Pensar Acadêmico, Manhuaçu, v.24, n.2, p. 306-351, 2026

ISSN 1808-6136

ISSN on-line 2674-7499

BRIDGING BIM AND SUSTAINABILITY: GLOBAL TRENDS AND INFORMATION REQUIREMENTS FOR IFC-BASED WORKFLOWS

LUCAS ANDRADE NUNES[1]; JOSÉ MARIA FRANCO DE CARVALHO[2]; GUILHERME PALLA TEIXEIRA[3]; KARINE DE OLIVEIRA SANTOS[4]; KLÉOS MAGALHÃES LENZ CÉSAR JÚNIOR[5]; JOSÉ CARLOS LOPES RIBEIRO[6]; DIÔGO SILVA DE OLIVEIRA[7]

[1]Master of Science, Department of Civil Engineering, Federal University of Vicosa, lucas.a.nunes@ufv.br. ORCID: https://orcid.org/0009-0003-9659-5618
[2]Doctor of Science, Department of Civil Engineering, Federal University of Vicosa, josemaria.carvalho@ufv.br. ORCID: https://orcid.org/0000-0001-5785-3213
[3]Doctor of Science, Federal Center for Technological Education of Minas Gerais, CEFET/MG, g.palla@cefetmg.br. ORCID: https://orcid.org/0000-0002-7704-906X
[4]Master of Science, Department of Civil Engineering, Federal University of Vicosa, karine.o.santos@ufv.br . ORCID: https://orcid.org/0000-0003-0005-5688
[5]Doctor of Philosophy, Department of Civil Engineering, Federal University of Vicosa, kleos@ufv.br. ORCID: https://orcid.org/0000-0003-4779-4226
[6]Doctor of Science, Department of Civil Engineering, Federal University of Vicosa, jcarlos.ribeiro@ufv.br. ORCID: https://orcid.org/0000-0003-4069-7001
[7]Doctor of Science, Department of Civil Engineering, Federal University of Vicosa, diogooliveira@ufv.br. ORCID: https://orcid.org/0000-0002-4771-8971

ABSTRACT
Climate change and global warming have accelerated the adoption of sustainable development strategies. As a major emitter and energy consumer, the construction sector is a primary target for energy efficiency and low-carbon initiatives. This study investigates how Building Information Modeling (BIM) facilitates the transition toward eco-efficient construction. A bibliometric analysis conducted using the Scopus database identifies China, the United Kingdom, and the United States as the most influential contributors to this field of research. Key thematic clusters include energy efficiency, green building, life cycle assessment (LCA), and circular economy, with Digital Twin emerging as a prominent trending topic for monitoring and maintenance. Despite this potential, information quality and interoperability remain critical barriers due to data gaps and a lack of standardization. Addressing these challenges, this paper presents a conceptual framework for creating, structuring, and verifying BIM data to ensure traceability through the IFC schema. Findings suggest that BIM-driven sustainability requires a maturity level characterized by open standards, high-fidelity models, and collaborative workflows. The analyses underscore the necessity of investing in technology and standardization to fully leverage BIM for sustainable development in the AECO industry.
Keywords: Building Information Modeling (BIM); Sustainability; Industry Foundation Classes; Data Interoperability; Digital Twin.

INTEGRANDO BIM E SUSTENTABILIDADE: TENDÊNCIAS GLOBAIS E REQUISITOS DE INFORMAÇÃO PARA FLUXOS DE TRABALHO BASEADOS EM IFC

RESUMO
As mudanças climáticas e o aquecimento global aceleraram a adoção de estratégias de desenvolvimento sustentável. Como grande emissor e consumidor de energia, o setor da construção civil é um dos principais alvos das iniciativas de eficiência energética e de baixo carbono. Este estudo investiga como a Modelagem da Informação da Construção facilita a transição para uma construção ecoeficiente. A análise bibliométrica realizada a partir da base de dados Scopus identifica a China, o Reino Unido e os Estados Unidos como os principais contribuintes para esse campo de pesquisa. Os principais grupos

Recebido em 28/03/2026 e aprovado para publicação em 07/04/2026.

temáticos incluem eficiência energética, *green building*, Avaliação do Ciclo de Vida e economia circular, com o *Digital Twin* emergindo como um tema de destaque para monitoramento e manutenção. Apesar desse potencial, a qualidade da informação e a interoperabilidade continuam sendo barreiras críticas devido a lacunas nos dados e à falta de padronização. Abordando esses desafios, este artigo apresenta uma estrutura conceitual para a criação, estruturação e verificação de dados BIM para garantir a rastreabilidade por meio do esquema IFC. As conclusões sugerem que a sustentabilidade impulsionada pelo BIM requer um nível de maturidade caracterizado por padrões abertos, modelos de alta fidelidade e fluxos de trabalho colaborativos. As análises ressaltam a necessidade de investir em tecnologia e padronização para aproveitar plenamente o BIM para o desenvolvimento sustentável no setor de AECO.
Palavras-chave: Modelagem da Informação da Construção; Sustentabilidade; *Industry Foundation Classes*; Interoperabilidade de Dados; Gêmeo Digital.

1 INTRODUCTION

According to the Global Status Report for Buildings and Construction 2024/2025 (UNEP, 2025), the construction sector remains a primary driver of the climate crisis, generating approximately two billion tons of waste annually—nearly one-third of the global total—while consuming 32% of global energy and accounting for 34% of worldwide CO_2 emissions. This significant environmental impact is largely driven by a heavy reliance on carbon-intensive materials like steel and cement, which alone represent about 18% of global emissions, and by unsustainable waste management where only a small fraction of debris is recycled or reused. Such practices accelerate natural resource depletion and increase greenhouse gas emissions through both the production of virgin materials and improper disposal in landfills. Consequently, improving industry performance necessitates urgent measures to enhance building energy efficiency, strengthen sustainable construction practices, and adopt low-carbon technologies (UNEP, 2025).

In this context, Building Information Modeling (BIM) has emerged as a transformative methodology for designing, constructing, and managing buildings. Grounded in parametric modeling, interoperability, and collaboration (Eastman et al., 2011), BIM is defined as the combination of policies, processes, and technologies that enable the creation of virtual construction models (Succar, 2009). These object-oriented, data-rich models digitally represent the physical and functional characteristics of a building (NIBS, 2007), serving as a shared knowledge repository throughout its entire life cycle.

As a data repository, BIM enables precise quantity take-offs for materials and equipment, information maintenance over time (when associated with the IFC – Industry Foundation Classes open standard), and various types of simulations. This study investigates its application in fields related to sustainable construction and eco-efficiency. To this end, a bibliometric analysis was conducted to identify emerging themes, predominant areas of interest, and influential countries. Subsequently, a thematic analysis was performed on a select sample of studies to identify applied methodologies, objectives, technologies, and factors influencing the use of BIM in sustainability analyses.

Beyond identifying trends, the analysis revealed that a recurring challenge in the literature relates to the availability, quality, and structuring of data within BIM models. Although BIM is widely used for performance analysis, energy efficiency, and Life Cycle Assessment (LCA), many studies point to limitations associated with a lack of information standardization, missing relevant data, and interoperability issues between tools. Given this scenario, this paper presents a conceptual framework for the creation, structuring, and verification of information in BIM models. Aligned with state-of-the-art practices—specifically the Level of Information Need and buildingSMART's IDS (Information Delivery Specification)—the framework is based on openBIM solutions, clear definition of information requirements, and systematic data verification.

Section 2 presents the research method used, while Section 3 provides an overview of the main findings, including the most influential countries, trends in the number of publications, and thematic areas. Section 4 analyzes the main areas of interest, discussing proposals, methodologies, and technologies applied. Section 5 presents a discussion of the results of the bibliometric analysis, highlighting emerging topics and proposing a conceptual framework for the creation of IFC-based BIM models, in addition to analyzing the requirements necessary to support the BIM applications studied. Finally, Section 6 presents the concluding remarks.

2 METHOD

The bibliometric data were retrieved from the Scopus database, selected for its position as one of the largest curated repositories of peer-reviewed literature. The initial phase of the study involved defining the search strategy through specialized thematic sets. To ensure a robust and representative sample, preliminary analyses were conducted to map the specific terminology linking Building Information Modeling to diverse domains of sustainable construction and eco-efficiency.

Table 1 summarizes the document yields for each keyword combination. Search parameters included titles, abstracts, and keywords (TITLE-ABS-KEY). Terms were structured into two thematic sets: the first comprises BIM-related terminology (acronym and full definition), while the second encompasses sustainability and eco-efficiency descriptors. The final search string integrated these sets using the AND operator, with internal terms linked by OR. All data collection was finalized in November 2025.

Table 1 – Bibliometric Search Strategies and Document Yields

ID	Research Focus	Applied Search String (TITLE-ABS-KEY)	Document Yield
1	General Preliminary Analysis	("Building Information Modeling" OR BIM) AND ("Green Building" OR "Sustainable Construction" OR "Ecodesign" OR "Energy Efficiency")	2,389
2	Life Cycle Assessment (LCA)	("Building Information Modeling" OR BIM) AND ("Life Cycle Assessment" OR LCA)	749
3	Waste Management	("Building Information Modeling" OR BIM) AND ("Waste Management" OR "Construction Wastes" OR "Waste Reduction" OR "Waste Disposal" OR "Construction and Demolition Waste")	452
4	Materials and Carbon Metrics	("Building Information Modeling" OR BIM) AND ("Sustainable Materials" OR "Recycled Materials" OR "Embodied Carbon" OR "Embodied Energy")	327
5	Eco-efficiency and Performance	("Building Information Modeling" OR BIM) AND ("Resource Efficiency" OR "Circular Economy" OR "Performance Assessment" OR "Environmental Performance" OR "Building Performance")	1,228

Source: Authors, based on results obtained from the Scopus database.

Where applicable, an incremental analysis was conducted to quantify the impact of each keyword. At each stage, a new term was added to the search string, recording the total document yield and the specific increment generated by that term. The intersection between terms—defined as the volume of documents simultaneously containing the new keyword and at least one previously accumulated term—was also measured. This verification utilized the AND operator to combine the analyzed term with the preceding keyword group (structured with OR). Consequently, the total documents retrieved by combining a specific keyword with BIM terms corresponds to the sum of the increment and the intersection.

While increments may vary based on the sequence, this approach assesses term relevance and interdependency. The sequence was established in ascending order based on the individual results of each keyword when combined with BIM terms. The incremental analysis for Search 1 is presented in

Table **2**.

Stage 1 yielded 237 documents, serving as the baseline with no prior increment or intersection. In Stage 2, the total rose to 658 documents, an increment of 421. This substantial expansion indicates that "sustainable construction" maintains a robust presence in the literature when integrated with BIM.

Table 2 – Incremental Bibliometric Analysis for Search 1

Step	Search String (TITLE-ABS-KEY)	Cumulative Yield	Increment	Intersections	Individual Search
1	("Building Information Modeling" OR BIM) AND "Ecodesign"	237	237	0	237
2	... AND ("Ecodesign" OR "Sustainable Construction")	658	421	30	451
3	... AND ("Ecodesign" OR "Sustainable Construction" OR "Green Building")	1,348	690	117	807
4	... AND ("Ecodesign" OR "Sustainable Construction" OR "Green Building" OR "Energy Efficiency")	2,389	1,041	298	1,339

Source: Authors, based on results obtained from the Scopus database.

The inclusion of "green building" in Stage 3 resulted in 1,348 total documents—a 690-item increment—highlighting its central role in the BIM-sustainability domain. Finally, the addition of "energy efficiency" in Stage 4 produced the sequence's largest increment (1,041). This identifies "energy efficiency" as the most representative and extensively explored term within research linking BIM to sustainable development.

Table 3 presents the keyword co-occurrence within the BIM-related sample. The data reveals that "Ecodesign" and "Sustainable Construction" (30) are related yet distinct themes with limited overlap. "Ecodesign" shows a moderate correlation with "Green Building" (40) and a slightly stronger link with "Energy Efficiency" (44); the latter is conceptually consistent, as energy performance is a fundamental pillar of sustainable design strategies.

A significant relationship is observed between "Sustainable Construction" and "Green Building" (80), reflecting the latter's role as a primary sub-concept of the broader sustainable construction framework. Similarly, "Sustainable Construction" maintains a strong correlation with "Energy Efficiency" (69), though less pronounced than its link to green building concepts.

Finally, "Green Building" and "Energy Efficiency" exhibit the highest co-occurrence (229). this indicates a substantial thematic overlap and suggests that a significant portion of green building research integrates energy performance analysis. Representative studies within this intersection include (Ercal; Shafique, 2026; Khan et al., 2024; Mohamed et al., 2024; Nguyen; Cao, 2025; Peng; Zhang; Fang, 2026).

Table 3 – Heatmap Matrix of Keyword Co-occurrence for Search 1

Keyword	Ecodesign	Sustainable Construction	Green Building	Energy Efficiency
Ecodesign	—	30	40	44
Sustainable Construction	30	—	80	69
Green Building	40	80	—	229
Energy Efficiency	44	69	229	—

Note: All intersections were calculated using the Boolean string: ("BIM Terms") AND ("Row Term") AND ("Column Term").
Source: Authors, based on results obtained from the Scopus database.

For Search 2 (Table 1), an incremental analysis was not performed, as the search string was restricted to the combination of BIM terms with "Life Cycle Assessment" and its acronym. The significant volume of documents identified (749) suggests high research interest in integrating BIM models with Life Cycle Assessment data. Consequently, these terms were included in the final search string.

Search 3 focused on keywords related to construction waste management, including "Waste reduction," "Construction and demolition waste," "Construction wastes," and "Waste management," yielding a total of 452 documents. The incremental analysis in Table 4 demonstrates that all terms contributed positively to the document yield. When evaluated individually in combination with BIM, each term returned over 100 documents; "Waste management" exhibited the highest impact with 263 documents.

This trend confirms that the "BIM + Waste" intersection is a prominent research topic, particularly concerning general waste management and Construction and Demolition (C&D) waste. These findings align with industry expectations, given the construction sector's significant contribution to global waste generation.

Table 4 – Incremental Bibliometric Analysis for Search 3 (Waste Management)

Step	Search String (TITLE-ABS-KEY)	Cumulative Yield	Increment	Intersections	Individual Search
1	("Building Information Modeling" OR BIM) AND "Waste Reduction"	106	—	—	106
2	... AND ("Waste Reduction" OR "Construction and Demolition Waste")	217	111	16	127
3	... AND (... OR "Construction Wastes")	328	111	66	177
4	... AND (... OR "Waste Management")	452	124	139	263

Source: Authors, based on results obtained from the Scopus database.

Search 4 comprised terms related to sustainable materials and environmental indicators, specifically "embodied carbon" and "embodied energy," yielding a total of 327 documents. The analysis revealed that "embodied carbon" returned the highest volume of documents when combined individually with BIM terms. This was followed by "embodied energy," "sustainable materials," and finally, "recycled materials."

