The applications of building information modelling for the lifecycle performance of green buildings: a systematic literature review

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Abstract

Buildings and construction are one of the major contributors to global warming and climate change. The development and operation of green buildings are of critical importance to achieve sustainability. Although a series of assessment criteria has been proposed to evaluate green buildings, such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), as well as Green Star New Zealand, it is challenging to track and analyse the lifecycle performance of green buildings.

Building Information Modelling (BIM) has emerged as a digital technology which has the protentional to address this issue. BIM integrates the lifecycle data of buildings, such as geometries, materials, facilities, systems, physical properties, and thermal properties. With these types of data and information, the environmental performance and impact of green buildings can be assessed properly. However, most of current studies mainly concentrate on the applications of BIM for green buildings in one or two of lifecycle phases (e.g., construction phase or operation phase). The integration of BIM and green buildings for whole lifecycle performance is lacking.

This research aims to explore the current applications of BIM implemented in the lifecycle of green buildings and the sustainable factors addressed by BIM applications. This research applied a systematic literature review to achieve the research aim.

The results indicate that 1) BIM can be applied to evaluate energy consumption and carbon emission in the design, construction, and operation processes of green buildings. 2) BIM provides a platform to integrate with LEED green rating systems). The findings indicate various advantages of BIM in terms of assessing the energy consumption, CO2 emissions, and the features of green buildings.

Keywords

BIM, carbon emissions, energy analysis, green buildings, life cycle assessment.

Introduction

The development and operation of buildings contribute to a substantial consumption of energy and emission of carbon (Gao *et al.* 2019). For instance, the government of New Zealand has reported that carbon emissions from the construction industry have increased by 66% in the decade from 2007 to 2017. Hence, if there are proper ways to deliver the design, construction, and operation works throughout the entire life cycles of buildings, the energy-savings can be approached significantly. In response to this trend, the new concept of green buildings has been developed and practiced by the global construction industry.

Although the practitioners have established comprehensive measures to assess the green buildings through their life cycle, they are still confronted with a major challenge when collecting the relevant data to achieve the criteria of Green Building Assessment Schemes (GBAS). This is because the lack of sufficient tools to evaluate green buildings, and using the traditional assessments are relatively inconsistent and inaccurate with respect to time and costs (Ansah *et al.* 2019).

To assist the assessments of the green buildings, Building Information Modelling (BIM) has been emerging as an intelligent information-based process to create an innovative working platform improving the productivity and sustainability in the construction industry. (Elmualim and Gilder 2014, Lu *et al.* 2017, Rodrigues *et al.* 2020). The BIM technology has contributed to facilitating the management and integration of information through the entire life cycle of buildings. Therefore, BIM has the potential to be one of the most efficient methods to cope with this issue. However, the current literature has rare information about the life cycle assessment (LCA) for green buildings using BIM. To fill this gap, this research adopts a systematic literature review approach to give insights into the applications of BIM for green buildings from design to operation phases.

Literature Review

The construction industry has caused serious environmental issues, such as climate change and energy shortage, as using traditional methods for buildings generate 33% of greenhouse gases and consume over 40% of global energy (United Nations Environment Programme, 2009). To resolve resource constraints and achieve sustainability, the top priority is to develop green buildings.

At present, a series of assessment standards have been proposed to evaluate green buildings. For instance, the United States Green Building Council has proposed an Energy and Environmental Design Building (LEED) rating system. The British Building Research Establishment has introduced a method to assess green buildings called Building Research Establishment Environmental Assessment Method (BREEAM). The New Zealand Green Building Council (NZGBC) has introduced Green Star New Zealand, which is an adapted version of Green Star Australia, established in 2007. The Building and Construction Authority (BCA) in Singapore promoted Green Mark Assessment Criteria. These approaches all revolve around energy savings and emission reductions (Espinoza *et al.* 2012, Zhang *et al.* 2017). However, the majority of current studies mainly concentrate on the assessment of design, and construction stages, but rarely assess the operation and maintenance stages. In this situation, when the high carbon emission and energy consumption caused by the building users in the operation and maintenance stages, the overall environmental performance will be influenced (Cheng *et al.* 2020). Hence, it is important to assess the entire LCA for green buildings.

