A Review Of Bim-Driven Environmental Optimization In Construction Practices

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Abstract

The construction industry remains one of the largest contributors to global energy use and carbon emissions, which emphasizes the continuing importance of sustainable approaches. This literature review investigates how Building Information Modeling (BIM) has been employed to support sustainability in construction, drawing on academic publications from 2014 to 2024. The review considers the ways in which BIM has been integrated into design, construction, operation, and end-of-life processes to improve environmental performance. Attention is given to its interaction with methods such as lifecycle assessment, waste management, offsite construction, and energy analysis. Through the synthesis of recent research, the study highlights how BIM has evolved from a digital modeling tool into a broader framework that enables more informed decision-making and responsible resource management within the built environment.

Keywords

BIM; life cycle assessment; sustainability; buildings

JEL Classification

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Introduction

The construction industry is a major contributor to global pollution, responsible for 36% of global energy consumption and 39% of energy-related carbon dioxide (CO2) emissions annually due to its fragmented value chain and resource-intensive processes [1]. As climate change continues to intensify extreme weather events, the need to reduce the environmental impact of construction has become increasingly critical. The United Nations Sustainable Development Goals (SDGs) highlight the significance of creating better living spaces in cities and communities [2]. This necessitates a sustainable approach to building, incorporating energy and water savings, reduced material use, and emission controls throughout the building lifecycle [3].

To address these challenges, the construction industry is transitioning towards a circular economy (CE), a model that enhances resource efficiency and minimizes waste by converting the traditional linear construction supply chain into a circular one [4]. This shift is essential for retaining the value of building materials and components even after years of use. However, achieving CE targets poses significant challenges, such as ensuring the availability of materials for future construction and effectively repurposing salvaged materials [5]. Research on design for deconstruction and disassembly has demonstrated the benefits of reusing demolition waste and using buildings as material banks, facilitated by digital tools like material passports [6].

Building Information Modeling (BIM) is a transformative technology that significantly enhances sustainability in the construction industry. When integrated with appropriate project delivery methods, BIM improves resource efficiency and reduces waste. While traditional project delivery methods like Design-Bid-Build are less compatible with BIM, modern methods such as Prefabrication and Design-Build show greater synergy [7]. BIM's potential for improving construction techniques and environmental impact assessment makes it an essential tool for sustainable construction practices [8].

Moreover, the advent of Industry 4.0 technologies supports the transition to a circular economy by providing enhanced intelligence, connectivity, and analytical capabilities. These technologies address the challenge of data fragmentation among stakeholders and leverage IoT data to predict material flows throughout a building's lifecycle [9]. Additionally, blockchain technology has emerged as a reliable means of tracking repurposed materials, ensuring transparency and security in the construction process [10].

Life cycle assessment (LCA) is another critical tool that complements BIM in promoting sustainability. LCA assesses a building's environmental impact from production to end-of-life stage [11]. The integration of BIM with LCA streamlines this process, reducing the effort required for comprehensive environmental assessments [4]. This synergy represents a significant advancement in promoting sustainable practices in the construction industry.

Research Methodology

The objective of this literature review is to identify the primary thematic areas in scientific literature published over the last ten years, pinpoint research gaps, and define the objectives and barriers in the field of sustainable construction facilitated by digital technologies. The search was conducted using academic database Scopus.

Search Strategy and Evaluation

The literature review process was divided into two main stages: initial identification and screening, followed by a detailed evaluation using established frameworks and checklists. The methodology was supported by the SPIDER tool framework and the Critical Evaluation of Article (CEA) checklists. SPIDER stands for: Sample, Phenomenon of Interest, Design, Evaluation, and Research type. The SPIDER tool was selected as a recommended method for conducting literature searches, leading to higher search yields and reducing the time required for researchers to review search results.

