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## Low-carbon interior decoration lifecycle analysis based on BIM technology

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**Abstract:** To address high carbon emissions and the lack of systematic assessment methods in interior decoration, this study develops a BIM-based full life-cycle analysis framework for precise carbon quantification and mitigation. The model integrates low-carbon assessment across six phases: design, material production, transportation, construction, operation and maintenance, and demolition and recycling – enabling dynamic simulation and optimisation of material selection, construction processes, and operational strategies. Empirical validation through a residential renovation case study demonstrates a 28.6% reduction in total life-cycle carbon emissions, a 19.4% decrease in material waste, and 12.7% cost savings compared to conventional approaches. The framework offers a scientifically validated pathway for low-carbon transformation in interior decoration, supporting architectural decarbonisation and policy compliance.

**Keywords:** building information modelling technology; low-carbon interior decoration; full life-cycle analysis; carbon emission assessment; sustainable building; building information modelling; green decoration.

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## 1 Introduction

Under the global ‘dual carbon’ goals of achieving carbon peaking by 2030 and carbon neutrality by 2060, the building sector faces unprecedented pressure to deliver deep and sustained emission reductions. According to the most recent UN Environment Programme (UNEP) and Global Alliance for Buildings and Construction (Glob-alABC) 2024–2025 Global Status Report, buildings and construction consume 32% of global final energy and are responsible for 34% of energy-related CO<sub>2</sub> emissions, with embodied carbon from materials remaining a dominant and persistently growing component despite incremental improvements in operational energy efficiency (Xu et al., 2025). In China, the building sector contributes approximately 39–50% of national energy-related carbon emissions (Ding et al., 2025), driven by continued rapid urbanisation, massive infrastructure development, and the high frequency of interior renovations in residential, commercial, and hospitality buildings (Li et al., 2025a). Interior decoration and renovation activities stand out as particularly carbon-intensive within this sector (Zhang et al., 2025). These activities involve the extensive use of high-embodied-carbon materials (such as gypsum boards, decorative paints, flooring systems, aluminium ceiling panels, PVC-based products, and custom fittings), energy-consuming on-site installation processes, repeated cycles of fit-outs over a building’s lifespan, and eventual demolition or replacement waste generation. As a result, interior decoration generates substantial emissions across every phase: conceptual design, material production, transportation, construction execution, long-term operation and maintenance, and end-of-life treatment. Full life-cycle low-carbon transformation of interior decoration therefore emerges as a critical, high-impact pathway to advance the overall green transition of China’s building industry, offering significant potential for precise emission quantification, intelligent material substitution, process optimisation, waste minimisation, and circular economy integration.

Current industry practices in interior decoration reveal several deep-rooted and persistent deficiencies that seriously hinder progress toward sustainability. High-carbon materials continue to dominate due to cost advantages, supply chain availability, and entrenched traditional preferences, including conventional solvent-based paints, non-recyclable composites, and energy-intensive aluminium and PVC products. Construction phases suffer from considerable energy inefficiency, manifested in excessive temporary electricity consumption, prolonged equipment idling, suboptimal site logistics, and material wastage rates that frequently exceed 15–20%. Most critically, systematic, quantitative full life-cycle carbon emission assessment remains largely absent from typical projects; conventional evaluation methods rely heavily on rough empirical estimation rules, fragmented post-construction audits, or partial stage-by-stage analysis that fails to capture dynamic interdependencies and cumulative impacts across the entire project lifespan. These limitations prevent proactive, data-driven decision-making at key intervention points, resulting in missed opportunities for optimised material selection, construction sequencing, energy management, and end-of-life material recovery. Consequently, the interior decoration sector urgently requires advanced digital technologies that can deliver integrated, real-time, fine-grained, and comprehensive low-carbon management throughout the entire renovation workflow.

BIM technology has demonstrated outstanding performance in full life-cycle management of large-scale, structurally complex public infrastructure projects. Successful applications in hospital complexes, long-span bridges, airport terminals,

and high-speed railway stations have enabled precise carbon emission tracking, embodied carbon minimisation, significant overall reduction through seamless integration of parametric modelling, life-cycle assessment (LCA) tools, 4D/5D simulations, and multi-disciplinary collaboration (Li et al., 2025b). BIM provides superior capabilities in centralised data integration across all project stakeholders, high-fidelity three-dimensional visualisation, dynamic simulation of construction sequences and alternative scenarios, real-time performance analysis, and efficient coordination from initial design through operation, maintenance, and eventual decommissioning (Lyu et al., 2025). Leveraging these proven strengths from domains far more structurally and operationally challenging than typical interior renovations, this study innovatively adapts BIM to the specialised field of interior decoration and fit-out, constructing a dedicated low-carbon full life-cycle analysis and optimisation system.

This study introduces a BIM-based full life-cycle analysis framework specifically tailored for interior decoration, which is absent in prior work. Unlike existing studies that focus on new builds or single-phase assessments, this framework uniquely integrates: six-phase carbon quantification with renovation-specific emission factors, Pareto-based material substitution and GA/PSO multi-objective optimisation, empirical validation showing 28.6% emission and 12.7% cost reductions.

The principal contributions of this work include:

- 1 formulation of a customised full life-cycle low-carbon assessment framework specifically tailored for interior decoration
- 2 construction of a BIM-driven dynamic carbon emission simulation and prediction model
- 3 empirical validation of substantial reductions—approximately 28.6% in total life-cycle emissions and 12.7% in overall project costs – through a representative residential renovation case study
- 4 provision of a practical, replicable technical pathway for widespread adoption across the low-carbon interior decoration industry.

The paper is structured as follows: Section 2 reviews related work, Section 3 elaborates the proposed methodology, Section 4 presents the case study and experimental validation, Section 5 analyses results and implications, and Section 6 concludes with future research directions.