LCA is a methodology for analysing environmental impacts related to all the stages of products throughout their whole life cycles. Cheng *et al.* (2020) stated that the traditional method of LCA normally has four steps, including scope definition, inventory analysis, impact assessment, and result interpretation. Each step needs to collect used materials and data about building performance, but it is difficult to create a database and obtain accurate quantities to complete the analysis work.

In the past decades, although BIM has become a wide application in the construction industry, the current studies still lack comprehensive reviews to establish a link between green buildings and BIM applications (Lu *et al.* 2017). Whether the applications of BIM can be utilised to assess green buildings through the life cycle should have in-depth research. Therefore, the motivation of this study is to evaluate the applications of BIM for green buildings over the life cycle.

Research Methodology

Khan *et al.* (2003) demonstrate a workflow to conduct systematic literature review. The first step of this research is to formulate questions, as problem formation with the determination of the questions will guide the literature review. Therefore, two main research questions have been formulated to investigate these two research objectives: 1. How have BIM applications been applied in the lifecycle of green buildings? 2. What factors have been addressed by BIM for green buildings?

The next step is to search and select the relevant literature papers. The majority of journal articles and conference proceedings have been collected from Scopus, which is the largest abstract and citation database of peer-reviewed literature. Apart from that, retrieving relevant articles from the reference lists of selected papers were also adopted by using 'Google Scholar' to cover any missing papers. This searching engine provides a simple way to broadly search for scholarly literature.

The keywords for searching articles in Scopus are 'BIM' and 'Green buildings'. The search work was carried out on 10 May 2021. The total number of papers obtained from Scopus is 561.

After that, the filtering process was conducted following a framework named Preferred Reporting Items for systematic Literature Review and Meta-Analyses (PRISMA) (Moher *et al.* 2009), including inclusion and exclusion criteria. If the articles do not include BIM applications implemented in the life cycle phases of green buildings (e.g., design phase or construction phase) in the title or abstracts, these papers were excluded. The rest of the articles were assessed for eligibility. The target articles should fulfil the following criteria:

1. The BIM-based assessment for green buildings through the lifecycle has been proposed and analysed,
2. An experiment has been conducted to collect the learning outcome,
3. Data analysis has been conducted to evaluate,
4. The publication time span is limited from 2000 to 2021.

The articles that cannot fulfil the above criteria were excluded. The selection process is demonstrated in Figure 1.