Stage1: Initial Identification and Screening

- *Sample:* The review focused on studies investigating the application of BIM data to achieve more sustainable construction. The search was limited to studies published between 2014 and 2024, within the subject area of engineering, and in English. No further limitations were applied. The search query for research replication is:

  (TITLE-ABS-KEY (construction) AND TITLE-ABS-KEY (sustainability) AND TITLE-ABS-KEY (building AND information AND modeling) AND TITLE-ABS-KEY (buildings) OR TITLE-ABS-KEY (BIM) OR TITLE-ABS-KEY (life AND cycle AND costs) OR TITLE-ABS-KEY (life AND cycle AND assessment) OR TITLE-ABS-KEY (digital AND technologies) OR TITLE-ABS-KEY (circular AND economy) OR TITLE-ABS-KEY (deconstruction) OR TITLE-ABS-KEY (disassembly) OR TITLE-ABS-KEY (prefabrication) OR TITLE-ABS-KEY (offsite AND construction) OR TITLE-ABS-KEY (additive AND manufacturing) OR TITLE-ABS-KEY (digital AND twin) OR TITLE-ABS-KEY (artificial AND intelligence) OR TITLE-ABS-KEY (waste AND management) OR TITLE-ABS-KEY (big AND data) OR TITLE-ABS-KEY (sensors) OR TITLE-ABS-KEY (energy AND management) OR TITLE-ABS-KEY (environment)) AND PUBYEAR > 2013 AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (LANGUAGE , "English"))

- *Phenomenon of Interest:* The studies examined how various digital technologies are applied to achieve sustainability in construction, focusing on BIM databases. Search terms included combinations such as “digital technologies in sustainable construction,” “BIM for sustainability,” “data in construction,” and “AI in construction sustainability” to ensure comprehensive coverage of relevant literature.
- *Design:* The review covered qualitative, quantitative, and mixed-method study designs to comprehensively capture the diverse approaches to using BIM data in sustainable construction.
- *Evaluation:* The review targeted studies assessing the effectiveness of BIM technologies in promoting sustainable construction practices, including life cycle assessments and circular economy principles
- *Research Type:* Various research types, including case studies, empirical research, theoretical analyses, and experimental studies, were included to provide a robust and diverse collection of insights.

Initial search results were gathered, and duplicates were removed. The remaining articles were ordered by citations and then screened based on titles and abstracts. Articles unrelated to the research topic or outside the scope were excluded.

Stage 2: Detailed Evaluation

The second stage involved a thorough evaluation using the CEA checklists to determine the relevance and quality of the selected articles. The following criteria were applied:

- *Relevance to the Construction Industry:* Does the paper focus on the construction industry, particularly on buildings?
- *Alignment with Review Objectives:* Is the article aligned with the objectives of the review?
- *Contribution to Knowledge:* Does the article provide a significant contribution to the knowledge base for this literature review?

Only high-quality and relevant studies were included based on these criteria. Full-text evaluations of the shortlisted articles were conducted to assess their methodological rigor and relevance. The process is presented in Figure 1 below.

