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A Review of Collaborative Research on BIM Technology in the Whole Life Cycle of Green Buildings

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Abstract

In light of both the global climate change phenomenon and the digital revolution affecting the construction business, green buildings are viewed as one important channel through which sustainable development within construction can be achieved. The technology of Building Information Modeling (BIM) proves important in tackling problems associated with information silos, weak communication efficiency, and evaluation problems experienced at the design, construction, and use phases of green buildings. On the basis of a comprehensive literature review, this paper will provide a summary of the current status of BIM technology use in green buildings. With emphasis on sustainability and low-carbon targets, it examines BIM applications strategies, associated technologies, and integration strategies throughout the planning, design, construction management, operation and maintenance, renovation, and demolition processes. It turns out that BIM is not just a simple tool of functional simulation but also a platform that integrates and manages every bit of relevant data on the building, which shows significant efficiency in energy usage computation, carbon emission evaluation, green construction supervision, and smart operation and maintenance. Nevertheless, the absence of standardised data formats between various software platforms is preventing smooth interconnectivity, leading to difficulties in cross-stage workflows. Moreover, an insufficiency in the interdisciplinary workforce poses a serious hindrance to the advancement of the same. The importance of this paper is based on systematically discussing the common practices and core technologies of BIM throughout the entire life cycle of green buildings - including planning, design, construction, operation and maintenance, and renovation and demolition - and explaining how information flows and value transforms between each stage.

Keywords

building information modeling (BIM), green building, sustainability, low-carbon, whole life cycle

1. Introduction

Since the beginning of the 21st century, the issue of global climate change has become increasingly severe, posing a major challenge to humanity. The construction industry is a vital component of national economies and a significant source of energy consumption and carbon dioxide emissions. Globally, the building sector accounts for approximately 40% of total energy consumption, 30% of raw material consumption, 25% of freshwater consumption, and generates over 30% of greenhouse gas emissions [1-5, 8].

In this context, the concept of “green building” has emerged and continues to evolve. Initially based on energy-efficient buildings, it has gradually developed into a comprehensive system encompassing energy, water, materials, indoor environmental quality, and other aspects. In recent years, with the goal of achieving “carbon neutrality”, low-carbon building design has been incorporated, continuously enriching and refining the concept [6, 7]. Various countries have established their own green building assessment standards, such as LEED in the United States, BREEAM in the United Kingdom, and China's Assessment Standard for Green Building, providing quantifiable benchmarks and bases for industry development [8, 9]. However, the realization of green buildings requires multidisciplinary collaboration, data-driven decision-making, and performance evaluation, all of which pose significant challenges to traditional practices.

The concept of BIM first emerged in the 1970s, referring to the digital representation of the physical and functional characteristics of a building throughout its entire lifecycle [10, 11]. Traditional computer-aided design (CAD) only handles geometric data, whereas BIM is an object-oriented, parametric, and computable model, representing a fundamental difference. In a BIM model, any element—such as walls, windows, or beams—is not just a drawing but an “intelligent object” containing extensive information, including material properties, cost data, manufacturer information, and even maintenance history [12]. As practical work progresses, the scope of BIM continues to expand and refine. Initially, a 3D geometric model for construction schedule simulation (4D), BIM later incorporated the cost dimension for cost estimation (5D), then the performance dimension for energy analysis and asset management (6D), and even higher-level sustainability dimensions [10, 13]. This evolution clearly demonstrates that BIM has transformed from a simple 3D modeling tool into an information management and integration platform covering the entire building lifecycle. To meet the need for information exchange across different stages and between various software applications, open standards play a crucial role. Industry Foundation Classes (IFC) is a very popular BIM data exchange standard, providing a neutral and open way to transfer data between different software applications, thereby enabling seamless information sharing [1]. Green Building XML (gbXML) is a specific format designed to transfer data between energy analysis and simulation software [14, 15].

