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Carbon emission measurement and reduction analysis of typical campus buildings using building information modeling and life cycle assessment

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Abstract

Under the dual carbon goals, carbon emission reduction in the building sector has become a critical step in advancing sustainable development. As a type of intensively used public building, campus buildings significantly influence the overall carbon footprint of campuses due to their high emission profiles. This study employs building information modeling and life cycle assessment to develop a systematic life-cycle carbon emission analysis model for a university building in Hangzhou, China, covering stages from material production and construction to operation and demolition. The carbon footprint of each phase was quantitatively measured. Results indicate that the total life-cycle carbon emissions of the project reached 15,718.97 tCO_2e. After accounting for a reduction of 13,11.48 tCO_2e achieved through material recycling and green carbon sinks, the carbon emission intensity per unit area was 18,84.74 $kgCO_2e$/sqm. In terms of emission distribution, the operational phase contributed 85.01 percent of the total emissions, with the heating, ventilation, and air conditioning system identified as the primary energy consumer. The material production phase accounted for 18.36 percent of emissions, largely due to the use of carbon-intensive materials such as steel and concrete. This study provides empirical data support and methodological references for the low-carbon design and management of campus buildings, facilitating the implementation of energy-saving and emission-reduction requirements in universities.

Keywords: Carbon emissions; Campus buildings; Emission intensity; Building information model; Life cycle assessment

1. Introduction

The building sector plays a critical role in addressing global climate change, and its energy consumption and carbon emissions have drawn significant attention (A. Atmaca & Atmaca, 2022; Z. Sun *et al.*, 2022). Globally, the construction industry accounts for over 40 percent of total energy use, while in China, building-related carbon emissions represent approximately 20 percent of the national total energy consumption (H. Gao *et al.*, 2023; Hu *et al.*, 2022). Therefore, integrating carbon emission indicators into the life-cycle assessment framework during the early design phase is essential for holistic management of building-related greenhouse gas emissions (M. Chen *et al.*, 2022). This approach enables a systematic evaluation of the cumulative carbon impact across stages such as construction and demolition (Z. Huang *et al.*, 2024).

In public buildings, operational carbon emissions are primarily influenced by equipment usage duration and energy consumption levels (N. Atmaca *et al.*, 2021). Although design-phase interventions have limited impact on operational emissions, they can significantly reduce embodied carbon during the materialization stage (Peng, 2016). Compared to residential buildings, public buildings are characterized by functional complexity, diverse user groups, and pronounced social attributes. Accurate measurement and effective control of carbon emissions in such buildings are crucial for achieving emission reduction targets in the construction sector (Kairies-Alvarado *et al.*, 2021). As densely occupied spaces, campus buildings have attracted growing attention regarding their emission profiles and management strategies.

Building information modeling (BIM) serves as a digital tool for integrating and managing comprehensive building information, including geometry, materials, and equipment. Life cycle assessment (LCA), on the other hand, is a systematic environmental management method used to evaluate the environmental impacts of products, processes, or activities from raw material extraction to end-of-life disposal (K. Li *et al.*, 2022). In recent years, LCA has been increasingly applied in building carbon emission accounting, with its core objective being to identify and quantify environmental burdens throughout the life cycle, thereby providing scientific support for decision-making (Kairies-Alvarado *et al.*, 2021; K. Li *et al.*, 2022).

Integrating BIM and LCA allows for precise quantification of life-cycle carbon emissions by leveraging detailed building data from BIM models (Heydari & Heravi, 2023). However, the current carbon accounting system in the construction industry—particularly for public buildings—remains underdeveloped (Z. Huang *et al.*, 2024; Rabani *et al.*, 2021). Some regions have begun incorporating BIM and LCA requirements into approval procedures, such as submitting BIM models with preliminary LCA results during design review to illustrate emissions related to materials and energy use (R. Chen *et al.*, 2023; Z. Huang *et al.*, 2024). Nevertheless, inconsistencies in regional and industrial standards often lead to procedural challenges (Ding *et al.*, 2024; H. Gao *et al.*, 2024). Challenges such as lack of unified norms, complex data management, and technical capacity gaps continue to hinder the formal adoption of BIM–LCA in regulatory processes (Z. Huang *et al.*, 2024; X. Li *et al.*, 2022).

To address these issues, this study focuses on campus buildings and develops a carbon emission calculation model based on the emission-factor approach. By integrating BIM technology with carbon emission analysis, we propose a consolidated approach for quantifying life-cycle carbon emissions, enabling stakeholders to clearly identify emission characteristics at each stage and formulate effective mitigation strategies.

2. Methodology

2.1. Research scope

In the pursuit of dual carbon goals, campuses as pioneering zones for socioeconomic development should play a demonstrative role in sustainability (K. Liu & Leng, 2022). Accurately quantifying building carbon emissions, particularly from daily teaching activities, is fundamental to developing low-carbon campuses (K. Liu & Leng, 2022; Y. Liu *et al.*, 2023). Accordingly, this study developed a comprehensive carbon emission assessment framework for typical campus buildings based on whole-life-cycle evaluation theory and the functional characteristics of campus architecture, as illustrated in Figure 1 (Kairies-Alvarado *et al.*, 2021; K. Liu & Leng, 2022). The quantification process includes defining system boundaries, identifying emission sources, collecting activity data, calculating emissions, evaluating uncertainties, and performing analytical corrections (Heydari & Heravi, 2023; Rabani *et al.*, 2021).