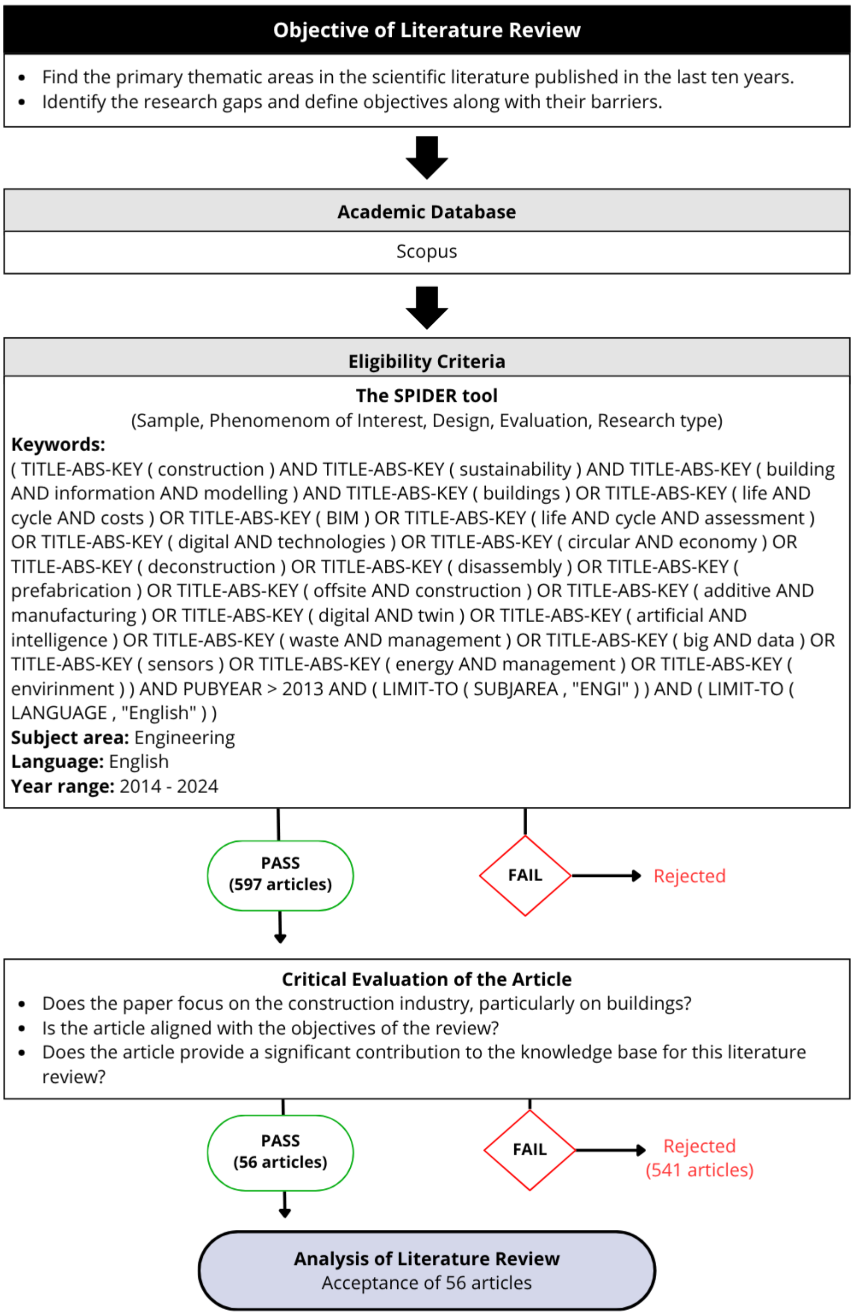

Figure 1: Literature review workflow

Data Extraction and Analysis

In the data extraction and analysis phase, a comprehensive screening process was used to evaluate the relevance and quality of key articles. Initially, a total of 597 articles were identified and assessed based on their alignment with the review's objectives. This preliminary selection process filtered studies that addressed the enhancement of sustainable construction practices through Building Information Modeling (BIM). The *Figure. 2* illustrates the number of publications per country related to sustainable construction and digital technologies, with the United Kingdom leading, followed by

China and the United States. This distribution highlights a significant focus on these topics across various regions. Furthermore, the overall upward trend in research, as demonstrated in the *Figure. 3*, suggests a growing global interest.

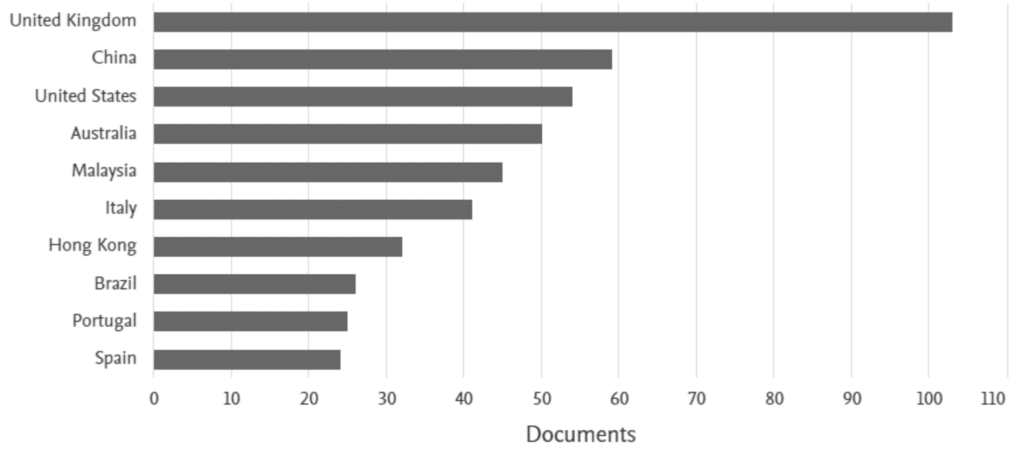

Figure 2: Number of publications per country

Following this initial selection, the focus was narrowed to 56 articles chosen for in-depth review. This detailed review involved extracting and cataloging critical metadata, including keywords, study designs, findings, and their implications for sustainable construction. The systematic extraction of this information facilitated a comprehensive analysis of primary thematic areas, revealing significant research gaps and barriers.

