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POST-PANDEMIC BUILDING RESILIENCE: BUILDING INFORMATION MODELING AND GREEN BUILDING INTEGRATION

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Abstract. This research explores how Building Information Modeling (BIM), green building design, and post-pandemic resilience contribute to sustainable, healthy buildings. Although studies have explored BIM's impact on green buildings, its role after COVID-19 remains largely unexplored. This study fills this gap through a "Green BIM post-pandemic square" taxonomy, integrating findings from a 1999–2024 literature review and BIM software evaluation. The taxonomy delves into project phases, green attributes, BIM features, and post-pandemic considerations to uncover links between BIM, green buildings, and post-pandemic cycles. It reveals how BIM enhances green design, construction, operation, and retrofitting. Additionally, BIM scrutinizes green building parameters such as energy efficiency and supply chain management. The study underscores BIM's potential in sustainability, occupant health, and supply chain resilience through Green Building Evaluations (GBE). Ultimately, it synthesizes data to guide building researchers and practitioners, identifying gaps and suggesting future initiatives. Relevant journals and software are incorporated to provide comprehensive insights into the subject.

Keywords: Building Information Modeling (BIM), green building, pandemic, supply chain, sustainability.

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1. Introduction

The building and construction sectors have increasingly adopted green building solutions to address sustainability challenges, such as CO2 emissions and fossil fuel dependency (Karamoozian & Zhang, 2025; Lin et al., 2021b). Building Information Modeling (BIM) has emerged as a transformative technology in the Architecture, Engineering, and Construction (AEC) industry, enabling seamless data integration and management across a building's lifecycle. BIM supports sustainable design and performance analysis by leveraging comprehensive design data. Despite the growing adoption of BIM and green construction, perspectives diverge among academics and practitioners regarding BIM's impact on green building design and construction. A McGraw-Hill Construction survey indicated that BIM could significantly enhance sustainable building processes, provided key barriers are addressed (Holzer, 2016).

The COVID-19 pandemic has emphasized the necessity for resilient and sustainable construction practices (Amirzadeh et al., 2023). It has disrupted the construction industry's supply chain, highlighting the significance of health, safety, and well-being in the built environment. The evolving industry necessitates addressing the relationship between BIM and green building in a post-pandemic world (Karamoozian et al., 2024).

Since its inception in 1999, ongoing initiatives have explored how BIM assists with the design and building of green dwellings (Raouf & Al-Ghamdi, 2019). BIM's applications, including energy performance simulation, lighting analysis, and construction waste management, have been investigated (Ghisellini et al., 2018). While BIM has received appreciation regarding its role in advancing green construction practices, a comprehensive analysis of its current status in relation to green construction development is lacking. There is a need for academic research and industry standards to guide this exploration (Lin et al., 2021b; Santos et al., 2019). Despite efforts by researchers, there remains a gap in understanding BIM applications for green buildings, particularly regarding their significance in a) sustainable construction, b) capabilities for sustainability evaluation, c) potential to support green building evaluation frameworks, and d) especially in advancing industry practices in critical situations such as supply chain disruptions. Therefore, addressing these gaps is crucial.

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This paper offers a comprehensive review to address these research gaps and illuminate the intersection of BIM and green construction, both during and after the COVID-19 pandemic. It encompasses an analysis of over 1550 academic articles from prominent AEC publications spanning from 1999 to 2024, along with evaluations of 15 prominent BIM software programs, including The IES Virtual Environment (IESVE). Through a rigorous sequential four-stage classification process, the present research introduces the "Green BIM post-pandemic square" systematization, categorizing the interaction between BIM and green building design and construction across four dimensions: project phases, green qualities, BIM features, and novel post-pandemic considerations. This taxonomy provides a comprehensive framework for understanding the integration of BIM and green building principles, offering insights for future research and industry implementation (Jin et al., 2019).

This research is structured as follows. Section 2 outlines the study design and critical review methods. Section 3 details the "Green BIM post-pandemic square" taxonomy, highlighting BIM's role in green construction design, construction, operation, and retrofitting, as well as its contribution to green building analyses and assessments. Section 4 presents the Findings and Discussion, examining the practical implications of BIM in various stages of green building projects. The fifth section identifies research gaps and suggests future directions. Finally, Section 6 summarizes key findings and emphasizes integrating BIM development with sustainable building practices post-pandemic.

This study aims to address the following research objectives:

(1) to synthesize the role of BIM in enhancing green building design, construction, operation, and retrofitting in the post-pandemic context;

(2) to develop and validate a "Green BIM post-pandemic square" taxonomy that integrates BIM features, green attributes, project phases, and post-pandemic considerations; and

(3) to identify research gaps and propose future directions for advancing BIM-supported green building practices amidst supply chain disruptions and health-focused building requirements.

The guiding research questions are:

(1) How does BIM facilitate sustainable and resilient green building practices in the post-pandemic era?

(2) What are the key dimensions and practical applications of the "Green BIM post-pandemic square" taxonomy?

(3) What are the current limitations and future opportunities for integrating BIM with green building evaluations under post-pandemic conditions? By addressing these objectives and questions, this study fills critical gaps in understanding BIM's applications for sustainable construction, particularly in response to COVID-19-induced challenges.

2. Research methodology

The concept of "green BIM" involves integrating BIM with environmentally sustainable building practices. Prior research has explored this concept, focusing on areas such as green structures (Guo et al., 2021), sustainable architecture and design and sustainable construction (Bynum et al., 2013).

This study investigates the intersection of BIM, green buildings, and the post-pandemic environment in light of the global COVID-19 crisis and its impact on the building and construction industries. By utilizing a refined four-step taxonomy, this study rigorously reviews scholarly publications and BIM software to assess their applicability to post-pandemic and environmental concerns, including the integration of *The IES Virtual Environment* (*IESVE*) software. While previous studies have addressed "green BIM" in sustainable design and construction (Wang et al., 2021), our research uniquely considers the challenges and opportunities presented by the COVID-19 crisis.

Wong and Zhou (2015) define green BIM as a model-based approach that enhances energy efficiency and supports sustainability objectives throughout a project's lifecycle. Building upon this concept, our study elucidates the scope and characteristics of BIM tools for green construction, informed by both academic literature and practical BIM software. Our methodology includes a comprehensive evaluation of scholarly publications and BIM software, employing a sequential four-stage categorization and method of assessment to develop the "Green BIM post-pandemic square" taxonomy, as illustrated in Figure 1.

The dynamic relationships between BIM and green buildings in COVID-19 are examined using a four-step taxonomy and assessment approach. This approach thoroughly reviews the chosen scholarly publications and BIM software, emphasizing their applicability to post-pandemic and environmental concerns. This thorough investigation assists the "Green BIM post-pandemic square" classification in Figure 1 that incorporates sustainability, health, and resilience.

2.1. Selecting academic articles

The selection of scholarly papers in this study follows common review article methods (He et al., 2017). Review articles involve defining literature databases, setting research criteria, conducting an initial search, and double-checking the literature.

The research focuses exclusively on peer-reviewed academic journals to ensure reliability and detail in the conclusions (Gusenbauer & Haddaway, 2020). Authors specifically include journal articles on green BIM and sustainable building practices to analyze the impact of the pandemic on green construction.

The selection process began with an initial search and literature screening, where article titles and abstracts were examined to exclude irrelevant studies. Subsequently, all chosen publications underwent thorough evaluation for pandemic-related green BIM assessments.

To select publications, three criteria were used: journals listed in the Science Citation Index (SCI)-Expanded or Engineering Index (EI) Compendex databases, recognized or supported by the American Society of Civil Engineers (ASCE) and the Worldwide Council for Research and Innovation in Building and Construction (CIB), and influential in BIM, sustainability, or building and construction research. Thirty-three peer-reviewed journals meeting these criteria were selected.

To provide a comprehensive overview of the distribution of the selected papers, we have visualized the data in the following figures. Figure 2a illustrates the geographical distribution of the papers reviewed, highlighting the countries contributing most to the research. Figure 2b presents the institutes of the reviewed papers, providing insights into the primary academics in green BIM and sustainable building research.