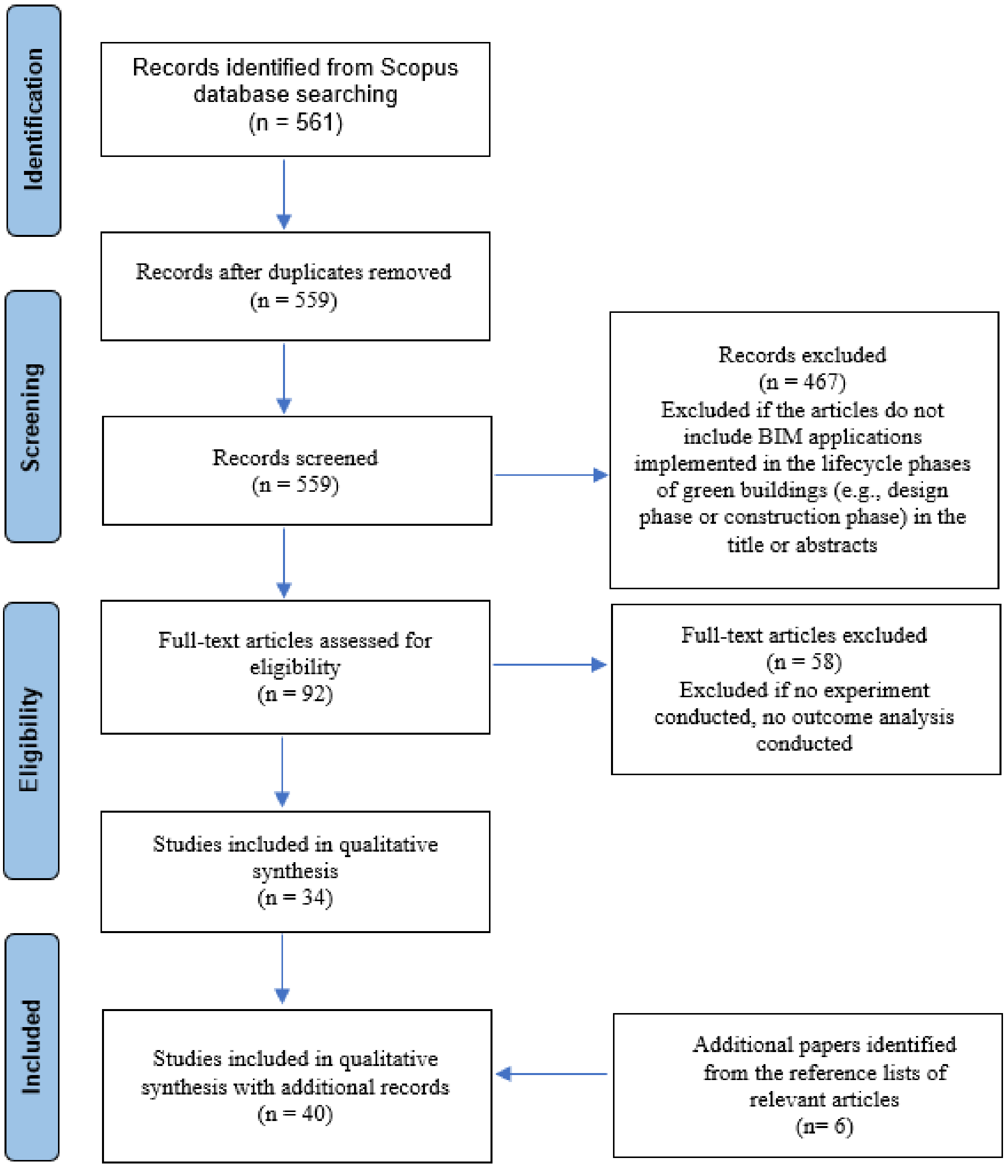

Figure 1. The process of research article selection

Consequently, 40 papers were identified as the target articles for this systematic literature review (Abanda and Byers 2016, Ajayi *et al.* 2015, Alothman *et al.* 2021, Azhar and Brown 2009, Azhar *et al.* 2010, Azhar *et al.* 2011, Bonenberg and Wei 2015, Chen and Hsieh 2013, Chen and Nguyen 2015, Cheng *et al.* 2020, Doan *et al.* 2018, Doan *et al.* 2019, Ebrahim and Wayal 2019, El Sayary and Omar 2021, Gandhi and Jupp 2014, Gardezi and Shafiq 2019, Ghaffarianhoseini *et al.* 2017, Jalaei *et al.* 2020, Jalaei and Jrade 2014, Jalaei and Jrade 2015, Khahro *et al.* 2021, Krisel and Nies 2008, Lee *et al.* 2015, Lee *et al.* 2015, Li *et al.* 2012, Lin *et al.* 2019, Lu *et al.* 2019, Maltese *et al.* 2017, Najjar *et al.* 2017, Nguyen *et al.* 2010, Rathnasiri *et al.* 2021, Rodrigues *et al.* 2020, Ryu and Park 2016, Singh and Sadhu 2019, Solla *et al.* 2016, Uddin *et al.* 2021, Wen *et al.* 2020, Wu and Issa 2014, Yang *et al.* 2018, Zhang and Xing 2015). Among these papers, 38 were published in the journal articles, with the remaining two published as conference proceedings. Most of the papers were published after 2010, with only two were published in 2008 and 2009.

Findings and Discussion

This research implements qualitative data analysis. The focus of this review is the previous research outcomes, which is to extract data from each paper and integrate these outcomes. To support this stage, a matrix will be established by using Microsoft excel to list all the analyses and outcomes that the previous studies identified. When the previous researchers obtain the same outcome, the evidence will be integrated and listed in the matrix.