The findings highlighted the potential of BIM in areas such as Lifecycle Assessment, Construction and Demolition Waste Management, End of Lifecycle Decision Making, Offsite Construction, and Energy Performance Management. Additionally, key research gaps and barriers were identified, which must be addressed to further progress in the field.

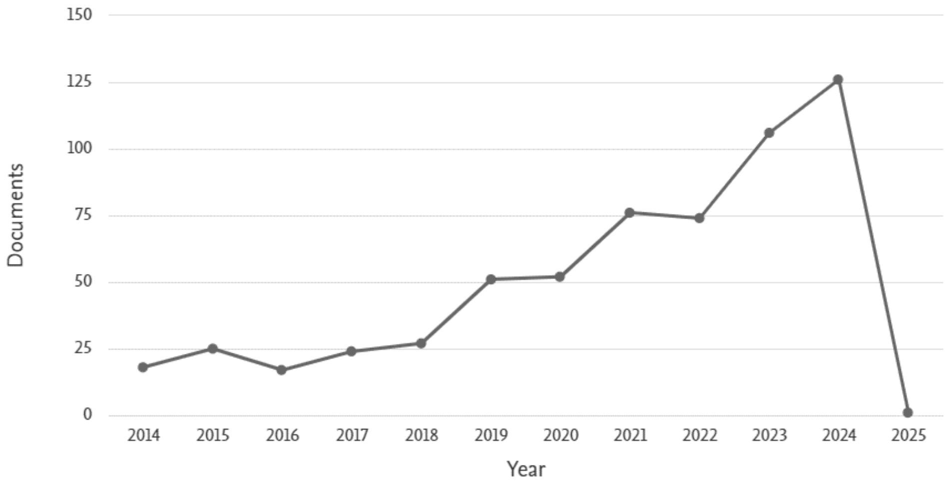

Figure 3: Number of publications per year

Research Findings

The integration of digital tools such as Building Information Modeling (BIM) has significantly advanced construction processes and sustainability evaluation. BIM enables optimization of design, material use, and lifecycle decisions, drawing attention from both researchers and industry stakeholders [12]. The following subsections summarize key research findings on BIM use across major sustainability domains, including lifecycle assessment, waste management, end-of-life decisions, offsite construction, and energy performance management.

Lifecycle Assessment

BIM databases have become essential for conducting Lifecycle Assessments (LCA), which evaluate environmental impacts throughout a building's life—from material extraction to demolition. LCA supports sustainability by quantifying material and process burdens. BIM simplifies this by providing material quantities that can be linked to environmental data, usually through third-party databases [8].

Automation of LCA has progressed from manual to semi-automated and fully automated approaches. Typical integrations use bills of quantities (BoQ), Industry Foundation Classes (IFC), or LCA plug-ins [13]. One dynamic approach links Revit data with environmental databases via Dynamo scripts, allowing real-time visualization of design impacts [14].

Despite these advances, accurate input data remains a major limitation. Environmental Product Declarations (EPD) and Product Environmental Footprints (PEF) improve precision, yet data availability and consistency still hinder broader implementation [15]. Early-stage modelling using probability functions has also been proposed to reduce uncertainty [16].

Future work focuses on automating LCA to support combined Lifecycle Costing (LCC) and Lifecycle Sustainability Assessment (LCSA). These integrations can link environmental, economic, and social indicators to support cost-benefit analysis and sustainable decision-making [17].

Construction and Demolition Waste Management

BIM plays a critical role in reducing construction and demolition waste (CDW) through better planning and data integration. By providing accurate material quantities and linking them to waste indicators, BIM supports waste prediction, tracking, and recycling. Automated quantity takeoffs and prefabrication workflows help minimize waste and support circular economy principles [18].

A common workflow involves exporting BIM data in IFC format and connecting it to databases with waste generation indices (WGI). Open-source tools, such as Python-based scripts, are often used for external analysis [19]. Alternatively, in-model waste estimation tools link BIM data directly to databases through APIs, providing designers with immediate feedback [20].

However, reliable CDW estimation still faces challenges. Regional data scarcity, inconsistent reporting, and varying waste classification systems reduce the accuracy of results. The absence of standardized methodologies and interoperable tools also limits broad adoption [21]. Furthermore, industry resistance to digital transformation slows implementation [12].