Table 5 – Incremental Bibliometric Analysis for Search 4 (Materials and Carbon Metrics)

Step	Search String (TITLE-ABS-KEY)	Cumulative Yield	Increment	Intersections	Individual Search
1	("Building Information Modeling" OR BIM) AND "Recycled Materials"	22	—	—	22
2	... AND ("Recycled Materials" OR "Sustainable Materials")	104	82	2	84
3	... AND (... OR "Embodied Carbon")	248	144	5	149
4	... AND (... OR "Embodied Energy")	327	79	17	96

Source: Authors, based on results obtained from the Scopus database.

Search 5, comprising terms associated with eco-efficiency and performance, identified 1,228 documents. Among the terms evaluated individually in combination with BIM, "building performance" was the most influential, retrieving 556 documents and generating the largest increment in its respective stage. "Circular economy" followed with a significant impact of 347 documents. The terms "performance assessment" (204 documents) and "environmental performance" (164 documents) exhibited moderate influence, while "resource efficiency" was the least representative, with 66 documents.

Table 6 – Incremental Bibliometric Analysis for Search 5 (Eco-efficiency and Performance)

Step	Search String (TITLE-ABS-KEY)	Cumulative Yield	Increment	Intersections	Individual Search
1	("Building Information Modeling" OR BIM) AND "Resource Efficiency"	66	—	—	66
2	... AND ("Resource Efficiency" OR "Environmental Performance")	224	158	6	164
3	... AND (... OR "Performance Assessment")	413	189	15	204
4	... AND (... OR "Circular Economy")	728	315	32	347
5	... AND (... OR "Building Performance")	1,228	500	56	556

Source: Authors, based on results obtained from the Scopus database.

Following the incremental validation of keyword relevance and thematic impact, a comprehensive search string was synthesized to capture the multidimensional interface between

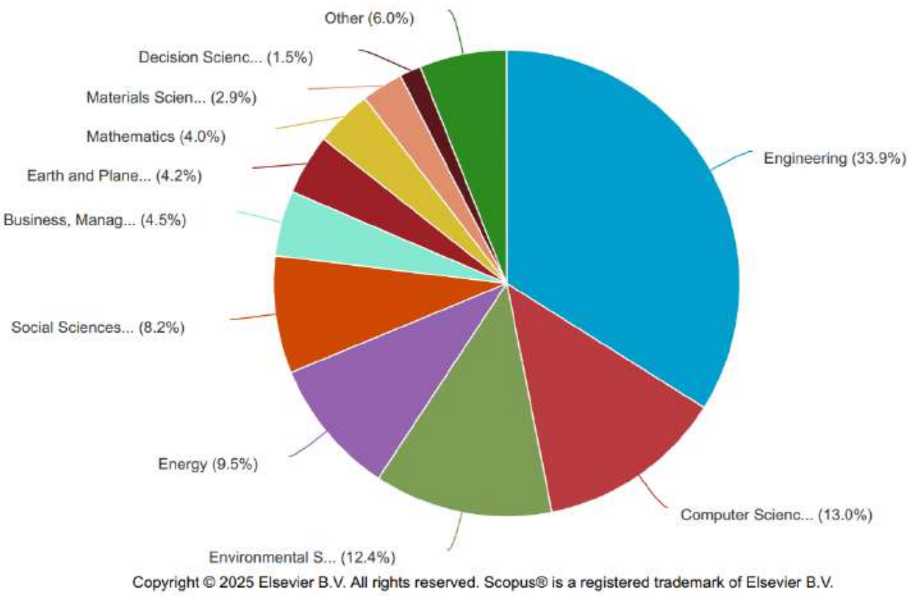
BIM and sustainable development. The search was executed in the Scopus database using the following Boolean logic: TITLE-ABS-KEY (("Building Information Modeling" OR BIM) AND ("Ecodesign" OR "Sustainable Construction" OR "Green Building" OR "Energy Efficiency" OR "Life Cycle Assessment" OR "LCA" OR "Waste Reduction" OR "Construction and Demolition Waste" OR "Construction Wastes" OR "Waste Management" OR "Recycled Materials" OR "Sustainable Materials" OR "Embodied Carbon" OR "Embodied Energy" OR "Resource Efficiency" OR "Environmental Performance" OR "Performance Assessment" OR "Circular Economy" OR "Building Performance")). This integration of 19 validated terms ensured high sensitivity in data retrieval, providing a robust and representative dataset for the subsequent bibliometric and thematic analysis.

3 OVERVIEW

The execution of the final search string—targeting titles, abstracts, and keywords—initially retrieved 3,885 documents. To refine the analysis, the sample was filtered by thematic areas to ensure alignment with the research scope. The selected categories included: Engineering (2,672), Computer Science (1,021), Environmental Science (973), Energy (748), Social Sciences (642), Business, Management and Accounting (355), Earth and Planetary Sciences (331), Materials Science (227), and Decision Sciences (117).

This filtering process resulted in a refined sample of 3,754 documents. The marginal reduction in volume indicates a high degree of interdisciplinary correlation and validates the effectiveness of the search terms in capturing relevant literature. Figure 1 illustrates the relative distribution of these thematic areas.

Figure 1 - Documents by thematic areas

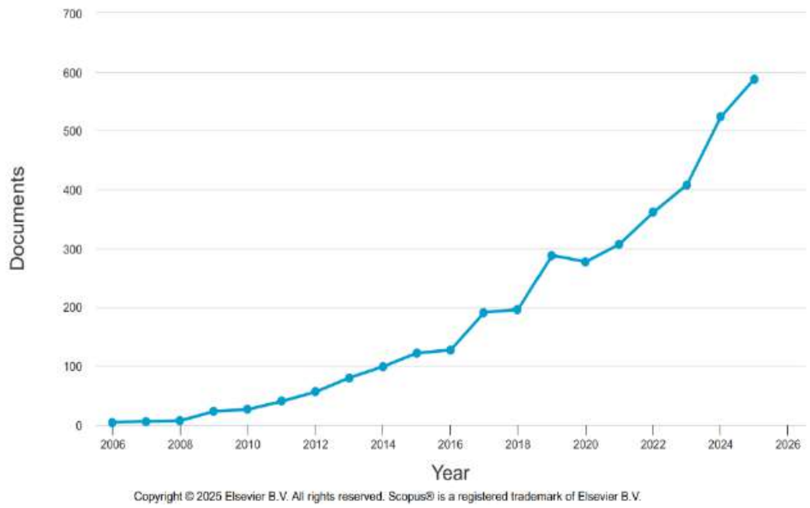


Source: Scopus, based on the search criteria applied.

Figure 2 illustrates the annual evolution of publications, revealing a clear upward trend over the last two decades. A progressive and continuous increase in article volume is observed starting in 2010, with significant acceleration post-2016 and particularly between 2020 and 2025. This trajectory indicates both the global maturation of BIM methodology and the expansion of its application within sustainability, eco-efficiency, and environmental performance research.

This growth is strongly associated with the consolidation of public policies and governmental mandates that incentivize or mandate BIM adoption. These initiatives position BIM as a primary instrument for improving design quality, reducing waste, enhancing cost predictability, and minimizing environmental impacts—factors directly aligned with the sustainable construction agenda. Furthermore, the intensified research into the intersections of BIM with embodied energy, circular economy, and waste management reinforces its strategic role in making the Architecture, Engineering, Construction, and Operation (AECO) sector more efficient, sustainable, and resilient.

Figure 2 – Publications by year

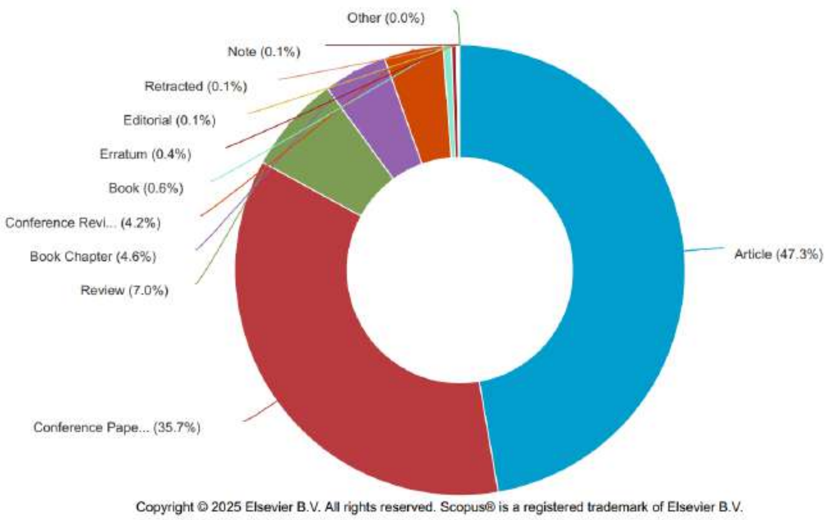


Source: Scopus, based on the search criteria applied.

Figure 3 illustrates the distribution of document types within the identified sample. Peer-reviewed articles represent the majority of the publications (47.3%), confirming a robust presence in scientific journals. Conference papers account for 35.7% of the total, indicating a highly active engagement in technical and scientific events—a common characteristic of emerging and rapidly evolving fields such as BIM and sustainability.

The remaining document categories each represent less than 10% of the sample, including review articles (7.0%), book chapters (4.6%), and conference reviews (4.2%). Other formats, such as books, errata, editorials, and notes, account for proportions below 1%.

Figure 3 – Document types

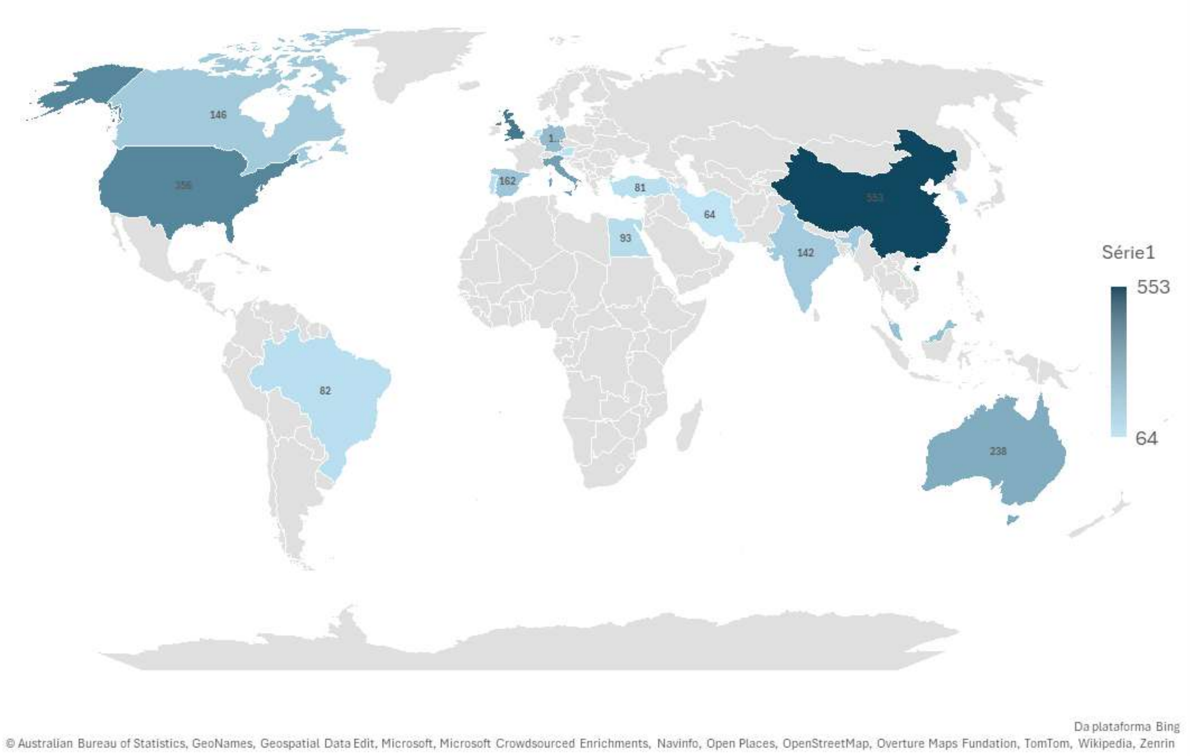


Source: Scopus, based on the search criteria applied.

Figure 4 illustrates the geographical distribution of publications based on author affiliation. China holds the leading position with 553 documents (≈15%), reflecting rapid digitalization policies within its construction sector and a robust national interest in sustainable technologies. The United Kingdom follows with 405 publications (≈11%), maintaining its status as a pioneer and global leader in the institutionalization of BIM.

The United States ranks third with 356 documents (≈9.5%), followed by Italy (281 documents; ≈7.5%) and Australia (238 documents; ≈6%). These results demonstrate that research on BIM, sustainability, and eco-efficiency is concentrated in nations with well-established innovation policies in the AEC sector. Within Latin America, Brazil emerges as the primary contributor with 82 publications.

Figure 4 – Documents by country



Source: Authors, based on results obtained from the Scopus database.

Table 7 summarizes representative review articles from recent years, identifying their core themes, key observations, and scientific contributions. The integration of advanced technologies—such as Artificial Intelligence (AI), BIM, Internet of Things (IoT), Digital Twins, and Machine Learning—is identified as a fundamental driver for the transformation of the construction and facility management sectors, fostering a more efficient, sustainable, and data-driven industry. However, significant challenges persist, including a lack of standardization, poor model quality, data scarcity, high implementation costs, domain fragmentation, and limited interoperability. These barriers must be addressed to facilitate industry-wide advancement within this digital landscape.