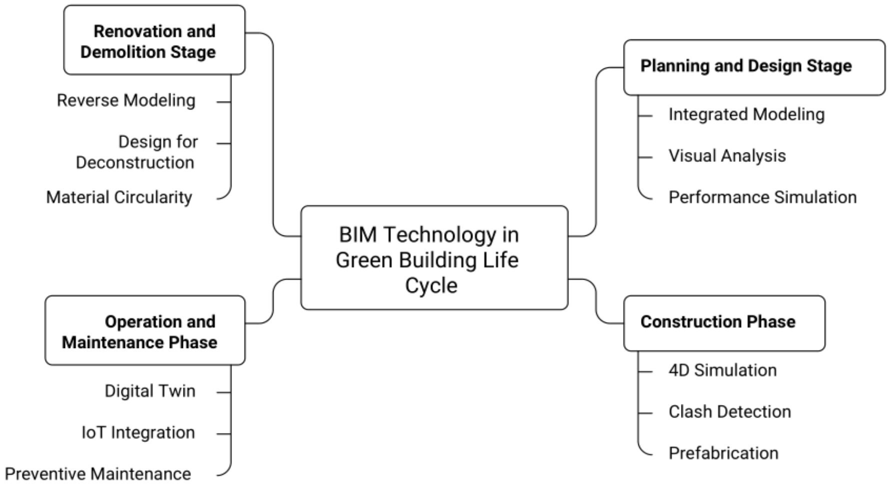
The construction industry is undergoing a revolution driven by BIM. BIM transcends a mere three-dimensional geometric model. It acts as a comprehensive instrument for storing, organizing, managing, and utilizing information across a building project's entire lifecycle. Green buildings carry multiple, often recondite requirements. BIM's attributes—visualization, collaboration, simulation, and optimization—fully address these needs [16-18]. BIM integrates geometric dimensions, material properties, costs, and timelines of various building components, offering a complete information platform for green building design, construction, operation, and eventual deconstruction and reuse [19-21].

A large body of research has shown that integrating BIM technology with green buildings can effectively address a series of challenges, including low design efficiency, extensive construction management, high operational energy consumption, and difficulties in carbon emission traceability [22-29]. This integration is of great significance for promoting the green development of China's construction industry and achieving the “dual carbon” goals. Summarizing research in this area facilitates the coordinated advancement of greening and digitalization in the construction industry. Although many review studies have focused on BIM applications in green buildings [1, 8, 10, 30], they often pay less attention to the construction, operation and maintenance, renovation, and demolition stages. They also lack detailed explanations of information flow across the entire lifecycle and the resulting benefits. Furthermore, research on the integration of emerging technologies such as AI, IoT, and Digital Twins remains scarce. Therefore, this study summarizes recent research achievements on BIM in green or sustainable buildings, reviews application examples, key technologies, integration methods, and challenges across the whole lifecycle—including design and planning, construction, operation and maintenance, and renovation and demolition—identifies current research hotspots and gaps, and predicts future research directions. The structure of this paper is as follows: Section 1 is the introduction; Section 2 presents the application and enhancement of BIM across the whole life cycle of green buildings; Section 3 discusses the BIM technology system and integration in the whole life cycle of green buildings; Section 4 outlines development prospects; and Section 5 concludes the study.

2. Application and Enhancement of BIM Across the Whole Life Cycle of Green Buildings

The primary goal of this work is to systematically summarize the literature on BIM technology in the context of green buildings, particularly with respect to sustainability and low-carbon attributes. With a view to this purpose, this paper has conducted an exhaustive analysis of the use of BIM software during the planning and design phase, construction phase, operational phase, and retrofit and disposal phases of green buildings, as indicated by Figure 1.