BIM supports resource recovery by identifying reusable materials in existing buildings, encouraging urban mining and material circularity [22]. Closed-loop BIM systems further promote recycling and reuse, aligning with circular economic objectives [23].

End of Lifecycle Decision Making

At the end of a building's life, decisions typically involve demolition or deconstruction. Demolition is faster but less sustainable, while deconstruction allows materials to be salvaged for reuse [24]. BIM enhances deconstruction planning by providing detailed as-built models that catalogue materials and components. These models support sequencing, cost estimation, and material tracking, improving both environmental and economic outcomes [25].

BIM also enables digital deconstruction through tools such as ResourceApp, which uses 3D scanning and real-time point clouds to create inventories and support planning [26]. Another framework, the

BIM-based Deconstructability Assessment Score (BIM-DAS), evaluates how easily a building can be dismantled and how much material can be recovered [27].

Integration with Geographic Information Systems (GIS) has further improved end-of-life management by mapping available materials and supporting localized recovery strategies [28]. Yet, differences in BIM and GIS data models—such as geometry and semantics—still limit interoperability[29].

Key challenges remain. Uncertainty about the reuse potential of recovered materials complicates planning [30]. The absence of clear regulations and limited training among professionals restrict practical adoption [31]. Additionally, most tools depend on proprietary platforms like Revit, which reduces interoperability and scalability [32]. Streamlined standards, shared databases, and improved training could help overcome these barriers and support sustainable end-of-life strategies.

Offsite Construction

Offsite construction (OSC) including prefabrication, modular systems, and panelization is reshaping the construction industry through efficiency and reduced waste. BIM supports OSC by coordinating design, manufacturing, and assembly processes in a single digital environment. Prefabricated components built under controlled conditions ensure quality and minimize on-site errors [33].

BIM helps determine a project's suitability for offsite methods by integrating client requirements, design parameters, and manufacturing constraints into parametric models. Frameworks using Revit and Dynamo link design data with OSC decision-making, improving project accuracy [34]. Integration with simulation tools allows for optimized production, scheduling, and logistics [35].

RFID and IoT sensors have been applied to track prefabricated elements through BIM models, enhancing traceability and lifecycle data management [36]. Although promising, high sensor costs and data integration issues remain significant challenges. Blockchain-based solutions have recently been proposed for secure logistics and data exchange [37].

BIM-based scheduling also supports assembly optimization. Algorithms can simulate assembly sequences and reduce project durations [38]. Despite these advancements, OSC faces barriers such as poor interoperability between software platforms, limited skilled labor, and high implementation costs [39]. Broader adoption depends on increased digital literacy, standardization, and demand for prefabrication [40].

Energy Performance Management

Energy Performance Management (EPM) is central to reducing energy use and emissions in buildings. Machine learning and IoT integration with BIM have improved predictive accuracy and operational control [41]. Real-time data from IoT sensors enhance building performance analysis by allowing continuous monitoring and visualization within BIM environments [42].

Early research demonstrated BIM–IoT integration for live monitoring and web-based dashboards, where facility managers could visualize energy data and receive performance insights [43]. Further developments connected sensor data with BIM models through APIs and external databases, enabling detailed spatial energy analyses [44].

Machine learning models, including deep neural networks, have been trained on large datasets to predict annual building energy consumption based on geometry, material data, and local climate [45]. These models outperform traditional physics-based methods by adapting to new data and providing faster results.

Nevertheless, several limitations persist. High-quality operational data are often unavailable or inconsistent [46]. Integration between BIM, IoT, and cloud platforms faces technical barriers, including data formatting and update delays [47]. Moreover, variations in occupant behavior and weather introduce uncertainty into predictions. Developing standardized, cloud-based BIM frameworks with real-time data pipelines could address these gaps and support more efficient energy management in future projects.

Discussion and Future Research

The advancement of Building Information Modeling (BIM) has profoundly influenced sustainability initiatives in the construction sector. Initially used for tasks such as automated quantity take-offs and visualizations, BIM has evolved into a fundamental methodology for sustainable construction practices, as evidenced by the growing body of literature addressing its role in achieving higher sustainability standards.