Table 7 – Selection of Recent Review Articles: Themes, Observations, and Contributions

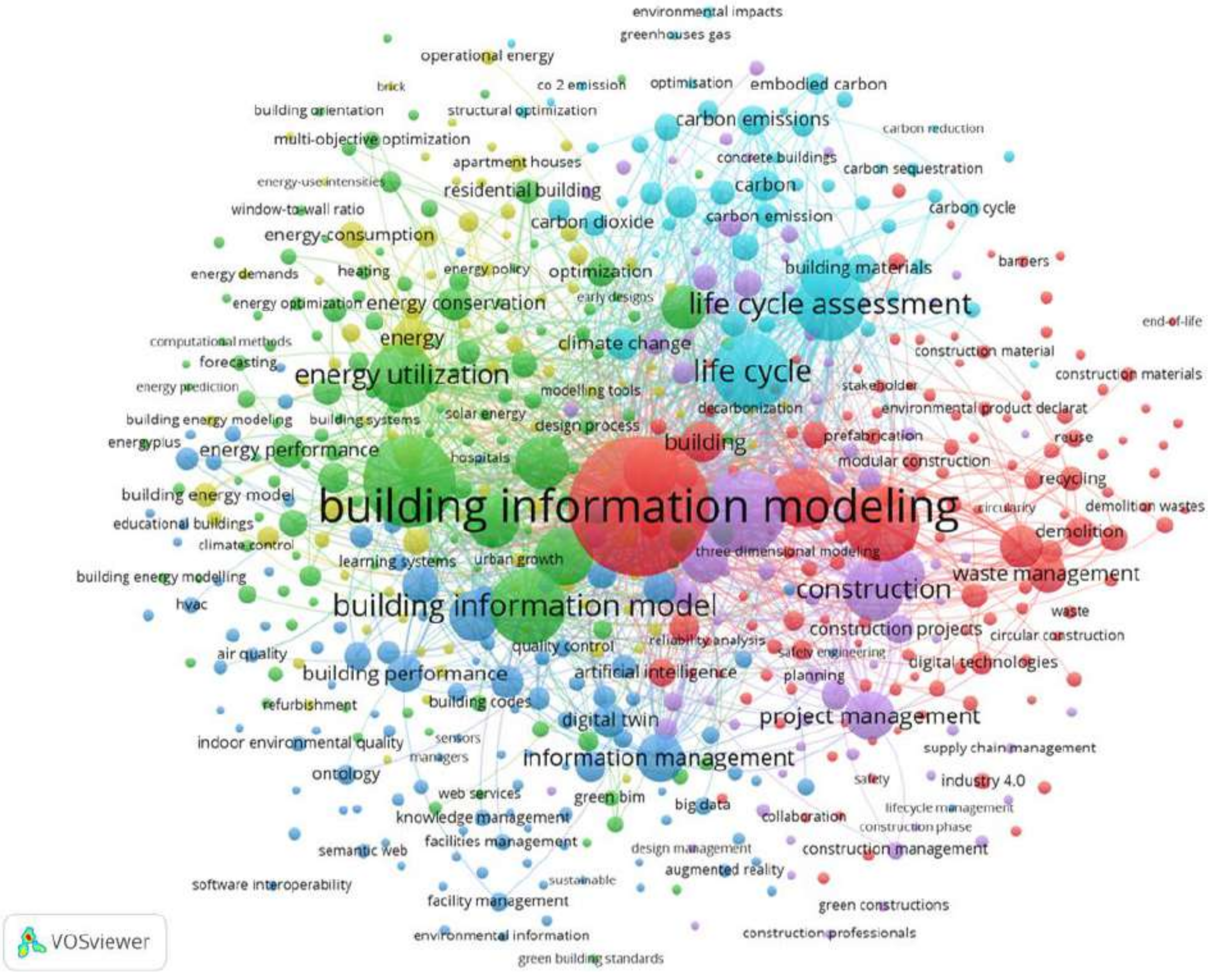
Ref.	Primary Theme	Key Observations and Contributions
(Sesana et al., 2026)	Integration of Building LCA and Digital Technologies	Systematic review of LCA integration with BIM, Digital Twin (DT), and AI. Highlights potential for inventory automation and decarbonization. Identifies interoperability and standardization as primary barriers.
(Tan et al., 2026)	Circular Economy (CE) in Railway Infrastructure	Investigates 10R principles across the railway lifecycle. Positions BIM, DT, GIS, and IoT as enablers for circularity and reduction of environmental impacts.
(Ahmadi et al., 2026)	CE, Digital Material Passports, and Digital Twins	Notes that material passports are predominantly static; DT integration enables dynamic lifecycle tracking. Emphasizes BIM and IoT as catalysts for circular construction strategies.
(El-Abbasy, 2025)	AI Applications in Civil Engineering Domains	Comprehensive review of AI in safety monitoring, resource planning, and risk prediction. Discusses AI support for sustainability metrics (carbon footprint/energy efficiency). Notes data scarcity and high computational costs.
(Li; Widén; Shadram, 2025)	Life Cycle Net-Zero Energy/Emissions (LCNZE)	Identifies a research gap in non-residential buildings with complex HVAC. Notes recurring incomplete LCAs. Highlights the emerging role of AI and sensitivity analysis in lifecycle optimization.
(Abd El-Hameed, 2025)	Digital Technologies for Resource Circularity	Identifies 15 technologies supporting 25 CE strategies. BIM acts as the central data repository and decision-support platform. Highlights gaps in real-time DT feedback and fragmented data ecosystems.
(Bouhmoud et al., 2025)	BIM for Waste Management and Circular Economy	Positions BIM as essential for managing Construction and Demolition Waste (CDW). Proposes the nD BIM-WMS (Waste Management System) focusing on 4R strategy maximization.
(Rodrigo et al., 2024)	Digital Tech for Circular Economy in Construction	Maps 365 studies, categorizing "Advanced Technologies" (AI, ML, Big Data) and "Sustainable Construction Tech" (BIM, IoT, Blockchain). Highlights BIM as the structural foundation for waste management.
(Asif; Naeem; Khalid, 2024)	Digitalization Applied to Building Sustainability	Systematic review of 13 technologies (BIM, IoT, DT, AI). Contributions include increased integration and operational flexibility. Challenges include high initial costs and a lack of skilled professionals.
(Chen et al., 2024)	BIM–LCA Integration Methods	Systematizes integration workflows, evidencing efficiency gains and error reduction. Highlights the critical influence of Level of Development (LOD) and automation on result reliability.
(Cespedes-Cubides; Jradi, 2024)	Digital Twins in Building Operation & Maintenance	Focuses on existing buildings. Identifies five DT applications: monitoring, anomaly detection, operational optimization, predictive maintenance, and scenario simulation.
(Banihashemi et al., 2024)	Circular Economy and Digital Transformation	Analyzes how Open-BIM, DT, and Blockchain support CE. Identifies barriers in digital retrofit costs and the absence of twins for demolished structures.
(Pan; Zhang, 2022)	BIM–AI Integration for Smart Construction	Identifies six research areas: automated design, rule checking, as-built reconstruction, performance analysis, VR/AR, and DT. Suggests future directions in human-machine integration.

(Tahmasebinia et al., 2023)	Digital Twins for Building Energy Management	Review of DT for energy monitoring and forecasting. Integrates BIM, sensors, and ML. Notes limitations in data quality and model maturity.
(Aziminezhad; Taherkhani, 2023)	BIM–Deconstruction (BIMfD) Integration	Documents growth in BIMfD since 2016. Identifies gaps in Design for Deconstruction (DfD) and end-of-life performance assessment.
(Zheng et al., 2023)	BIM–CFD Integration for External Environments	BIM serves as the source for geometric parameters in Computational Fluid Dynamics (CFD). Notes limitations in unidirectional data transfer and heavy API dependence.
(Ciccozzi et al., 2023)	BIM–BEM Interoperability for Energy Analysis	Reviews strategies from 2004–2023. Identifies four approaches (Real-time, Standardized formats, MVDs, Proprietary). Concludes that interoperability remains a barrier to practical use.

Source: Authors, 2026.

Figure 5 illustrates the keyword co-occurrence network. To generate the visualization, a minimum threshold of 10 occurrences per term was established, initially yielding 726 terms. Following a refinement process—which involved the removal of generic descriptors and the standardization of synonyms—the selection was narrowed to 602 keywords from a total pool of 14,457.

Figure 5 – Keyword co-occurrence network



Source: Authors, 2026, based on processing in VOSviewer.

The keywords exhibiting the strongest correlation were: Building Information Modeling, Sustainable Development, Energy Efficiency, Life Cycle, Construction Industry, Life Cycle Assessment, Energy Utilization, Decision Making, and Environmental Impact.

Table 8 identifies the thematic clusters within the network, listing their primary terms and providing a detailed description of each research front.

Table 8 – Thematic Clusters Identified via Keyword Co-occurrence Analysis (n = 602)

Cluster	Research Front	Primary Associated Terms	Cluster Description
1 – Red (136 items)	Construction Management, Decision-Making, and Circular Economy	Building Information Modeling, decision making, construction industry, sustainability, circular economy, waste management, demolition, performance assessment, recycling, artificial intelligence, construction and demolition waste.	Represents the integration of BIM with construction management and sustainability practices. It encompasses decision-support systems, performance assessment, waste management, and circular economy strategies applied throughout the building lifecycle.

2 – Green (132 items)	Energy Efficiency	Energy efficiency, energy utilization, building information model, green buildings, energy performance, energy simulation, energy management, Autodesk Revit.	Focused on the energy analysis of buildings, including simulation, modeling, and optimization. It highlights the application of BIM tools in evaluating and enhancing energy performance.
3 – Blue (111 items)	Information Management, Interoperability, and Emerging Technologies	Information management, interoperability, IFC, digital twin, internet of things, intelligent buildings, office buildings, building performance, facility management, data integration, semantic web, machine learning, virtual reality.	Focuses on BIM as a platform for information management and digital integration. Includes IFC-based interoperability, emerging technologies (Digital Twin, IoT, AI, VR), data visualization, and applications for smart buildings and O&M (Operation & Maintenance).
4 – Yellow (89 items)	Energy Modeling	Energy consumption, building energy model, building energy simulations, retrofitting, energy efficient building, zero energy buildings, energy modeling.	Comprises terms related to energy efficiency, including retrofitting, building energy modeling (BEM), performance simulations, and NZEB (Net Zero Energy Buildings) concepts. This cluster is closely linked to Cluster 2.
5 – Purple (82 items)	Sustainable Development	Sustainable development, sustainable building, sustainable construction, project management, construction projects, planning, built environment.	Focused on sustainability management, bringing together terms related to sustainable development, environmental assessment, and project management. It highlights BIM as a vehicle for planning and executing sustainable projects.
6 – Cyan (52 items)	Life Cycle Assessment (LCA)	Life cycle, life cycle assessment, environmental impact, global warming, carbon footprint, carbon emission, greenhouse gas, climate change, embodied carbon, embodied energy.	Dedicated to the quantification of environmental impacts through LCA and carbon indicators, integrating BIM with environmental assessment methodologies and decarbonization metrics.

Source: Authors, 2026.

4 THEMATIC ANALYSIS

In this stage, representative articles were selected for an in-depth qualitative analysis. To identify studies addressing BIM applications across various dimensions of sustainable development, high-impact keywords were extracted from the co-occurrence network and utilized as focal points for targeted searches.

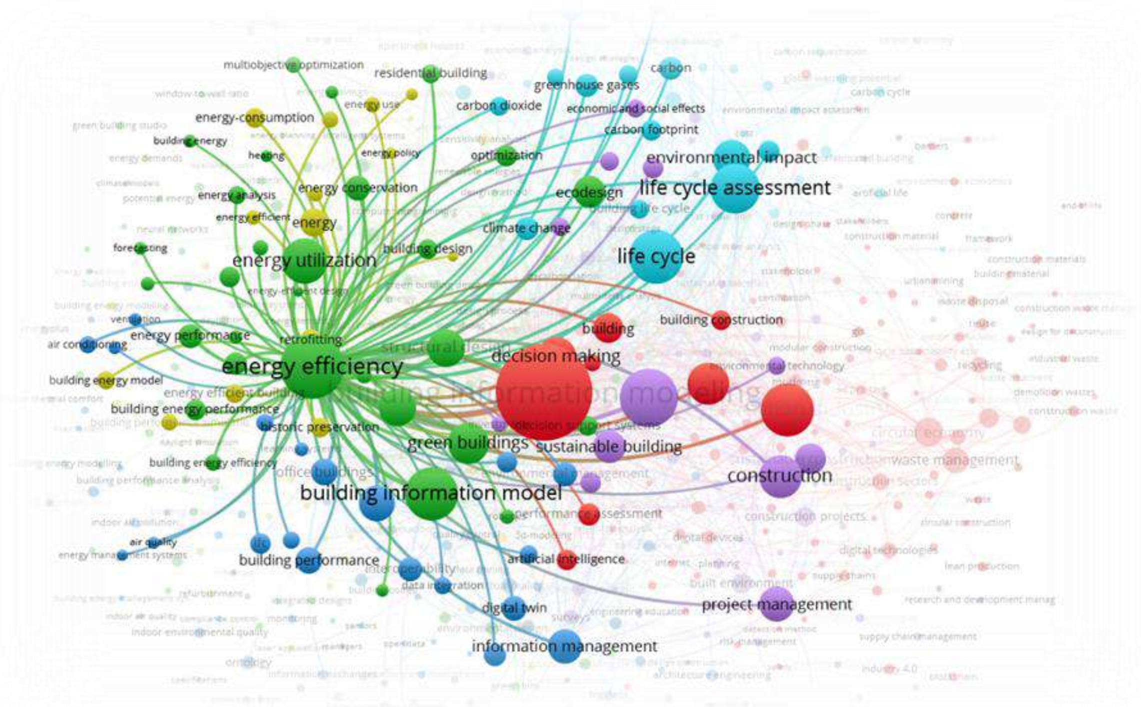
For each selected keyword, individual search rounds were conducted in combination with the core BIM terms. The selection criteria focused on the five most-cited articles published within the last five years. Beyond citation metrics, priority was given to studies demonstrating actual BIM implementation, practical application, experimentation, or case study validation. In instances where an article appeared in multiple search results, the next most-cited unique paper was selected to ensure a diverse sample.

The following sections are organized by keyword, detailing the findings and discussions for each thematic pillar.

4.1 Energy Efficiency

"Energy efficiency" was selected from the green cluster (Figure 6). As illustrated in the network, this term exhibits high frequency and strong correlation with multiple research fronts, justifying its selection as a primary thematic pillar.

Figure 6 – Energy efficiency keyword network



Source: Authors, 2026, based on processing in VOSviewer.

Hosamo et al. (2022) proposed a predictive maintenance framework based on Digital Twins (DT) for Air Handling Units (AHUs). The study was motivated by the limitations of traditional building maintenance, which typically relies on reactive or preventive approaches. The authors argue that reactive maintenance fails to anticipate failures, while preventive maintenance often replaces functional components prematurely, leading to wasted time and resources. The proposed framework is based on predictive maintenance and utilizes Digital Twin technology to support fault detection and diagnostics (FDD). The framework consists of an operational fault detection module based on the Air Handling Unit Performance Assessment Rules (APAR), a condition prediction module using Machine Learning techniques, and a maintenance planning module. The system integrates BIM models, IoT sensor networks, Machine Learning techniques, semantic metadata, and expert rules, enabling a continuous data flow.

Zaballos et al. (2020) proposed and implemented the integration of BIM and IoT sensor networks to collect environmental parameters and assess Indoor Environmental Quality (IEQ) within the context of a Digital Twin applied to a smart campus. The experimentation was carried out in Autodesk Revit, using Dynamo as middleware to process data from IoT sensors, previously stored in a database, compute IEQ indices, and visualize comfort levels in a virtual environment. Preliminary results underscore the importance of continuous monitoring, given the strong correlation between environmental conditions and occupant productivity.

Zhuang et al. (2021) developed a Performance Integrated BIM (P-BIM) framework to support data-driven building energy efficiency and environmental optimization throughout the building life cycle. The authors highlight that traditional BIM lacks the capability to effectively integrate performance data, limiting efficiency and environmental impact analysis. The proposed framework integrates multiple types of data, including ontological, external, simulated, and monitored performance data, within a structured architecture combining BIM models, external databases, and a digital design platform. Applied to a school building case study, P-BIM enabled the simultaneous evaluation of Indoor Environmental Quality (IEQ) and Life Cycle Cost (LCC), along with energy performance, demonstrating the potential of performance data integration for building optimization.