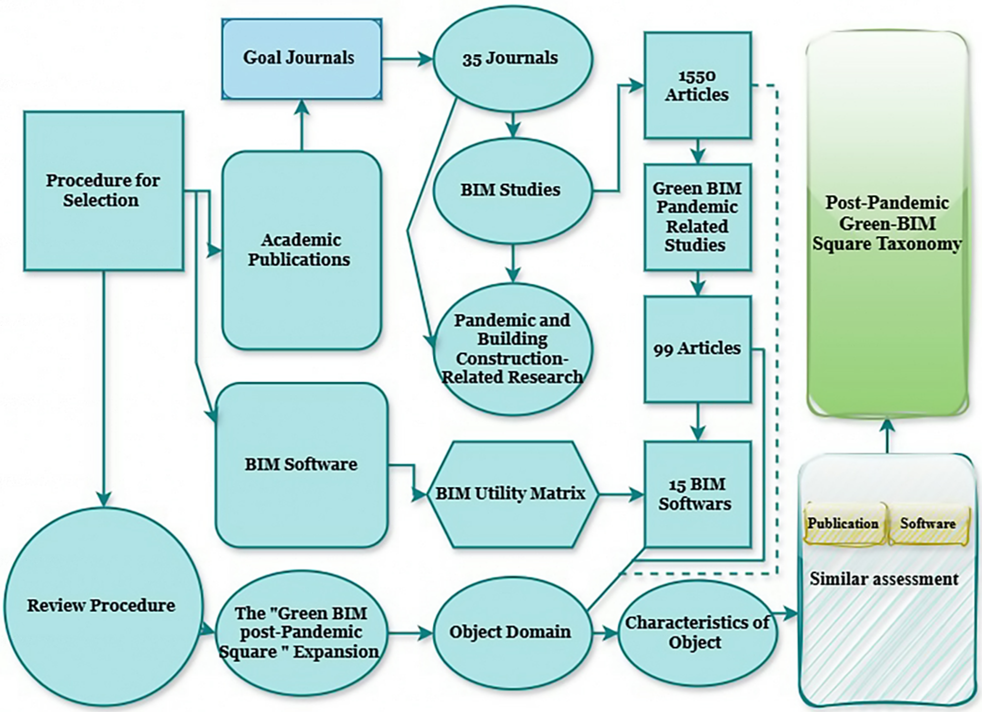

Figure 1. Research methodology diagram

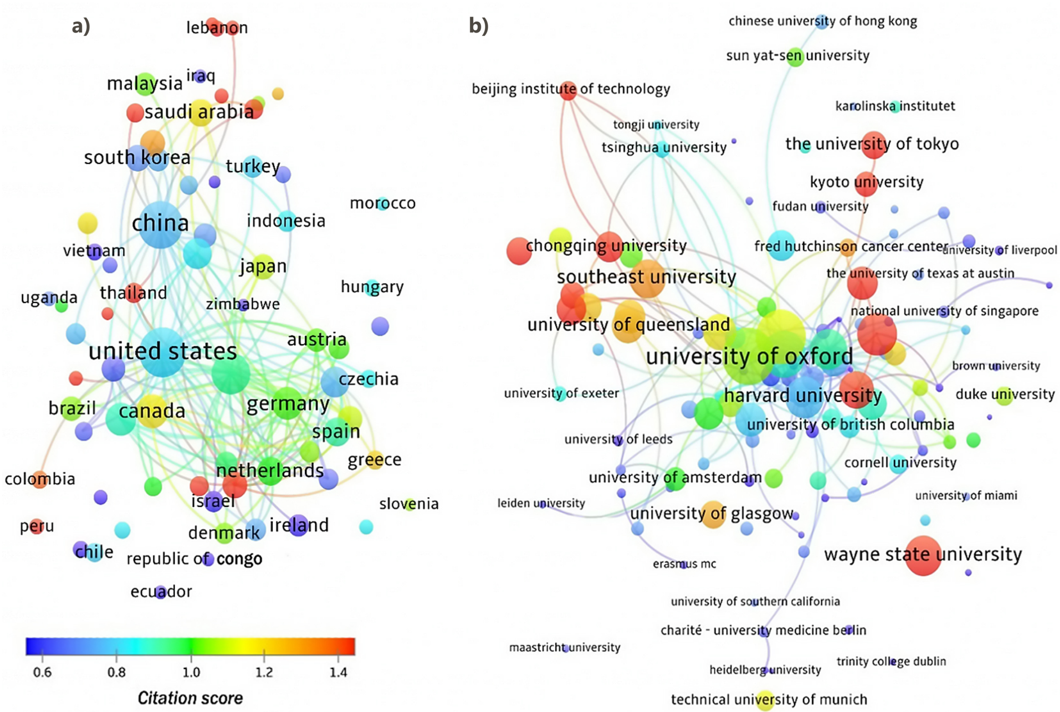

Figure 2. Bibliometric distribution of papers by: a – countries; b – universities. Generated using VOSviewer software for data visualization and formatting

Table 1. Summary of the sources of 35 scholarly journals and the detected articles from 1999 to 2024

Journal name	Total count of publications published between 1999 and 2024		
	Building Information Modeling (BIM)	Covid19 pandemic & building constructions	Green building & Sustainability
Applied energy	7	6	25
Architecture Science Review	8	6	26
Advanced Engineering Informatics	88	2	2
Architectural Engineering and Design Management	54	4	14
Automation in Construction	447	3	30
Building and Environment	43	6	110
Building Research and Information	18	3	40
Construction Innovation	87	1	10
Construction Management and Economics	30	0	10
Computer-Aided Civil and Infrastructure Engineering	10	0	0
Developments In Built Environment	84	1	57
Energy and Buildings	44	1	115
Engineering, Construction and Architectural Management	138	6	35
Facilities	27	3	43
International Journal of Green Energy	4	0	21
International Journal of Project Management	14	0	7
Journal of Asian Architecture and Building Engineering	26	0	25
Journal of Building Performance Simulation	5	1	4
Journal of Civil Engineering and Management	21	0	2
Journal of Cleaner Production	35	2	110
Journal of Computing in Civil Engineering	25	0	2
Journal of Construction and Building Materials	0	3	20
Journal of Construction Engineering and Management	89	0	32
Journal of Engineering Design and Technology	36	1	16
Journal of Industrial Information Integration	2	3	0
Journal of Management in Engineering	50	17	11
Proceedings of Institution of Civil Engineers – Civil Engineering	8	1	2
Project Management Journal	37	0	16
Renewable and Sustainable Energy Reviews	0	12	61
Smart and Sustainable Built Environment	33	1	24
Sustainable Materials and Technologies	0	0	5
The International Journal of Construction Management	75	11	17
Urban Forestry and Urban Greening	0	2	70
Journal of Science and Technology for Built Environment	5	3	18
Total	1550	99	980
BIM & Green building and sustainability & covid19 pandemic	99 scholarly articles		

Table 1 shows the specified process, 35 journals were searched for BIM-related papers from 1999 to 2024 using keywords "Green building", "Building Information Modeling" (BIM), and "pandemic". The search focused on article titles, keywords, and abstracts, resulting in 99 selected papers specifically addressing green construction and COVID-19.

2.2. The AEC industries' use of BIM applications

To advance academic research, this study investigates the impact of COVID-19 and post-pandemic conditions on sustainability objectives within the AEC industries. Amid pandemic challenges, it assesses current BIM systems and software, including *The IES Virtual Environment* (*IESVE*), contributing to the lifelong sustainability of buildings. Aligned with the concept of green BIM and post-pandemic demands, 15 prominent BIM software products were selected from the BIM Forum's Matrix, designed to facilitate sustainable design and meet post-pandemic needs. It's crucial to note the absence of a globally accepted standard for defining BIM (Eastman et al., 2010). Succar (2010) defines BIM as an interconnected collection of rules, procedures, and technology managing construction design and project information digitally throughout a project's lifecycle. BIM software serves various purposes including architectural design and sustainability analysis. Abanda and Byers (2016), Abanda et al. (2015) identified 122 BIM programs used across architectural, structural engineering and sustainability analysis domains. This comprehensive review highlights the importance of incorporating building characteristics into BIM tools to address post-pandemic challenges. Research underscores the need for BIM teamwork procedures to enhance data flow and outcomes.

Additionally, popular BIM-based environmental sustainability analysis software has been identified. Building on this, the study evaluates 15 BIM analysis applications selected from the BIM Tools Matrix to assess their applicability for post-pandemic green building challenges. Table 2 lists 15 BIM software kinds. These software programs offer insights into energy use, carbon dioxide emissions, ventilation systems, material management, solar radiation, illumination, acoustics, and water use in green buildings. Section 3.2 will elaborate on these 15 BIM software programs, focusing on their post-pandemic significance.

2.3. Literature study and "Green BIM post-pandemic square" taxonomy development

To develop the "Green BIM post-pandemic square" taxonomy, this study adopts the iterative taxonomy development method proposed by Nickerson et al. (2013), tailored to integrate sustainability, health, and pandemic resilience in BIM and green building practices. The process involved the following steps:

(1) Defining the Purpose and Scope: The taxonomy aims to synthesize BIM's role in green building across project phases, green attributes, BIM features, and post-pandemic considerations, covering peer-reviewed literature (1999–2024) and 15 BIM software programs relevant to post-COVID-19 challenges.

(2) Identifying Dimensions: Four key dimensions – project phases (design, construction, operation, retrofitting), green attributes (e.g., energy efficiency, waste reduction), BIM features (e.g., energy simulation, visualization), and post-pandemic considerations (e.g., occupant health, supply chain resilience) – were derived through thematic analysis of 1550 articles and software capabilities, guided by foundational BIM and sustainability frameworks (Wong & Zhou, 2015).

(3) Classifying and Grouping: Literature and software were systematically analyzed using thematic coding to align with the four dimensions, identifying patterns in their contributions to sustainable and resilient building practices (Solihin & Eastman, 2015).

(4) Validating and Refining: The taxonomy was validated by cross-referencing with green building standards (e.g., LEED, BREEAM) and incorporating feedback from a pilot review by two AEC industry experts, ensuring theoretical rigor and practical applicability. This iterative process, visually represented in Figure 3, produces a robust taxonomy that guides researchers and practitioners in leveraging BIM for post-pandemic green building applications.

Table 2. Fifteen widely utilized BIM software programs that operate upon the principles of green BIM and post-pandemic requirements

BIM software program	Green BIM and post-pandemic analysis*							Utilizing users**	Utilizing users***	Software's website
	EU	CR	VS	MM	SR	A	W			
Autodesk Revit	√	√	√	√	√		√	AR/DE/EN	DE/CO	https://www.autodesk.com/
Tekla Structures				√				DE/EN	DE/CO	https://www.tekla.com/
Vectorworks Architect				√	√		√	AR/DE	DE	https://www.vectorworks.net/
TRNSYS	√		√		√			AR/EN	CO	https://www.trnsys.com/
FloVENT			√					EN	DE/CO	https://www.flovent.com/
eQUEST	√	√	√		√			AR/EN/CO	DE/CO/MO	https://www.doe2.com/equest/
HEED	√							OW/AR/DE/CO	DE	https://energy-design-tools.sbse.org/heed/
AECOsim	√	√		√	√		√	DE/EN/CO	DE/CO	www.bentley.com
Bentley Hevacomp	√	√	√	√			√	DE/EN/CO	DE/CO	www.bentley.com
Autodesk Green Building Studio	√	√	√		√		√	AR/DE	DE/CO/MO	www.autodesk.com
ODEON Room Acoustics Software						√		AR/EN	DE/MO	https://odeon.dk/
DOE2	√	√	√		√			AR/EN/CO/UC/GO	DE/CO	https://doe2.com/
Design Builder Simulation	√	√	√		√		√	AR/EN/CO	DE/CO	https://designbuilder.co.uk/
EnergyPlus	√	√			√		√	AR/EN	DE/CO	https://energyplus.net/
IES Virtual Environment (IESVE)	√	√	√	√	√		√	EU/CR/VS/MM/SR/W	AR/EN	https://www.iesve.com

Notes: *EU: Energy Use; CR: Carbon Dioxide Release; VS: Ventilating Systems; MM: Material Management; SR: Solar Radiation and Illumination; A: Acoustic; W: Water; **AR: Architects; DE: Designers; EN: Engineers; OW: Owners; CO: Consultants; UC: Utility Companies; GO: Government; ***DE: Design; CO: Construction; MO: Maintenances and Operations.