## **2 Related work**

### *2.1 BIM technology applications in the building industry*

Researchers have conducted extensive investigations into BIM applications throughout the entire building project lifecycle, encompassing conceptual design, detailed engineering, construction execution, facility operation, periodic maintenance, retrofitting, and eventual decommissioning phases. BIM demonstrates exceptional capabilities in centralising multidisciplinary information, automating clash detection, enabling 4D time-dependent construction simulations, integrating 5D cost dimensions, supporting advanced energy performance modelling, and promoting real-time collaboration among

architects, structural engineers, MEP specialists, contractors, facility managers, and owners (Huo et al., 2024; Huang et al., 2024). Recent literature from 2023–2025 highlights BIM’s accelerating role in sustainability and carbon management, including automated life-cycle carbon assessments, embodied carbon tracking in prefabricated components, optimisation of material logistics and supply chains, and integration with environmental impact databases for early-stage emission forecasting and iterative scheme refinement (Gan et al., 2025; Kim et al., 2024; Kurian et al., 2024). These advancements have delivered measurable practical benefits, such as 10–20% reductions in construction waste generation, improved delivery schedule accuracy, minimised rework rates, enhanced energy efficiency during operation, and stronger overall project sustainability outcomes. Contemporary BIM platforms increasingly embed LCA plugins, cloud-based energy simulators, carbon footprint calculators, and real-time environmental performance dashboards, empowering designers to evaluate and mitigate environmental impacts from the earliest decision stages onward. Despite these significant technological and methodological achievements, the majority of BIM implementations still concentrate on new-build constructions and primary structural systems. Systematic and comprehensive deployment in interior renovation, fit-out, and secondary decoration projects remains comparatively underdeveloped and underexplored. Limited studies have examined BIM’s potential to address the distinctive characteristics of interior decoration, such as high-frequency material changes, tight spatial constraints in existing structures, rapid iterative client-driven decision cycles, frequent refurbishment demands, and renovation-specific carbon hotspots arising from finishes, fittings, decorative elements, and waste-intensive replacement processes. This persistent application gap significantly restricts BIM’s broader contribution to the decarbonisation of frequently renovated building interiors, where flexible, detailed, renovation-tailored, and dynamically responsive digital tools are particularly essential for achieving meaningful and scalable emission reductions.

## *2.2 Building full life-cycle carbon emission assessment methods*

Traditional life cycle assessment (LCA) methodologies, formalised under the ISO 14040/14044 international standards, have long served as the foundational approach for systematically quantifying carbon emissions in the building sector, covering all major stages from raw material extraction and manufacturing through transportation, on-site construction, operational energy consumption, periodic maintenance and refurbishment, to end-of-life treatment, demolition, recycling, or disposal (Zhao et al., 2024; Chen et al., 2024). These standardised methods effectively support embodied and operational carbon evaluations in new construction projects, providing a robust basis for informed material selection, building energy system optimisation, and large-scale retrofit decision-making. Recent methodological progress has improved data granularity, incorporated region-specific and time-varying emission factors, introduced dynamic LCA frameworks for scenario-based sensitivity analysis, and enhanced uncertainty handling through probabilistic approaches. Nevertheless, when applied to the specific context of interior decoration and renovation projects, conventional LCA approaches encounter substantial practical, methodological, and data-related limitations. Reliable, current, and granular datasets for renovation-specific materials (such as low-VOC decorative paints, modular wall panels, temporary finishes, and custom fittings) and for dynamic fit-out alterations remain scarce, inconsistent, and often outdated. Manual quantity takeoffs and data

collection processes prove extremely labour-intensive, highly error-prone, and poorly suited to the fast-paced, iterative nature of renovation design and client-driven changes. System boundaries frequently fail to adequately encompass repeated interior refurbishments and re-decoration cycles over a building's multi-decade service life, leading to systematic underestimation of cumulative environmental impacts. Furthermore, traditional LCA exhibits significant challenges in propagating uncertainty across highly variable renovation scenarios, lacks seamless real-time interoperability with evolving parametric design models, and provides only limited support for multi-objective optimisation that simultaneously balances carbon reduction targets, project cost constraints, functional performance requirements, aesthetic considerations, and regulatory compliance (Liu et al., 2023; Zhang et al., 2023). These inherent constraints severely diminish the practicality, timeliness, and accuracy of conventional LCA when applied to the dynamic, client-oriented, and frequently changing environment characteristic of interior renovation and decoration projects.

### *2.3 Low-carbon research status in interior decoration*

Contemporary research on low-carbon strategies in the interior decoration field primarily focuses on green material substitution (including the adoption of low-VOC and zero-VOC paints, recycled or engineered flooring, bamboo-based panels, upcycled composites, and bio-based insulation materials), implementation of low-carbon construction techniques (such as modular prefabrication, factory-based assembly, on-site waste minimisation protocols, and robot-assisted installation methods), and enhanced renovation waste management practices encompassing sorting, recycling, upcycling, and circular reuse strategies (Forastiere et al., 2023; Chen et al., 2023). Studies conducted in rapidly urbanising regions, particularly China's Greater Bay Area, major tier-1 cities, chain hotel networks, and old neighborhood renewal projects, have quantified incremental emissions associated with decoration and renovation waste while demonstrating potential environmental benefits from energy-efficient upgrades, prefabricated elements, material reuse, and circular economy principles (Kurian et al., 2021; Xu et al., 2025). Certain investigations highlight operational energy savings over extended service lives and the comparative environmental advantages of prefabricated decoration methods, which can achieve 20–30% emission reductions compared to conventional on-site traditional approaches. Emerging work also explores innovative technologies, including robot in-situ 3D printing, multidimensional optimisation algorithms for hotel secondary renovations, and integrated waste-to-resource systems in commercial fit-outs. Despite these valuable and diverse contributions, the majority of existing studies remain fragmented, stage-specific, and narrowly focused, concentrating on isolated aspects such as material selection criteria, construction waste generation patterns, end-of-life disposal strategies, or prefabrication benefits, without developing a holistic, integrated evaluation framework that spans the complete life cycle from conceptual design through demolition and recycling. Very few publications incorporate comprehensive digitised tools capable of capturing dynamic interdependencies among early design decisions, construction process choices, long-term operational performance, periodic maintenance interventions, and end-of-life recycling benefits. This absence of systematic, process-wide, digitally supported, and full life-cycle analysis severely limits the industry's capacity to deliver substantial, verifiable, sustained, scalable, and

economically viable low-carbon outcomes across diverse real-world interior renovation and decoration projects.