2.2. Carbon emission calculation

Methodologically, the emission-factor approach was adopted due to its high data availability and operational simplicity. With the continuous improvement of authoritative emission factor databases, this method has been widely applied in building carbon accounting (Min *et al.*, 2022; Rabani *et al.*, 2021). Core procedures involve identifying greenhouse gas sources, selecting appropriate emission factors, integrating activity data, and accumulating results to determine total emissions (Hu *et al.*, 2022; Kairies-Alvarado *et al.*, 2021). This study primarily employed emission factors from the *Standard for Building Carbon Emission Calculation* (GB/T 51366-2019). For data gaps or parameters difficult to obtain through direct measurement, supplementary factors were drawn from existing databases and relevant literature (Erdogan, 2021; Lai *et al.*, 2023).

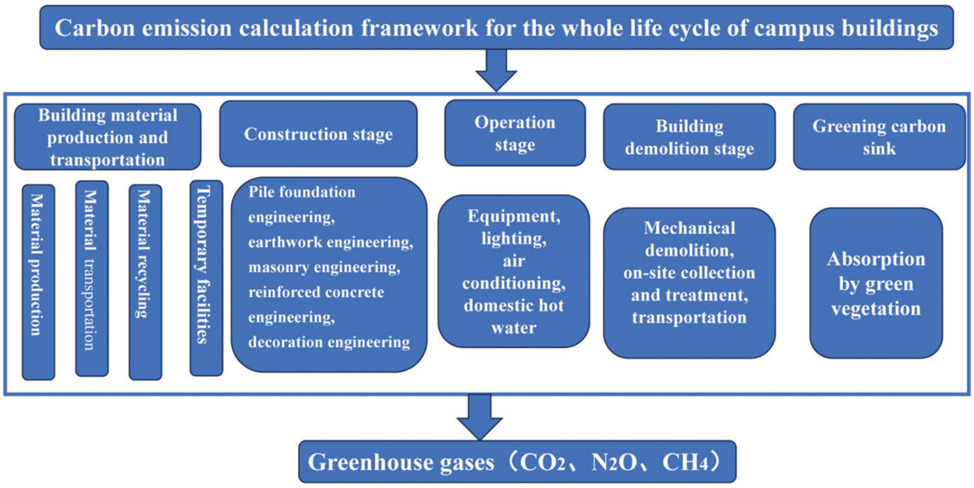

Figure 1. Carbon emission activities of typical campus buildings
Source: Diagram by the authors.

Given the diversity and complexity of carbon emission activities throughout a building's life cycle, not all emission-related data can be fully measured (Forth *et al.*, 2023; Luo & Chen, 2020). Therefore, this study focuses on key activities with substantial emission contributions, while excluding those that are difficult to quantify or have a negligible impact. The collected activity data cover four phases: Production, construction, operation and maintenance, and demolition (Luo & Chen, 2020; Peng, 2016). The production phase focuses on the quantities and energy consumption of materials, components, and equipment (B. Huang *et al.*, 2024; Su *et al.*, 2023). The construction phase includes transport, machinery operation, water consumption, and on-site energy use for management (Min *et al.*, 2022; Zhang *et al.*, 2023). The operation and maintenance phase covers energy consumption of building systems as well as material and energy use for maintenance and replacements (Al-Obaidy *et al.*, 2022; L. Huang *et al.*, 2018). The demolition phase comprises energy consumed by demolition machinery and waste transportation (N. Atmaca *et al.*, 2021; Cai *et al.*, 2022). By extracting and analyzing these key datasets, a systematic evaluation of the building's overall carbon emissions can be achieved (Z. Huang *et al.*, 2024).

For the operational phase carbon accounting, this study utilized the Donghe Building Carbon Emission Analysis Software (Jiangsu Dongyin Intelligent Engineering Technology Research Institute, China) (Y. Sun *et al.*, 2024; Zhao *et al.*, 2024). Input parameters include fundamental building information and detailed specifications for hot water, lighting, elevators, heating, ventilation, and air conditioning (HVAC), natural gas, photovoltaic systems, and solar water heating (L. Huang *et al.*, 2018; Y. Liu *et al.*, 2023). Operational variables, such as occupant density, occupancy rates, lighting and equipment utilization, and HVAC operating schedules, were determined based on data from comparable buildings and the *Zhejiang Public Building Energy Efficiency Design Standard*.