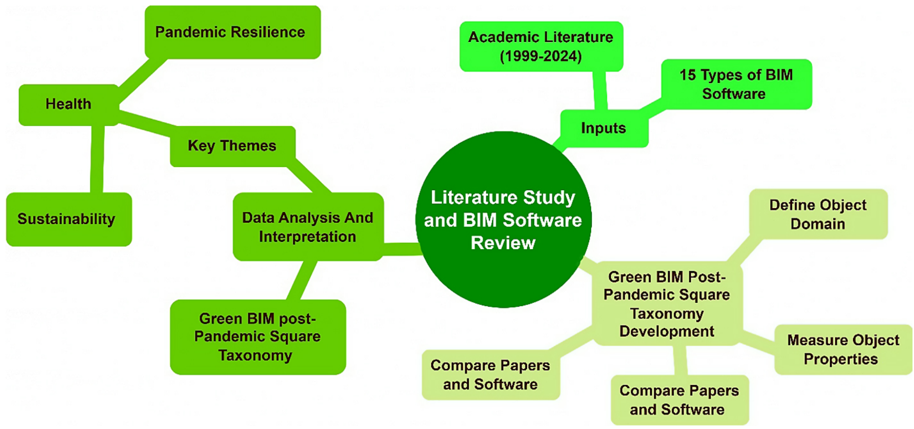

Figure 3. "Green BIM post-pandemic square" taxonomy mind map

3. The intersection of BIM and green buildings, incorporating COVID-19 and post-pandemic contributions

The COVID-19 pandemic introduced unprecedented challenges to the AEC industry, including supply chain disruptions, labor shortages, and heightened health and safety requirements, necessitating a re-evaluation of BIM's role in green building practices. Lessons learned include the critical need for remote collaboration tools, real-time data for supply chain management, and designs prioritizing occupant health (e.g., enhanced ventilation, social distancing layouts). These challenges underscored BIM's potential to address post-pandemic resilience by enabling virtual design reviews, optimizing material logistics, and simulating health-focused building systems (Amirzadeh et al., 2023; Wang et al., 2024). This section explores how BIM integrates with green building principles to tackle these challenges, emphasizing sustainability, health, and supply chain resilience in the post-pandemic era.

The relationship between BIM and green buildings involves two critical components: BIM features and green qualities. BIM features encompass analytical functionalities offered by BIM software, including databases interchange, documentation management, analysis visualization, and sustainability assessments. Green buildings are characterized by project stages, covering design, construction, operation, maintenance, and deconstruction, as well as green qualities such as energy efficiency, thermal comfort, and waste reduction. BIM software addresses these sustainability issues while considering post-pandemic concerns such as building codes, health, supply chain disruptions, and resilience. See Figure 4 for the taxonomy.

The intersection amidst green buildings and BIM is evaluated according to lifecycle support, environmental features, and assessment methods, considering the impacts of COVID-19 and the post-pandemic era.

The "Green BIM post-pandemic square" taxonomy advances knowledge by providing a structured framework that integrates BIM's analytical capabilities with green building principles and post-pandemic resilience requirements. Theoretically, it builds on established BIM and sustainability frameworks (e.g., Succar, 2010; Wong & Zhou, 2015) while incorporating health and supply chain resilience concepts from post-COVID-19 literature (e.g., Amirzadeh et al., 2023). The four dimensions – project phases, green attributes, BIM features, and post-pandemic considerations – were derived through thematic analysis of 1550 articles and 15 BIM software evaluations, ensuring comprehensive coverage of lifecycle and environmental concerns. Practically, the taxonomy guides AEC professionals in aligning BIM tools with green building standards (e.g., LEED, BREEAM) and addressing pandemic-driven challenges, such as supply chain disruptions and occupant health. By synthesizing these elements, the taxonomy offers a roadmap for developing resilient, sustainable buildings and identifies research gaps for future exploration, enhancing both academic and industry applications.

3.1. Using BIM for green building's lifecycle

3.1.1. BIM-Assisted green construction design

Following the COVID-19 pandemic, the importance of building sustainability has escalated, necessitating the development of healthier and more resilient habitats. BIM plays a crucial role in designing green buildings that address these concerns.

BIM facilitates collaboration among architects and engineers to enhance building sustainability post-pandemic, with recent studies highlighting its role in optimizing health-focused designs (Chen et al., 2024).

By allowing design teams to integrate data from various disciplines, BIM enables a comprehensive sustainable design approach, minimizing conflicts and inefficiencies early in the design phase (Wang et al., 2021). The pandemic highlighted the need for BIM to support remote design collaboration and health-focused simulations, such as ventilation for airborne disease prevention, aligning with post-COVID-19 priorities (Kim et al., 2021).

BIM's real-time modeling optimizes energy-efficient layouts and ventilation for health-focused designs. Simulations help optimize energy use and indoor air quality, contributing to occupant comfort and well-being (Meng et al., 2021; Wen et al., 2014; Zhang et al., 2016).

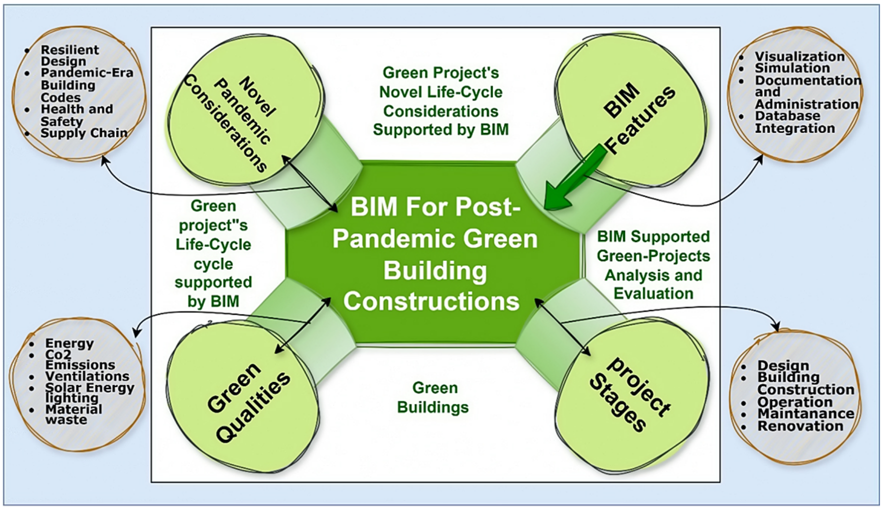

Figure 4. Post-pandemic green BIM square taxonomy

Energy efficiency is a critical component of sustainable building design. The Energy Performance Index (EPI) is calculated using the formula:

$$\text{EPI} = \frac{\text{Total Energy Consumption}\left(\text{kWh}\right)}{\text{Total Floor Area}\left(\text{m}^2\right)}. \quad (1)$$

This index, widely used in building energy assessments (International Organization for Standardization, 2017), quantifies annual energy consumption per unit area, enabling comparisons across buildings and identification of energy-saving opportunities. In BIM applications, EPI is derived from simulation outputs, accounting for factors such as building design, occupancy, and climate conditions, ensuring accurate energy performance evaluations in the post-pandemic context (Crawley et al., 2008).

BIM has helped monitor and optimize building air quality and ventilation to decrease pandemic airborne diseases (Kim et al., 2021).

Moreover, BIM aids in addressing supply chain challenges by enabling data-based modeling for material procurement and delivery management, with recent research emphasizing its resilience benefits, particularly during crises such as the COVID-19 pandemic (Li et al., 2024). It also facilitates prefabrication and modular construction, reducing on-site labor and supply chain interruptions (Deng et al., 2019; Xu et al., 2019b).

BIM has been used to aid designers in making energy conservation decisions and minimizing construction waste (Liu et al., 2017). Integration of BIM with virtual and augmented reality enhances sustainable building design visualization and stakeholder collaboration, particularly valuable during the pandemic for remote design critiques (Du et al., 2018; Sidani et al., 2021). Overall, BIM-supported green building designs have evolved during and after the pandemic, enabling multidisciplinary collaboration, real-time simulations, environmental performance analysis, and supply chain management. These capabilities contribute to the development of sustainable and resilient buildings prioritizing occupant health, well-being, and environmental responsibility (Liang et al., 2016; Mergos, 2022).

3.1.2. Utilizing BIM for green buildings construction in the pandemic context

Building on BIM's design applications (Section 3.1.1), this section explores its construction role. The COVID-19 pandemic has reshaped the construction industry, particularly impacting BIM-enabled green building projects. Construction, notorious for its environmental impact, grapples with issues such as carbon emissions, resource utilization, and waste generation during the pandemic (Sepasgozar et al., 2021; Zhang et al., 2022). COVID-19 exacerbated supply chain disruptions, making BIM's role in optimizing material procurement and reducing on-site labor through prefabrication critical for project continuity (Hong et al., 2019).