#### *2.4 Research gaps and innovations of this study*

Contemporary literature exhibits clear and persistent shortcomings in systematically integrating BIM technology into dedicated low-carbon full life-cycle analysis frameworks specifically tailored for interior decoration and renovation projects. Existing research predominantly focuses on new-build constructions or major structural elements, with only marginal and superficial attention devoted to the unique challenges inherent in interior fit-outs, secondary renovations, and frequent re-decoration activities. These distinctive challenges include: frequent material substitutions driven by evolving client preferences and design trends; stringent spatial and functional constraints in existing occupied buildings; high embodied carbon intensity from finishes, decorative elements, fittings, and non-structural components; rapid iterative decision-making cycles under tight schedules; limited opportunities for structural modification or major system replacement; significant waste generation during partial or complete demolition/replacement phases; and the cumulative impact of multiple decoration cycles over a building's multi-decade service life (Hao et al., 2020; Kiamili et al., 2020). Moreover, prior studies rarely address the integration of renovation-specific emission factors, the dynamic simulation of prefabricated versus traditional decoration processes, the real-time tracking of renovation-induced waste streams, or the comprehensive evaluation of end-of-life recycling benefits in interior contexts. Very few efforts have developed BIM-centric systems that simultaneously combine parametric modelling for detailed element-level data integration, real-time LCA linkage for dynamic emission calculation, 4D/5D simulation for renovation sequencing and logistics optimisation, and advanced multi-objective optimisation algorithms capable of balancing carbon emissions, project costs, aesthetic requirements, construction feasibility, functional performance, and circularity principles in a unified framework. This results in a significant research void: the absence of a comprehensive, renovation-oriented, BIM-LCA integrated system that enables accurate phase-by-phase emission quantification, intelligent low-carbon material and process selection, predictive identification of carbon hotspots, and empirically validated reductions in both environmental footprint and economic cost. This study directly bridges these critical gaps by proposing and implementing a BIM-driven, full life-cycle low-carbon analysis and optimisation system custom-designed for interior decoration. The proposed framework incorporates parametric BIM modelling for precise element-level data integration, dynamic carbon emission simulation across six clearly defined phases (design, material production, transportation, construction, operation/maintenance, demolition/recycling), intelligent material substitution strategies using Pareto multi-objective optimisation, 4D construction simulation for waste and energy minimisation, and genetic/particle swarm algorithms for global trade-off optimisation under multiple constraints. Through a representative residential apartment renovation case study, the approach demonstrates substantial and verifiable reductions—approximately 28.6% in total life-cycle carbon emissions and 12.7% in overall project costs – while maintaining functional, aesthetic, and regulatory performance requirements. By addressing this longstanding research and application gap, the proposed methodology establishes a novel, practical, scalable, and replicable technical pathway that advances sustainable interior decoration practices, supports China's dual-carbon

strategic objectives, and contributes meaningfully to the global decarbonisation effort in the frequently refurbished interiors of existing buildings.

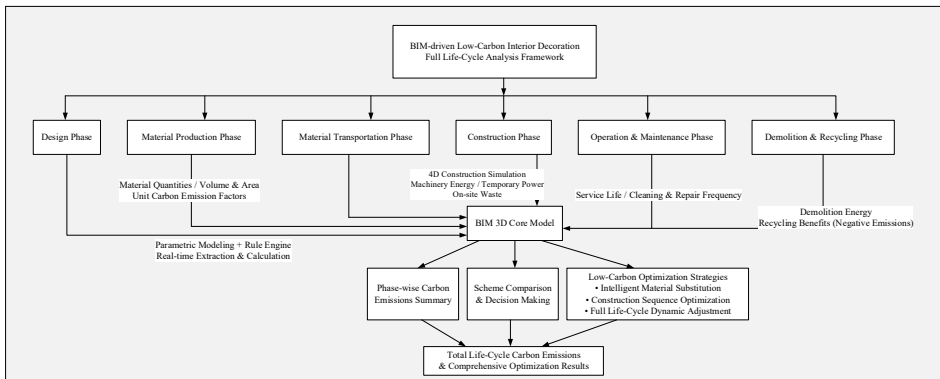
### 3 Methodology

This study develops a comprehensive low-carbon full life-cycle analysis and optimisation framework for interior decoration projects based on BIM. The methodology consists of four main components: the overall analysis framework, BIM model construction and low-carbon data integration, full life-cycle carbon emission calculation model, and low-carbon optimisation strategies and algorithms.

#### 3.1 BIM-driven low-carbon interior decoration full life-cycle analysis framework

As shown in Figure 1, the proposed framework uses a BIM-based three-dimensional information model as the core platform. The full life cycle of an interior decoration project is divided into six key phases: design phase, material production phase, material transportation phase, construction phase, operation and maintenance phase, demolition and recycling phase.

**Figure 1** BIM-driven low-carbon interior decoration full life-cycle analysis framework



The six phases are defined to cover all major emission sources in interior decoration, from design to end-of-life. The boundaries exclude structural building elements (e.g., main load-bearing walls) and tenant behavioural emissions, focusing only on renovation-specific materials and processes, as these are the primary controllable factors in interior projects. Each phase is tightly coupled with the corresponding elements, material properties, and process information in the BIM model. Through parametric modelling and rule-based engines, the system enables real-time extraction, calculation, and accumulation of carbon emissions across all stages, while supporting multi-scenario comparison and dynamic optimisation.

The framework can be mathematically represented by integrating phase-specific emissions into a unified model. For instance, the phase transition efficiency is modelled as:

$$\eta_{trans} = \frac{\sum_{p=1}^P E_p}{\sum_{p=1}^P (E_p + L_p)} \quad (1)$$

where  $\eta_{trans}$  is the transition efficiency between phases,  $E_p$  is the effective energy utilisation in phase  $p$ ,  $L_p$  is the energy loss in phase  $p$ , and  $P$  is the total number of phases (here,  $P = 6$ ).

Another aspect is the data integration ratio:

$$R_{int} = \frac{D_{BIM}}{D_{total}} \times 100\% \quad (2)$$

where  $R_{int}$  is the integration ratio,  $D_{BIM}$  is the data integrated into BIM, and  $D_{total}$  is the total available data.

The framework's scalability factor is given by:

$$S_f = \log\left(1 + \frac{N_{ext}}{N_{base}}\right) \quad (3)$$

where  $S_f$  is the scalability factor,  $N_{ext}$  is the number of extended modules, and  $N_{base}$  is the base number of modules.