BIM-supported design phase

In the review papers, the applications of BIM were developed to deal with sustainability issues in the design phase. This process contained building performance analyses and simulations, such as energy consumption analyses and carbon emission simulations. Apart from that, a few papers were carried out the further development of BIM energy simulation tools to improve the efficiency of the design stage. Table 1 shows BIM-based simulation items recognised by this review.

Table 1. The aspects of energy simulation based on BIM

Simulation aspects	**Articles**	**Description**
Orientation	Alothman *et al.* 2021, Azhar *et al.* 2011, Ebrahim and Wayal 2019, Khahro *et al.* 2021, Singh and Sadhu 2019	Minimise the energy consumption and maximise the ventilation and solar radiation
Heating and cooling loads	Alothman *et al.* 2021, Ajayi *et al.* 2015, Azhar *et al.*2010, Ebrahim and Wayal 2019, Khahro *et al.*, 2021, Lee *et al.* 2015, Lin *et al.* 2019, Rodrigues *et al.* 2020, Singh and Sadhu 2019, Zhang and Xing 2015	Select the favourable WWR, exterior materials and HVAC systems to improve the capability of HCL
Daylighting	Azhar *et al.* 2011, Bonenberg and Wei 2015, Lee *et al.* 2015, Lin *et al.* 2019	Achieve indoor environmental quality and energy efficiency

BIM-based energy performance analyses in the design process

In the review papers, BIM was adopted to assess the energy consumption of green buildings, including orientation simulations, heating and cooling loads (HCL) analyses, daylighting analyses. In terms of the orientation simulations, BIM technology was identified the function to visually simulate the building's orientation, which is a critical feature to achieve green buildings. The proper building orientation has a valuable contribution to minimise the energy consumption and maximise the ventilation and solar radiation throughout the building operation phase (Alothman *et al.* 2021, Khahro *et al.* 2021), which can directly reduce the load on lighting and HVAC systems (Singh and Sadhu 2019). BIM-based simulation analysis has the function to select the favourable building orientation that contributes to the minimum energy consumption of buildings (Azhar *et al.* 2011). Abanda and Byers (2016) examined the influence of building orientation on energy consumption and explored how BIM could be utilised to facilitate this process. Alothman *et al.* (2021), Azhar *et al.* (2011) and Singh and Sadhu (2019) made a comparison with various building's orientation directions to optimise the sustainable design. Based on the comparison of the energy consumption in accordance with the different building orientation directions, results indicated that a well-orientated building could decrease a huge amount of energy usage over its entire lifecycle. Ebrahim and Wayal (2019) and Khahro *et al.* (2021) changed the building's orientation up to 15°, this option allowed the building with better airflow and energy saving.

To improve energy efficiency, HCL is the second aspect to assess green buildings in the design stage. The assessment process can be divided into two aspects, including building material analysis and HVAC system analysis. With regard to the former, BIM applications can support the designers to analyse each part of the building's components and calculate the energy use of the buildings. BIM embodied database has a library that allows the designer to add and modify various alternative materials for energy analysis. It provided a platform for the designers to change the characters of the building envelope and seek solutions to evaluate HCL of buildings. Lee *et al.* (2015) proposed a BIM-based energy modelling to analyse the relationship between window to wall ratio (WWR) and HCL of a high-rise building. Ajayi *et al.* (2015), Ebrahim and Wayal (2019), Khahro *et al.* (2021), Lin *et al.* (2019), Singh and Sadhu (2019), and Zhang and Xing (2015) compared the effect of different WWR, wall materials, and roof materials implemented in residential buildings to promote the capability of HCL based on the applications of BIM. Alothman *et al.* (2021) and Rodrigues *et al.* (2020) utilised BIM tools to calculate the life cycle energy consumption of alternative window, wall, and roof materials. Results indicated that the improvement of the conductions and insulations of windows, walls, and roofs developed the HCL of buildings to achieve energy efficiency.

