perform studies to optimize BIM capabilities, to reduce the expenditure and improve the quality of BIM utilization in the green buildings' facility management.

Overall, this study provides a comprehensive systematic review and analysis of the BIM capabilities in the operation and maintenance phase of green buildings. Based on these, researchers can obtain a comprehensive overview of BIM utilization in green building facility management, which can prompt the development of BIM applications in the O&M phase. In addition, this study can facilitate other researchers to address the challenges mentioned in this content and provide the future directions for their studies. Besides that, some mentioned BIM capabilities could also be utilized in green buildings' design, construction, or demolition phase. It can assist other researchers in performing studies about the BIM implementation in other phases of green buildings.

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