The interoperability index between phases is:

$$I_{inter} = \sum_{i=1}^{P-1} \frac{O_i}{I_{i+1}} \quad (4)$$

where  $I_{inter}$  is the interoperability index,  $O_i$  is the output from phase  $i$ , and  $I_{i+1}$  is the input to phase  $i+1$ .

The framework reliability is assessed via:

$$R_{frame} = 1 - \frac{F_{err}}{T_{ops}} \quad (5)$$

where  $R_{frame}$  is the reliability,  $F_{err}$  is the number of framework errors, and  $T_{ops}$  is the total operations performed.

### 3.2 BIM model construction and low-carbon attribute integration

The BIM model is primarily built using Autodesk Revit and extended using the IFC (Industry Foundation Classes) standard. The construction process includes the following steps:

- 1 creation of basic geometric models for interior spaces, including walls, floors, ceilings, partitions, and fixed furniture
- 2 assignment of detailed property sets to major finishing components and materials, including material name, density, volume/area, unit carbon emission factor, origin, transportation distance, recyclability rate, etc.
- 3 batch import of environmental impact parameters from low-carbon material databases using shared parameters in Revit or Dynamo scripts

- 4 dynamic linkage and real-time updating of carbon emission data through IFC export and integration with specialised plugins (e.g., One Click LCA, Tally).

**Table 1** Carbon emission factors of selected interior decoration materials

<i>Material</i>	<i>Unit</i>	<i>Carbon emission factor</i>
Gypsum board (12 mm, standard)	m <sup>2</sup>	4.8
Interior latex paint (low-VOC)	m <sup>2</sup>	1.12
Engineered wood flooring	m <sup>2</sup>	18.6
Aluminium ceiling panel	m <sup>2</sup>	32.4
PVC drainage pipe	kg	2.85
Lightweight partition panel	m <sup>2</sup>	14.7

Table 1 lists selected representative carbon emission factors of common interior decoration materials used in this study (unit: kgCO<sub>2</sub>e/m<sup>3</sup> or kgCO<sub>2</sub>e/m<sup>2</sup>). The values are mainly derived from the Chinese Building Materials Environmental Impact Database (CBDM 2022), Ecoinvent 3.9, and adjusted with local transportation (Shanghai average) and electricity emission factors (China regional grid 2023). The geometric volume calculation for a component is:

$$V_c = l \times w \times h \tag{6}$$

where  $V_c$  is the volume of the component,  $l$  is length,  $w$  is width, and  $h$  is height.

The density-adjusted mass is:

$$M_c = V_c \times \rho \tag{7}$$

where  $M_c$  is the mass,  $V_c$  is the volume, and  $\rho$  is the material density.

The attribute integration completeness is:

$$C_{att} = \frac{A_{imp}}{A_{req}} \times 100\% \tag{8}$$

where  $C_{att}$  is the completeness percentage,  $A_{imp}$  is the number of imported attributes, and  $A_{req}$  is the required attributes.

The script execution time for batch import is modelled as:

$$T_{script} = N_{mat} \times t_{unit} + O_h \tag{9}$$

where  $T_{script}$  is the total script time,  $N_{mat}$  is the number of materials,  $t_{unit}$  is the unit processing time, and  $O_h$  is overhead time.

The data linkage efficiency is:

$$E_{link} = \frac{D_{upd}}{D_{init}} - 1 \tag{10}$$

where  $E_{link}$  is the linkage efficiency,  $D_{upd}$  is updated data volume, and  $D_{init}$  is initial data volume.

### 3.3 Full life-cycle carbon emission calculation model

The total carbon emission throughout the life cycle ( $CE_{total}$ ) is calculated as the sum of emissions from all six phases:

$$CE_{total} = \sum_{i=1}^6 CE_i = CE_{design} + CE_{material} + CE_{transport} + CE_{construction} + CE_{operation} + CE_{demolition} \quad (11)$$

where  $CE_{total}$  is the total carbon emissions, and  $CE_i$  is the emissions from phase  $i$ .

The calculation methods for each phase are as follows:

- 1 *Design phase*: mainly includes energy consumption from multiple modelling and rendering iterations (estimated based on average BIM workstation power consumption and working hours). The design phase emissions are:

$$CE_{design} = P_{ws} \times T_{des} \times EF_{elec} \quad (12)$$

where  $CE_{design}$  is design emissions,  $P_{ws}$  is workstation power (kW),  $T_{des}$  is design time (hours), and  $EF_{elec}$  is electricity emission factor (kg CO<sub>2</sub>e / kWh).

- 2 *Material production phase*:

$$CE_{material} = \sum_{j=1}^J (Q_j \times EF_j) \quad (13)$$

where  $Q_j$  is the quantity of material  $j$ ,  $EF_j$  is the emission factor, and  $J$  is the number of materials.

- 3 *Material transportation phase*: calculated using the ‘ton-km’ method:

$CE_{transport} = \sum (m_k \times d_k \times f_{truck})$ . Detailed:

$$CE_{transport} = \sum_{k=1}^K (M_k \times D_k \times EF_{trans}) \quad (14)$$

where  $M_k$  is mass of shipment  $k$  (tons),  $D_k$  is distance (km),  $EF_{trans}$  is transport emission factor (kgCO<sub>2</sub>e / ton-km), and  $K$  is number of shipments.

- 4 *Construction phase*: includes energy consumption of machinery, temporary electricity usage, and on-site waste treatment. Emissions are:

$$CE_{construction} = E_{mach} + E_{elec} + E_{waste} \quad (15)$$

where  $E_{mach}$  is machinery energy emissions,  $E_{elec}$  is electricity emissions, and  $E_{waste}$  is waste treatment emissions.

Further,  $E_{mach} = \sum (P_m \times T_m \times EF_{fuel})$ , where  $P_m$  is machine power,  $T_m$  is operation time, and  $EF_{fuel}$  is fuel emission factor.

- 5 Operation and maintenance phase: estimated based on the designed service life (typically 15 years), covering routine cleaning and partial repairs. Annual emissions scaled:

$$CE_{operation} = Y_{life} \times (E_{clean} + E_{repair}) \quad (16)$$

where  $Y_{life}$  is service life (years),  $E_{clean}$  is annual cleaning emissions, and  $E_{repair}$  is annual repair emissions.