Efficient material management is essential for reducing waste in construction projects. The Material Disposal Rate (MDR) is calculated as:

$$\text{MDR}\left(\%\right) = \frac{\text{Total Waste Generated}\left(\text{kg}\right)}{\text{Total Material Used}\left(\text{kg}\right)} \times 100. \quad (2)$$

This metric, adapted from waste management studies (Lu & Yuan, 2011), measures the proportion of materials discarded during construction, aiding in the evaluation of waste reduction strategies. In BIM, MDR is estimated using material takeoff data and waste tracking modules, enabling precise resource management and alignment with post-pandemic sustainability goals.

BIM software emerges as a resilient solution, offering effective environmental interventions. 3-D BIM models assess the carbon footprint of residential buildings, improving project schedules and reducing emissions (Hao et al., 2020b; Heydari & Heravi, 2023). Studies highlight BIM's role in waste reduction (Soust-Verdaguer et al., 2017; van Eldik et al., 2020). BIM-enabled projects demonstrate reduced material disposal rates, as will be illustrated in the case studies presented in Section 4.3. Real-time BIM and structural dynamics approaches address rework and coordination issues (Tang et al., 2019; Xu et al., 2019a). BIM aids in identifying and managing construction waste, addressing concerns like project delays, supply chain disruptions, and remote collaboration challenges. The pandemic has heightened corporate awareness of sustainability, leading to increased BIM adoption in green construction to address health, safety, and resource optimization concerns in the post-pandemic construction landscape.

3.1.3. BIM-enhanced green buildings' functionality in the pandemic context

The sustainability of buildings must be monitored for compliance with design targets, especially amid and post-pandemic situations. BIM plays a pivotal role in green building operations in such contexts.

During the pandemic, BIM enables remote monitoring of green building performance by integrating and managing data on energy usage and occupant comfort, with IoT integration further enhancing post-pandemic operational efficiency (Arayici et al., 2012; Asif et al., 2024; Gao & Pishdad-Bozorgi, 2019). This capability proves invaluable when physical access to buildings is limited. Facility managers can make informed decisions and optimize building performance using real-time energy usage data and ventilation insights provided by BIM-based technologies.

Additionally, BIM aids in diagnosing and maintaining green buildings during the pandemic, with its 3D modeling and data visualization features facilitating the identification and rectification of HVAC faults to optimize energy use and indoor air quality. Troubleshooting critical building systems becomes more efficient with BIM-based automated methods. However, BIM integration for facilities management (FM) during operations still faces challenges, requiring practitioners to understand the benefits of BIM for managing green building operations and the necessity of clear guidelines and standards for MF data exchange.

Beyond the pandemic, BIM remains crucial for green building operations, enabling real-time data collection and analysis to demonstrate building efficiency, energy usage, and occupant health. Facility managers can utilize BIM throughout operations to enhance facilities, conserve energy, and enhance sustainability. Moreover, BIM can enhance monitoring and optimization of building operations by integrating Internet of Things (IoT) devices and smart building technology.

In summary, BIM plays a vital role in creating and operating green buildings during and after the pandemic, measuring and reducing carbon emissions during construction, and remotely monitoring and managing building performance throughout processes. Stakeholders can leverage BIM to improve sustainability, energy efficiency, occupant comfort, and overall building performance, contributing to the development of healthier, more resilient, and sustainable built environments (Ma et al., 2024; Teicholz, 2013).

3.1.4. BIM-enhanced renovations and retrofits of green projects in the post-pandemic era: Enhancing sustainability and optimizing the supply chain

BIM facilitates sustainable deconstruction procedures for remodeling projects, enabling practitioners to assess building component energy and capital investments and optimize resource consumption through salvaging and reusing materials. This not only reduces waste but also eases supply chain strain caused by pandemic disruptions. BIM facilitates sustainable deconstruction for retrofits, with recent studies noting its role in addressing post-COVID supply chain constraints (Kylili et al., 2024; Mowafy et al., 2023).

Post-pandemic, sustainable building renovations and retrofits gain prominence, with BIM playing a pivotal role in enhancing sustainability and streamlining the supply chain (Cheng & Ma, 2013). Furthermore, BIM's integration with additional data technologies empowers stakeholders to make informed decisions regarding energy rehabilitation and retrofitting. By analyzing energy performance and identifying improvement opportunities, BIM assists renovators in adopting energy-efficient techniques, thereby enhancing resource efficiency and reducing operational costs (Eleftheriadis et al., 2017).

Beyond energy efficiency, BIM aids in managing demolition and remodeling debris, enabling construction companies to estimate waste accurately and optimize resource allocation, thus minimizing waste and streamlining the supply chain. However, challenges persist in estimating waste from construction on new projects, necessitating improvements in BIM-based methods for broader applicability (El Sayary & Omar, 2021). Moreover, BIM optimizes material procurement, reduces on-site labor through prefabrication, and addresses pandemic-related disruptions (Section 3.1.2) among designers, contractors, suppliers, and manufacturers. By centralizing information sharing and integration, BIM reduces disruptions, errors, and inefficiencies in the supply chain, crucial for timely and cost-effective project completion post-pandemic (Irizarry et al., 2013).

In summary, BIM-supported green building renovations and retrofits contribute to sustainability, waste reduction, energy performance improvement, and supply chain management. The integration of BIM technologies with sustainable renovation strategies fosters healthier and more resilient built environments while enhancing supply chain efficiency and adaptability, addressing not only the challenges posed by COVID-19 but also future disruptions.

3.1.5. Project lifecycles aided by BIM: Using BIM to its optimum in the post-pandemic period to optimize the supply chain, design, build, and operating green buildings

In the post-pandemic period, green building project lifecycles have leveraged BIM for efficient supply chain management, design, construction, and operation, resulting in three primary benefits, as depicted in Figure 5.

Firstly, BIM facilitates data sharing among users from diverse disciplines, integrating various analysis methods to evaluate sustainability. Modular web service architecture based on BIM has been developed to seamlessly incorporate essential data for green building planning, streamlining design assessment processes and enabling decentralized modifications to the construction model.

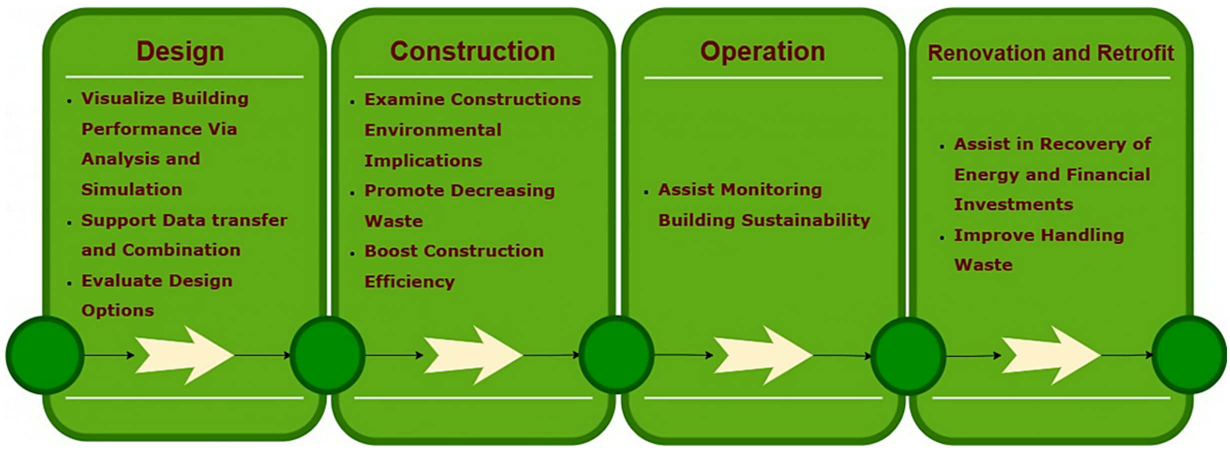

Figure 5. Green initiatives lifecycles that are supported by BIM

By enhancing decision-making and fostering collaboration from the project's inception, BIM contributes to sustainability.

Secondly, BIM systems provide designers, contractors, and owners with visible information on building performance and processes, enabling informed green decisions. For example, energy consumption assessments based on BIM display energy performance indices graphically, enhancing understanding and facilitating energy-efficient strategy decisions, thus optimizing green building design and operation (Hardin & McCool, 2015).

Thirdly, BIM improves stakeholder communication and collaboration in green architecture, construction, and operation. By centralizing information sharing, streamlining workflows, and enhancing project management, BIM fosters collaboration and strengthens project partnerships, especially crucial in the post-pandemic era of remote work and dispersed teams.

However, despite its benefits for green buildings, BIM supports green building lifecycles, with limitations addressed in Section 5. Additionally, organizational divides and technological difficulties hinder the full realization of BIM's potential for sustainable building. To maximize its benefits, addressing awareness, training, and interoperability issues is crucial.

Presently, BIM software primarily focuses on project design with limited assistance for construction and operation. However, the emergence of full-project-lifecycle BIM software, coupled with advancements in analytical capabilities for green building lifecycles, suggests promising future developments in green BIM applications (Arenas & Shafique, 2023).

Ultimately, BIM supports green building programs throughout planning, construction, and operation, enabling sustainable decision-making, energy efficiency improvement, and effective project management. Despite challenges, BIM is poised to become a vital tool for sustainable construction and design services, with increasing coverage of the full project lifecycle expected to drive the proliferation of green BIM applications, contributing to the development of sustainable and resilient post-pandemic habitats.