Based on the reviewed articles, several challenges have been identified in utilizing BIM for sustainable construction. The most significant challenge, representing 34% of the identified barriers, is the lack of standardization, which limits the consistent application of BIM across projects. Data quality (16%) and interoperability (14%) also complicate efforts to integrate BIM into sustainable construction strategies. Other notable challenges include data acquisition (14%), education (9%), user-friendly tools (7%), and regional differences (5%), further emphasizing the need for improvements in standardization, education, and technology. All these challenges are shown in Figure 4.

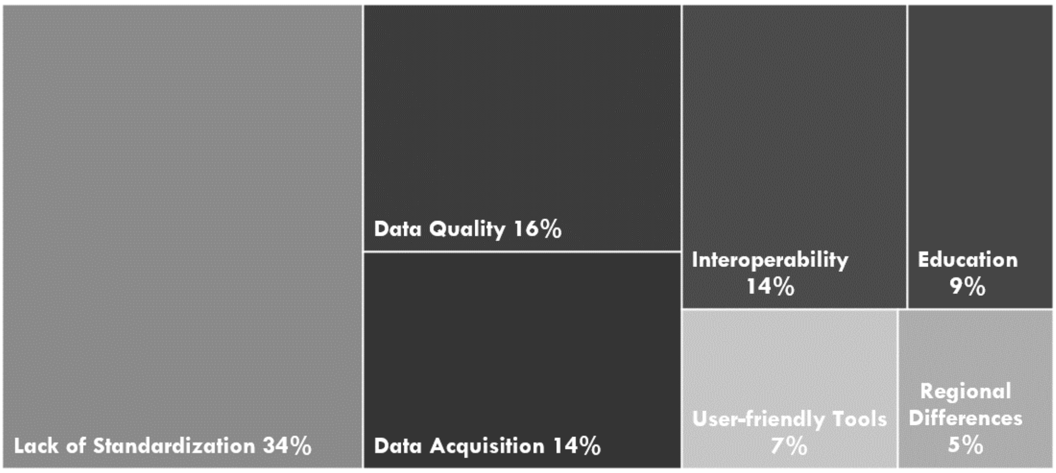

Fig. 4: Percentage representation of challenges based on research

Future research should address these challenges by advancing BIM's capabilities for sustainability. One key area is the development of open-source BIM tools and frameworks that enhance accessibility and promote standardization across industry. Additionally, research should focus on creating automated workflows that integrate BIM with environmental data and lifecycle assessment tools to streamline sustainability assessments. There is also a need to explore the potential of AI and machine learning in BIM to enhance decision-making processes and optimize resource use in sustainable construction. Finally, future studies could investigate how BIM can be better integrated with circular economic principles, including material reuse and the reduction of construction waste, to further improve sustainability outcomes in the built environment.

Conclusion

The literature review was structured to provide a comprehensive examination of how sustainable construction is contributed to by Building Information Modeling (BIM). An introduction to the importance of sustainability in the construction industry was provided, highlighting the critical role of digital technologies such as BIM in enhancing environmental performance. The methodology section detailed the data extraction and analysis processes, which involved a systematic review of relevant literature to identify key themes and research gaps.

Specific applications of BIM, including Lifecycle Assessment (LCA), Construction and Demolition Waste Management, End-of-Lifecycle Decision Making, Offsite Construction, and Energy Performance Management, were explored in subsequent sections. How BIM integration addresses sustainability challenges were discussed in each section and practical and theoretical issues that need to be resolved were identified.

The findings from this review underscore BIM’s evolution from a tool for automated quantity take-offs and visualizations to a fundamental methodology for advancing sustainability in construction. BIM's integration with digital technologies like IoT and machine learning has enhanced capabilities in performance optimization, lifecycle assessment, and resource management.

Despite these advancements, challenges remain, such as data acquisition, data accuracy, interoperability issues, and the need for comprehensive environmental data integration and supporting standardization of processes on a state level. Future research should focus on automating LCA through advanced BIM capabilities, improving data standardization, and exploring real-time performance monitoring solutions. Developing robust ontologies and data dictionaries for BIM objects will also be crucial for enhancing the effectiveness of environmental assessments.

In summary, the integration of BIM and digital technologies offers substantial potential for advancing sustainability in the construction industry. Achieving more sustainable building practices and reducing environmental impacts can be achieved by addressing the identified gaps and leveraging industry drivers

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