

Integration of BIM and Parametric Modeling for Sustainable Building Design

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Due to increasingly stringent environmental regulations and the significant environmental impact associated with the construction, execution, operation, and renovation of buildings, sustainability is receiving growing emphasis in the construction industry. The short- and long-term environmental impact of a building is influenced by numerous factors: during the design phase, for example, location, geometry, materials used, and building services systems play a key role, but the methods applied during construction, the logistical aspects, the organization and quality of operational and maintenance processes, as well as waste management during renovation or demolition at the end of the building's life cycle are also of great importance. This study explores how parametric modelling and BIM can be integrated to support sustainable building design and practices. This literature review presents modern procedures and toolsets applicable in the design, construction, operation, and demolition/renovation phases of buildings, and identifies current research trends, gaps, and challenges. The review highlights that the integration of Building Information Modelling BIM and parametric modelling provides significant opportunities for improving sustainability performance throughout the building life cycle. In the design and construction phases, these tools enable optimisation of energy use, material efficiency, and embodied carbon reduction, while in operation and refurbishment, they support data-driven maintenance and circular material management. The findings indicate that despite rapid technological development, major challenges remain in interoperability, standardisation, and the integration of social and economic sustainability indicators.

1. Introduction

The construction industry has a significant environmental burden, particularly in terms of energy consumption and carbon emissions. According to Gan et al. (2023), material choices and design alternatives greatly influence the lifecycle carbon footprint of buildings. Sghiri et al. (2025) highlight that advanced technologies such as digital twins offer considerable potential for improving operational energy performance. Metvaei et al. (2025) further demonstrate how BIM-supported prefabrication workflows can contribute to reducing embodied emissions in the construction phase.

Considering the whole life cycle of buildings from design and construction to operation, renovation or demolition, it is essential to integrate sustainability considerations. As environmental requirements become more stringent and construction processes more complex, there is an increasing need for digital tools that can support effective, environmentally conscious decision-making (Metvaei et al., 2025).

Building Information Modelling (BIM) is a data-driven methodology that organises building information within a structured 3D model, enabling coordination across all stages of the building lifecycle. Parametric modelling works in parallel with an algorithmic basis, allowing for the automatic modification and optimisation of design variables. The integration of the two methods, i.e., the BIM-based application of the parametric approach, opens up new possibilities for sustainable building design.

The aim of this paper is to show how the integration of BIM and parametric modelling can be applied throughout the life cycle of a building to achieve sustainability goals, presenting current research and practical application trends in the design, construction, operation and demolition or renovation phases.

The novelty of this paper lies in its comprehensive synthesis of recent research focusing on the integration of BIM and parametric modelling for sustainable building design and operation. Unlike previous reviews that often examine either BIM-based sustainability assessment or parametric optimisation separately, this study analyses their combined application across all phases of the building life cycle—design, construction, operation, and demolition or refurbishment. By mapping current research trends and identifying methodological gaps and challenges, the paper contributes to a more holistic understanding of how digital tools can jointly support environmental performance improvement throughout the built environment.

2. Research methodology

This study explores how the integrated application of Building Information Modelling (BIM) and parametric modelling can support sustainable design and operation practices throughout the building life cycle. The research follows a qualitative literature review approach based on peer-reviewed papers and case studies published in English after 2018. The process is illustrated in Figure 1, which presents the workflow.

Literature identification. A keyword-based search was carried out across the ScienceDirect, ResearchGate, and Scopus databases. Search terms included combinations such as “BIM and sustainability”, “parametric design and lifecycle analysis”, “carbon optimisation in building design”, and “digital construction tools for low-energy buildings”.

Screening and selection. The collected papers were screened to exclude duplicates, non-peer-reviewed, and non-English sources. Only studies with a clear methodological structure and a direct link between BIM, parametric modelling, and sustainability performance were retained.

Classification. The selected literature was grouped according to the four primary phases of the building life cycle—design, construction, operation, and refurbishment or demolition—and by their analytical focus, such as optimisation, digital workflows, or lifecycle assessment.

