# Reducing Carbon Footprints in Construction: The Impact of BIM and Digital Twins

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***Abstract:***

The construction industry significantly contributes to global carbon emissions, necessitating innovative solutions for sustainability. Building Information Modeling (BIM) and Digital Twin technologies offer a transformative approach to achieving carbon-neutral construction. BIM enables efficient resource management, energy optimization, and material waste reduction, while Digital Twins provide real-time monitoring and predictive analytics to enhance operational efficiency. By integrating these technologies, the industry can minimize embodied and operational carbon, optimize renewable energy integration, and ensure regulatory compliance. This paper explores how BIM and Digital Twins complement each other in reducing environmental impact and advancing global sustainability initiatives.

***Keywords:***

*Building Information Modeling (BIM), Digital Twin, Carbon-Neutral Construction, Energy Efficiency, Sustainable Building Technologies*

## 1. Introduction:

The construction industry is responsible for nearly 40% of global carbon emissions through embodied carbon (materials, construction processes) and operational carbon (energy use in buildings). Building Information Modeling (BIM) and Digital Twin technologies play a crucial role in reducing these emissions and achieving carbon neutrality in construction. BIM is a digital representation of a building's physical and functional characteristics. It enables stakeholders to collaborate effectively throughout the lifecycle of a building.

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A Digital Twin is a real-time digital replica of a physical asset that enables continuous monitoring and optimization. When applied to buildings, Digital Twin technology enhances energy efficiency in several ways. BIM enhances resource efficiency by enabling precise material quantification, reducing excess ordering, and minimizing construction waste by up to 30% through optimized material use and prefabrication. Digital Twins complement this by providing real-time monitoring of material consumption, identifying inefficiencies, and enabling corrective actions during construction, further supporting sustainability and cost savings. Additionally, BIM aids in designing energy-efficient HVAC systems by optimizing duct layouts and thermal insulation, while Digital Twins dynamically adjust heating and cooling based on occupancy and weather conditions, reducing energy consumption by up to 30%. These technologies collectively drive the construction industry toward zero waste and carbon neutrality, making buildings more sustainable, cost-effective, and environmentally responsible (Badenko et al., 2024).

BIM enables designers to simulate energy efficiency strategies early in the design phase, ensuring buildings align with net-zero energy goals through performance-based design, integrating passive solar heating, daylighting, and high-performance insulation. Digital Twins enhance this by providing real-time energy performance monitoring, optimizing HVAC, lighting, and insulation dynamically to reduce operational carbon emissions, achieving up to 40% energy savings. Additionally, BIM and Digital Twins facilitate the integration of renewable energy sources by assessing and optimizing solar panels, wind turbines, and geothermal systems. Digital Twins continuously monitor and adjust renewable energy output based on weather conditions and demand, allowing buildings to generate their energy, reduce reliance on fossil fuels, and lower operational carbon emissions, with studies showing a 50% reduction in grid electricity dependence through BIM-based solar energy modeling (Liu et al., 2025).

Tracking emissions throughout a building's lifecycle is one of the biggest challenges in achieving carbon neutrality, and BIM plays a crucial role by enabling precise carbon footprint calculations, considering both embodied carbon in materials like cement, steel, and glass and operational carbon from heating, cooling, and electricity use. Digital Twins enhance this by continuously collecting real-world emissions data, offering instantaneous carbon analytics that aid in carbon offset planning and ensure real-time compliance with green building certifications like LEED and BREEAM. With governments and industry bodies enforcing stricter carbon regulations, BIM streamlines regulatory compliance by embedding carbon emission calculations into building models, while Digital Twins provide real-time reports on carbon footprint, energy usage, and material efficiency for Environmental, Social, and Governance (ESG) reporting. This transparency helps businesses demonstrate sustainability efforts, secure green funding, and avoid penalties for carbon-intensive construction, with companies using Digital Twin technology reporting 20-30% lower emissions, faster regulatory approvals, and increased investor confidence in sustainable projects (Rose Morrison, 2022).

The construction industry is experiencing a digital transformation with technologies like Building Information Modeling (BIM)

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and Digital Twin playing a crucial role in optimizing energy efficiency. With rising concerns about climate change and sustainable development, adopting these technologies is essential for designing and managing energy-efficient buildings. This paper explores how BIM and Digital Twins improve energy performance in the construction sector.

## 2. Methodology

This study employs a qualitative, literature-based methodology grounded in secondary research that follows a narrative review approach, systematically collecting, analyzing, and synthesizing findings from academic literature, institutional reports, and case studies related to BIM, Digital Twin technologies, and sustainable construction. Sources were selected based on relevance, recency from the last decade (specifically published between 2013 and 2025), and alignment with the study's thematic focus on carbon reduction, energy efficiency, lifecycle assessment, and digital transformation in the built environment.