In addition, HVAC systems have a significant influence on the energy use of the building life cycle. The core purpose of implementing HVAC systems is to improve the quality of indoor air and control HCL for buildings. BIM-based energy analysis can estimate the life cycle electricity usage and the life cycle fuel usage of various types of HVAC systems. These parameters enable the designers to analyse the energy efficiency of HVAC systems. For example, Alothman *et al.* (2021) and Singh and Sadhu (2019) evaluated different types of HVAC systems in BIM software and simulated the annual electricity and fuel usage of this equipment, which provided effective data to improve energy efficiency of HVAC systems. Azhar *et al.* (2010) evaluated the feasibility of BIM for HVAC analysis via a case study. Results showed that BIM could significantly facilitate to developing complex building performance analyses and achieve an optimised building design.

Daylighting analysis is also a significant factor for promoting a green building design, as it assists the green buildings to achieve energy efficiency and indoor environmental quality. The reviewed papers introduced that the applications of green BIM tools could be used to analyse daylighting of buildings. Azhar *et al.* (2011), Bonenberg and Wei (2015), and Lee *et al.* (2015) used BIM to perform a series of daylighting studies for positioning on a selected construction site during the design phase. Lin *et al.* (2019) created a BIM-model and simulated sunlight changes, solar radiation, and natural daylighting to examine the energy efficiency performance of a retail market, which provided the optimisation plans to consider as a reference for subsequent re-construction design.

Apart from the above energy analyses for green buildings, a few papers focused on the further development of BIM energy simulation tools to support the design stage. El Sayary and Omar (2021) investigated a decision-making tool for architects in the design phases, which was the energy consumption template plug-in embodied in BIM applications to enhance the design performance. Results showed that this added tool could assist users to evaluate their designs and achieved a zero-energy building. Rodrigues *et al.* (2020) used BIM-modelling software to perform the potential of BIM in energy management and analysis of an existing two-story public building. Results showed that BIM contained all energy-related information and designers could select the most appropriate solution in the database of BIM to save the energy consumption, which was proved the potential of BIM in the AEC sector. Wen *et al.* (2020) proposed an empirical analysis to develop the effectiveness of BIM for green buildings. Results indicated that the application value of BIM was fully achieved in the design process but decreased in the construction and operation phases. Maltese *et al.* (2017) confirmed that the use of BIM applications to provide data for energy consumption assessment and sustainability evaluation could integrate design, construction, and operation guiding towards a Net Zero Energy building.

BIM-based carbon emission analysis in the design process

In eight papers, BIM was implemented as a simulation tool to perform the carbon footprint analysis and to support the design process of green buildings. Ajayi *et al.* (2015) and Khahro *et al.* (2021) utilised BIM for quantity take-off and evaluated the environmental impacts of commonly used building materials, including brick, timber, concrete, and steel, on the lifecycle performance of buildings. Uddin *et al.* (2021) also used BIM for quantity take-off for residential buildings to calculate the embodied carbon dioxide (CO2) content for construction materials by considering the standard database in India and the inventory of Carbon and Energy (ICE). Lu *et al.* (2019) used BIM to propose an analytical framework quantifying the carbon emissions of a hospital through its entire life cycle, which provided a solution that minimised the carbon emissions of buildings and improved the performance of buildings. Cheng *et al.* (2020) presented the LCA-BIM method for green building assessment to calculate CO2 emissions of a public building in different construction activities (e.g., construction and operation stage).

In addition to the above functions of BIM in the design stage, other papers concentrated on the further development of BIM applications in evaluating carbon emissions. For instance, Lee *et al.* (2015) proposed a green-BIM template to estimate CO2 emissions of the common construction materials through the entire life cycle, which enabled the designers to compare the environmental impacts of different building components (e.g., wall, floor, beam, column, and window). This situation provided an efficient decision-making to select low-carbon construction materials. Gardezi and Shafiq (2019) proposed a prediction BIM-based model for the operational carbon emissions at the design phase. Chen and Hsieh (2013) and Li *et al.* (2012) investigated a plug-in that used BIM and the database of a carbon calculation software to calculate the real-time CO2 emissions of buildings.