3.2. Using BIM to address post-pandemic green issues

This section delves into how 15 BIM software systems contribute to achieving green building objectives, handling sustainability issues such as energy use, carbon dioxide emissions, natural ventilation, solar and lighting analysis, acoustic performance, and water conservation (Ansah et al., 2019; Meng et al., 2019). Moreover, given the ongoing COVID-19 pandemic and its impact on the construction industry, this discussion underscores the necessity of these BIM features in the post-pandemic era. Table 2 illustrates that each of the 15 software options possesses unique characteristics, targets specific user groups, and suits various project phases. For instance, acousticians may utilize ODEON Rooms Acoustics Programs, while designers, contractors, engineers, and other project collaborators can employ Green Building Studio (GBS) for sustainability analyses. Additionally, Vectorworks Architect (VA) aids owners in understanding sustainability issues throughout project execution, enabling the adoption of improved green design strategies to address them.

In the post-pandemic era, these BIM software solutions play a critical role in addressing sustainability issues within construction projects. Professionals from diverse disciplines can leverage their functionalities to integrate sustainable practices, utilize data-driven insights, and create healthier, more resilient built environments. BIM's integration with Internet of Things (IoT) devices and smart building technology enhances its capacity to monitor and optimize building operations to meet pandemic-related demands (Pavón et al., 2020). Overall, the comprehensive review of these twelve BIM software solutions underscores the significance of their role in addressing crucial environmental concerns within the built environment while also considering the specific challenges posed by COVID-19. Sustainable, resilient, and healthy buildings can become a reality in the post-pandemic era if stakeholders effectively leverage these technologies (Lin et al., 2021a). Table 3 illustrates the evaluation criteria for the selected BIM software programs, highlighting their features in addressing post-pandemic green building challenges.

Table 3. BIM software evaluation criteria

Software Program	Energy Use (EU)	Carbon Dioxide Release (CR)	Ventilating Systems (VS)	Material Management (MM)	Solar Radiation (SR)	Acoustic (A)	Water (W)
Autodesk Revit	√	√	√	√	√	√	√
2Tekla Structures	√						
Vectorworks Architect	√		√		√		
TRNSYS	√				√		√
FloVENT	√		√				
eQUEST	√	√		√	√		√
HEED	√				√		
AECOsim	√	√			√		√
Bentley Hevacomp	√	√		√	√		
Autodesk Green Building Studio	√	√	√		√		
ODEON Room Acoustics Software						√	
DOE2	√	√	√		√		√
Design Builder Simulation	√	√	√		√		√
EnergyPlus	√		√	√	√	√	√
IES Virtual Environment (IESVE)	√	√	√	√	√	√	√

3.2.1. Assessments and analyses of energy performance

BIM software offers four primary functionalities for conducting energy performance studies and assessments, considering the influence of COVID-19 and supply chain difficulties:

1. Comprehensive Building Energy Analysis: BIM's real-time modeling (Section 3.1.1) supports energy efficiency, CO2 emissions reduction, and assessments of lighting, thermal comfort, and water consumption, even amidst supply chain disruptions caused by COVID-19. An important advantage is the enhanced utility of comprehensive building energy estimates achieved through standardized procedures and parameters. Unlike conventional approaches, BIM software employs a standardized procedure for estimating energy consumption based on various characteristics such as building usage patterns, form, materials, and weather conditions, thereby reducing the need for extensive time and effort in modeling. By utilizing default settings obtained from surveys of conventional practices, BIM software reduces reliance on individual user experience and expertise, thereby enhancing objectivity (Motalebi et al., 2022; Nizam et al., 2018).
2. Comprehensive Evaluation of Energy-Saving Solutions: BIM software enables thorough evaluations of various energy-saving solutions, considering the impacts of the pandemic and evolving tenant habits. Occupant behaviors significantly influence energy consumption during a building's operational phase. Simulation tools in BIM software incorporate occupant effects to assess energy conservation under different scenarios, such as changes in occupancy patterns and equipment schedules. Through the use of BIM software, users can effectively analyze and compare the outcomes of different energy-saving techniques, allowing them to optimize their solutions in response to the changing demands brought about by the pandemic.
3. Assessment of the Viability of Renewable Energy: Certain BIM software, such as GBS and VE, can evaluate the feasibility of implementing renewable energy sources like solar and wind energy, considering the impact of the pandemic on the accessibility and availability of these resources. For greater accuracy, these assessments require project-specific data that account for local conditions and anticipated disruptions resulting from the pandemic. However, challenges persist in fully integrating crucial factors, such as the combined effects of surrounding structures. Studies on inter-building effects (IBE) have shown that reflections and shadows cast by nearby buildings significantly impact the energy efficiency of a structure. While there have been studies examining the impact of IBE on energy usage, there has been limited exploration of the potential for incorporating renewable energy in buildings during the pandemic and supply chain disruptions (Singh & Sadhu, 2019).
4. Identifying and Diagnosing Defects in Real Time Online: BIM software enables real-time detection and diagnosis of building energy defects, facilitating efficient energy performance maintenance over the building's lifespan, especially in the presence of supply chain obstacles. BIM-supported Fault Detection and Diagnosis (FDD) techniques provide a flexible and customizable information system that integrates various energy performance evaluation and simulation technologies. By utilizing these capabilities, facility managers and designers can optimize information sharing, bridge stakeholder divides, and proactively address energy-related challenges, including those arising from the pandemic and disruptions in the supply chain (Gao et al., 2024).

These adaptations ensure that the key themes addressed in every aspect of energy performance studies and evaluations are aligned with the influence of the pandemic, COVID-19, and supply chain difficulties on building operations and energy management. While the significance of BIM software in energy performance analysis has been widely recognized, it is crucial to consider the impacts of COVID-19 and the constraints faced by the supply chain. Implementing BIM with preloaded energy performance parameters in existing structures may be challenging due to the gradual deterioration of heat transfer conditions in building components over time (Ghansah & Lu, 2025; Li et al., 2020). To overcome this constraint, significant developments have been made in semi-automated and automated techniques for BIM reconstruction, including methods such as automated 3D modeling from point clouds and image-based thermal BIM reconstruction approaches. By utilizing unaltered BIM data for BIM-assisted energy evaluations, the disparity between the data on energy efficiency in the original BIM design and the real-world construction conditions can be significantly reduced (Kim & Anderson, 2013). In addition to addressing these technological challenges, BIM software offers several methods for displaying energy analysis data. Energy analysis results can be presented at various intervals, including annual, monthly, daily, and hourly. Generally, BIM tools feature user-friendly interfaces that do not require users to have extensive knowledge of computer coding or energy analysis. Certain BIM tools, like GBS, can automatically translate projected energy usage into energy costs using default utility rates (Kamel & Memari, 2019). However, it is important to note that specific BIM tools, such as EnergyPlus, still utilize a text-based user interface, predominantly processing and generating information in the form of text files. Given the ramifications of COVID-19, BIM software can significantly impact indoor air quality, ventilation systems, and occupant well-being. These factors underscore the evolving role of BIM software, which now encompasses energy performance analysis, addressing post-pandemic issues, and enhancing supply chain resilience in the building sector.

In summary, BIM software enhances energy performance analysis by providing comprehensive building energy estimates, evaluating energy-saving solutions, assessing renewable energy viability, and enabling real-time defect diagnosis, all while addressing post-pandemic challenges.

3.2.2. Evaluation and analyses of carbon emissions during the pandemic and in the post-pandemic period

BIM software plays a vital role in assessing carbon emissions, especially amid the COVID-19 pandemic and afterward. It enables a thorough evaluation of the carbon footprint while considering pandemic-related challenges and supply chain disruptions (Liu et al., 2017). Utilizing data on local electricity emissions and on-site hydrocarbon generation, BIM software provides estimates that encompass the building's internal systems and environmental factors. By analyzing building-system components and external elements, it offers insights into carbon emissions throughout the building's lifecycle. Some BIM platforms use global databases to enhance accuracy (Zhang et al., 2018). To estimate the total carbon emissions of a building, the following formula can be used:

$$\text{Carbon Emissions (kg } CO_2) = \sum_{i=1}^{n} \Big(\text{Energy Consumption (kWh)}_i \times \text{Emission Factor (kg } CO_2/\text{kWh)}_i \Big). \quad (3)$$

In this formula $\text{Energy Consumption (kWh)}_i$ represents the energy consumption for each energy source i $\text{Emission Factor (kg } CO_2/\text{kWh)}_i$ represents the emission factor for each energy source i, which indicates the amount of CO_2 emissions per unit of energy consumed.

This calculation helps in understanding the environmental impact of building operations and identifying opportunities for carbon reduction. By incorporating pandemic-related factors like energy usage and material availability, BIM software helps minimize carbon emissions and enhance supply chain resilience. It empowers stakeholders to make informed decisions, optimize operations, and create a greener, more efficient environment post-pandemic.

Additionally, BIM software monitors carbon emissions and suggests carbon-neutral strategies to optimize design plans. For instance, it may recommend selecting local utility suppliers that utilize renewable energy sources (GBS). Researchers have developed BIM-based optimization models considering factors like cost balancing and supply chain obstacles to aid decision-making Predicting embodied and operational carbon emissions using BIM software enhances material selection and environmental decisions.

Incorporating pandemic-related factors like energy usage and material availability, BIM software helps minimize carbon emissions and enhance supply chain resilience. It empowers stakeholders to make informed decisions, optimize operations, and create a greener, more efficient environment post-pandemic.

3.2.3. Examination and enhancement of natural ventilation systems

During and after the COVID-19 pandemic, BIM software plays a crucial role in analyzing and improving natural ventilation systems, addressing concerns related to energy efficiency and indoor air quality. By integrating BIM software, it becomes possible to assess ventilation strategies aimed at reducing the transmission of airborne pollutants, aligning with the increasing focus on fostering healthy indoor environments.

BIM software facilitates the evaluation of natural ventilation capabilities by considering factors such as occupancy rates, equipment usage, and airflow dynamics. Through the simulation of diverse scenarios, it aids in gauging the effectiveness of ventilation systems in curbing the spread of infectious particles.