Keyword-driven searches were performed using various databases, including ScienceDirect, Google Scholar, MDPI, SpringerLink, and Elsevier. Some of the keywords included "BIM carbon reduction," "Digital Twin energy optimization," "smart buildings," "net-zero buildings," and "sustainable construction technologies." The review prioritized materials that addressed intersections between digital construction technologies and global sustainability goals, particularly the United Nations SDGs (SDG 7, 11, 12, and 13), the Paris Agreement on Climate Change, the EU Green Deal, and the Circular Economy Action Plan. Data synthesis involved thematic analysis, identifying core areas of application such as energy optimization, carbon footprint reduction, regulatory compliance, renewable energy integration, and predictive maintenance. The review also highlights measurable impacts and implementation challenges, providing a comprehensive framework for understanding the environmental benefits of BIM and Digital Twin integration in construction.

## 3. BIM and Digital Twins: Key Differences and Synergies for Green Construction

BIM is essential for pre-construction carbon reduction, optimizing materials and energy-efficient design, while digital twins drive operational carbon neutrality, ensuring real-time energy and waste management (Abdelalim et al., 2024; Arsecularatne et al., 2024; Cespedes-Cubides & Jradi, 2024; Jiang et al., 2024; Jradi, 2024). BIM and Digital Twins create a holistic approach to achieving carbon-neutral construction (Deng et al., 2021). A comprehensive comparison between BIM and digital twins in the context of carbon-neutral construction is shown in Table 1 below.

**Table 1:** BIM vs. Digital Twin- A Comparative Analysis for Carbon-Neutral Construction

| Aspect | BIM | Digital Twin |
|---|---|---|
| **Definition** | A static digital model for planning, designing, and managing buildings (Khattra & Jain, 2024). | A real-time, data-driven replica of a physical asset, integrating AI, IoT, and analytics (Dihan et al., 2024). |

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| **Stage of Use** | Primarily in the design and construction phases (Khattra & Jain, 2024). | Primarily in the operation and maintenance phase (Bao & Bu, 2025). |
| **Carbon Footprint Reduction** | Optimizes materials and processes to reduce embodied carbon (Heydari & Heravi, 2023). | Tracks real-time emissions, energy use, and carbon footprint across the lifecycle (Arsecularatne et al., 2024). |
| **Energy Efficiency** | Simulates building performance to optimize energy efficiency before construction (Pereira et al., 2021a). | Continuously monitors and adjusts energy consumption dynamically (Yeom et al., 2024). |
| **Lifecycle Perspective** | Focuses on early-stage design and initial maintenance (Heydari & Heravi, 2023). | Covers entire lifecycle, including retrofitting and decommissioning. |
| **Data Integration** | Uses static 3D models and historical data (Khattra & Jain, 2024). | Integrates IoT sensors, real-time AI, and predictive analytics (Dihan et al., 2024). |
| **Circular Economy** | Supports recyclable and modular materials selection in the design phase (Zheng et al., 2025). | Tracks resource efficiency and waste management during building operations (Barth et al., 2023). |
| **Smart Material Management** | Optimizes material selection for low carbon impact (Heydari & Heravi, 2023). | Uses IoT and AI to monitor material degradation and replacement needs (Dihan et al., 2024). |
| **Smart Building Operations** | Helps design energy-efficient systems but lacks real-time adaptation (Pereira et al., 2021a, 2021b). | Adapts to occupant behavior, climate, and energy demand dynamically (Lee et al., 2025). |
| **Predictive Maintenance** | Provides preventive maintenance schedules based on initial design parameters (K. Das et al., 2025). | Uses real-time data and AI to predict failures, reducing maintenance costs (Dihan et al., 2024). |
| **Compliance & Policy Integration** | Helps ensure compliance with LEED, BREEAM, and green building regulations at the design | Ensures continuous compliance with evolving sustainability policies using real-time monitoring (Alhadi et al., 2025). |



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| | | |
|---|---|---|
| | stage (Di Gaetano et al., 2023). | |
| **Waste Reduction** | Reduces construction waste by optimizing design and prefabrication (Zheng et al., 2025). | Minimizes operational waste through sensor-based optimization (Barth et al., 2023). |
| **Sustainability Compliance** | Aids in obtaining green building certifications before construction (Abdel-Hamid et al., 2025). | Ensures ongoing compliance with energy efficiency and sustainability regulations (Alhadi et al., 2025). |
| **Automation & AI** | Limited AI, mainly for design automation (Pereira et al., 2021b). | Uses machine learning for real-time adjustments and automated energy management (O. Das et al., 2024). |
| **Cost Efficiency** | Reduces costs in design, materials, and labor (K. Das et al., 2025) | Reduces long-term operational costs via predictive analytics (Omoniyi Babatunde Johnson et al., 2024). |
| **Interoperability** | Works within architectural and engineering platforms (Dihan et al., 2024). | Connects with BIM, IoT devices, smart grids, and urban digital twins (Dihan et al., 2024). |

## 4. BIM and Digital Twin: Driving Carbon-Neutral Construction in Line with Global Initiatives

Table 2 offers a structured and data-enriched overview of how BIM and Digital Twin technologies contribute to sustainable construction across key functional areas. It systematically connects each technological application with its associated benefits, implementation challenges, alignment with major global climate goals (including the UN SDGs and the Paris Agreement), and quantitative performance metrics drawn from recent studies. The table emphasizes the dual role of these technologies in reducing environmental impacts, such as improving energy efficiency, minimizing material waste, and enabling renewable energy integration, while also revealing practical hurdles that must be addressed for successful deployment at scale.