Figure 1: Application of BIM Technology in the Life Cycle of Green Buildings



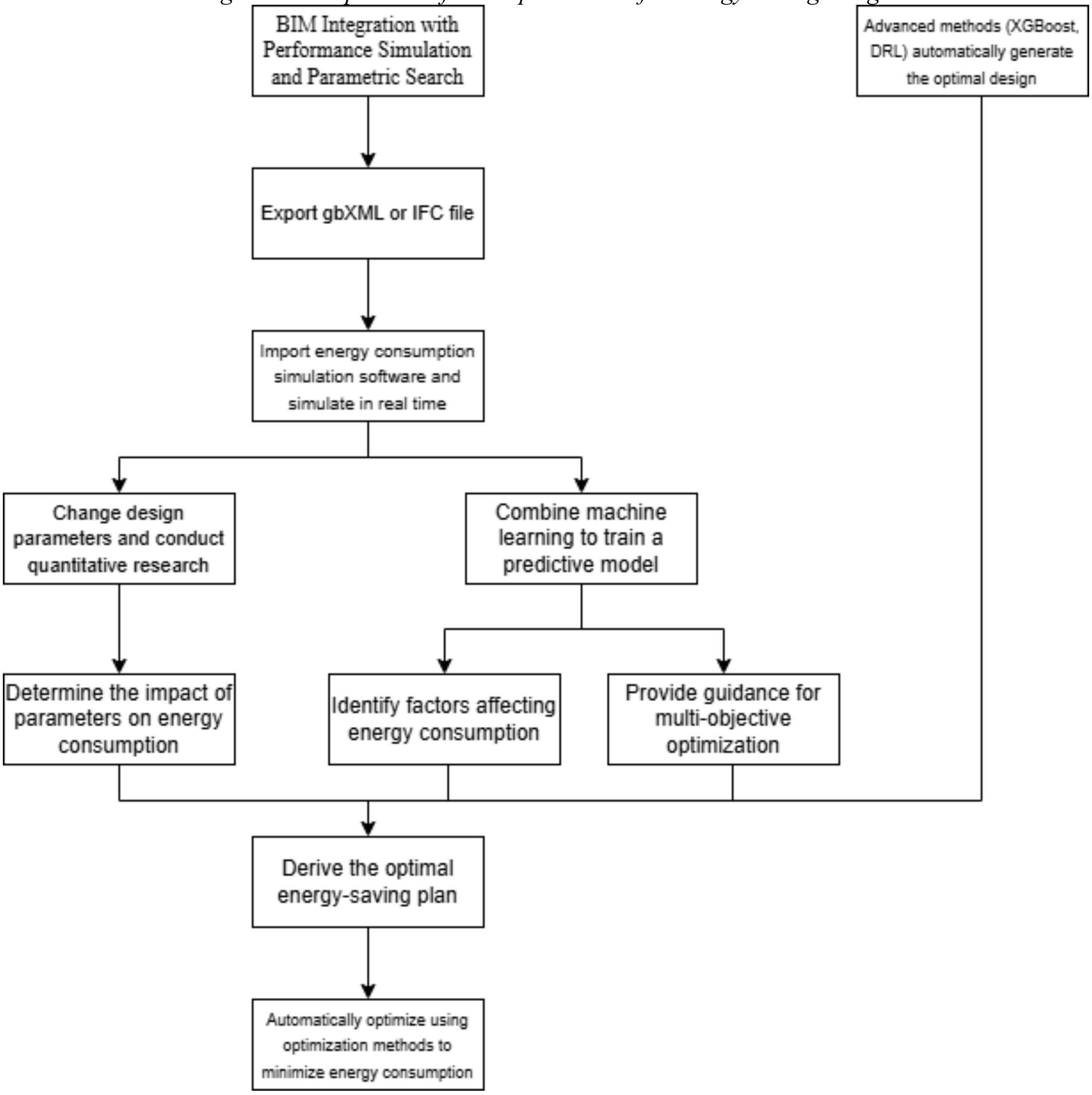
2.1 Performance Optimization-Oriented Planning and Design Stage

Green performance can be effectively impacted during the planning and design phase of a building. Two major problems occur during this phase: first, low efficiency in design, mostly demonstrated through challenges in interdisciplinary cooperation, long design iteration time, and bad communication; second, inability to ensure design quality because there is not sufficient data available in key parameters like building energy use, lighting, and carbon dioxide generation that make it difficult to design the best solution based on experiences only, resulting into very subjective and less than optimal designs.

To address these issues, BIM leverages integrated modeling and visual analysis to improve design efficiency and quality. In traditional design processes, information silos in CAD lead to numerous design conflicts. In contrast, the BIM model acts as a “shared information platform”, enabling architects, structural engineers, HVAC engineers, and others to collaborate effectively. This systematic information exchange ensures timely feedback on design changes. For example, if a designer changes the window-to-wall ratio, the modification is immediately reflected in the energy model, avoiding delays in information transfer across disciplines. Furthermore, BIM's visual analysis capabilities effectively mitigate design blindness. By integrating BIM models with Geographic Information System (GIS) data, site conditions such as sunlight, wind patterns, and surrounding environments can be simulated and analyzed, providing valuable references for building orientation, massing, and location, thereby facilitating optimal site layout and form design.