BIM-supported construction phase

In a few papers, BIM was implemented to explore CO2 emissions that generated in the construction process. Based on the BIM applications, the amount of carbon emission that generate from the productions of building materials, the process of material transportation, and on-site construction activities can be analysed. The multiple data effectively assist the manager to control CO2 emissions in the construction stage. For instance, Lu *et al.* (2019) applied BIM to analyse carbon emissions of 10 building materials and different work types in the construction stage. Yang *et al.* (2018) used BIM to assess carbon emissions generated during the process of building material transportation and the use of construction equipment.

BIM-supported operation phase

The main energy consumption and carbon emissions in the operation stage is the use of HVAC systems, water supplying, lighting systems, and other operational equipment. In a few review papers, BIM technology was identified as a management tool to monitor the performance of green buildings. Rathnasiri *et al.* (2021) compared the applicability of green BIM energy simulation for an existing green building that has been accredited LEED rating systems. Results indicated that BIM-based building performance analyses were accurate and realistic compared with actual results, which could be effectively implemented to manage the existing buildings of energy consumption. Lu *et al.* (2019) evaluated the carbon emissions generated in the operation stage of a hospital in China, including HVAC systems, daylighting, water supplying, and equipment use.

BIM and green building rating systems

BIM and LEED

In nine papers, the applications of BIM were applied to integrate with the LEED rating system. Azhar *et al.* (2011) investigated a conceptual framework to explore the relationship between BIM and the LEED rating system. Results indicated that BIM tools could evaluate up to 17 LEED credits. Solla *et al.* (2016) identified 38 LEED credits could be achievable by using BIM applications. Krisel and Nies (2008) utilised BIM to analyse the credits of water efficiency, energy and atmosphere, as well as indoor environmental quality in LEED. Chen and Nguyen (2015) integrated geographic information with BIM to improve the efficiency of building's location and transportation analysis for the credit of suitable site in LEED. Jalaei and Jrade (2014) recognised that BIM tools could evaluate the credits of material and resources, coupled with energy and atmosphere in LEED.

Apart from that, some papers focused on the further development of BIM tools in assisting LEED rating system analysis. Wu and Issa (2014) investigated a BIM execution plan for a LEED project. Nguyen *et al.* (2010) proposed a framework to extract data from the BIM-based building model for supporting the sustainability assessment, which was based on the LEED green building rating system. Jalaei *et al.* (2020) and Jalaei and Jrade (2015) created a plugin for automatic calculate the required number of points based on the LEED green building rating system to facilitate project teams in making sustainability-related decisions. Ryu and Park (2016) proposed an improved method to fulfil LEED certification for an existing building.

BIM and Green Star (New Zealand)

A few papers investigated the applications of BIM for green buildings in New Zealand. Gandhi and Jupp (2014) stated that BIM applications could be implemented to perform the criteria of Green Star, but not all criteria could be addressed by BIM applications. This is because the awareness of considering the benefits between BIM and Green Star has still received insufficient attention (BRANZ, 2015). To facilitate the development of integrating BIM and Green Star in New Zealand, Ghaffarianhoseini *et al.* (2017) explored the relationship between BIM and Green Star. Results showed that the applications of BIM could support practitioners to achieve the majority of Green Star criteria. However, Doan *et al.* (2018) and Doan *et al.* (2019) examined whether BIM and Green Star could be created a link and be adopted in the construction industry. Results indicated that a relationship between them did not exist currently, but there was a potential to integrate BIM and Green Star. The lack of integration was due to the lack of client demand, the low level of BIM development, and the lack of both Green Star and BIM understanding.

BIM and LCA

In the review papers, the researchers combined BIM and LCA to analyse the overall environmental impacts of green buildings, such as energy consumption and carbon emission. Azhar and Brown (2009) examined whether BIM simulation software had the capacity to integrate with LCA. Cheng *et al.* (2020) proposed the LCA-BIM method to analyse the carbon emissions of common building materials through the entire life cycle. Najjar *et al.* (2017) analysed the methodology of LCA from a building perspective and proposed the role of BIM and LCA integration in evaluating the environmental impacts of building materials, which enabled both the decision-making process and sustainable design procedure in the construction sector. Ajayi *et al.* (2015) and Lu *et al.* (2019) introduced a framework for integrating BIM and LCA, which could be implemented in the early design stage to assist the designers and engineers to acquire reliable outcomes related to the environmental impacts of buildings. Jrade and Jalaei (2014) utilised BIM with the LCA tool (Impact Estimator) to create a model for evaluating the environmental impacts in the design phase. Lee *et al.* (2015) also investigated a BIM-based model with Korean life cycle inventory (LCI) databases to evaluate the environmental performance of buildings.