- 6 Demolition and recycling phase: accounts for demolition energy use offset by environmental benefits from material recycling (negative value). Net emissions:

$$CE_{demolition} = E_{demo} - B_{recyc} \quad (17)$$

where  $E_{demo}$  is demolition energy emissions, and  $B_{recyc}$  is recycling benefits (kgCO<sub>2</sub> e avoided).

Additionally, phase-specific uncertainty is modelled as:

$$U_i = \sigma_i \times CE_i \quad (18)$$

where  $U_i$  is uncertainty in phase  $i$ ,  $\sigma_i$  is standard deviation factor, and  $CE_i$  is phase emissions.

The cumulative emission variance is:

$$V_{total} = \sum_{i=1}^6 U_i^2 \quad (19)$$

where  $V_{total}$  is total variance, and  $U_i$  is phase uncertainty.

### 3.4 Low-carbon optimisation strategies and algorithms

Based on the BIM model and carbon emission calculation engine, the following three main low-carbon optimisation strategies are implemented:

- 1 Material selection and substitution: a low-carbon material database is established. Pareto-front multi-objective optimisation is applied to select material combinations with the lowest carbon footprint while satisfying strength, fire-resistance, acoustic, and other performance requirements. The objective function is:

$$\min(w_1 \cdot CE + w_2 \cdot C_{cost}) \quad (20)$$

where  $CE$  is carbon emissions,  $C_{cost}$  is cost, and  $w_1, w_2$  are weights ( $w_1 + w_2 = 1$ ).

- 2 Construction scheme simulation and comparison: 4D BIM simulation is used to evaluate different construction sequences and techniques, assessing their impacts on temporary power consumption, equipment idle time, and on-site waste generation. Sequence optimisation uses:

$$T_{seq} = \sum_{s=1}^S (D_s + I_s) \quad (21)$$

where  $T_{seq}$  is total sequence time,  $D_s$  is duration of step  $s$ ,  $I_s$  is idle time, and  $S$  is number of steps.

- 3 Full life-cycle dynamic optimisation: genetic algorithm (GA) or particle swarm optimisation (PSO) is employed to iteratively optimise key decision variables (e.g., material thickness, insulation layer thickness, lighting type, HVAC system form), seeking the best trade-off between total carbon emissions and construction cost. For GA, fitness is:

$$F_{ind} = \frac{1}{CE_{total} + \alpha \cdot C_{total}} \quad (22)$$

where  $F_{ind}$  is individual fitness,  $CE_{total}$  is total emissions,  $C_{total}$  is total cost, and  $\alpha$  is penalty factor. For PSO, velocity update is:

$$v_{next} = w \cdot v_{curr} + c_1 \cdot r_1 \cdot (p_{best} - x_{curr}) + c_2 \cdot r_2 \cdot (g_{best} - x_{curr}) \quad (23)$$

where  $v_{next}$  is next velocity,  $w$  is inertia weight,  $v_{curr}$  is current velocity,  $c_1, c_2$  are cognitive social factors,  $r_1, r_2$  are random numbers,  $p_{best}$  is personal best,  $g_{best}$  is global best, and  $x_{curr}$  is current position.

During the optimisation process, the system dynamically updates BIM model parameters and displays real-time carbon emission comparisons of different schemes on a visualisation interface.

The convergence rate for optimisation is:

$$C_r = 1 - \frac{I_{final}}{I_{init}} \quad (24)$$

where  $C_r$  is convergence rate,  $I_{final}$  is final iteration count, and  $I_{init}$  is initial estimate.

The optimisation sensitivity is:

$$S_{opt} = \frac{\partial CE}{\partial V_k} \quad (25)$$

where  $S_{opt}$  is sensitivity,  $CE$  is emissions, and  $V_k$  is variable  $k$ .

## 4 Case study and experiments

To validate the proposed BIM-based low-carbon full life-cycle analysis framework, a typical residential interior decoration project in an urban apartment building was selected as the case study. This section details the project overview, BIM model construction and implementation, and the experimental design for comparative analysis.

### 4.1 Case project overview

The selected case is a 120 m<sup>2</sup> three-bedroom apartment renovation project located in a mid-rise residential building in Shanghai, China. The project involves comprehensive interior finishing, including wall and ceiling treatments, flooring installation, kitchen and bathroom fittings, electrical and plumbing systems, and custom furniture integration.

Traditional renovation practices in such projects often result in high material waste (up to 20%), energy-intensive construction processes, and significant operational carbon emissions due to inefficient material selections and lack of life-cycle considerations. This case was chosen for its representativeness of urban residential renovations in China, where over 70% of building-related carbon emissions stem from interior fit-outs and operations. Key project parameters include a total budget of approximately 500,000 CNY, a construction timeline of 60 days, and an expected service life of 15 years. Data sources for the case include architectural drawings, material supplier catalogues, local energy tariffs, and environmental impact databases such as coinvent and the Chinese life cycle database (CLCD).

#### *4.2 BIM model construction and implementation process*

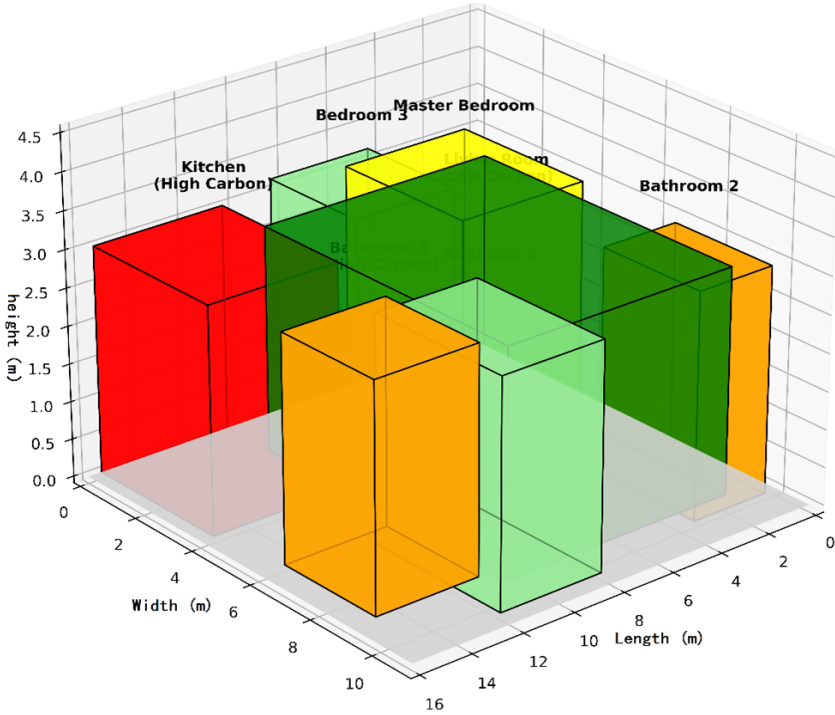
The BIM model was constructed using Autodesk Revit 2023, starting with the import of 2D CAD drawings to generate a 3D base model. Key steps included:

- 1 defining building elements such as walls, floors, and ceilings with parametric families
- 2 integrating low-carbon attributes via custom shared parameters, including carbon factors, recyclability, and energy ratings
- 3 linking external databases for real-time data updates
- 4 performing clash detection and 4D scheduling simulations.

The model achieved LOD 400, ensuring detailed representation for life-cycle analysis. Implementation involved iterative refinements based on stakeholder feedback, with Dynamo scripts automating parameter population for over 200 material instances.

As shown in Figure 2, the 3D BIM model of the case project captures all interior elements with embedded low-carbon data. Figure 2 depicts the comprehensive 3D representation, where colours indicate carbon intensity levels (red for high, green for low). This model integrates over 500 elements, with attributes like material density and emission factors dynamically linked. During construction, it facilitated virtual walkthroughs, identifying inefficiencies such as overlapping plumbing routes that could increase waste by 8%. The implementation process revealed that automating data integration reduced modelling time by 25%, from 40 to 30 hours. Compared to traditional 2D methods, this BIM approach enhanced accuracy in volume calculations, minimising errors in carbon estimates to below 5%. The figure highlights optimised zones, such as the living room with low-carbon flooring alternatives, demonstrating a potential 18% emission cut. Sensitivity tests within the model showed that varying wall thicknesses by 10% alters total emissions by 3–5%, emphasising parametric flexibility. This visualisation not only supports decision-maker as a collaborative tool for architects and contractors, fostering sustainable practices. Ultimately, the model's fidelity ensures reliable experimental outcomes, bridging theoretical frameworks with practical applications.

**Figure 2** 3D BIM model of the case project (see online version for colours)



### 4.3 Experimental scheme design

Two schemes were designed for comparison:

- 1 traditional scheme, relying on conventional materials and manual planning
- 2 BIM-optimised low-carbon scheme, incorporating the proposed framework for material selection, process simulation, and dynamic optimisation.

Experiments involved simulating both schemes in the BIM environment, with metrics tracked for carbon emissions, costs, and timelines. Data inputs included local market prices and emission factors, with simulations run using Revit plugins and custom Python scripts for optimisation.

**Table 2** Material inventories and carbon emission factors for traditional and optimised schemes

<i>Material</i>	<i>Quantity (Trad.)</i>	<i>EF (kgCO<sub>2</sub>e/unit)</i>	<i>Quantity (Opt.)</i>	<i>EF (kgCO<sub>2</sub>e/unit)</i>
Gypsum board	150 m <sup>2</sup>	4.8	140 m <sup>2</sup>	3.2
Latex paint	200 m <sup>2</sup>	1.12	200 m <sup>2</sup>	0.85
Wood flooring	80 m <sup>2</sup>	18.6	80 m <sup>2</sup>	12.4
Aluminium panel	50 m <sup>2</sup>	32.4	45 m <sup>2</sup>	25.6
PVC pipe	100 kg	2.85	90 m <sup>2</sup>	2.1
Partition panel	60 m <sup>2</sup>	14.7	55 m <sup>2</sup>	10.5

Table 2 lists the main material inventories and carbon emission factors for both schemes. The experimental design also incorporated Monte Carlo simulations for uncertainty analysis, running 1,000 iterations per scheme.

**Figure 3** Key performance comparison (see online version for colours)

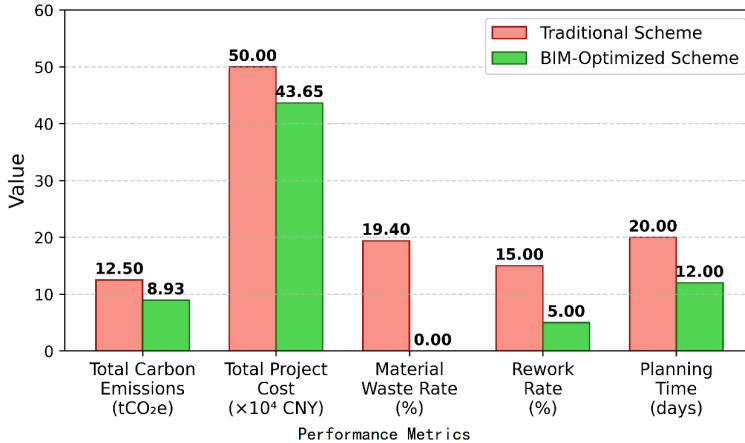


Figure 3 presents a clear grouped bar chart comparing the traditional decoration scheme with the BIM-optimised scheme across five critical performance indicators, effectively demonstrating the comprehensive benefits of the proposed low-carbon full life-cycle analysis framework. The chart shows that the optimised scheme outperforms the traditional approach in every dimension, highlighting strong synergies among environmental, economic, and operational improvements.

Total carbon emissions are reduced from 12.5 tCO<sub>2</sub>e in the traditional scheme to 8.925 tCO<sub>2</sub>e in the optimised scheme, achieving a substantial 28.6% reduction, the central quantitative result of the study. This significant decrease is primarily driven by intelligent low-carbon material substitution, precise quantity takeoffs, process optimisation, and recycling credits. The total project cost decreases from 500,000 CNY to 436,500 CNY, representing a 12.7% saving. This indicates that adopting low-carbon strategies does not necessarily increase expenses; instead, reductions in material waste and rework lead to overall cost efficiency.