The process of optimizing energy-efficient design through BIM incorporates the use of performance simulation and parametric searches to fulfill the needs of a green building, as demonstrated in Figure 2**.** The process of BIM optimization for energy-saving design. An approach widely practised in this industry involves integrating BIM with an energy simulation program. The BIM models are exported in gbXML or IFC formats and then imported into applications like Energy Plus, Design Builder, or Green Building Studio (GBS), where they will undergo real-time simulations and analyses of annual heating, cooling, and light energy expenditure [31, 32]. Research has been performed using parametric studies based on different variables, including the window-to-wall ratio, window height, and floor level, with a quantitative investigation of the effects of these variables on energy consumption and determination of the best way to save energy. With the help of optimization techniques such as genetic algorithms, it is possible to automatically search for design parameters to minimize energy use. Furthermore, coupling results from energy simulators to Machine Learning (ML) allows developing a very precise predictive model to find out what factors greatly affect energy usage, i.e., window-to-wall ratio, HVAC efficiency, and building orientation. Such models offer assistance in solving multi-objective optimization problems associated with energy use, carbon footprint, and thermal comfort [33, 34]. More sophisticated approaches, such as XGBoost and Deep Reinforcement Learning (DRL) have been applied to automatically produce optimal design options [35, 36].

Figure 2: The process of BIM optimization for energy-saving design



In terms of carbon emissions, the percentage of embodied carbon within construction materials is gaining more attention in low-carbon design. With a link between the building material carbon footprint database and the BIM model, designers will be able to calculate and compare embodied carbon of every design option in real-time, helping to make better informed decisions [37, 38]. As an example, IBLAT is a system that performs cumulative carbon emissions calculations depending on various Levels of Development (LODs). The levels of carbon emitted from several material groups may be compared by designers and they can select low-carbon materials that help minimize emissions at this stage [19]. At last, such usage gives considerable environmental benefits. The pre-emptive reduction of operational energy consumption and carbon emissions through BIM driven performance assessment and optimisation. Moreover, BIM supports entire-life cycle carbon emission measurement. Connecting to material carbon footprint databases allows designers to accurately compare embodied carbon of various materials (recycled steel), wood and regular concrete among others at an early stage of design, thus directing them towards choosing low-carbon materials.

2.2 From Extensive Management to Precise Control in the Construction Phase

The construction phase is an important element in implementing the objectives of sustainable buildings. The following are some major problems in conventional building processes: firstly, inefficient management which results in a large amount of resources wasted and much higher energy usage; secondly, significant pollution - such as dust, sound, and waste - that can not be managed well. Application of BIM technology improves the quality and green qualities of construction activities via process simulation, energy saving and reducing emissions, and waste disposal.

With these aims, the 4D construction simulation and clash detection are used in BIM to improve plans of construction and prevent rework-related wastage, i.e., waste caused by rework. By using the 4D (3D + time) simulation feature of BIM, it is possible to plan sites well, set positions of cranes, define areas of storage of materials and access roads rationally, minimizing double handling and economizing on land. The simulation of the construction process makes it possible to find out any conflict or intersection between the construction sequences of various disciplines early and thus prevent rework which would use up extra resources and result in delay [12, 13]. It is possible with the help of BIM to simulate the diffusion of dust and the distribution of sound around the construction site, promoting the use of better environmental measures in construction [39].

The use of BIM facilitates prefabrication and assembly construction which in turn limits on-site pollution and material waste at its initial point and increases resource efficiency. The incorporation of BIM into Prefabricated Building (PB) is an efficient way to save materials and minimize on-site pollution. The precise component information in a BIM model can be utilized by the factory to process, eliminating the need to cut and create waste on site. Several researchers have used BIM to simulate and optimize the movement, storage, and lifting of prefabricated elements [40]. BIM has also been employed to formulate intricate designs of prefabricated elements including composite beams, precast columns, precast stairs, and integrated bathrooms, where the reserved openings and joints are well defined to ensure that they can be produced in factories. The combination of factory production and on-site assembly approaches greatly decreases the amount of work done on site, reducing noise and dust pollution, conserving materials, and speeding up the completion of buildings.

Finally, BIM enables resource conservation through refined material management and waste control. Quantity take-offs derived from the BIM model allow for accurate calculation of required amounts of rebar, concrete, blocks, etc., enabling “just-in-time” procurement planning and reducing material waste. BIM models can guide on-site brick layout and rebar cutting, significantly reducing steel waste. Accurate material quantity calculation based on BIM helps formulate more reasonable material procurement plans, avoiding unnecessary over-purchasing and waste from on-site stockpiling. BIM can also predict the amount of waste generated during different construction periods, facilitating its classification, recycling, and disposal [41]. For example, integrating BIM with Agent-Based Modeling (ABM) allows for simulating the impact of factors such as worker behavior, management level, and weather on construction carbon emissions and costs, and comparing the effectiveness of different optimization measures, such as hiring highly skilled workers or providing more training [39].