Moreover, BIM software enables the integration of additional features into ventilation systems, such as advanced air filtration technologies and smart controls. These enhancements elevate indoor air quality and create a safer environment for building occupants (Li et al., 2023; Sporr et al., 2019).

In the face of supply chain disruptions caused by the pandemic, BIM software can optimize ventilation system designs by addressing component availability and sourcing challenges. By evaluating supply chain constraints and interruptions, BIM software facilitates the exploration of alternative ideas and the efficient implementation of ventilation methods.

In summary, BIM software provides valuable insights for monitoring and improving natural ventilation systems; especially amidst the COVID-19 pandemic and its impact on supply chains. It integrates health considerations, addresses indoor air quality issues, and considers resource accessibility, thereby fostering the development of healthier and more resilient built environments.

3.2.4. Analysis of solar radiation and lights

In light of the repercussions of the COVID-19 pandemic and the subsequent period, BIM software plays a vital role in assessing the impact of light on both the exteriors and interiors of buildings. BIM software with a comprehensive module for solar radiation assessment allows architects and engineers to evaluate and enhance the sun's influence on buildings. In response to the pandemic, predesign BIM software now considers factors such as social distancing and occupant safety when optimizing building location, layout, and orientation. By providing information on the sun's position and trajectory relative to the building model, engineers and designers can make informed decisions at any given time and location.

Additionally, BIM software enables the assessment of solar gain, temperatures, and radiation exchange on building surfaces, with evaluation findings displayed at various time intervals during thermal studies. Certain kinds of BIM software, including VE, offer analyses of both interior and exterior solar shading impacts, allowing designers to select shading systems based on simulated results compared to design predictions. BIM software employs advanced lighting-condition analysis to maximize natural sunlight usage and enhance visual comfort within buildings. It offers a detailed examination of lighting conditions throughout the structure, enabling designers and engineers to visually assess the effectiveness of their lighting solutions. Furthermore, BIM software facilitates detailed simulations that directly compare natural and artificial illumination, with adjustments made for varying weather conditions (Kota et al., 2014).

Despite the benefits, integrating green BIM with lighting and solar radiation models faces challenges due to simulation data shortages. Researchers have identified a lack of necessary data within BIM for producing radiation and DAYSIM input files. To address this issue, automated BIM-based simulation approaches such as Thermal Opt have been developed for trans-disciplinary design optimization. Future research should aim to develop a more universal technique that can work seamlessly with most simulation systems, taking into account post-pandemic dynamics.

3.2.5. Analysis of water use during and after the COVID-19

The COVID-19 pandemic has accentuated the significance of leveraging BIM software for water management, necessitating a thorough examination of water usage patterns and optimization strategies. Increased emphasis on hygiene and sanitation during the pandemic has led to heightened water consumption, particularly in healthcare facilities and public spaces. BIM software plays a pivotal role in estimating water usage by considering various factors such as building layout, occupancy rates, and hygiene practices. However, it's important to acknowledge that these estimates may not fully capture the dynamic shifts in water consumption patterns brought about by the pandemic (Liu et al., 2020). As we navigate the post-pandemic landscape, BIM software must evolve to incorporate a broader spectrum of factors influencing water usage. This includes adapting to changing consumption habits and integrating water-saving measures into design and renovation projects. BIM facilitates informed decision-making by assessing and optimizing water distribution networks, enabling stakeholders to prioritize water efficiency initiatives effectively.

Specialized BIM tools focused on water distribution systems, such as LicA, streamline design processes and ensure the reliability and efficiency of building water systems. The insights gleaned from BIM-enabled analysis during and after the pandemic offer valuable opportunities to refine water management strategies and enhance sustainability practices (Wang et al., 2021). In summary, BIM software remains indispensable for advancing resilient and sustainable water management practices in the post-pandemic era, offering a robust framework for optimizing water usage and promoting environmental stewardship.

3.2.6. Acoustic analyses conducted during the outbreak

BIM software enables architects to conduct early-stage acoustic simulations for efficient optimization. Integration of BIM data with acoustic simulation tools streamlines workflows and reduces simulation time while maintaining accuracy. A prototype acoustic simulation program using BIM can drastically reduce simulation time from days to minutes, automatically re-simulating whenever changes are made to the model.

BIM-based acoustic simulation software generates visual maps of acoustic properties and offers immersive 3D audio effects, enhancing the auditory experience (Sušnik et al., 2021). Looking ahead, BIM-based acoustic simulation may integrate virtual reality to further enhance the auditory experience, particularly relevant in the post-pandemic landscape where remote work and virtual meetings are prevalent (Mastino et al., 2021). In conclusion, post-pandemic BIM software plays a crucial role in optimizing acoustic design for enhanced comfort and functionality.

3.2.7. Analysis of thermal comfort standards

Thermal comfort is crucial in green buildings; particularly in the context of the COVID-19 pandemic and its impact on supply chains. The efficiency and healthiness of these structures depend on occupants' comfort levels and well-being. While thermal comfort may not directly relate to infectious diseases like COVID-19, it plays a significant role in promoting a healthy indoor lifestyle.

ASHRAE Standard 55-2013 (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013) defines thermal comfort as the subjective satisfaction with the thermal environment, factors such as room temperature, humidity, airflow speed, and clothing level influence thermal comfort (Cheng et al., 2022). BIM applications are vital for assessing and improving thermal comfort. Integrating wireless sensor networks (WSN) with BIM models allows for spatial measurement and recording of temperature and humidity, enabling building managers to monitor thermal comfort effectively. Furthermore, tools like IES-VE utilize thermal models to identify comfort issues such as overheating and under-heating, aiding in the optimization of thermal comfort during design and post-occupancy monitoring. By simulating airflow using Computational Fluid Dynamics (CFD) software within BIM, optimal layouts for thermal comfort in various office settings can be identified. Additionally, IES-VE can simulate metrics like Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) to assess thermal comfort against established standards.

In summary, BIM technologies play a crucial role in evaluating, monitoring, and optimizing thermal comfort in green buildings, especially in the context of COVID-19 and the post-pandemic era. These applications contribute to creating pleasant and sustainable indoor environments by addressing factors such as temperature, humidity, and airflow speed.

3.2.8. Overview of BIM features for environmental concerns

While current BIM applications focus on various sustainability aspects, they often lack integration and may not cover all facets of sustainability, limiting their adoption (Xu et al., 2022). In response to COVID-19 and supply chain disruptions, there's a need for a comprehensive green BIM tool that thoroughly examines a building's sustainability. Challenges arise from BIM software's reliance on external datasets, requiring regular updates to ensure accuracy (Olawumi et al., 2017). Integration with new technologies, including GIS, along with cloud computing, may improve BIM's sustainability. Ongoing research aims to improve BIM's green assessment capabilities through stakeholder participation and simulation accuracy. COVID-19 and post-pandemic dynamics present opportunities to advance sustainability in the built environment. Figure 6 outlines the main BIM functionalities in green analyses. In conclusion, a comprehensive eco-friendly BIM program is needed to address sustainability concerns, considering the supply chain and post-pandemic phase (Le et al., 2022; Papadonikolaki et al., 2015). Ensuring accurate data in external databases and compatibility with emerging technologies are crucial for leveraging BIM's capabilities fully.

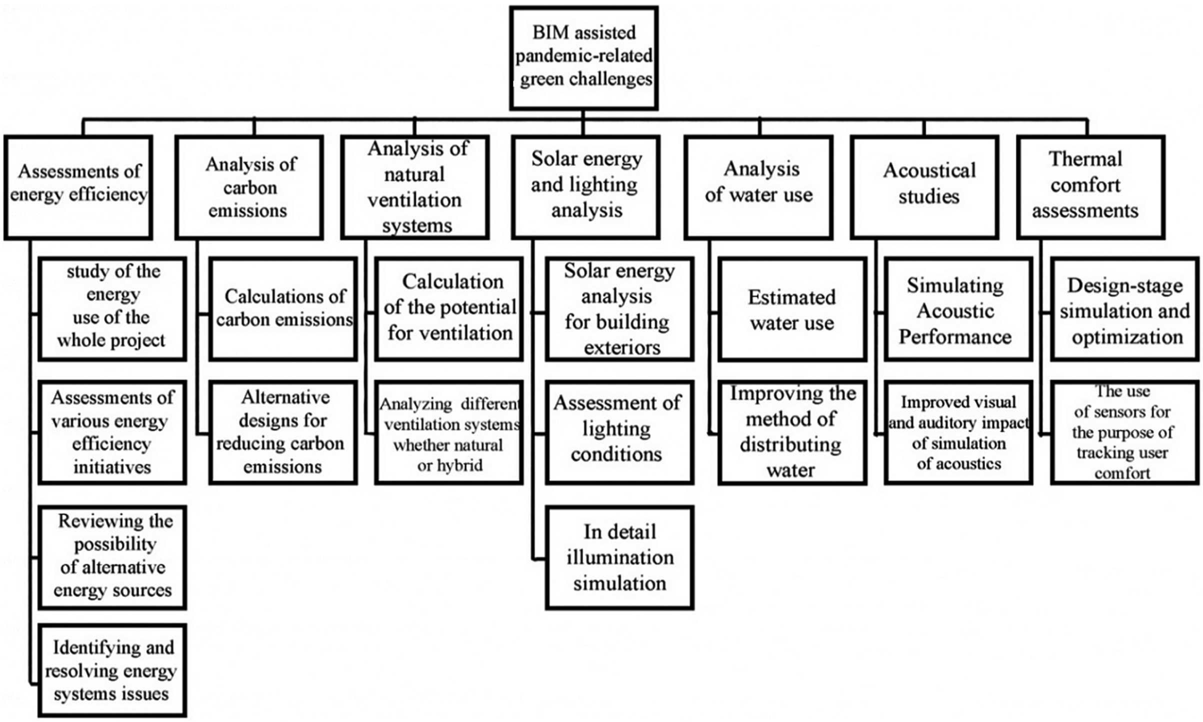

Figure 6. Standard applications of BIM for conducting sustainability evaluations

3.3. Green Building Evaluation (GBE) with BIM assistance

In light of COVID-19, the post-pandemic era, and supply chain disruptions, this section explores how BIM enhances Green Building Evaluation (GBE) processes comprehensively. The objective of GBE is to supply thorough quantitative evaluations of construction effectiveness, covering aspects like location election, energy usage, indoor environmental quality, CO_2 emissions, material consumption and water efficiency. While attempts are currently being undertaken to incorporate BIM into diverse GBE methodologies, a systematic evaluation of BIM software against common GBE standards is essential. BIM enhances GBE processes by aligning with certification standards, with recent research emphasizing its post-pandemic relevance (Wang et al., 2024).