Tushar et al. (2021) presented a workflow that integrates BIM (Revit), energy simulation (FirstRate5), sensitivity analysis and optimization (@Risk), and Life Cycle Assessment (LCA) using the Tally plugin, with the aim of identifying more sustainable design alternatives. The study evaluates passive design strategies, such as insulation, shading, orientation, glazing, and air infiltration. The approach was applied in a case study involving six scenarios, where passive parameters were varied to assess the energy performance of the scenarios. Integration with Tally enables the estimation of life-cycle environmental impacts and embodied energy. The analyses identify the parameters that most strongly influence energy consumption and the most suitable materials from an energy and environmental standpoint. The workflow enables the comparison of design alternatives from a life-cycle perspective, thereby contributing to more efficient and sustainable solutions.

Shen & Pan (2023) present a data-driven and automated framework for building energy performance analysis that integrates BIM models (Revit) with energy simulation in DesignBuilder, explainable machine learning (XAI) for prediction and interpretation, and multi-objective optimization. The model combines data derived from BIM with ML techniques and optimization algorithms to predict and optimize energy consumption, CO_2 emissions, and thermal discomfort, supporting decision-making in sustainable building design. The predictive model demonstrates good accuracy, while the explainable approach enables the identification and quantification of variable contributions, highlighting that features related to the HVAC system have a greater influence on the prediction results. The optimization stage identifies optimal solutions to improve building energy performance.

In summary, the first two studies demonstrate genuine DT applications, focusing on predictive maintenance and real-time comfort analysis, respectively. The remaining studies focus on the design and conceptual phases, integrating energy simulation, LCA, and multi-objective optimization to mitigate emissions. Collectively, these studies confirm that integrating BIM with advanced technologies (IoT, DT, AI) is essential for aligning the built environment with global sustainability targets. Table 9 presents a summary of the five most-cited studies from the last five years, identified through a targeted search using the string BIM Terms AND "Energy efficiency" within the Scopus database (Title, Abstract, and Keywords).

Table 9 – Most cited articles focused on Energy Efficiency

Ref.	Citations (Scopus)	Research Objective	Core Technologies	Application Phase
(Hosamo et al., 2022)	232	Predictive maintenance for Air Handling Unit (AHU) components.	BIM, Digital Twin, IoT Sensors, Machine Learning	Operation & Maintenance (O&M)
(Zaballos et al., 2020)	164	Indoor environmental comfort and quality assessment.	Revit, Dynamo, Digital Twin, IoT Sensors	Operation & Maintenance (O&M)
(Zhuang et al., 2021)	128	Performance data integration for energy and environmental lifecycle optimization.	Revit, EnergyPlus, Rhino.Inside, Grasshopper, MySQL, Genetic Algorithms	Early Design and Lifecycle Support
(Tushar et al., 2021)	127	Integrated BIM-based workflow combining energy simulation and LCA for evaluating and optimizing design alternatives	BIM (Revit), Energy Simulation (FirstRate5), BIM-enabled LCA (Tally), Sensitivity/Optimization (@Risk)	Conceptual Design and Decision Support

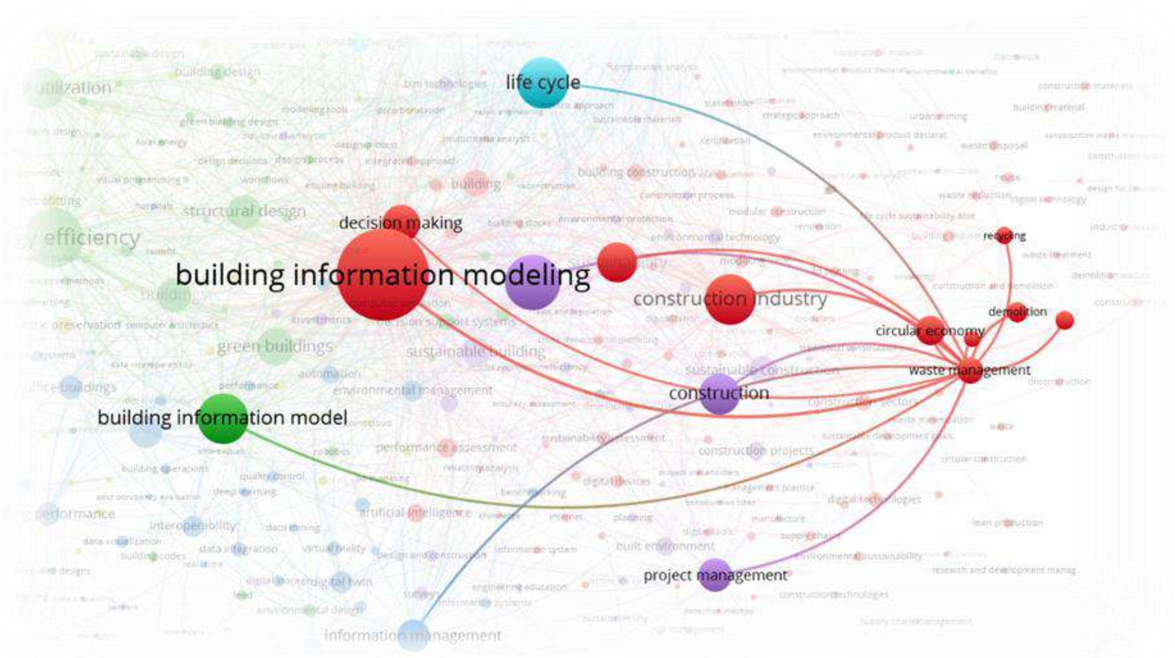
(Shen; Pan, 2023)	112	Energy performance analysis and optimization using BIM and machine learning	BIM (Revit), DesignBuilder, Machine Learning (XAI), Multi-objective Optimization	Design Phase and Decision Support

Source: Authors, 2026.

4.2 Waste Management

The term "waste management" exhibits strong correlations with several research fronts (Figure 7), including life cycle, decision making, the construction industry, circular economy, demolition, recycling, and project management, as well as BIM both as a modeling tool and a methodology.

Figure 7 – Waste management keyword network



Source: Authors, 2026, based on processing in VOSviewer.

Guerra; Leite & Faust (2020) proposed time-based algorithms integrated into 4D-BIM to estimate and plan for on-site reuse and off-site recycling of concrete waste, as well as off-site recycling of drywall waste, during the construction phase. Two non-residential case studies in Texas demonstrated the approach, which synchronizes BIM models, construction schedules, and purchase records. Implementation of the method requires: (1) BIM geometry with a minimum level of development (LOD) of 300; (2) a detailed schedule; and (3) purchase records for concrete and drywall. The waste estimate is based on the mass balance principle, calculating, for each sequential section of the project, the difference between the materials purchased and the materials required in the structure. At the project level, the model breaks down the estimated waste into portions intended for on-site reuse, off-site recycling, and landfill disposal. In the case studies, the difference between the estimated concrete waste and the actual values was 11.1% in Case Study A and 16.7% in Case Study B.

Kang et al. (2022) developed a conceptual framework based on Smart BIM for demolition waste management, integrating BIM, IoT, Artificial Intelligence, and Digital Twins. The framework encompasses three main services: data collection and modeling for generating BIM models, demolition planning with integration between physical and virtual spaces, and waste transportation with route optimization and selection of logistics providers. The approach enables waste quantification, demolition planning, and the definition of management strategies. Its application was illustrated through a case study in Hong Kong, including a cost-benefit analysis considering different recycling scenarios.

Mostert et al. (2021) compared the climate and resource footprints of recycled and conventional concrete, considering climate, material, energy, and water indicators. The analysis covers modules A1–A3 (concrete production) and C1–C3 (demolition and waste treatment for the generation of recycled aggregate in mobile or stationary plants). The Life Cycle Assessment (LCA) was conducted using openLCA with GaBi databases, with integration into a BIM environment (Revit/SURAP) for spatial visualization. The results indicate that the use of concrete with 43% recycled aggregate can reduce primary raw material consumption by up to 37%, and that production in a mobile plant presents lower environmental impacts.

Jayasinghe & Waldmann (2020) proposed a web-based BIM tool to support the circular economy in the construction sector. The solution comprises a centralized database of materials and components, developed using PHP and MySQL, which is capable of storing detailed information extracted from BIM models. The data flow from the BIM model to the database is enabled through a Dynamo script. The database organizes information into three main groups: project data, components, and materials. These data enable waste quantification, support demolition planning (DfD), allow the estimation of component reuse potential, and support recycling strategies.

Zoghi & Kim (2020) used System Dynamics to analyze the economic efficiency of BIM-supported construction and demolition waste management. The model assesses the effects of the time required to accept the investment risk associated with BIM, the use of modular/prefabricated elements, and landfill costs on waste generation and disposal. The results indicate that BIM can significantly reduce waste management costs, while the use of modular elements helps reduce waste generation.

Table 10 summarizes the five most-cited studies from the last five years, identified using the search string BIM Terms AND "Waste management" within the Scopus database (Title, Abstract, and Keywords).

Table 10 – Most cited articles focused on Waste Management

Ref.	Citations (Scopus)	Research Objective	Core Technologies	Application Phase
(Guerra; Leite; Faust, 2020)	142	Plan and optimize the reuse of concrete waste and the recycling of concrete and drywall waste during construction	BIM, 4D-BIM, Temporal Algorithms	Waste Management Planning
(Kang et al., 2022)	86	Conceptual framework for smart demolition waste management through integration of BIM, IoT, AI, and Digital Twins	BIM, IoT, Digital Twin, AI	Demolition Planning & Waste Management
(Mostert et al., 2021)	76	Evaluate and compare environmental footprints of conventional and recycled concrete, with BIM-based visualization support	BIM (Revit), LCA (openLCA + GaBi), Impact Visualization (SURAP)	Design & Environmental Analysis (Circular Economy)
(Jayasinghe; Waldmann, 2020)	75	Create a digital materials and components bank to support circular economy strategies	BIM (Revit), Web Application (PHP/MySQL), Dynamo	Demolition Planning, Material Reuse & Recycling
(Zoghi; Kim, 2020)	72	Evaluate the economic efficiency of BIM-supported C&D waste management using system dynamics modeling	BIM, System Dynamics Modeling	Waste Management & Lifecycle Economic Analysis

Source: Authors, 2026.

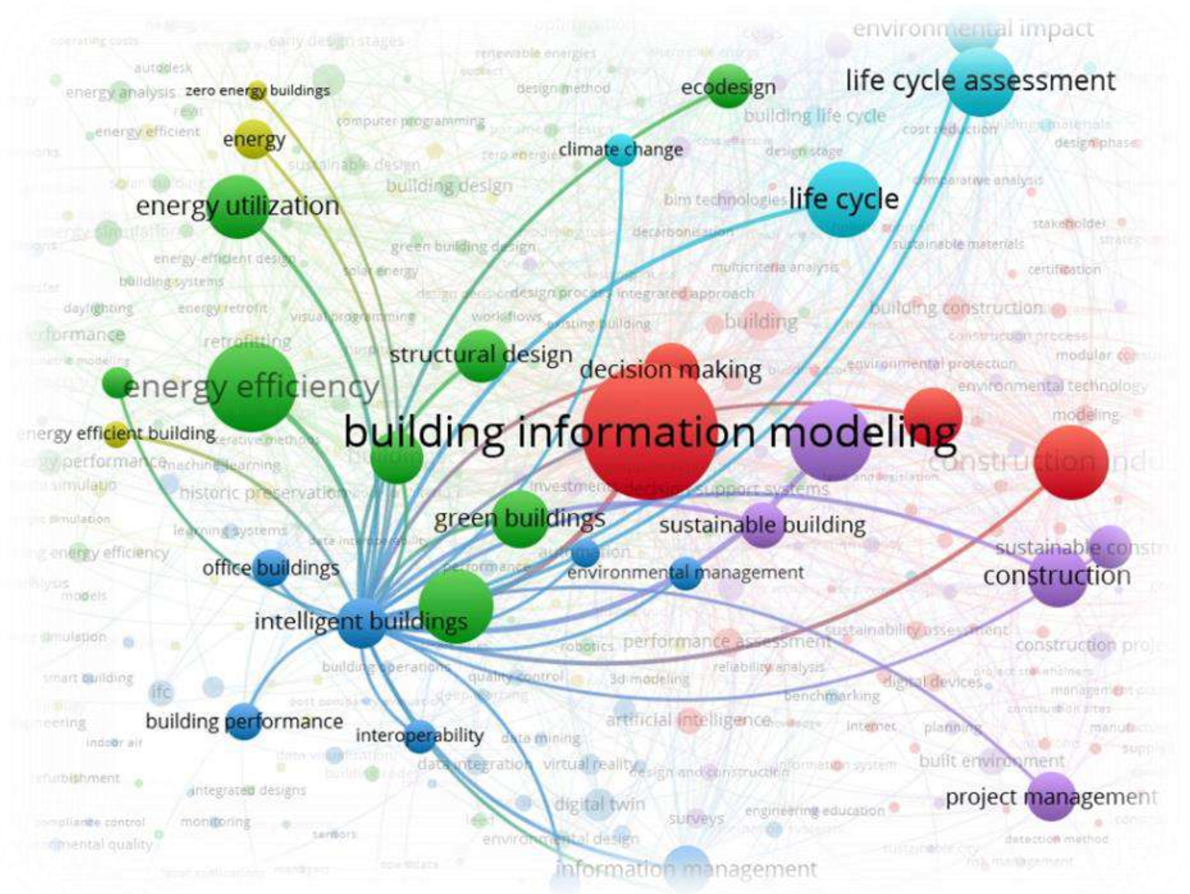
4.3 Intelligent Buildings

The current industry trend centers on Intelligent Buildings (Tang et al., 2020), which utilize integrated technologies to enable real-time monitoring and advanced analytics for maintenance, occupant comfort, and energy efficiency. Within the co-occurrence network (Figure 8), this term exhibits strong correlations with the Internet of Things (IoT), energy efficiency, energy utilization, building performance, information management, and decision-making processes.

Figueiredo et al. (2021) presented an integrated framework for selecting sustainable building materials, combining BIM, Life Cycle Sustainability Assessment (LCSA), and Fuzzy-AHP. The approach was illustrated using a 10-story residential building, employing a “cradle-to-grave” scope that encompassed construction, operation, maintenance, and end-of-life.

Environmental, economic, and social criteria were evaluated. Revit and Tally were utilized to assist with quantity takeoff, energy modeling, and environmental impact assessment. The final ranking of the four material alternatives was obtained using Fuzzy-AHP, with the best option corresponding to the lowest overall weight.

Figure 8 – Intelligent buildings keyword network



Source: Authors, 2026, based on processing in VOSviewer.

Cheng et al. (2022) presented an integrated BIM-LCA approach to assess embodied environmental impacts throughout the life cycle of buildings. The methodology uses BIM to automate material quantity takeoff during the life cycle inventory phase. Applied to a reinforced concrete building, the approach considers the impacts associated with material production and transportation, on-site construction, demolition, and waste disposal. Based on the quantities extracted from the BIM model, 24 environmental impact factors are initially calculated and linked to 10 environmental issues, and are subsequently characterized, normalized, and quantified. The results indicate that the consumption of mineral resources, wood, and fossil fuels poses the most significant environmental challenges, while concrete, steel, and wood are the materials that contribute most to these impacts. Environmental performance depends heavily on the material production stage.