2.3 From Passive Response to Intelligent Prediction in the Operation and Maintenance Phase

The building operation period is generally long and represents the phase with the highest energy consumption and carbon emissions. It faces several challenges, such as information silos, where data on equipment operation, energy consumption, and environmental conditions are distributed across different systems like Building Automation Systems (BAS) and Energy Management Systems, preventing integrated analysis; and passive maintenance, where repairs are often performed only after problems occur, leading to low efficiency and energy waste. BIM primarily addresses these issues by establishing a “Digital Twin” platform.

In first place, the merging of BIM to BAS as well as the Internet of things includes linking a network of sensors (IoT) throughout the building according to the BIM model, which would allow real-time synchronization between the physical environment and the digital model. It is an effective method towards intelligent green operations and maintenance [42, 43]. The static building data offered by BIM includes spatial topology, equipment characteristics, and materials properties whereas the dynamically updated information available through IoT includes temperature, humidity, CO2 levels, condition of equipment, use of energy, and other related factors that will help create an intelligent operation maintenance platform. The combined system allows fine-tuned energy management, prompt identification of problems and their solutions, and proactive maintenance.

The mentioned BIM-FM systems employ big data analysis to change the perspective on maintenance from reactive maintenance to preventive maintenance. Such a preventive stance significantly prolongs the lifespan of equipment and eliminates waste brought about by unplanned shutdowns. Based on the information available within the BIM model of BIM-based Facility Management (BIM-FM) regarding the equipment, such as its manufacturer, brand name, installation time, warranty period, and maintenance history, there is adequate data that can be used in preventive maintenance which will help avoid unscheduled downtime and avoid excessive consumption of energy without any reason, making buildings more durable [12, 30]. The BIM model consists of equipment dimensions, brands, manufacturers, and maintenance cycles. The system can use this data to predict the chances of failure of equipment, create maintenance work orders automatically, switch focus from reactive repair to proactive prevention, improve equipment life and save resources.

The application of BIM yields significant energy savings and emission reduction benefits. The BIM-IoT platform enables monitoring and diagnosis of building energy consumption, quickly identifying problems and implementing corrective measures, achieving refined management. For example, methodologies based on deep learning and BIM digital twins can assess building occupant satisfaction and improve energy consumption. Moreover, this intelligent operation and maintenance transforms the building during its operational phase from a “data black hole” into an entity that can be sensed, analyzed, and improved, laying a solid foundation for continuous optimization and energy conservation. For instance, integrating BIM with BAS allows for intelligent control of HVAC systems, minimizing energy consumption while maintaining comfortable temperatures.

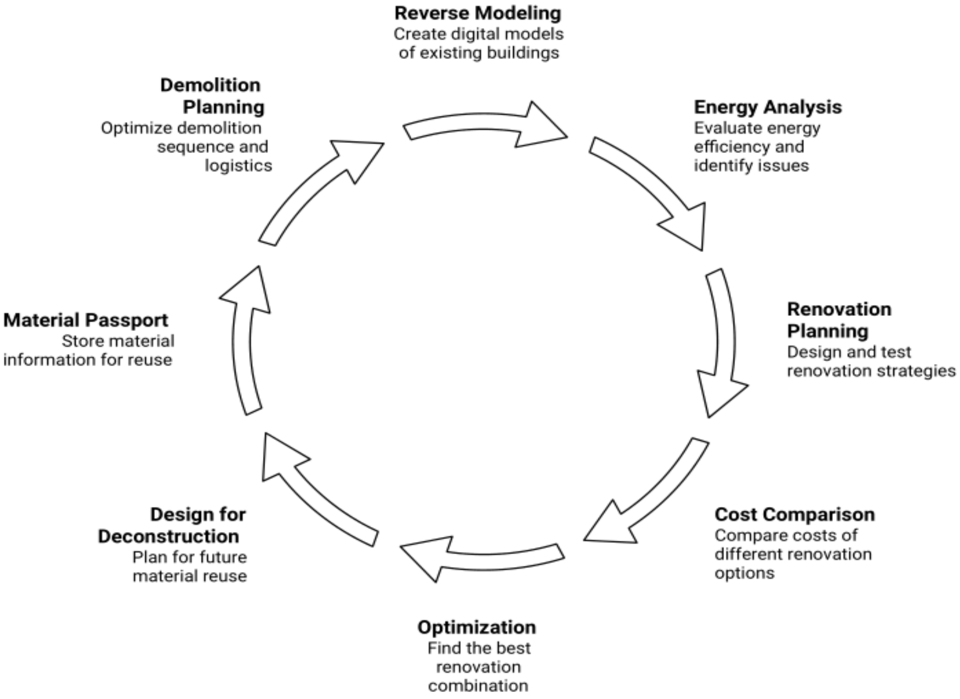
2.4 Renovation and Demolition Stage Guided by Circular Economy