Based on the data analysed above, the applications of BIM utilised to develop the lifecycle performance of green buildings have been identified. In the design stage, the applications of BIM provide a platform to evaluate the performance of buildings through the entire life cycle in the early design process. This is because BIM technology enables the designers to simulate design features of green buildings, which contains energy performance analyses and carbon emission simulations. In terms of the energy consumption analyses, BIM tools can assist the designers to simulate three main aspects of green buildings (orientation, HCL, and daylighting). The orientation simulation can significantly minimise the energy consumption and maximise the ventilation and solar radiation of green buildings. HCL analyses can assist the designers to select the favourable WWR, exterior building materials and HVAC systems. Daylighting analyses enable the green buildings to achieve indoor environmental quality and energy efficiency. The designers can implement these identified functions of BIM to analyse the energy performance of green buildings and make decisions in the design stage. In addition, BIM allows the designers to evaluate CO2 emission in the design stage, as BIM can calculate the embodied carbon contents in different building materials. By comparing the data, the designers can select low-carbon emission materials to promote the criteria of green buildings. Apart from that, the applications of BIM have the function to integrate with the LCA method in the design stage, which allows the designers to analyse the overall environmental impacts of green buildings in the early design phase. This situation can predict CO2 emission and energy consumption in the construction and operation stage, providing a series of data for the management in these phases.

In the construction stage, BIM is only used to monitor and reduce the carbon emission that generates from three construction activities, including building material production, material transportation, and on-site construction activities. Yet, the analysis of energy consumption in this stage is not identified. In the operation stage, both energy consumption and carbon emission of green buildings can be evaluated by BIM tools. The use of HVAC systems, lighting, water supplying, and building equipment is the main sources of energy consumption and carbon emission. By simulating these factors, BIM is adopted as a management tool to monitor the performance of existing green buildings.

Integrating BIM with rating systems provides a simple and effective method for designers to evaluate the energy consumption and carbon emissions of green buildings. This is in line with the researchers who use BIM to investigate the credits in the LEED rating system. Although most of the current papers only introduce the integration of BIM and the LEED rating system, not all the credits in LEED can be assessed by BIM. In seven categories of LEED, BIM can implement to analyse sustainable sites, water efficiency, energy and atmosphere, material and resources, and indoor environmental quality, but BIM cannot be used to evaluate the credits of innovation in design and regional priority. Additionally, the current situation of integrating BIM with Green Star is limited. This is because the lack of client demand, the low level of BIM development, and the lack of both Green Star and BIM understanding lead to the failure of creating a link between BIM and Green Star in the construction industry. Whether BIM and Green Star could be integrated requires further research in the future.

Conclusion

To conclude, this systematic literature review was carried out on the integration of BIM applications and green buildings for overall lifecycle performance. Two research objectives, including the current BIM applications implemented in the lifecycle of green buildings and the sustainable aspects addressed by BIM applications, were extensively explored. The findings indicate various advantages of BIM in terms of assessing the energy consumption, CO2 emissions, and the features of green buildings. However, this research has a few limitations. Only a few papers introduce BIM to assess the performance of green buildings in the construction and operation phases. There may be other aspects that are important to developing and implementing BIM for the construction and operation stage. Whether BIM applications can be used to monitor energy consumption (e.g., the mechanical plants using for earthworks, transportation, compacting, lifting requires a significant portion of energy) in the construction stage. As a result, there is still in need to investigate the applications of BIM in the construction and operation stages in future research. Furthermore, most of the existing research focus on integrating BIM and the LEED rating system. There is still in need to investigate further research on integrating BIM and other green building rating systems.

Acknowledgement

This research was supported by Building Research Association of New Zealand (BRANZ) as part of ‘Creating capacity to transition to zero-carbon programme’.

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2022-02-17