To address this gap, a comparative matrix examines how BIM aligns with prominent GBE certification standards such as LEED, BREEAM, Green Star, and BEAM Plus. Table 4 details BIM's alignment with GBE standards. By analyzing relevant literature, this research assesses the value that BIM brings to each standard, particularly in addressing COVID-19 challenges and supply chain disruptions. It underscores BIM's role in enhancing GBE efficiency and its application in LEED certification, while also highlighting its limitations.

The integration of BIM into GBE processes enables stakeholders to evaluate building performance in the context of the pandemic and supply chain disruptions, facilitating the adoption of sustainable solutions and resilient construction principles. Ultimately, this leads to the creation of a more sustainable and resilient built environment.

3.3.1. BIM's role to end users in the GBE procedure

BIM significantly supports the Green Building Evaluation (GBE) process in three key ways. Firstly, it aids customers in adopting green building certification strategies by facilitating the implementation of health and safety measures like optimizing indoor air quality and ensuring social distancing protocols. Secondly, BIM assists in analyzing and estimating GBE standard credits while considering pandemic-related and supply chain requirements. It ensures adherence to sustainable supply chain practices such as sourcing sustainable materials and optimizing logistics post-pandemic (Jun et al., 2015). Thirdly, BIM expedites GBE certificate acquisition and ongoing documentation management by leveraging pandemic guidelines and supply chain considerations. This streamlines administration processes and reduces post-pandemic GBE certification management costs. Integrating BIM, COVID-19 guidelines, and supply chain considerations enhances the efficiency and sustainability of the GBE process (Ansah et al., 2019; Olanrewaju et al., 2022).

3.3.2. Difficulties in linking BIM and GBE in the post-COVID-19 environments

BIM's GBE integration faces limitations (Section 5), such as incomplete sustainability metrics rendering it insufficient for GBEs. Most BIM software focuses on specific features, such as lighting or carbon emission assessment, with limited connectivity across different BIM tasks, hindering a thorough analysis of building sustainability in societal and environmental terms (Ilhan & Yaman, 2016).

Moreover, BIM software does not support all GBE credits, particularly in environmental (e.g., BREEAM) and management (e.g., Green Star) categories, as well as in innovative techniques and performance (e.g., BEAM Plus, Green Star, LEED), and shipping (e.g., BREEAM). Assessing the effects of buildings on biological diversity using BIM poses significant challenges due to reliance on professional judgment and expertise, making automation difficult (Ghaffarianhoseini et al., 2017). Another issue is the complexity of previous methods and users' lack of familiarity with BIM.

Table 4. World-wide green building evaluation (GBE) systems supported by BIM

GBE system	LEED 4.1	BREEAM	Green Star v1.3	BEAM Plus v2.0
Location / Organization	United states/ USGBC	United Kingdom/ Construction Research Establishment	Australia/ Australian Green Building Council	Hong Kong/HKGBC
Overall points / credits	110 points	6 stars	6 stars	100%
Minimum required points	40 points	30 credits 1 star	4 stars, N. A	20% of each category
Management credits supported by BIM	10.5% points	10.5% points	N. A	N. A
Transport credits supported by BIM	8 points	2/5 credits	26% points	2/15 credits
Energies and emission supported by BIM	54.2% points	4/9 credits	51.8% points	5/21 credits
Water usage credits supported by BIM	3 points	2/4 credits	91.7% points	2/5 credits
Material and waste credits supported by BIM	7 points	2/5 credits	95.2% points	7/15 credits
Credits for indoor quality supported by BIM	7/10 points	4/6 credits	70.3% points	4/23 credits
Novelty credits supported by BIM	½ points	All credits	N. A	5 credits
BIM supported Health and Wellbeing (HWB)	½ points	78.6% credits	71.2% points	21/9 credits
Other credits supported by BIM	3/6 points	N. A	N. A	N. A
Scheme that has widespread application	(BD + C)	BREEAM (NC)	Design & as Built	BEAM Plus New Buildings
Samples of BIM applications	Revit, GBS	Revit, GBS	GBS	Revit, VE

While LEED integration into BIM is feasible, the software's complexity may pose challenges for non-BIM users.

Inefficiently created BIM models can lead to discrepancies between manual and BIM-supported GBE outcomes, further complicating the integration process.

Furthermore, supply chain issues such as material shortages and transportation problems can significantly impede sustainable design and construction efforts. To facilitate the integration of post-pandemic BIM and GBE and enhance supply chain adaptability, these challenges must be addressed.

Future research in BIM programming should focus on developing flexible, qualitative tools to assess unsupported credentials and integrate BIM-based green analytical tools into an integrated BIM platform encompassing all aspects of GBE, COVID-19, the post-pandemic era, and supply chain management. Modern green BIM techniques often prioritize technology over process, but a balanced approach is necessary to effectively address LEED project procedures and execution planning. In summary, the integration of BIM with GBE faces challenges related to software capabilities, unsupported credentials, user expertise, and supply chain issues. Addressing these challenges is essential to advancing BIM in sustainable building and design amidst the context of COVID-19, the post-pandemic era, and supply chain concerns.

4. Findings and discussion

4.1. BIM in green building design

As established in Section 3.1.1, BIM enhances sustainable design through collaboration and optimization of energy and indoor air quality. BIM's real-time modeling and analysis tools enable designers to make data-driven decisions that minimize construction waste and improve building sustainability. During the COVID-19 pandemic, BIM proved essential in monitoring and optimizing building air quality and ventilation, thus decreasing the spread of airborne diseases.

4.2. BIM in green construction

Following design applications (Section 4.1), BIM supports green construction. BIM addresses construction's environmental impact, as shown in Section 4.3. BIM offered effective solutions for addressing these challenges, particularly in waste reduction and supply chain management. For example, BIM-enabled data collection at the Shanghai Center led to a significantly lower material disposal rate compared to the national average. By integrating BIM with prefabrication and modular construction methods, on-site labor and supply chain interruptions were minimized, ensuring smoother project execution.

4.3. Case studies

In addition to the qualitative findings from the case studies, Table 5 provides a quantitative summary of key energy efficiency and sustainability metrics. To further illustrate the outcomes, Figure 7 presents a visual comparison of the reduction in energy consumption and water usage for the Green Office Tower in Shanghai and the Residential Green Building in Melbourne. This visual representation highlights the effectiveness of BIM in achieving sustainability goals for both projects.

Table 5. Energy efficiency and sustainability metrics from case studies

Metric	Green Office Tower (Shanghai)	Residential Green Building (Melbourne)
Energy Consumption Reduction	25%	20%
Water Usage Reduction	30%	15%
Material Disposal Rate	4.1%	5.5%
Carbon Emissions Reduction	22%	18%
Improvement in Indoor Air Quality	Significant	Moderate

Case Study 1: Green Office Tower in Shanghai, China

- Location: Shanghai, China
- Project Type: Commercial Office Building
- Project Details: A 45-story office tower with a focus on sustainability and energy efficiency.
- BIM Tools Used: Autodesk Revit, Green Building Studio (GBS)
- Green Building Strategies Employed: Energy simulations, solar shading analysis, waste management, and water-saving measures.
- Challenges Faced: Supply chain disruptions and remote collaboration due to the pandemic.
- Outcomes Achieved: The project achieved a 25% reduction in energy consumption and a 30% decrease in water usage. BIM enabled precise material management, resulting in a 4.1% material disposal rate, significantly lower than the national average.

Case Study 2: Residential Green Building in Melbourne, Australia

- Location: Melbourne, Australia
- Project Type: Residential Building
- Project Details: A multi-story residential building designed to achieve high levels of sustainability.
- BIM Tools Used: Bentley Hevacomp, Autodesk Green Building Studio (GBS)
- Green Building Strategies Employed: Energy performance simulations, natural ventilation analysis, and green material selection.
- Challenges Faced: Material shortages and logistical delays due to pandemic-related supply chain issues.
- Outcomes Achieved: The project achieved a 20% reduction in carbon emissions and improved indoor air quality through optimized natural ventilation. BIM facilitated better collaboration among stakeholders and streamlined the construction process.

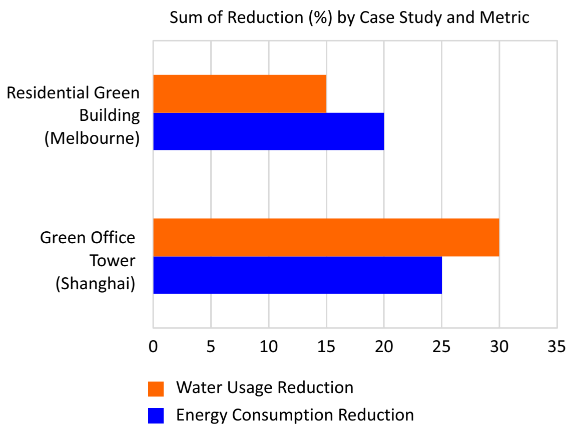

Figure 7. Reduction in energy consumption and water usage

4.4. BIM in building operations

In the context of building operations, BIM's role became even more critical during the pandemic. It allowed for remote monitoring and maintenance of green buildings, ensuring energy efficiency and occupant comfort. BIM's capabilities in data visualization and real-time energy usage monitoring enabled facility managers to make informed decisions and optimize building performance. The integration of BIM with IoT devices further enhanced monitoring and optimization efforts.