On the extensive existing building inventory, the renovation, expansion and demolition phase will be the ultimate opportunity of reusing any resources. It is based on two points: the first one is that there is not enough information - the fact that there are no complete as-built drawings and other supporting documents complicates making a decision regarding a renovation and affects determining the amount of energy consumed; the second issue is that it is hard to recycle - due to absence of efficient means of assessing and planning material recovery, lots of recoverable materials end up landfilled. The significance of BIM in this field is becoming increasingly significant.

The BIM allows the reverse modeling and energy analysis of existing buildings in order to renovate them as needed. Techniques like point cloud scanning are employed to reverse model existing buildings so that they can detect the issues related to energy efficiency. Improvement measures like adding or increasing insulation, replacing windows, or applying shading devices can be tested, evaluated and their costs compared in order to provide decision-making assistance. The effectiveness of different renovation choices can be measured by means of BIM energy simulation, which will allow making comparative decisions. When combined with Life Cycle Costing (LCC), the most suitable combinations can be found. Optimization algorithms such as MILP were applied to determine the best combination of envelope, HVAC system, electrical apparatus, and renewable energy solutions under certain financial limits [13]. An investigation into a multi-storey apartment building in Iran, employing both an integrated BIM-LCA approach and mathematical optimization, resulted in reductions in energy use between 24% - 58%, plus more than 45% in Global Warming Potential (GWP) [41].

Secondly, BIM acts as an information carrier, enabling “Design for Deconstruction” and material circularity. This means designing buildings with future deconstruction and recycling in mind, known as Design for Deconstruction (DfD). BIM can store information such as material types, quantities, connection methods, and recyclability, creating a “Building Product Passport (BPP)” to facilitate future material reuse. During the demolition stage, BIM can be used to predict the types and quantities of demolition waste, plan the optimal demolition sequence and logistics routes, and maximize material reuse rates [41], achieving economic circularity, as shown in Figure 3.

Figure 3: BIM guidance for achieving the economic circulation process



3. BIM Technology System and Integration in the Whole Life Cycle of Green Buildings

Interoperability between performance analysis software and BIM is the foundation for achieving "BIM and analysis integration". Currently, commonly used energy simulation software like EnergyPlus, daylighting analysis software like Radiance, and CFD simulation software can communicate with BIM platforms (e.g., Revit, ArchiCAD) via gbXML or IFC formats [14, 15, 32, 34]. Simultaneously, the integration of BIM with the Internet of Things (IoT) is crucial, as IoT brings real-world physical environmental information into the BIM virtual space, which is particularly important for intelligent operation and maintenance. Various sensors—for temperature, humidity, energy consumption, CO2, etc.—collect data and transmit it to the BIM platform via wireless networks (e.g., MQTT protocol), forming a building "Digital Twin". This enables monitoring, early warning, accurate problem diagnosis, and informed decision-making [42, 43].

The convergence of BIM with big data analytics and Artificial Intelligence (AI) is also significant. Buildings generate substantial time-series data during operation, and the BIM model contains extensive information. Machine learning, particularly deep learning, can be applied to discover hidden patterns, enabling more accurate energy consumption prediction, equipment fault prediction, and anomaly detection. Deep Reinforcement Learning (DRL) can interact with the building environment to learn and ultimately find optimal HVAC control strategies or optimal design parameter combinations, achieving system self-optimization [36, 43] The Digital Twin, an advanced form based on the integration of BIM, IoT, and AI, not only digitally represents the physical building but also enables interaction, simulation prediction, and intelligent decision-making [43]. In green buildings, the Digital Twin can manage and continuously optimize performance throughout the entire lifecycle.