Arsiwala; Elghaish & Zoher (2023) proposed a Digital Twin solution to automate the monitoring and prediction of equivalent CO2 (eCO2) emissions in existing buildings by integrating IoT, BIM, and machine learning. The proposed architecture consists of four layers: the IoT system layer, responsible for data collection, transmission, and storage; the 3D digital model layer of the existing asset, reconstructed through surveying techniques (LiDAR/photogrammetry, for example); the data-model integration layer, which connects real-time readings to the digital model; and the data analytics layer, which uses machine learning to predict future emissions. The solution was demonstrated through a case study involving an apartment, in which sensors were installed in different rooms to monitor eCO2, TVOC, temperature, and relative humidity, with interactive 3D and dashboard-based visualization. The study highlights the synergy between BIM and IoT in creating a functional Digital Twin to support facility management and data-driven retrofit strategies.

Valinejadshoubi et al. (2021) proposed an automated BIM–IoT alert system for thermal comfort monitoring during building operation. The prototype integrates temperature and humidity sensors with a BIM model through a MySQL database and a Dynamo-based workflow, enabling real-time visualization and remote monitoring. In the case study, the system identified the time and location of thermal comfort and discomfort conditions based on predefined thresholds.

Tang et al. (2020) applied the IDM and MVD methodologies to define a subset of the IFC schema, called the BACnet MVD, to enable the representation and exchange of BACnet-compliant BAS information in IFC models. In a prototype test, the BACnet MVD was demonstrated using Revit for export and a web browser for import and visualization. The exported file was converted to ifcXML and displayed in the browser with CSS support, allowing the structured visualization of BAS information.

Table 11 summarizes the five most-cited studies from the last five years, identified using the search string BIM Terms AND "Intelligent buildings" within the Scopus database (Title, Abstract, and Keywords).

Table 11 – Most cited articles focused on Intelligent Buildings

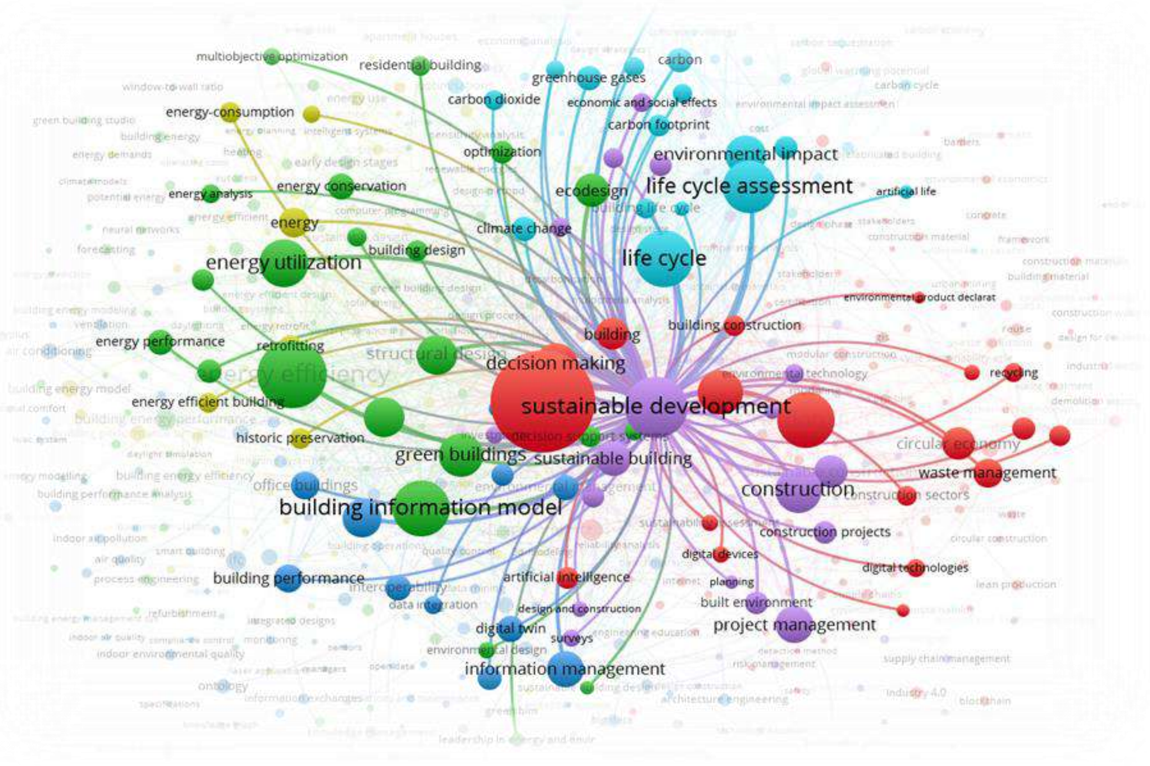
Ref.	Citations (Scopus)	Research Objective	Core Technologies	Application Phase
(Figueiredo et al., 2021)	181	Sustainable material selection through BIM-LCSA integration and multi-criteria decision-making.	BIM (Revit), LCSA, Fuzzy-AHP, Tally, Energy Modeling	Design Phase (Material Evaluation)
(Cheng et al., 2022)	156	Evaluation of embodied environmental impacts through BIM–LCA integration	BIM (Revit), LCA	Design Phase (Embodied Impact Assessment)
(Arsiwala; Elghaish; Zoher, 2023)	144	Digital Twin-based monitoring and prediction of CO_2-equivalent emissions in existing buildings	BIM (Revit), Digital Twin, IoT, Machine Learning	Operation & Facility Management
(Valinejadshoubi et al., 2021)	122	BIM–IoT-based real-time thermal comfort monitoring in buildings	BIM (Revit + Dynamo), IoT Sensors, MySQL, Cloud Collaboration	Operation (Environmental Monitoring)
(Tang et al., 2020)	114	Method for representing and exchanging BACnet-compliant BAS data in IFC using IDM/MVD	BIM, IFC, BACnet, IDM, MVD	BIM–BAS Interoperability

Source: Authors, 2026.

4.4 Sustainable Development

The term Sustainable Development serves as an "umbrella concept" encompassing various research fronts within the construction industry. This scope includes themes such as Life Cycle Assessment (LCA), waste management, green building certification, material reuse analysis, energy efficiency, and circular economy strategies, among others (Figure 9). Consequently, the literature associated with this term reflects a diverse range of methodologies aimed at mitigating environmental impacts across the design, construction, operation, and end-of-life phases.

Figure 9 – Sustainable development keyword network



Source: Authors, 2026, based on processing in VOSviewer.

Santos et al. (2020) proposed an automated BIM-based approach to integrate Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA). Their prototype tool, BIMEELCA, imports environmental, economic, and physical data from Excel spreadsheets into the BIM model, allowing automated life cycle analysis and visualization of impacts and costs by building element. The approach was demonstrated through a case study of an office building in the Netherlands.

Kaewunruen et al. (2021) presented a BIM-supported conceptual framework for the assessment of vulnerability and risk-based maintenance planning for bridges exposed to extreme conditions. The study highlights the potential of combining BIM modeling, inspection data, monitoring data, and structural simulations to support the identification of internal, natural, and human risks, as well as decision-making regarding inspection and maintenance.

Honic et al. (2021) demonstrated the application of the Material Passport (MP) method to an existing building at the end-of-life stage, evaluating its potential for recycling. To compile the MP, they combined laser scanning to capture the building geometry with demolition acquisition (DA) and urban mining assessment (UMA) to characterize the materials. Based on the enriched BIM model, element and material lists were exported and mapped to recycling rates and environmental indicators. In the case study, the recycling potential was approximately 52% for the external walls and 20% for the foundation.

Jalaei; Jalaei & Mohammadi (2020) presented an integrated BIM–LEED methodology to automate the sustainability assessment of buildings during the conceptual design phase. The authors developed a Revit plug-in that uses BIM model data, simulations, and geographic information to calculate potential LEED credits. For credits that cannot be directly obtained from project data, the tool employs a machine learning method to estimate the missing scores. The approach enables the calculation of the project's cumulative potential score across different LEED categories at the early design stage.

Atta; Bakhoum & Marzouk (2021) developed a Material Passport (MP) tool with three quantitative sustainability indicators, namely deconstructability score, recovery score, and environmental score, to support the evaluation and comparison of construction alternatives. The MP was digitalized in a BIM environment using Autodesk Revit and Dynamo, allowing the automated calculation of the indicators as well as the storage and sharing of information. In the case study, a traditional residential building was compared with modular alternatives, showing that the modular solution with dry connections achieved the best results in terms of deconstructability, recovery, and environmental performance. Additionally, the modular solution with wet connections outperformed the traditional alternative in some indicators.

Table 12 summarizes the five most-cited studies from the last five years, identified using the search string BIM Terms AND "Sustainable development" within the Scopus database (Title, Abstract, and Keywords).

Table 12 – Most cited articles focused on sustainable development

Ref	Citations (Scopus)	Research Objective	Core Technologies	Application Phase
(Santos et al., 2020a)	142	Automated BIM-based evaluation of life cycle environmental impacts and costs	BIM (Revit), BIMEELCA Prototype Tool	Design Phase (LCA and LCC Assessment)
(Kaewunruen et al., 2021)	134	Vulnerability assessment and risk-based maintenance planning for bridges under extreme conditions	BIM, Digital Twin Concept	Bridge O&M (Operation Phase)

(Honic et al., 2021)	131	Implementation of the Material Passport method for an existing end-of-life building to assess recycling potential and environmental impacts	BIM, Laser Scanning/Point Cloud, Demolition Acquisition, Urban Mining Assessment	End-of-Life / Pre-demolition (Circular Economy)
(Jalaei; Jalaei; Mohammadi, 2020)	118	Automated sustainability assessment by calculating and estimating LEED credits during the conceptual design phase	BIM (Revit), Revit API, Google Maps API, Machine Learning, Energy/Daylight Simulation	Conceptual Design (LEED Pre-certification)
(Atta; Bakhoum; Marzouk, 2021)	118	Digitization of a Material Passport to assess sustainability through deconstructability, recovery, and environmental indicators	BIM (Revit), Dynamo, OpenLCA, ecoinvent	Design Phase (Sustainability Assessment)

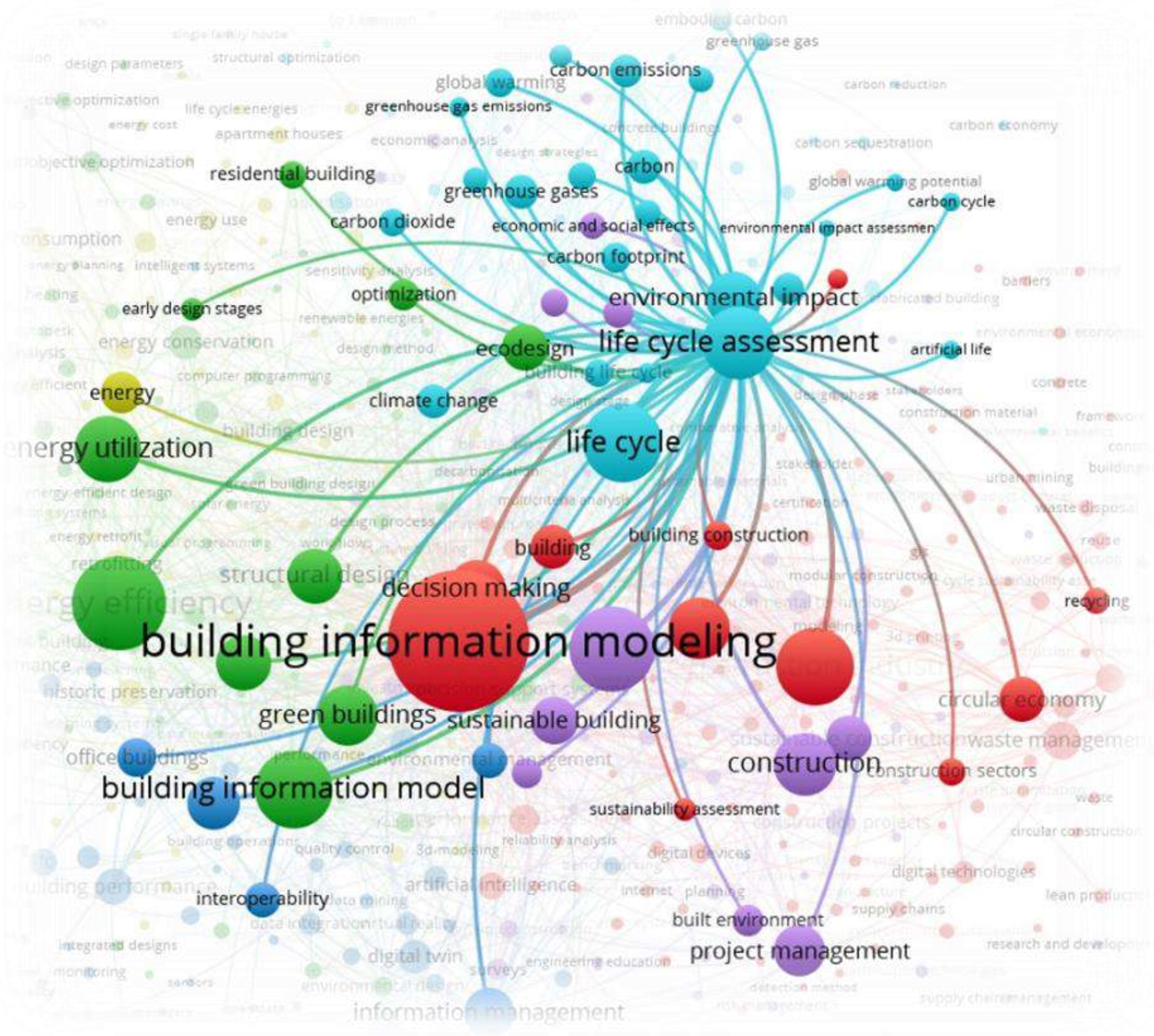
Source: Authors, 2026.

4.5 Life Cycle Assessment (LCA)

As a core term within the cyan cluster, Life Cycle Assessment (LCA) appears extensively integrated with BIM (Figure 10). BIM plays a pivotal role in the Life Cycle Inventory (LCI) stage, enabling the extraction of material and component quantities with high precision. This integration significantly reduces manual entry errors and automates critical phases of the assessment process, transforming the BIM model into a rich data repository for environmental impact calculations.

Hao et al. (2020) developed an integrated BIM-LCA approach to estimate the reduction of carbon emissions in prefabricated building projects during the materialization phase. The method considers emissions associated with material production, transportation, and on-site construction, based on emission factors for materials and energy sources. Applied to a public building in China with a 50% adoption of prefabricated components, the approach utilized BIM to automate quantity takeoff, and the resulting quantities served as the basis for calculating emissions across the different stages. The results indicated that prefabrication can reduce carbon emissions by approximately 15%, mainly due to greater production accuracy and reduced waste.

Figure 10 – Life Cycle Assessment keyword network



Source: Authors, 2026, based on processing in VOSviewer.

Hollberg; Genova & Habert (2020) combined BIM and LCA to assess embodied Global Warming Potential (GWP) throughout the design process of a real building. The approach links BIM model materials to LCA data and uses Dynamo to calculate embodied impacts based on quantities extracted from the model. By analyzing 34 model states, the authors found that embodied GWP during design reached up to twice the final building value, mainly due to the use of placeholder materials and simplified modeling in the early stages. To reduce this overestimation, the study proposes the use of predefined components, simplified surface area-based methods, and automatic assumptions for temporary materials in BIM-LCA tools.