Evaluation. Within each category, the studies were compared based on their applied methods, tool integration, and measurable sustainability indicators (operational energy use, embodied carbon reduction, material efficiency).

Synthesis. The findings were synthesised to identify research trends, methodological gaps, and emerging directions for integrating BIM and parametric modelling in sustainable building design and management.

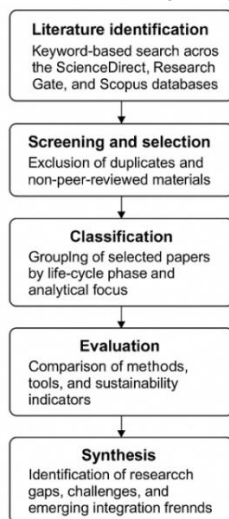


Figure 1: Investigation procedure

This structured process ensures transparency and reproducibility in analysing how digital tools jointly contribute to sustainability objectives across all life cycle phases.

3. Design phase

In sustainable building design, early-stage decisions related to geometry, material selection and energy strategy are critical in determining long-term environmental impacts. Parametric modelling and Building Information Modelling (BIM) integration enable the generation, analysis and optimisation of multiple design alternatives, supporting environmentally responsible decision-making from the initial concept phase.

Najjar et al. (2019) demonstrated that the window-to-wall ratio is one of the most influential parameters for energy performance. Their study found that a 15% increase in window surface area could lead to a 20–45 % increase in annual energy use, particularly in warm climates. While the thermal performance of wall and roof materials plays a secondary role, it can still contribute to overall efficiency when optimised appropriately.

Mowafy et al. (2023) developed a modular parametric BIM-based life cycle assessment framework that compares conventional and circular design approaches. Their model incorporates five key components: data collection, emission quantification, Life Cycle Assessment LCA, Non-dominated Sorting Genetic Algorithm II (NSGA-II) -based optimisation, and Data Envelopment Analysis DEA-supported decision-making. Applied to a residential case study, the framework evaluated over 2,000 design variants and revealed that while circular strategies reduce embodied emissions, they may increase operational loads, requiring careful balancing.

Gan et al. (2023) introduced a parametric BIM framework for the carbon performance prediction and optimisation of residential high-rises. Their findings showed that adjusting building orientation could result in annual energy savings of up to 29 MWh, while the use of alternative materials such as PFA and GGBS contributed to a 52 % reduction in embodied carbon. The study also compared two global climate scenarios (1.5 °C Net-Zero and 3 °C Hot House), highlighting the design implications of stricter decarbonisation targets.

In terms of structural design, Ajtayné and Szép (2023) presented a parametric BIM-based method for assessing the environmental impact of alternative geometries. They analysed 48 different hall configurations and found that changes in span and grid spacing significantly affected embodied emissions, particularly due to the increased use of reinforced concrete in wider structural modules. Their model enables real-time feedback on environmental indicators, facilitating early-stage optimisation during conceptual design.

Altogether, these studies confirm that parametric BIM tools provide powerful means of embedding sustainability into the design process. By quantifying both operational and embodied impacts across a wide range of configurations, these methods support evidence-based decisions aligned with long-term environmental performance objectives.

3.1 Detailed case study: Parametric BIM-based LCA framework (Mowafy et al., 2023)

Scope and aim. Mowafy et al. (2023) develop a parametric BIM-based life-cycle assessment (LCA) framework to evaluate conventional (cradle-to-grave) and circular cradle-to-cradle design approaches by jointly quantifying embodied (initial, recurrent, EoL/reuse) and operational emissions. The goal is to support material selection and trade-off exploration in early design.

Framework and toolchain. The framework comprises five modules: (1) Data acquisition, (2) Operating & embodied emissions, (3) LCA, (4) Optimisation, and (5) Decision-making. It integrates Autodesk Revit with Rhino/Grasshopper, using Rhino-Inside-Revit and BHoM for quantities; Honeybee/Ladybug (EnergyPlus/OpenStudio) for operational simulation; Bombyx with the KBOB database for embodied factors and thermal data; NSGA-II via Wallacei X for multi-objective optimisation; and DEA (OSDEA, EMS) to rank Pareto-optimal solutions.