The main integration and application pathways for BIM are divided into three parts. The first is tool-level integration, often referred to as "BIM plus analysis software", which is currently common. This involves creating the model in BIM software, exporting it to specialized performance analysis software for calculation, and then importing the results back into the BIM environment. While feasible, this approach has drawbacks, including fragmented workflows and the need for repeated data import/export, which can lead to information loss.

The second is platform-level integration, a more advanced form where analysis-related functions are integrated directly into the BIM platform. This can be achieved by developing plugins—such as Tally for Life Cycle Assessment or Insight for energy analysis—embedded within the BIM software. Alternatively, visual programming languages—such as Dynamo for Revit or Grasshopper for Rhino—can be used to write custom analysis processes within the BIM environment, call external databases, and perform parametric design and automatic optimization.

Finally, cloud-based BIM collaboration enables a collaborative working model where all project participants—architects, engineers, green consultants, contractors, and facility managers—can communicate and collaborate on a shared BIM model, ensuring effective control of green building goals throughout the entire project lifecycle [44].

4. Development Prospects

(1) The transition from "BIM+" to "AI × BIM" is a significant trend. Current research is moving from tool-level integration ("BIM + analysis software") towards platform-level integration ("BIM + IoT + AI"). Future research needs to further explore the integration of technologies such as deep reinforcement learning, generative design, and digital twins with BIM. A feasible approach is to regard the BIM model as the "digital skeleton", IoT real-time data as the "neural network", and AI as the "decision-making brain" to build an intelligent building management system capable of autonomous learning, adaptation, and optimization.

(2) Expanding BIM from individual buildings to the entire city ("BIM-CIM"). If a sufficient number of buildings possess robust BIM models that can be aggregated into a city information model, unprecedented research can be conducted on urban energy planning, microclimate analysis, and distributed energy systems. Future research should focus on how BIM models can be lightweight and standardized for upward aggregation, and conversely, how urban-level insights can be passed down to optimize individual buildings.

(3) Transitioning from the traditional "cradle-to-grave" approach to a "cradle-to-cradle" circular economy. In a circular economy, it is crucial that materials can be reused across multiple lifecycles. Therefore, BIM can serve as a tool to store the "identity card" of materials, including raw material sources, carbon emissions during production and processing, service life, maintenance history, post-demolition reusability, and destination. Future research needs to develop methods for establishing a "Building Product Passport" based on BIM and address the challenge of seamlessly importing deconstruction material information into new BIM models.

(4) Moving from solely focusing on environmental benefits to a comprehensive "environmental-economic-social" benefit evaluation system. Research limited to environmental benefits is insufficient to convince owners or developers. Future work needs to establish a comprehensive assessment method encompassing environmental, economic, and social aspects, calculate the benefits of each, and accumulate empirical data through case studies. For example, quantifying the cost savings for owners enabled by BIM-based green building design, or the improved health and comfort for occupants, requires further research and substantiation.

5. Conclusions

The research offers an in-depth examination of the use of BIM in all the phases of the life cycle of green buildings. The ability of BIM to integrate information during its lifetime has considerable advantages in terms of energy saving, emission control, and resource efficiency at each stage of this cycle - design, construction, use and disposal.

(1) BIM is now regarded as a comprehensive management tool of all phases of the life cycle of the green building. By utilizing its performance assessment and digital twin abilities, BIM greatly minimizes energy usage and enhances the efficiency of resource use. Also, the incorporation of BIM with new technologies, including IoT (Internet of Things) and AI (Artificial Intelligence), is a key method to realize smart operations and maintenance and adaptive optimisation.

(2) The restrictions of this particular study lie mainly with the qualitative analysis that it employs, which does not have a quantitative bibliometric analysis of trends in research. Moreover, the discussion on other

emerging areas - namely, the deep integration between AI and BIM, as well as BIM-CIM cooperation - is also quite initial and should be followed through with ongoing monitoring and further studies.

(3) Driven by the “dual carbon” goals, BIM's role in green buildings will evolve from a “supportive tool” to a “core engine”. Achieving breakthroughs in these directions requires coordinated efforts across technology, management, and policy, as well as more interdisciplinary empirical research to provide support.

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Conflicts of Interest

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