Feng et al. (2020) evaluated renovation and reconstruction strategies for old single-family houses through a scenario-based BIM-LCA approach. Revit was used for material quantity takeoff, SimaPro for embodied emissions, and HOT2000 for operational simulations. The results showed that the embodied emissions of the reconstruction scenarios were 5 to 6 times higher than those of the renovation scenarios. Renovation strategies reduced operational emissions according to the level of retrofit. Among the alternatives analyzed, the Passivhaus reconstruction scenario performed best in terms of life-cycle emissions. The study highlights the importance of balancing embodied and operational emissions when choosing between renovation and reconstruction.

Kaewunruen; Peng & Phil-Ebosie (2020) utilised a BIM-based approach to assess the life-cycle cost and carbon footprint of the Dadongmen subway station in China. The results showed that the operation and maintenance phase accounts for approximately 67% of total carbon emissions, while material production contributes approximately 23%. The construction phase accounts for about 78% of the total life cycle cost. The study also compares retrofit alternatives in terms of cost and carbon footprint.

Santos et al. (2020) developed a tool integrated into the BIM environment to support Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). The tool automatically creates shared parameters in the model, which are used in the LCA and LCC analyses. Validated in a multi-story building, the tool reads the physical elements of the model, extracts quantities of elements and materials, integrates environmental, economic, and physical information, and performs streamlined and complete analyses. The results are integrated into the model elements, and the tool enables the generation of color-coded 3D visualizations within the BIM environment to highlight the elements with the highest impacts.

Table 13 summarizes the five most-cited studies from the last five years, identified using the search string BIM Terms AND "Life cycle assessment" within the Scopus database (Title, Abstract, and Keywords).

Table 13 – Most cited articles focused on Life Cycle Assessment

Ref.	**Citations (Scopus)**	**Research Objective**	**Core Technologies**	**Application Phase**
(Hao et al., 2020)	255	Evaluate the carbon reduction potential of prefabrication during the materialization phase through a BIM-supported LCA approach	BIM, LCA, Automated Quantity Takeoff	Design Phase (Carbon Assessment)
(Hollberg; Genova; Habert, 2020)	241	Analyze embodied GWP variations throughout the iterative BIM-based design process	BIM (Revit), LCA, Dynamo, KBOB database	Design Phase (Conceptual to Detailed)
(Feng et al., 2020)	110	Compare renovation and reconstruction scenarios based on life cycle GHG emissions	BIM (Revit), LCA (SimaPro + Ecoinvent), Energy Simulation (HOT2000)	Residential Retrofit & Reconstruction
(Kaewunruen; Peng; Phil-	107	Lifecycle carbon and cost assessment for infrastructure,	BIM (Revit, Navisworks), Life	Infrastructure O&M and

Ebosie, 2020)		comparing retrofit alternatives	Cycle Cost and Carbon Assessment	Retrofit Decision Support
(Santos et al., 2020)	108	Develop a BIM-integrated tool for simultaneous LCA and LCC	BIM (Revit), Revit API, C#, BIMEELCA, Ecoinvent	Design Phase (Environmental and Economic Lifecycle Assessment)

Source: Authors, 2026.

5 DISCUSSIONS

5.1 Bibliometric and Thematic Analysis

The bibliometric analysis underscores the growing academic interest in BIM-based methodologies designed to enhance sustainability within the construction and facility management industries. The most influential and collaborative nations are largely those that pioneered BIM adoption policies and lead in infrastructure innovation. For instance, in the United Kingdom, the NBS Report (2020) indicates that BIM awareness and usage surged from 13% in 2011 to 73% in 2020—a 60-percentage-point increase (NBS, 2020).

In the Latin American context, Brazil emerges as the most influential nation, driven by recent institutional initiatives such as the National BIM Dissemination Strategy (2018) and the New Tendering Law (No. 14.133/2021), which establishes a preferential mandate for BIM in public engineering works and services.

Furthermore, the keyword co-occurrence network synthesizes critical sustainability-related BIM applications, as detailed below:

- **Energy Efficiency**: Encompasses studies utilizing BIM for energy simulation during early design stages, facilitating the comparison of architectural and construction alternatives. Research also investigates energy performance monitoring during the operational phase.
- **Intelligent Buildings**: Involves structures equipped with sensors and interconnected systems. When integrated with digital models, these buildings serve as the physical counterpart of a Digital Twin, enabling continuous visualization and monitoring.
- **Life Cycle Assessment (LCA)**: Extensively integrated with BIM to evaluate environmental impacts and support sustainable material selection. BIM is particularly effective in the Life Cycle Inventory (LCI) stage by automating quantity take-offs and centralizing data critical for analysis.
- **Waste Management**: Covers strategies such as recycling and reuse planning, automated quantification, and demolition scheduling. Research also explores material

recycling potential based on construction characteristics, such as the use of dry connections, which significantly enhance reuse possibilities (Atta; Bakhoum; Marzouk, 2021).

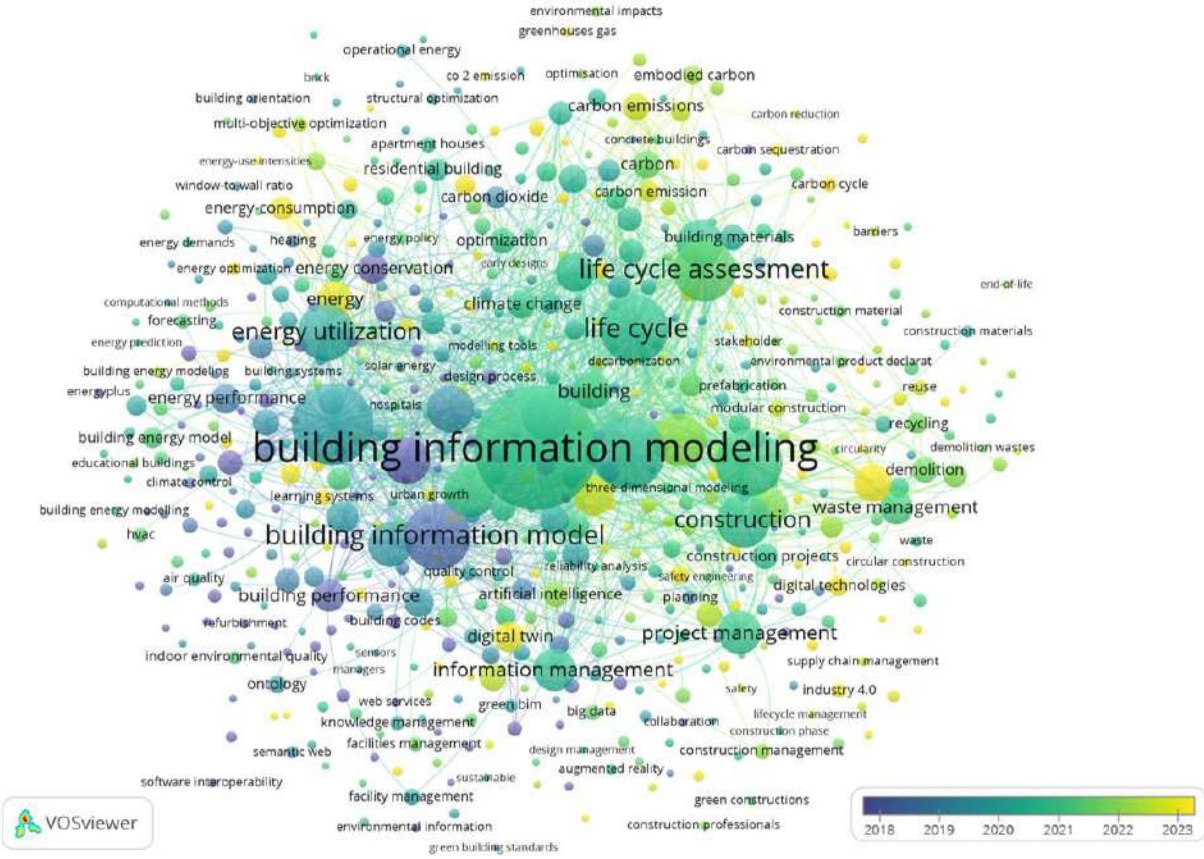
These domains reflect the multifaceted applications of BIM within the sustainability agenda and reinforce its role as a fundamental technology supporting the Architecture, Engineering, Construction, and Operation (AECO) industry.

Based on the thematic analysis and citation metrics, Life Cycle Assessment research garners the highest academic impact, followed by Energy Efficiency, Intelligent Buildings, Sustainable Development, and Waste Management. Despite increasing cross-disciplinary integration, the synergy between BIM, LCA, and energy performance analysis remains the most robust research frontier.

5.2 Trending Topic: Digital Twin

The primary "trending topic" identified in the bibliometric analysis is the Digital Twin (DT). This trend is corroborated by the temporal distribution shown in Figure 11, where DT appears as the most prominent recent term. This shift indicates not only the current focus of the scientific community but also the strategic direction toward which the construction and asset management industries are evolving—moving from static models to dynamic, real-time digital representations.

Figure 11 – Keywords temporal distribution



Source: Authors, 2026, based on processing in VOSviewer.

The primary function of a DT is to support facility management across various application domains. Of the 25 studies analyzed in depth, five implemented DT methodologies. It is noteworthy that, following the selection criteria, most of these studies were published between 2020 and 2021—the period during which the term began to gain significant momentum in the AECO sector.

Several authors have demonstrated this trend: Hosamo et al. (2022) applied DT for the predictive maintenance of Air Handling Units (AHUs); Zaballos et al. (2020) focused on environmental comfort monitoring; and Kang et al. (2022) explored the potential for intelligent demolition waste management. Furthermore, Arsiwala et al. (2023) utilized a DT approach for the predictive monitoring of CO_2 equivalent emissions in existing buildings, while Kaewunruen et al. (2021) proposed a conceptual framework for vulnerability assessment and risk-based maintenance of infrastructure.

Beyond these, the literature expands DT applications into structural health. Fawad et al. (2025) developed a platform for the real-time monitoring and visualization of Structural Health Monitoring (SHM) data in bridges. Nhamage (2023) proposed a DT for fatigue assessment in steel railway bridges, combining structural analysis with BIM. Adibfar & Costin (2022) created a DT of a bridge mockup, integrating data from a Weigh-In-Motion (WIM) system to monitor and issue alerts regarding overweight vehicles.

These works underscore that the creation of a DT depends on the continuous transfer of sensor data to a virtual model, enabling dynamic monitoring of the physical asset. According to Tao et al. (2019), a Digital Twin is composed of five core dimensions: the physical entity, the virtual entity, connections, data, and services. The physical entity serves as the foundation for the virtual counterpart, which digitally represents the real object. The connections facilitate information exchange and data control, while the DT must provide services such as simulation, monitoring, control, and decision support (Jiang et al., 2021).

The comparison between BIM and DT, as outlined by Jiang et al. (2021), highlights three key aspects: (i) both utilize a virtual model; (ii) DT presupposes the existence of a physical counterpart, whereas BIM does not. (iii) BIM can represent non-existent or unbuilt elements, while a DT must mirror the real-time state of the physical asset. A frequently associated concept is as-is BIM; however, a Digital Twin distinguishes itself by emphasizing the live connection with the physical object—a characteristic that BIM, even in its as-is state, does not inherently possess (Jiang et al., 2021).

5.3 Level of Development and the Evolution of Information Requirements

Analysis of the selected literature suggests that the level of geometric and informational development of BIM elements can strongly influence the reliability of embodied environmental assessments. Variations in model maturity may significantly distort results, as demonstrated by Hollberg et al. (2020). Their study showed that embodied environmental impacts estimated during early design stages could reach up to twice the final building values, mainly due to placeholder materials and simplified modeling assumptions.

Reliable BIM-based analyses require model elements with adequate informational granularity. Studies consider LOD 300 or LOD 400 appropriate for simulations and performance assessments. Most literature utilizes the LOD scale developed by the American Institute of Architects (AIA, 2008), subsequently disseminated through BIMForum specifications (BIMForum, 2025).

Despite its wide use, LOD is not an "umbrella term" for all BIM informational requirements. Created as a collaboration protocol, LOD expresses element reliability, indicating the extent of a component's development by its author to align expectations among stakeholders. As noted by Abualdenien & Borrmann (2022) and Bolpagni (2016), various derivative terms and protocols have emerged, often with inconsistencies regarding original guidelines. Common misconceptions include assigning a single LOD to an entire model—whereas LOD must be specified per element—and directly linking it to project phases, ignoring that different elements may possess distinct development levels within the same stage.

Diverse interpretations and the lack of a clear standard for specifying information led ISO 19650 to introduce the Level of Information Need concept (UK BIM FRAMEWORK, 2022). Unlike LOD, this concept is not structured in levels but is based on principles that guide the appropriate informational granularity for a specific purpose. Its primary objective is to prevent both data oversupply and data deficiency. It is recommended that the term not be abbreviated to avoid improper associations with established concepts (ISO 7817-1, 2024).

The Level of Information Need encompasses geometric, alphanumeric, and documentation definitions. In the 2024 BIMForum LOD Specification (BIMForum, 2025), LOD and Level of Information Need are described as complementary resources: while LOD aids in specifying geometric and graphical requirements (detail, dimensionality, location, appearance, and authorship), Level of Information Need establishes the broader set of information required for a specific model use. Consequently, LOD is integrated into the Level of Information Need.

From this perspective, defining clear information requirements becomes essential to ensure that BIM models contain consistent and usable data. Data standardization, availability, and quality are critical factors frequently highlighted in studies involving BIM-extracted information. It is indispensable to specify clear information requirements based on intended BIM uses to ensure the model contains sufficient and appropriate information. Furthermore, standardizing nomenclature is essential for facilitating data verification and localization.

The Information Delivery Specification (IDS), developed by buildingSMART International, is prominent in this context. Described as the standard for defining and verifying the Level of Information Need (BuildingSMART International, 2022), IDS specifies how objects, classifications, materials, and properties must be delivered in an IFC model (BuildingSMART, 2025). The methodology is based on a report that compiles information exchange requirements and a computer-interpretable file, enabling automated verification of model data.

Ensuring the availability and informational quality of a BIM model depends on four fundamental factors: (i) the use of open standards to ensure long-term information maintenance, notably IFC, recognized as a means to achieve interoperability (Lee; Eastman; Solihin, 2018); (ii) the clear definition of information requirements; (iii) data standardization; and (iv) automated verification of model content.

In this context, a conceptual framework consisting of four blocks was developed to guide the creation of BIM models with appropriate informational quality. This structure is not exhaustive and aims to support BIM model construction within the scope of information exchange requirements. Table 14 presents the function assigned to each block, while Figure 12 illustrates the conceptual structure.