The comparative insights highlight that BIM and Digital Twins are vital tools in advancing low-carbon and resource-efficient construction practices. For example, Digital Twins can lead to up to 40% energy savings through real-time building performance optimization, while BIM-driven prefabrication has been shown to reduce construction waste by up to 30% (Yeom et al., 2024; Liu et al., 2025; Zheng et al., 2025). These technologies not only optimize initial design and material use but also ensure continuous operational monitoring, enabling buildings to achieve carbon neutrality across their workflow and lifespans. Despite the diverse and several potential of these technologies, their adoption is hindered by challenges such as high implementation costs, fragmented data systems, and a lack of standardized carbon assessment methods. Nonetheless, the evidence presented reinforces their capacity

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to drive transformative change in the built environment, paving the way toward climate-resilient, smart, and sustainable infrastructure in the decades ahead.

**Table 2:** Integrating BIM and Digital Twins for Sustainable Construction and Global Complaince

| Aspect | Applications | Benefits | Challeng es | Alignment with Global Initiatives | Result |
|---|---|---|---|---|---|
| **Energy Efficienc y** | Real-time energy performance monitoring, optimizing HVAC & lighting systems | Reduced energy consum ption, improve d occupan t comfort | Data integratio n issues, need for IoT sensors | UN SDG 7 (Affordable & Clean Energy), Paris Agreement | Up to 30-40% reduction in energy consumption (Yeom et al., 2024; Liu et al., 2025) |
| **Lifecycle Carbon Analysis** | Embedded carbon assessment of materials, monitoring embodied & operational carbon | Lower carbon footprint , informe d material selectio n | Lack of standardiz ed carbon databases | Net Zero Carbon Buildings Commitment, LEED, BREEAM | BIM enables 20-25% reduction in embodied carbon through optimized design (Heydari & Heravi, 2023) |
| **Smart Construc tion & Prefabric ation** | Off-site modular construction, digital twin for real-time tracking | Reduces waste, lowers emissio ns from transpor tation | High initial investmen t in digital twin technolog y | EU Green Deal, Sustainable Development Goals (SDG 11 - Sustainable Cities & Communities) | Prefabrication can reduce construction waste by up to 30% (Zheng et al., 2025) |
| **Waste Reductio n** | Simulation of construction processes to minimize material waste | Lower landfill impact, cost savings | Resistanc e to digital transform ation | Circular Economy Action Plan (CEAP), SDG 12 (Responsible Consumption & Production) | Up to 90% construction waste reduction with BIM-based design optimization (Barth et al., 2023) |

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| Aspect | Applications | Benefits | Challenges | Alignment with Global Initiatives | Result |
|---|---|---|---|---|---|
| **Renewable Energy Integration** | Simulation of solar & wind energy potential for buildings | Maximized on-site renewable energy use | High initial setup cost for renewable tech | RE100 Initiative, SDG 13 (Climate Action) | BIM-assisted solar modeling reduces grid electricity dependency by 50% (Liu et al., 2025) |
| **Carbon Capture & Offsetting** | Digital Twin modeling of green walls, carbon-absorbing materials | Increased carbon sequestration in built environments | Lack of robust carbon offset measurement | Science-Based Targets Initiative (SBTi), Carbon Neutral Cities Alliance | Estimated 15–20% of operational carbon can be offset via green envelope strategies (O. Das et al., 2024) |

## 5. Conclusion

BIM and Digital Twin technologies collectively represent a paradigm shift in how the construction industry addresses carbon reduction, operational efficiency, and sustainable development. On one hand, BIM provides value during the planning and design stages through simulation, prefabrication, and optimized resource allocation, while Digital Twins extend these benefits into the operational phase, offering real-time monitoring, dynamic performance management, and predictive analytics. Together, these technologies support measurable reductions in embodied and operational carbon, improve building energy performance, and enhance alignment with green building certifications such as LEED and BREEAM.

This paper demonstrates that the integration of BIM and Digital Twin technologies is more than a technical evolution; it is a strategic response to pressing environmental challenges and policy mandates. By aligning their implementation with global sustainability frameworks such as the UN SDGs and the Paris Agreement, these tools provide scalable and data-driven pathways toward infrastructure that can withstand climate impacts. However, realizing their full potential requires overcoming challenges such as high initial costs, data interoperability issues, and a lack of standardization in carbon accounting. Future work should focus on creating unified carbon assessment standards, increasing accessibility of IoT-enabled platforms, and fostering collaboration between policymakers, technologists, and construction professionals. Ultimately, the fusion of digital innovation and environmental stewardship will be central to achieving net-zero targets and building smarter, greener cities of tomorrow.

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