Case setup. A two-storey residential villa in Cairo (climate 2B) is analysed. Building elements considered are external/internal walls, floors, roofs, and windows (structural frames and foundations excluded). Thermal transmittance (U-value) constraints are applied (e.g., walls 1 W/m²K; roof 0.6 W/m²K; windows 3.98 W/m²K). Simulations generate 2,000 feasible design solutions per approach; Pareto fronts contain 326 (conventional) and 498 (circular) solutions.

Optimisation & decision-making. Objectives include minimising embodied Global Warming Potential GWP, operating GWP, disposal/reuse impacts, and surface energy flow subject to U-value bounds. For the circular approach, reuse percentages for elements are optimisation variables. DEA treats each Pareto solution as a DMU to identify efficient and super-efficient options for final selection and cross-approach comparison.

Key findings from the study. Operating impacts dominate overall GWP in both approaches; embodied and EoL/reuse contribute less. The circular approach achieves lower embodied GWP bounds (min 18.14 vs. 19.53 kgCO₂ eq/(m²·y) for conventional), but tends to increase operating GWP due to the higher heat transmittance of some materials. Reported ranges include conventional embodied GWP up to 112.7 kgCO₂ eq/(m²·y), while circular peaks at 31.95 kgCO₂ eq/(m²·y). Many operational GWP values fall around 285–290 kgCO₂ eq/(m²·y). In the comparison DEA model, the top-ranked overall solution comes from the conventional set; however, a leading circular solution shows substantial embodied savings (e.g., 28.47 % reduction between first and intermediate cycles in one case). Reuse rates vary by element (e.g., walls often 11–47 %, roofs/windows frequently higher), and higher reuse does not uniformly translate to the lowest total impacts, reflecting trade-offs among element GWPs and thermal performance.

Relevance to this review. This case concretely illustrates how BIM-parametric integration operationalises life-cycle thinking: unified data flow, transparent LCA boundaries (A-C, D), multi-objective search, and non-subjective ranking (DEA). It also exemplifies a recurring theme in the literature—embodied-versus-operational

trade-offs—and the need for database interoperability and context-specific thermal/embodied data when comparing conventional and circular strategies.

4. Construction phase

During the construction phase, the integration of parametric design and BIM can significantly enhance material efficiency, energy performance, and overall process optimisation. Digital workflows involving robotic manufacturing and automated decision systems are increasingly enabling more sustainable construction methods, particularly in off-site and prefabricated contexts.

Mehdipoor et al. (2025) developed a generative parametric framework that combines BIM with robotic manufacturing to produce free-form façade panels in a resource-efficient manner. Their workflow integrates ArchiCAD-based modelling, energy analysis using Ladybug and EcoDesigner, and genetic algorithm-driven optimisation via Wallacei. CNC robotic arms are used to fabricate custom façade components based on solar radiation analysis, enabling the system to reduce solar exposure by 45 % while generating over 630 m² of tailored shading surfaces. The real-time feedback loop in their workflow points toward future improvements in responsive design and manufacturing.

Metvaei et al. (2025) proposed a BIM-enabled robotic manufacturing framework for the mass customisation of prefabricated building elements. Their two-phase digital process begins with a configurator that generates a BIM model incorporating Design for Manufacture and Assembly (DfMA) considerations. In the second phase, robot codes are directly generated from the BIM model using Autodesk Revit and ABB RobotStudio APIs, eliminating the need for file conversion. Their system supports full automation of material handling, assembly, and sequencing operations, and was successfully demonstrated through the prefabrication of light gauge steel panels for a two-storey residential building. While current applications are primarily focused on façade systems and wall panel prefabrication, these studies demonstrate how parametric BIM methods and robotic manufacturing can increase construction efficiency, reduce material waste, and advance sustainability objectives in practical workflows. Further research is needed to extend such methods to other structural and envelope components and to integrate life cycle impact assessments in the manufacturing process.