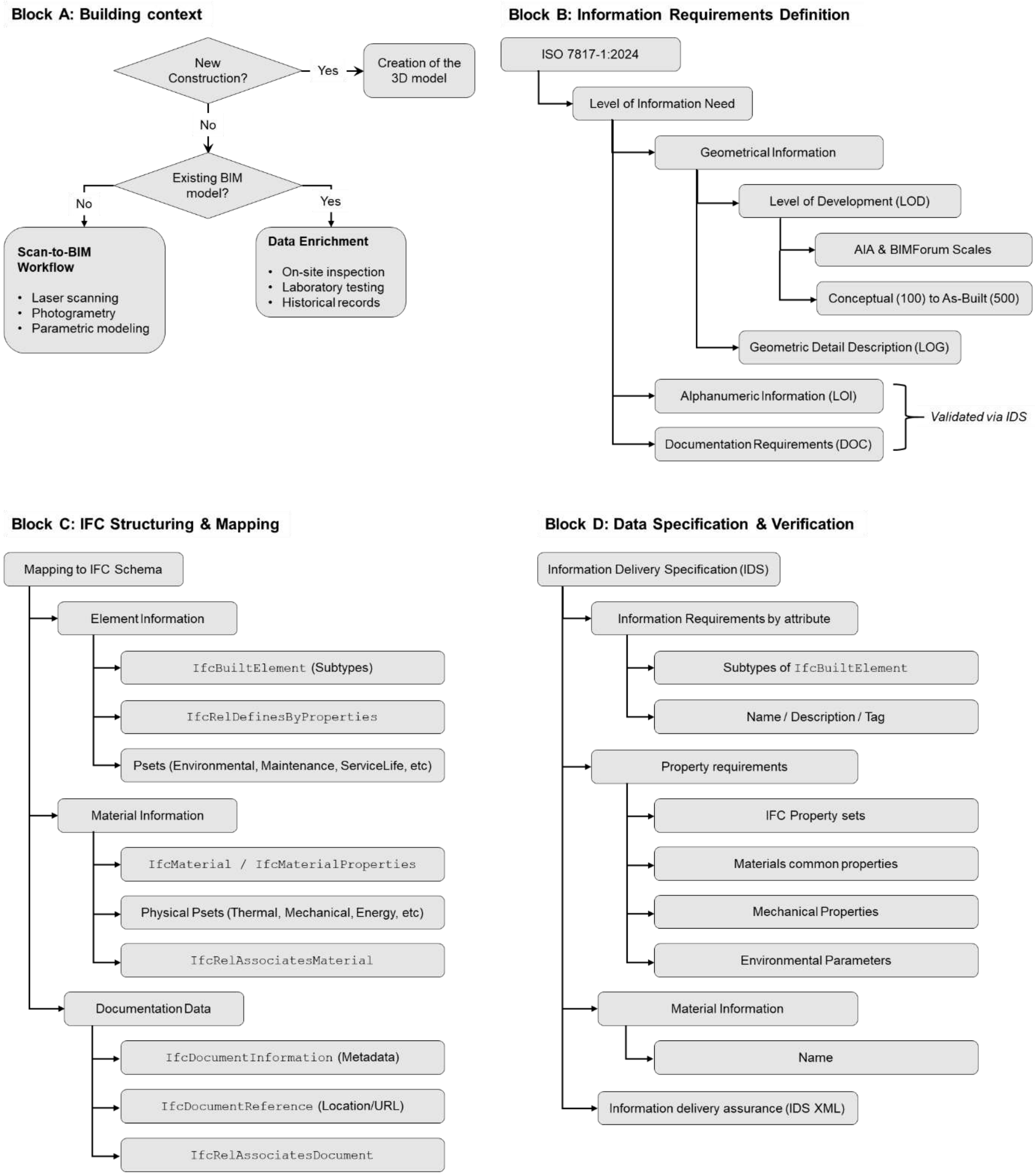
Table 14 – Idealization of the structure

Block	**Question Addressed**
A	Where does the BIM model originate?
B	What information is required and at what level?
C	How is this information structured within the IFC?
D	How is it verified and delivered?

Source: Authors, 2026.

Block A, building context, represents the starting scenarios for BIM model creation, distinguishing between new and existing buildings. For new buildings, the BIM model is developed directly from the design. For existing buildings, the workflow considers the verification of a previous BIM model; when nonexistent, digital reconstruction is performed using reality capture techniques such as laser scanning, photogrammetry, segmentation techniques, and parametric modeling. Examples of studies applying these techniques can be found in references (Alshawabkeh; Baik; Miky, 2021; Bassier; Vergauwen, 2020; Croce et al., 2021; Justo et al., 2021; Qin et al., 2021; Rodriguez Polania et al., 2025; Tang et al., 2022). With the existing building model created, on-site inspections and laboratory tests are used to obtain information on material composition and characteristics, aiming to enrich the model with relevant information.

Figure 12 – Conceptual structure for information creation, structuring and verification in BIM models



Source: Authors, 2026.

In Block B, the application of Level of Information Need principles and concepts is considered for specifying the necessary BIM model information. Geometric information, including shape, location, appearance, and dimensionality, can be defined based on the BIMForum LOD scale (BIMForum, 2025) or through textual descriptions, depending on the analysis purpose. Alphanumeric and documentation information can be specified and verified through IDS, which allows for the formalization of requirements for attributes, properties, classifications, and documents associated with model elements.

Block C, regarding IFC structuring and mapping, covers, in a non-exhaustive manner, the different types of data that can be represented through the IFC schema. Element information refers to common properties of IfcBuiltElement entity subtypes. These properties can be associated with their respective subtypes through the IfcRelDefinesByProperties relationship, using property sets (IfcPropertySet).

Examples of official IFC Property Sets (Psets) in this category include Pset_EnvironmentalCondition, Pset_EnvironmentalImpactIndicators, Pset_EnvironmentalImpactValues, Pset_InstallationOccurrence, Pset_MaintenanceStrategy, and Pset_ServiceLife. Each Pset is composed of properties with specific names, property types, and defined data types. For example, Pset_EnvironmentalImpactIndicators includes properties related to environmental indicators, such as TotalPrimaryEnergyConsumptionPerUnit, WaterConsumptionPerUnit, HazardousWastePerUnit, and NonHazardousWastePerUnit.

Considering that IFC 4.3 is available in the buildingSMART Data Dictionary (bSDD), model enrichment with these definitions can be facilitated by software tools that promote bSDD data distribution, such as usBIM.bSDD, BlenderBIM, and Revit plugins (bSI, 2025).

In addition to properties associated with elements, the IFC also includes specific property sets for materials. In IFC, a material definition is represented by the IfcMaterial entity. Properties are linked to material definitions through the IfcMaterialProperties entity. A material definition, characterized by its name (IfcMaterial.Name) and category (IfcMaterial.Category), can be associated with IFC objects, such as subtypes of IfcBuiltElement, via the IfcRelAssociatesMaterial relationship. Examples of official Psets for materials include Pset_MaterialCommon, Pset_MaterialEnergy, Pset_MaterialFuel, Pset_MaterialMechanical, and Pset_MaterialConcrete.

Based on the authors' experience, the use of custom property sets to represent information that could otherwise be described by official IFC Psets is a recurring practice. This practice can occur either by user initiative or due to limitations and configurations within the authoring software itself, which may export data in custom sets. The ability to create personalized Psets is an essential feature of the IFC schema, ensuring its flexibility and extensibility, as highlighted by Khemlani (2004); that is, this functionality allows for the representation of data not formally provided for in the schema.

However, the indiscriminate use of custom property sets can result in interoperability problems, difficulties in tracking information, and potential data loss. For this reason, it is recommended to prioritize, whenever possible, the use of official IFC Psets to ensure the standardization and traceability of information. This practice favors, for example, structural analyses (Pset_MaterialMechanical), maintenance planning (Pset_MaintenanceStrategy), equipment monitoring (Pset_ServiceLife, Pset_EnvironmentalImpactValues), and environmental analyses (Pset_EnvironmentalImpactIndicators), highlighting the need for rigorous control of IFC parameters based on project requirements.

Also within Block C, documentation information is included, which may cover calculation memorials, maintenance manuals, commissioning manuals, photographic records, and quality control reports, among others. Ensuring access to these documents over time is essential. In some of the studied articles, the building's history is used as a data source to enrich the BIM model.

In the IFC schema, the IfcDocumentReference entity can be used to store a document's location (IfcDocumentReference.Location). Furthermore, through its ReferencedDocument attribute, it is possible to associate metadata such as revision, ownership, and the purpose of the document using the IfcDocumentInformation entity. The association between documents and IFC objects is carried out by the IfcRelAssociatesDocument relationship, which can occur at a global level—for instance, associated with IfcProject or subtypes of IfcFacility—or at a more specific level, linking documents to individual model elements.

Finally, Block D refers to the specification and verification of data contained within the BIM model. In many workflows, information verification is performed through IFC viewers, adopting a predominantly visual approach. However, a critical aspect of this strategy relates to the suitability of the tool used, as some viewers may display data that others do not.

Information associated directly with constructive elements through the IfcRelDefinesByProperties relationship tends to have lower coding complexity and is therefore displayed relatively easily by most IFC viewers. Conversely, material information involves a more complex level of coding, which can compromise its visualization and interpretation.

In the case of materials, properties are defined and linked as a set to a material definition (IfcMaterial) via the IfcMaterialProperties entity. Subsequently, the material definition, containing associated properties, is related to the constructive elements through the IfcRelAssociatesMaterial relationship. This chain of relationships makes verification more susceptible to interpretation failures by the tools. For this reason, material data is often reported in IFC parameters that lack appropriate semantics, contrary to the principles of interoperability. Data loss associated with interoperability issues is a recurring research topic and is generally considered one of the challenges of BIM. The interoperability level assessment proposed in Teixeira et al. (2024) for information exchange helps quantify the success of data exchange between different tools, based on weights assigned to the necessary data requirements. This type of approach contributes to a more objective evaluation of the quality of information exchange in BIM workflows.

5.4 BIM Capability – Support for Analysis

In the research analyzed, the Autodesk Revit software is widely utilized. One factor explaining this dominance is its associated programming interface, Dynamo, which enables task automation and script creation without traditional coding, as observed in studies Zaballos et al. (2020), Valinejadshoubi et al. (2021), Atta et al. (2021), and Hollberg et al. (2020).

Academic research has explored BIM applications requiring a high level of development, compatible at least with Stage 2 of Succar's BIM capability scale (Succar, 2010). At this level, the use of BIM tools is consolidated, characterized by a higher degree of multidisciplinary collaboration and the exchange of models via proprietary or open formats, such as IFC.

Stage 3 of BIM capability introduces more advanced functionalities. At this stage, models become integrated, semantically rich, and collaboratively maintained throughout the entire project lifecycle. They enable complex analyses during early design phases, alongside more robust simulations and virtual construction. In this phase, model information products move beyond the semantic properties of objects, incorporating business intelligence, lean construction principles, sustainability guidelines, and life cycle cost analysis (Succar, 2010).

This panorama reinforces the need for design firms, companies, and public agencies to modernize by upgrading technological resources, training teams, investing in certified BIM tools, refining internal processes, and adopting open standards like IFC.

6 FINAL CONSIDERATIONS

This article examined the application of BIM as a support for sustainable and eco-efficient development in the construction industry. Based on the research criteria, China, the United Kingdom, and the United States were found to be the most influential and collaborative countries on the subject—a result justified by their pioneering role in adopting and promoting BIM. Furthermore, among the keywords tested, those returning the highest number of documents were: energy efficiency, green building, life cycle assessment, building performance, sustainable construction, and circular economy. The co-occurrence network revealed that relevant themes include life cycle assessment, smart buildings, waste management, energy utilization, and construction management and performance. These topics align with the recommendations of the Global Status Report for Buildings and Construction

2024/2025, which highlights these domains as priorities for improving the sector's environmental performance. Notably, research focused on energy efficiency and building performance is among the most significant.

The study also identified Digital Twin as the current trending topic—a model that enables real-time visualization and monitoring of data from sensors installed in buildings. Its primary function is to facilitate more effective facility management, including tracking building systems, monitoring environmental parameters, and continuously evaluating performance. This approach represents a clear trend for the future of construction management.

Another point of extreme relevance is the availability and quality of BIM model data. For reliable analysis, the model must contain sufficient information and elements with an appropriate level of development. Thus, its creation must be supported by collaboration and communication protocols that allow for the clear specification of information requirements, such as the Level of Information Need and the IDS standard, which provides means to specify and automatically verify data delivered in an IFC model.

This study presented a conceptual framework for the creation, structuring, and verification of data in BIM models, aiming for information organization, long-term maintenance, and guaranteed traceability and interoperability. These objectives are supported by the proper use of IFC, prioritizing formal definitions—especially official property sets—over the indiscriminate use of custom sets. Such an approach requires extensive mapping of IFC data to allow for the correct definition and specification of information requirements. Data verification can be performed through manual approaches using IFC viewers or automated approaches, which offer greater efficiency and reliability.

Finally, it is worth highlighting that the studies analyzed presuppose a level of maturity characterized by open standards, high-fidelity models, and collaborative workflows. This reinforces the need for investments in technological resources and in the training of professionals. Beyond these aspects, the advancement towards higher levels of BIM capability—particularly Stage 3, which presupposes fully integrated, interoperable, and data-rich models—also depends on the robustness of software support for open standards such as IFC.

Interoperability issues represent a challenge to achieving advanced BIM maturity. Encouraging software certification in relation to IFC and its latest versions is crucial for ensuring more consistent data exchanges. In general, the transition to a more sustainable and data-driven construction industry will require the consolidation of a BIM ecosystem in which standards, processes, and technological resources evolve in a coordinated manner to fully exploit the potential of the BIM methodology.

REFERENCES

ABD EL-HAMEED, Ahmed K. Digital technologies as supporting tools for resource circularity in the construction industry: A review reflecting on the building lifecycle. **Journal of Building Engineering**, v. 114, p. 114420, 15 nov. 2025.

ABUALDENIEN, Jimmy; BORRMANN, André. Levels of detail, development, definition, and information need: a critical literature review. **Journal of Information Technology in Construction**, v. 27, p. 363–392, 19 abr. 2022.

ADIBFAR, Alireza; COSTIN, Aaron M. Creation of a Mock-up Bridge Digital Twin by Fusing Intelligent Transportation Systems (ITS) Data into Bridge Information Model (BrIM). **Journal of Construction Engineering and Management**, v. 148, n. 9, p. 04022094, 13 set. 2022.

AHMADI, Leila *et al.* Enhancing Circularity in the Building Industry: A Review of Material Passports and Digital Twin Technologies. **Journal of Construction Engineering and Management**, v. 152, n. 2, p. 03125012, 17 fev. 2026.

AIA. **Building Information Modeling Protocol Exhibit**. The American Institute of Architects, , 2008.

ALSHAWABKEH, Yahya; BAIK, Ahmad; MIKY, Yehia. Integration of Laser Scanner and Photogrammetry for Heritage BIM Enhancement. **ISPRS International Journal of Geo-Information 2021, Vol. 10,** v. 10, n. 5, 7 maio 2021.

ARSIWALA, Arva; ELGHAISH, Faris; ZOHER, Mohammed. Digital twin with Machine learning for predictive monitoring of CO2 equivalent from existing buildings. **Energy and Buildings**, v. 284, p. 112851, 1 abr. 2023.