4.5. BIM in renovations and retrofits

Sustainable building renovations and retrofits gained prominence in the post-pandemic era, with BIM playing a pivotal role. BIM facilitated sustainable deconstruction procedures, enabling practitioners to assess building component energy and capital investments, optimize resource consumption, and manage demolition waste efficiently. The integration of BIM with additional data technologies supported energy rehabilitation and retrofitting efforts, enhancing resource efficiency and reducing operational costs.

4.6. Critical analysis of BIM and green building integration

The literature and software evaluations reveal both strengths and controversies in BIM's application to green building practices post-pandemic. Studies consistently highlight BIM's ability to enhance energy efficiency and waste management (e.g., Aung et al., 2019; Hao et al., 2020a), yet controversies exist regarding its suitability for comprehensive sustainability assessments. For instance, Ilhan and Yaman (2016) argue that BIM's focus on visualization and coordination limits its capacity to address complex environmental metrics, such as biodiversity impacts, a view contested by Guo et al. (2021), who demonstrate BIM's potential in lifecycle assessments. Methodological limitations in the literature include reliance on case-specific data (e.g., Shanghai Center's 4.1% MDR) and small sample sizes in software evaluations, which restrict generalizability. Comparing software tools, Autodesk Revit and IESVE excel in energy and ventilation analyses, but tools like Tekla Structures lack comprehensive green features, highlighting uneven capabilities across platforms (Table 2). These discrepancies underscore the need for integrated BIM solutions that cover all sustainability aspects. For post-pandemic resilience, BIM's real-time monitoring and supply chain optimization capabilities are critical, yet their effectiveness depends on overcoming interoperability issues and data accuracy challenges (Niknam & Karshenas, 2017). These findings imply that while BIM significantly advances green building practices, its full potential requires addressing software fragmentation, standardizing data exchange, and enhancing stakeholder training to ensure robust, resilient construction processes in the post-COVID-19 era.

5. Research deficiencies and recommendations regarding the supply chain and the post-pandemic phase of COVID-19

5.1. Limitations

1. **Reliance on External Datasets:** This study depends on external datasets for BIM simulations and evaluations. As the accuracy and relevance of these datasets change over time, regular updates and maintenance are essential to ensure the reliability of the findings.
2. **Challenges in Estimating Waste:** The study acknowledges the difficulties in accurately estimating waste from new construction projects. BIM-based methods for waste estimation need further development to enhance their precision and applicability across different project types and scales.
3. **Interdisciplinary Collaboration:** While the study highlights the importance of interdisciplinary collaboration, it does not fully explore the challenges and potential solutions for fostering effective collaboration among architects, engineers, environmental scientists, and IT professionals.

BIM faces compatibility issues, limited sustainability assessments (e.g., biodiversity), and user expertise challenges (Sections 3.1.5, 3.3.2).

5.2. Future work

1. **Advanced BIM Tools and Technologies:** Future research should explore the integration of emerging technologies such as Artificial Intelligence (AI) and Machine Learning (ML) with BIM to further enhance its capabilities in green building design, construction, and operation.
2. **Development of Comprehensive Standards:** There is a need for industry-wide standards and guidelines for green BIM integration. Future research should focus on developing clear and comprehensive standards to ensure consistent implementation across projects.

3. **Long-Term Performance Evaluation:** Future studies should focus on evaluating the long-term performance of BIM-integrated green buildings. This includes monitoring energy efficiency, occupant health, and sustainability metrics over extended periods.
4. **Case Studies and Practical Applications:** Conducting real-world case studies on projects that have successfully integrated green BIM practices will provide valuable insights into the practical challenges and benefits of such integrations.
5. **Enhanced User Training and Stakeholder Engagement:** Future research should develop comprehensive training programs for industry professionals to ensure they are well-versed in utilizing BIM tools for green building practices. Additionally, engaging stakeholders, including building owners, occupants, and policymakers, will provide valuable feedback and insights.

5.3. Specific research deficiencies and recommendations

Addressing the complexities arising from COVID-19, post-pandemic recovery, and supply chain management, this study identifies critical research gaps in BIM and green construction and offers novel recommendations:

1. **BIM Compatibility Challenges:** Research lacks in addressing the compatibility issues among various BIM software, hindering effective sustainability assessments. Future studies should focus on enhancing data exchange methods, particularly in visual connectivity and semantic interoperability, to better align with post-pandemic and supply chain dynamics (Niknam & Karshenas, 2017).
2. **Optimizing Existing BIM Applications:** There's a gap in utilizing current green BIM solutions beyond project design stages, overlooking planning and construction phases. Research should explore integrating prefabricated structures and lean construction with green BIM technologies. Additionally, there's a growing need for BIM-enabled facilities management solutions, warranting further investigation.
3. **Standardization for Green BIM:** Lack of industry-wide standards for green BIM integration poses a significant hurdle. Future research should focus on developing clear guidelines to drive BIM deployment in green construction, especially concerning building refurbishment and demolition (Alizadehsalehi et al., 2020).
4. **Enhancing Adoption of Green BIM Solutions:** Despite numerous studies, the adoption of green BIM solutions remains low among industry practitioners. Overcoming barriers such as the absence of comprehensive industry codes and cyber security concerns requires innovative approaches. Future research should design and evaluate new green BIM software concepts to address these challenges (Ghaffarianhoseini et al., 2017; Huang et al., 2021).
5. **Precision of BIM-Based Prediction Models:** With COVID-19 and supply chain disruptions, the accuracy of prediction models for building sustainability performance becomes paramount. Future studies should focus on aligning green BIM applications with actual performance metrics, addressing concerns raised by certification methods like LEED (Hijazi et al., 2021).
6. **Integration of Green BIM in Project Delivery:** The integration of green BIM practices with post-pandemic resilience and supply chain dynamics requires further exploration. Research should assess the impact of integrated project delivery methodologies on green BIM application in light of COVID-19 and supply chain disruptions (Ansah et al., 2019; Farghaly et al., 2018; Hu et al., 2018; Marzouk et al., 2022; Muller et al., 2019; Newsham et al., 2009; Wang et al., 2021).

Table 6 summarizes the key findings from the research, providing an overview of the insights and recommendations.

Table 6. Key findings from research

Category	Insights
Energy Efficiency	BIM integration leads to substantial energy savings and better performance evaluation.
Waste Management	Significant reduction in material disposal rates through precise management and planning.
Supply Chain Resilience	Enhanced through improved coordination and real-time data sharing, minimizing disruptions.
Occupant Health and Well-being	Better indoor air quality and thermal comfort through optimized design and real-time monitoring.
Long-Term Sustainability	Improved long-term performance and maintenance due to continuous monitoring and data integration.

Finally, addressing these research gaps is crucial for advancing green BIM deployment in the face of COVID-19, post-pandemic recovery, and changing supply chain dynamics. Continued research and collaboration across academia, industry, and government sectors will be instrumental in overcoming these challenges and creating resilient and sustainable built environments for the future.

6. Conclusions

BIM proves to be a versatile tool across various stages of green building projects, aiding in design, construction, facility management, and operations. It enhances data exchange, visualizes building performance, and fosters collaboration among stakeholders. BIM's utilization is hindered by limitations (Section 5), including compatibility and guideline issues. Addressing these challenges is crucial for advancing BIM in sustainable construction post-pandemic.

In conclusion, this study highlights the growing significance of BIM in the AEC industry, particularly in the context of sustainability and the challenges posed by the COVID-19 pandemic and supply chain disruptions. Through a comprehensive review of literature and BIM implementations, several key findings emerge:

1. **BIM's Role:** BIM proves to be versatile across various stages of green building projects, aiding in design, construction, facility management, and operations. It facilitates data exchange, visualizes building performance, and fosters collaboration among stakeholders amid supply chain challenges.
2. **Green Analysis with BIM:** BIM plays critical roles in evaluating environmental sustainability aspects such as energy efficiency, carbon emissions, ventilation, solar energy utilization, water consumption, acoustics, and thermal comfort. Integrating pandemic considerations enhances the design of resilient green buildings.
3. **GBE Support:** BIM supports green building evaluation by estimating scores, managing application documents digitally, and enhancing efficiency, aligning with post-pandemic health and sustainability priorities.

However, several challenges hinder the full utilization of BIM for green building development:

1. **Compatibility Issues:** Weak compatibility among green BIM applications poses a significant barrier.
2. **Support during Disruptions:** Insufficient support for green building design and operation during supply chain disruptions impedes progress.
3. **Lack of Guidelines:** The absence of comprehensive industry guidelines limits the adoption of green BIM solutions.
4. **Limited Understanding:** Industrial understanding of green BIM solutions remains low, hindering widespread adoption.
5. **Need for Precision:** More precise predictive models are needed to enhance sustainability assessments.
6. **Project Delivery Methods:** Developing suitable project delivery methods post-supply chain disruptions is crucial.

This study provides valuable insights for academics and practitioners, emphasizing BIM's role in sustainable construction post-pandemic. The "Green BIM post-pandemic square" taxonomy offers a framework for organizing information and identifying research opportunities, encouraging practitioners to align their approaches with industry expectations. Case studies, such as the Green Office Tower in Shanghai, illustrate BIM's effectiveness in reducing energy consumption and material waste, while critical analysis highlights both its strengths in energy efficiency and its limitations in comprehensive sustainability assessments. Addressing these challenges and advancing research in this area will be vital for fostering sustainable and resilient construction environments in the post-pandemic era.

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