5. Operation and maintenance

In the operational phase of buildings, data-driven technologies such as digital twins and predictive maintenance systems can significantly enhance energy efficiency, reduce operating costs, and improve sustainability outcomes. By integrating real-time sensor data with BIM and simulation tools, buildings can be managed in a more responsive and resource-conscious manner.

Sghiri et al. (2025) conducted a systematic literature review on the role of digital twins in building energy efficiency. They identified key applications such as real-time Heating, Ventilation and Air Conditioning (HVAC) control, occupancy-based lighting optimisation, predictive modelling of energy demands, and fault detection. The technologies supporting these applications include IoT sensors, machine learning algorithms (e.g., LSTM, CNN, SVM), and cloud-based or edge computing architectures. However, they also noted significant challenges related to interoperability between platforms, data privacy, and the variability of occupant behaviour.

Hauashdh et al. (2024) proposed an integrated framework for sustainable and efficient maintenance operations aligned with climate change adaptation and the United Nations Sustainable Development Goals. Their model is structured around three layers: identifying organisational and technological challenges, evaluating environmental, social, and economic impacts, and developing intervention strategies. Suggested approaches include predictive maintenance, material sustainability assessments, and the adoption of safety protocols. The framework was validated by industry experts and is particularly applicable to the public sector and organised maintenance service providers.

These studies highlight the potential of digital tools to support adaptive, low-carbon operations across building stock. However, widespread adoption still faces barriers such as legacy systems, a lack of standardised protocols, and technical complexity. Future efforts must focus on improving interoperability, securing data, and developing context-aware operational strategies that respond to both user needs and environmental pressures.

6. Refurbishment and demolition

The renovation and demolition phases present important opportunities to enhance the sustainability of the built environment through strategic planning, material reuse, and the integration of digital technologies. Parametric modelling and BIM can support data-driven decisions that optimise daylight access, thermal performance, and material flow management. Amoruso et al. (2019) proposed an integrated BIM-parametric workflow to improve daylight availability and visual comfort in the refurbishment of outdated apartment buildings in Seoul, South Korea. Their simulation-based approach combined Autodesk Revit and Rhinoceros–Grasshopper tools with

Radiance and EnergyPlus for environmental analysis. Interventions such as reducing the window-to-wall ratio, increasing g-values, and adding shading devices were shown to improve daylight autonomy by 30 % and useful daylight illuminance by 15 %. The integration of modular façade panels and building-integrated photovoltaics (BIPV) also contributed to improved thermal performance and renewable energy generation.

For end-of-life demolition planning, Han and Rajabifard (2024) introduced a BIM-based life cycle sustainability assessment framework that combines environmental, economic, and social indicators. Using Revit and Dynamo to link material quantities with impact data, and applying a hybrid AHP-TOPSIS method, they evaluated multiple demolition scenarios with varying recycling rates. Their case study on a four-storey residential building showed that a 90 % recycling rate scenario achieved the highest sustainability score, although marginal returns diminished beyond a certain point. The framework also included visualisation of high-impact materials directly within the BIM model. These applications demonstrate how digital tools can support the circular transformation of the construction sector. Parametric BIM environments provide a platform for optimising both retrofit strategies and demolition logistics, enabling more sustainable use of materials, improved energy performance, and reduced environmental impact.

7. Research trends and challenges

Recent years have seen the growing integration of parametric modelling and BIM as a central strategy for advancing sustainability in architecture, engineering, and construction. Emerging trends include the adoption of life cycle-based design models, AI-assisted optimisation, digital twins for real-time performance monitoring, and the use of cloud-based, interoperable platforms for managing the building life cycle.

Céspedes-Cubides and Jradi (2024) highlighted the role of digital twins in improving operational energy efficiency. Their systematic review found that digital twins support predictive maintenance, component-level monitoring, and anomaly detection, while enabling integration with BIM and IoT systems. However, they also noted that current implementations are often limited by the availability of reliable BIM models for existing buildings, and that digital twin functionality is frequently reduced to data visualisation rather than active control.