ASIF, Muhammad; NAEEM, Ghinwa; KHALID, Muhammad. Digitalization for sustainable buildings: Technologies, applications, potential, and challenges. **Journal of Cleaner Production**, v. 450, p. 141814, 15 abr. 2024.

ATTA, Islam; BAKHOUM, Emad S.; MARZOUK, Mohamed M. Digitizing material passport for sustainable construction projects using BIM. **Journal of Building Engineering**, v. 43, p. 103233, 1 nov. 2021.

AZIMINEZHAD, Mohamadmahdi; TAHERKHANI, Roohollah. BIM for deconstruction: A review and bibliometric analysis. **Journal of Building Engineering**, v. 73, p. 106683, 15 ago. 2023.

BANIHASHEMI, Saeed *et al.* Circular economy in construction: The digital transformation perspective. **Cleaner Engineering and Technology**, v. 18, p. 100715, 1 fev. 2024.

BASSIER, Maarten; VERGAUWEN, Maarten. Unsupervised reconstruction of Building Information Modeling wall objects from point cloud data. **Automation in Construction**, v. 120, p. 103338, 1 dez. 2020.

BIMFORUM. **Level of Development (LOD) Specification – BIM Forum**. Disponível em: <https://bimforum.org/resource/lod-level-of-development-lod-specification/>. Acesso em: 2 dez. 2025.

BOLPAGNI, Marzia. **The Many Faces of 'LOD'**. Disponível em: <https://www.bimthinkspace.com/2016/07/the-many-faces-of-lod.html>. Acesso em: 25 fev. 2023.

BOUHMOUD, Hanane; LOUDYI, Dalila; GIORDANO, Andrea. BIM-driven transformation of waste management toward enhanced reduction and circularity in the built environment. **Waste Management**, v. 207, p. 115105, 1 out. 2025.

BSI. **buildingSMART Data Dictionary - buildingSMART International**. Disponível em: <https://www.buildingsmart.org/users/services/buildingsmart-data-dictionary/>. Acesso em: 15 dez. 2025.

BUILDINGSMART. **Information Delivery Specification - buildingSMART International**. Disponível em: <https://www.buildingsmart.org/standards/bsi-standards/information-delivery-specification-ids/>. Acesso em: 28 maio. 2025.

BUILDINGSMART INTERNATIONAL. **Information Delivery Specification IDS - buildingSMART Technical**. Disponível em: <https://technical.buildingsmart.org/projects/information-delivery-specification-ids/>. Acesso em: 4 jun. 2025.

CESPEDES-CUBIDES, Andres Sebastian; JRADI, Muhyiddine. A review of building digital twins to improve energy efficiency in the building operational stage. **Energy Informatics 2024 7:1**, v. 7, n. 1, p. 11-, 26 fev. 2024.

CHEN, Zhonghao *et al.* Recent Technological Advancements in BIM and LCA Integration for Sustainable Construction: A Review. **Sustainability 2024, Vol. 16,** v. 16, n. 3, 4 fev. 2024.

CHENG, Baoquan *et al.* Comprehensive assessment of embodied environmental impacts of buildings using normalized environmental impact factors. **Journal of Cleaner Production**, v. 334, p. 130083, 1 fev. 2022.

CICCOZZI, Annamaria *et al.* BIM to BEM for Building Energy Analysis: A Review of Interoperability Strategies. **Energies 2023, Vol. 16,** v. 16, n. 23, 28 nov. 2023.

CROCE, Valeria *et al.* From the Semantic Point Cloud to Heritage-Building Information Modeling: A Semiautomatic Approach Exploiting Machine Learning. **Remote Sensing 2021, Vol. 13,** v. 13, n. 3, p. 1–34, 27 jan. 2021.

EASTMAN, Chuck *et al.* **BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors**. 2° ed. *[S.l.]*: John Wiley & Sons, 2011.

EL-ABBASY, Ahmed A. Abdou. Artificial intelligence-driven predictive modeling in civil engineering: a comprehensive review. **Journal of Umm Al-Qura University for Engineering and Architecture 2025 16:4**, v. 16, n. 4, p. 1322–1345, 11 jul. 2025.

ERCAL, Orhan; SHAFIQUE, Muhammad. Rethinking net zero: A new perspective on achieving net zero energy buildings. **Sustainable Horizons**, v. 17, p. 100163, 1 mar. 2026.

FAWAD, Muhammad *et al.* Development of immersive bridge digital twin platform to facilitate bridge damage assessment and asset model updates. **Computers in Industry**, v. 164, p. 104189, 1 jan. 2025.

FENG, Haibo *et al.* BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia. **Journal of Cleaner Production**, v. 250, p. 119543, 20 mar. 2020.

FIGUEIREDO, Karoline *et al.* Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP. **Building and Environment**, v. 196, p. 107805, 1 jun. 2021.

GUERRA, Beatriz C.; LEITE, Fernanda; FAUST, Kasey M. 4D-BIM to enhance construction waste reuse and recycle planning: Case studies on concrete and drywall waste streams. **Waste Management**, v. 116, p. 79–90, 1 out. 2020.

HAO, Jian Li *et al.* Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach. **Science of The Total Environment**, v. 723, p. 137870, 25 jun. 2020.

HOLLBERG, Alexander; GENOVA, Gianluca; HABERT, Guillaume. Evaluation of BIM-based LCA results for building design. **Automation in Construction**, v. 109, p. 102972, 1 jan. 2020.

HONIC, Meliha *et al.* Material Passports for the end-of-life stage of buildings: Challenges and potentials. **Journal of Cleaner Production**, v. 319, p. 128702, 15 out. 2021.

HOSAMO, Haidar Hosamo *et al.* A Digital Twin predictive maintenance framework of air handling units based on automatic fault detection and diagnostics. **Energy and Buildings**, v. 261, p. 111988, 15 abr. 2022.

ISO 7817-1. **ISO 7817-1:2024 - Building information modelling — Level of information need — Part 1: Concepts and principles**. *[S.l.: S.n.]*. Disponível em: <https://www.iso.org/standard/82914.html>. Acesso em: 1 jun. 2025.

JALAEI, Farzad; JALAEI, Farnaz; MOHAMMADI, Sepehr. An integrated BIM-LEED application to automate sustainable design assessment framework at the conceptual stage of building projects. **Sustainable Cities and Society**, v. 53, p. 101979, 1 fev. 2020.

JAYASINGHE, Laddu Bhagya; WALDMANN, Daniele. Development of a BIM-Based Web Tool as a Material and Component Bank for a Sustainable Construction Industry. **Sustainability 2020, Vol. 12, Page 1766**, v. 12, n. 5, p. 1766, 27 fev. 2020.

JIANG, Feng *et al.* Digital twin and its implementations in the civil engineering sector. **Automation in Construction**, v. 130, p. 103838, 1 out. 2021.

JUSTO, Andrés *et al.* Scan-to-BIM for the infrastructure domain: Generation of IFC-compliant models of road infrastructure assets and semantics using 3D point cloud data. **Automation in Construction**, v. 127, p. 103703, 1 jul. 2021.

KAEWUNRUEN, Sakdirat *et al.* Digital Twin Aided Vulnerability Assessment and Risk-Based Maintenance Planning of Bridge Infrastructures Exposed to Extreme Conditions. **Sustainability 2021, Vol. 13, Page 2051**, v. 13, n. 4, p. 2051, 14 fev. 2021.

KAEWUNRUEN, Sakdirat; PENG, Shijie; PHIL-EBOSIE, Olisa. Digital Twin Aided Sustainability and Vulnerability Audit for Subway Stations. **Sustainability 2020, Vol. 12, Page 7873**, v. 12, n. 19, p. 7873, 23 set. 2020.

KANG, Kai *et al.* Building demolition waste management through smart BIM: A case study in Hong Kong. **Waste Management**, v. 143, p. 69–83, 15 abr. 2022.

KHAN, Abdul Mateen *et al.* BIM Integration with XAI Using LIME and MOO for Automated Green Building Energy Performance Analysis. **Energies 2024, Vol. 17,** v. 17, n. 13, 3 jul. 2024.

KHEMLANI, L. **The IFC Building Model: A Look Under the Hood** . Disponível em: <https://www.aecbytes.com/feature/2004/IFC.html>. Acesso em: 28 fev. 2023.

LEE, Yong Cheol; EASTMAN, Charles M.; SOLIHIN, Wawan. Logic for ensuring the data exchange integrity of building information models. **Automation in Construction**, v. 93, p. 388–401, 1 set. 2018.

LI, Sin Yi; WIDÉN, Joakim; SHADRAM, Farshid. Towards realizing life cycle net-zero energy/emissions (LCNZE) buildings: A systematic literature review. **Journal of Building Engineering**, v. 114, p. 114387, 15 nov. 2025.

MOHAMED, Menna allah T. *et al.* Efficiency of utilizing building information modeling tools for examining smart materials behavior in a hot climate. **Journal of Building Engineering**, v. 87, p. 108924, 15 jun. 2024.

MOSTERT, Clemens *et al.* Climate and resource footprint assessment and visualization of recycled concrete for circular economy. **Resources, Conservation and Recycling**, v. 174, p. 105767, 1 nov. 2021.

NBS. **NBS' 10th National BIM Report | NBS**. Disponível em: <https://www.thenbs.com/knowledge/national-bim-report-2020>. Acesso em: 2 dez. 2025.

NGUYEN, Ngoc Mai; CAO, Minh Tu. Energy use intensity analysis of office buildings using green BIM-integrated Interpretable machine learning. **Journal of Building Engineering**, v. 108, p. 112760, 15 ago. 2025.

NHAMAGE, Settingsidilson Antonio. Development of BIM-Based Digital Twin Model for Fatigue Assessment in Metallic Railway Bridges. **U.Porto Journal of Engineering**, v. 9, n. 5, p. 12–23, 24 nov. 2023.

NIBS. **National Building Information Modeling Standard**. National Institute of Building Sciences, , 2007.

PAN, Yue; ZHANG, Limao. Integrating BIM and AI for Smart Construction Management: Current Status and Future Directions. **Archives of Computational Methods in Engineering 2022 30:2**, v. 30, n. 2, p. 1081–1110, 3 nov. 2022.

PENG, Jin; ZHANG, Haixin; FANG, Xu. Enhancing energy efficiency and reducing greenhouse gases in non-residential buildings using architectural design and multifunctional heat pipes integrated into advanced thermally activated building components. **Energy and Buildings**, v. 350, p. 116688, 1 jan. 2026.

QIN, Guocheng *et al.* Automated Reconstruction of Parametric BIM for Bridge Based on Terrestrial Laser Scanning Data. **Advances in Civil Engineering**, v. 2021, n. 1, p. 8899323, 1 jan. 2021.

RODRIGO, Navodana *et al.* Leveraging digital technologies for circular economy in construction industry: a way forward. **Smart and Sustainable Built Environment**, v. 13, n. 1, p. 85–116, 2 jan. 2024.

RODRIGUEZ POLANIA, D. *et al.* Bridges monitoring and assessment using an integrated bim methodology. **Innovative Infrastructure Solutions**, v. 10, n. 2, p. 1–18, 1 fev. 2025.

SANTOS, Rúben *et al.* BIM-based life cycle assessment and life cycle costing of an office building in Western Europe. **Building and Environment**, v. 169, p. 106568, 1 fev. 2020a.

SANTOS, Rúben *et al.* Development of a BIM-based Environmental and Economic Life Cycle Assessment tool. **Journal of Cleaner Production**, v. 265, p. 121705, 20 ago. 2020b.

SESANA, Marta Maria *et al.* Building life cycle assessment and digital technologies: A bibliometric and systematic literature review and recent advances on their integration to boost the decarbonization of the construction sector. **Energy and Buildings**, v. 352, p. 116833, 1 fev. 2026.

SHEN, Yuxuan; PAN, Yue. BIM-supported automatic energy performance analysis for green building design using explainable machine learning and multi-objective optimization. **Applied Energy**, v. 333, p. 120575, 1 mar. 2023.

SUCCAR, Bilal. Building information modelling framework: A research and delivery foundation for industry stakeholders. **Automation in Construction**, v. 18, p. 357–375, 2009.

SUCCAR, Bilal. Building Information Modelling Maturity Matrix. 2010.

TAHMASEBINIA, Faham *et al.* Exploring the Benefits and Limitations of Digital Twin Technology in Building Energy. **Applied Sciences 2023, Vol. 13,** v. 13, n. 15, 29 jul. 2023.

TAN, Juan *et al.* Circular economy applications in railway infrastructure: A comprehensive evidence-based review. **Transportation Geotechnics**, v. 56, p. 101677, 1 jan. 2026.

TANG, Shengjun *et al.* BIM generation from 3D point clouds by combining 3D deep learning and improved morphological approach. **Automation in Construction**, v. 141, p. 104422, 1 set. 2022.

TANG, Shu *et al.* BIM assisted Building Automation System information exchange using BACnet and IFC. **Automation in Construction**, v. 110, p. 103049, 1 fev. 2020.

TAO, Fei *et al.* Digital Twin in Industry: State-of-the-Art. **IEEE Transactions on Industrial Informatics**, v. 15, n. 4, p. 2405–2415, 1 abr. 2019.

TEIXEIRA, Guilherme Palla *et al.* Interoperability level for bridge structural analysis from the IFC data interpretation. **Gestão & Tecnologia de Projetos**, v. 19, n. 3, p. 49–67, 31 dez. 2024.

TUSHAR, Quddus *et al.* An integrated approach of BIM-enabled LCA and energy simulation: The optimized solution towards sustainable development. **Journal of Cleaner Production**, v. 289, p. 125622, 20 mar. 2021.

UK BIM FRAMEWORK. **ISO 19650 Guidance D: Developing information requirements**. , 2022.

UNEP. **Global Status Report for Buildings and Construction 2024/2025 | UNEP - UN Environment Programme**. *[S.l.: S.n.]*. Disponível em: <https://www.unep.org/resources/report/global-status-report-buildings-and-construction-20242025>. Acesso em: 3 dez. 2025.

VALINEJADSHOUBI, Mojtaba *et al.* Development of an IoT and BIM-based automated alert system for thermal comfort monitoring in buildings. **Sustainable Cities and Society**, v. 66, p. 102602, 1 mar. 2021.

ZABALLOS, Agustín *et al.* A Smart Campus' Digital Twin for Sustainable Comfort Monitoring. **Sustainability 2020, Vol. 12, Page 9196**, v. 12, n. 21, p. 9196, 5 nov. 2020.

ZHENG, Lang *et al.* A review of integration between BIM and CFD for building outdoor environment simulation. **Building and Environment**, v. 228, p. 109862, 15 jan. 2023.

ZHUANG, Dian *et al.* A performance data integrated BIM framework for building life-cycle energy efficiency and environmental optimization design. **Automation in Construction**, v. 127, p. 103712, 1 jul. 2021.

ZOGHI, Milad; KIM, Sungjin. Dynamic Modeling for Life Cycle Cost Analysis of BIM-Based Construction Waste Management. **Sustainability 2020, Vol. 12, Page 2483**, v. 12, n. 6, p. 2483, 22 mar. 2020.