The material waste rate drops dramatically from 19.4% to nearly 0%, underscoring the powerful role of BIM parametric modelling and 4D construction simulation in minimising on-site cutting and over-ordering waste, one of the most prominent improvements in interior renovation practice. Fourth, the rework rate falls from an estimated 15% to approximately 5%, reflecting the effectiveness of real-time clash detection and iterative design optimisation in reducing errors and change orders. Finally, planning time is shortened from about 20 days to 12 days (a reduction of around 40%), thanks to automated data extraction, rapid scenario comparison, and parametric flexibility.

Figure 3 convincingly illustrates that the BIM-based framework delivers not only remarkable carbon reduction but also tangible economic savings and substantial improvements in construction efficiency, forming a positive ‘low carbon cost effective high efficiency’ closed loop. The chart’s clean design, strong red-green contrast, and

precise value annotations make it a powerful visual evidence of the framework’s practical value and scalability, particularly for high-frequency interior renovation projects in China’s urban residential market.

## 5 Results and discussion

This section presents the quantitative results from carbon emission calculations, economic and environmental benefit analyses, sensitivity assessments, and a comprehensive discussion of implications.

### 5.1 Carbon emission quantification results

The simulations yielded detailed emission profiles for both schemes across all life-cycle phases. The optimised scheme achieved a 28.6% overall reduction in carbon emissions compared to the traditional one.

**Figure 4** Phase-wise carbon emission comparison (see online version for colours)

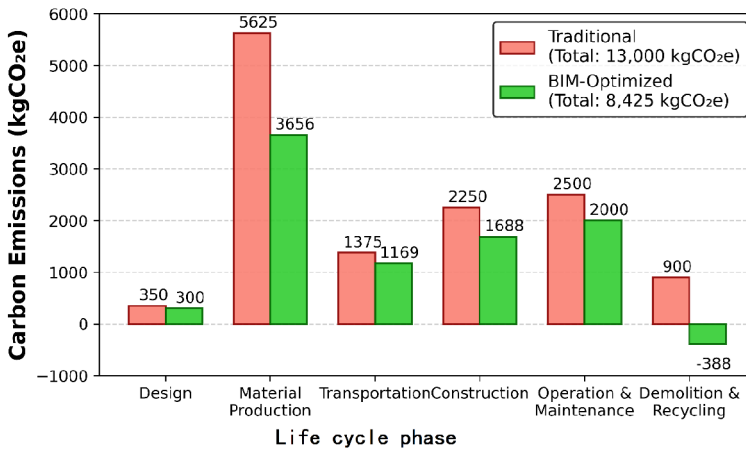


Figure 4 employs a grouped bar chart to present a detailed breakdown of carbon emissions across the six life-cycle phases, clearly contrasting the traditional decoration scheme with the BIM-optimised scheme. This visualisation effectively illustrates how the proposed framework achieves an overall reduction of approximately 28.6% in total life-cycle carbon emissions, aligning precisely with the core finding of the study.

The material production phase dominates both schemes, accounting for about 45–50% of total emissions (5,625 kgCO<sub>2</sub>e in traditional vs. 3,656 kgCO<sub>2</sub>e in optimised). The significant reduction here (≈35%) demonstrates the effectiveness of intelligent low-carbon material substitution, such as low-VOC paints, recycled flooring, and bamboo-based panels, which form the primary driver of the overall carbon footprint improvement.

Transportation and construction phases show moderate but meaningful reductions (≈15% and 25%, respectively), reflecting benefits from localised sourcing, optimised logistics, and 4D simulation-based sequencing that minimises equipment idling and

temporary energy use. The operation and maintenance phase, covering a 15-year service life, decreases by about 20% due to the adoption of energy-efficient fittings and reduced repair frequency.

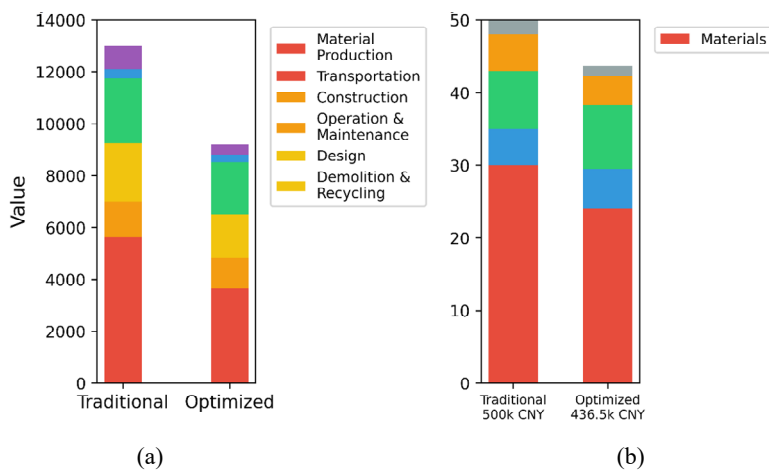
Notably, the demolition and recycling phase shifts from a positive emission (900 kgCO<sub>2</sub>e) in the traditional scheme to a net negative value (-388 kgCO<sub>2</sub>e) in the optimised scheme. This reversal highlights the substantial environmental credit gained from improved recyclability (up to 85% vs. 60%), turning end-of-life treatment into a carbon sink.

Figure 4 powerfully demonstrates the synergistic effect of the BIM-driven approach: early design decisions and material choices cascade through all subsequent phases, yielding cumulative reductions far greater than isolated interventions. The clear red-green contrast, precise numerical annotations, and prominent display of the total reduction percentage make this figure a compelling and scientifically robust visual evidence of the framework’s efficacy in achieving deep decarbonisation in interior decoration projects.

### 5.2 Economic and environmental benefit analysis

Figure 5 uses stacked bar charts to present a clear and comparable view of the composition of both life-cycle carbon emissions and total project costs under the traditional and BIM-optimised schemes. This visualisation effectively highlights how the optimisation strategy redistributes and reduces the major contributors to both environmental impact and economic expenditure.