Ba et al. (2025) reviewed digital twin applications across industrial and urban infrastructures. They reported that in building systems, digital twins can deliver up to 30 % energy savings and significantly reduce operational costs when integrated with AI-based control systems. Despite these benefits, high implementation costs, integration challenges, and security concerns remain critical obstacles.

Numan et al. (2024) analysed the use of BIM to support green certification schemes such as LEED and BEAM Plus. Their review emphasised that BIM-based optimisation can reduce energy consumption by up to 21 % and cut documentation time by more than half. However, the authors also pointed out persistent barriers to large-scale deployment, such as interoperability limitations, the lack of standardised protocols, and the underrepresentation of social and economic indicators in most evaluation frameworks.

Ajtayné and Szép (2023) identified methodological limitations in current parametric BIM models for structural design. Their framework, while capable of assessing embodied impacts during early-stage planning, is restricted to simple geometries and does not yet support full two-way feedback between structural analysis and design parameters. The study also noted that regional data dependencies (e.g., ÖKOBAUDAT) limit broader applicability. Collectively, these studies reveal both the technical potential and the structural limitations of current approaches. Widespread adoption is hindered by a combination of interoperability issues, high resource demands for digitalisation, and the insufficient integration of social and economic dimensions in sustainability assessments. Future research should aim to develop standardised, scalable, and adaptive frameworks that are able to incorporate real-time data, user behaviour, and broader life cycle considerations.

8. Conclusions

Achieving sustainability in the built environment requires integrated digital approaches that support informed decision-making across all phases of the building life cycle. The combined use of Building Information Modeling and parametric modelling offers powerful capabilities for early-stage design optimisation, material and energy efficiency, and lifecycle-based impact assessment.

This review has demonstrated that BIM-parametric frameworks can quantify and reduce embodied and operational carbon through scenario analysis, algorithmic optimisation, and material assessment. Studies have shown significant potential in areas such as adaptive façade design, robotic prefabrication, and real-time energy management using digital twins. In the operation phase, data-driven tools allow for predictive maintenance and responsive energy use, while in refurbishment and demolition, they support resource-efficient planning and circular practices. Despite these advances, several barriers remain. Challenges related to software interoperability, data quality, modelling complexity, and the lack of standardised protocols continue to limit widespread adoption. Most current models focus primarily on environmental criteria, while economic and social

aspects are still underrepresented in sustainability evaluation. Future research should focus on developing open, modular, and scalable frameworks that enable the integration of diverse sustainability indicators and support long-term lifecycle thinking. Emphasis should also be placed on retrofitting existing building stock, adapting tools to different regional contexts, and enhancing user-centric and adaptive system capabilities.

9. Discussion

The reviewed studies demonstrate that integrating BIM and parametric modelling is crucial to advancing sustainability across all phases of the building life cycle. In the design phase, the combined use of data-driven modelling and algorithmic optimisation enables the assessment of multiple design alternatives, improving both operational and embodied carbon performance. During construction, digital workflows and robotic manufacturing methods enhance material efficiency and reduce waste, indicating the growing relevance of automated, prefabricated systems. In the operation phase, digital twins and predictive maintenance approaches support energy-efficient management and adaptive control strategies, while in refurbishment and demolition, BIM-based life cycle assessment frameworks contribute to circular material use and sustainability evaluation. Across these phases, common trends include the increasing use of life cycle thinking, AI-assisted optimisation, and interoperable digital platforms. However, several challenges persist. The literature highlights barriers related to interoperability between software environments, high data and resource requirements, and the limited consideration of social and economic sustainability aspects. These findings underline the need for developing open, standardised frameworks capable of integrating real-time data, user behaviour, and comprehensive sustainability indicators. Overall, the review confirms that while significant progress has been achieved in linking BIM and parametric modelling, further methodological and technical developments are necessary to ensure their full potential in sustainable building practice.

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