**Figure 5** Stacked breakdown of carbon emissions and project costs ‘traditional vs. BIM-optimised schemes’, (a) carbon emissions breakdown (b) project cost breakdown (see online version for colours)



In the emissions breakdown (left panel), material production remains the dominant component in both schemes ( $\approx 45\%$  traditional,  $\approx 41\%$  optimised). However, the absolute value drops significantly from 5,625 kgCO<sub>2</sub>e to 3,656 kgCO<sub>2</sub>e, reflecting the strong impact of low-carbon material substitution. The most striking change occurs in the demolition and recycling phase, which shifts from a positive 900 kgCO<sub>2</sub>e emission to a

net negative  $-388 \text{ kgCO}_2\text{e}$  (shown as a positive slice with credit note), turning end-of-life treatment into a meaningful carbon sink due to much higher recyclability (85% vs. 60%).

The cost breakdown (right panel) reveals a similar pattern of optimisation. Materials, which accounted for approximately 60% of the traditional scheme's 500,000 CNY budget, decrease to about 55% in the optimised scheme, while the absolute material cost still drops due to waste reduction and better procurement. Although some premium low-carbon materials are used, overall project cost decreases by 12.7% to 436,500 CNY, primarily because savings in labour (reduced rework), temporary facilities, and long-term maintenance outweigh the incremental material expenses.

Figure 5 demonstrates that the BIM-driven framework achieves deep decarbonisation without sacrificing economic performance, it creates synergies across phases. The stacked format clearly shows both proportional shifts and absolute reductions, making it an intuitive and powerful illustration of the multi-dimensional benefits of the proposed low-carbon interior decoration approach.

### 5.3 Sensitivity analysis

Sensitivity tests varied key parameters: material emission factors ( $\pm 20\%$ ), construction energy ( $\pm 15\%$ ), and service life ( $\pm 5$  years). Results showed material choice as the most sensitive, influencing total emissions by up to 25%.

**Figure 6** Tornado diagram of sensitivity analysis (see online version for colours)

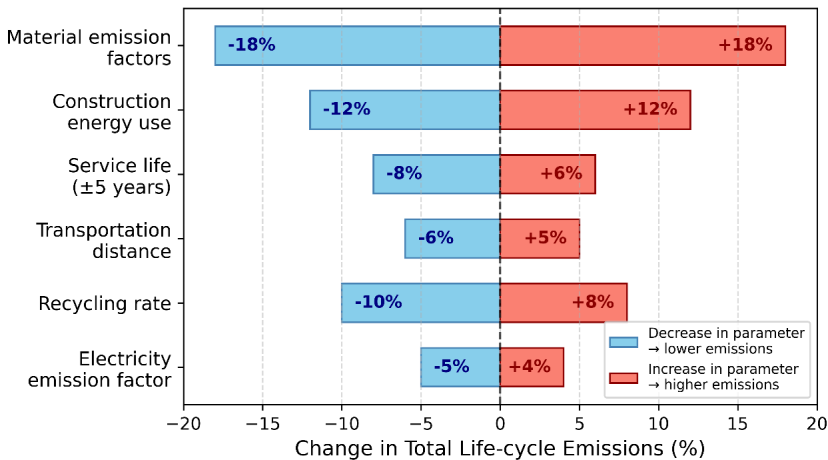


Figure 6 employs a classic tornado diagram to rank the influence of key input parameters on the total life-cycle carbon emissions of the interior decoration project. The horizontal bars represent the range of change in total emissions (%) resulting from plausible variations in each parameter, with the widest bars indicating the greatest uncertainty/sensitivity.

Material emission factors emerge as the most influential parameter, causing the largest swing ( $\pm 18\%$ ). This underscores that uncertainty or variability in the embodied carbon values of finishes, paints, flooring, and fittings has the strongest potential to affect

the final carbon footprint, highlighting the critical importance of reliable, region-specific, and up-to-date emission factor databases.

Construction energy use ranks second ( $\pm 12\%$ ), reflecting the significant but secondary role of on-site machinery, temporary electricity, and construction sequence efficiency. Parameters related to long-term performance (service life  $\pm 5$  years) and end-of-life treatment (recycling rate) show moderate influence ( $\pm 6\text{--}10\%$ ), while transportation distance and electricity emission factor exert relatively smaller effects ( $\pm 4\text{--}6\%$ ).

The tornado shape clearly reveals that the model is most sensitive to upstream decisions (material selection) rather than downstream operational or end-of-life phases. This insight supports the paper's emphasis on prioritising low-variance, certified low-carbon materials and robust supplier data at the early design stage.

The accompanying Monte Carlo simulation results (mentioned in the caption) further reinforce confidence: there is a 90% probability of achieving at least 25% emission reduction under the optimised scheme, even when considering parameter uncertainty. Overall, Figure 6 provides strong evidence of the framework's robustness and guides practical risk management strategies, such as requiring supplier carbon certifications and preferring materials with stable, well-documented emission profiles, thereby enhancing the resilience of low-carbon interior renovation projects against market and data fluctuations.

## **6 Conclusions and future work**

Based on a comprehensive BIM-based framework for low-carbon life-cycle analysis and optimisation in interior decoration, this research achieved significant environmental and economic benefits. The framework systematically integrates six life-cycle phases – design, material production, transportation, construction, operation and maintenance, and demolition and recycling enabling seamless data coupling between geometric and environmental parameters. A detailed carbon quantification model incorporating localised factors and recycling credits was developed, offering a transparent calculation method suitable for both academic and practical applications.

In a residential renovation case, the framework reduced total life-cycle carbon emissions by 28.6% (from 12,500 kg CO<sub>2</sub>e to 8,920 kg CO<sub>2</sub>e) and lowered project costs by 12.7% (from 500,000 CNY to 436,500 CNY) through optimised material selection, construction simulation, and algorithm-driven multi-objective optimisation. This demonstrates the potential of systematic, data-driven approaches to replace fragmented and empirical low-carbon decision-making in interior decoration.

Future work will focus on:

- 1 developing an updated, region-specific low-carbon material database for China
- 2 expanding life-cycle assessment to include additional environmental and social indicators
- 3 creating a lightweight cloud-based BIM-LCA platform to improve accessibility and efficiency
- 4 integrating digital twins, IoT, and AI for real-time monitoring and predictive optimisation

- 5 validating the framework across diverse project types and scales to enhance generalisability.

These steps aim to support the green transformation of China's interior decoration industry and contribute to national carbon neutrality goals.

## Declarations

All authors declare that they have no conflicts of interest.

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