2.3. Case study

The case study focused on a campus construction project in Hangzhou (Figure 2), located in a region with hot summers and cold winters. The structure employed a shear wall system, with a total gross floor area of 8,340.11 sqm (above-ground only), a building volume of 33,362.86 m^3, an exterior surface area of 8,313.70 sqm, and a shape coefficient of 0.25. The five-story building (with no basement) stands 18.4 m tall and has a designed service life of 50 years. Floors 1–3 are standard floors, sharing identical layout configurations and material specifications, making them representative for design analysis.

A detailed model was developed using Glodon measurement and costing software (Glodon Technology Co., Ltd, China) alongside BIM applications, generating a comprehensive bill of quantities (BOQ). During component modeling, particular attention was paid to dimensional and material attributes, with naming conventions following precise and concise principles to minimize data redundancy (H. Gao *et al.*, 2024; Luo & Chen, 2020). As the original quantity data could not be directly applied to carbon emission calculations, consumption quotas were utilized to refine the data, transforming it into actionable inputs for energy, water, and human activity parameters (H. Gao *et al.*, 2024; X. Li *et al.*, 2022).

Building on this processed BOQ and referencing the *Standard for Building Carbon Emission Calculation* (GB/T51366-2019) along with the Donghe Building Carbon

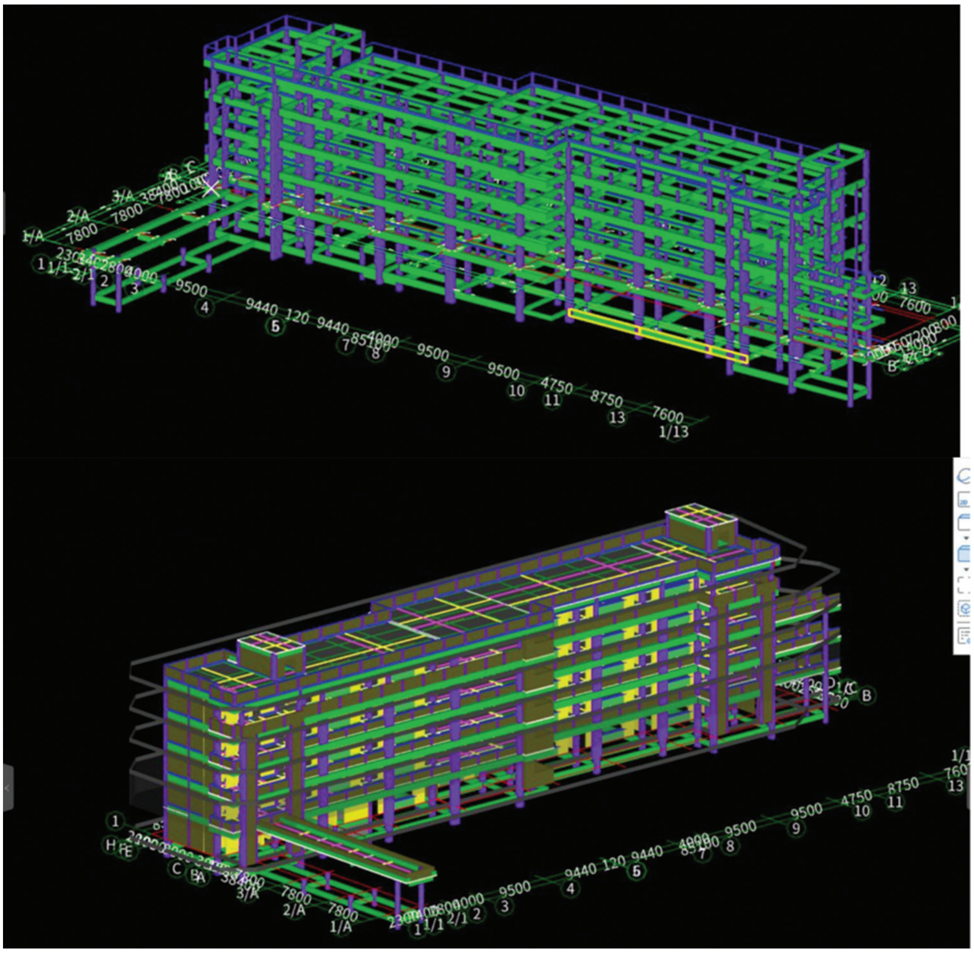

Figure 2. Architectural appearance generated using Glodon GTJ2021 software (building information modeling model)
Source: Diagram by the authors.

Emission Factor Database V1.0, appropriate emission factors were selected. Calculations were conducted within the framework established, as shown in Figure 1. Following the logical structure of the bill quantity-based cost estimation method, the system identifies material types and machinery specifications from project lists, obtaining unit carbon emission coefficients through standardized quotas and literature review (Ding *et al.*, 2024; X. Li *et al.*, 2022). By substituting original unit prices with corresponding carbon emission coefficients for construction materials and equipment, systematic carbon accounting was achieved (Z. Huang *et al.*, 2024; Kairies-Alvarado *et al.*, 2021).

3. Results and discussion

3.1. Building material production and transportation

As presented in Table 1, the total carbon emissions from building material production in this project were 2,885.57 tCO_2e. Structural analysis revealed that steel reinforcement accounted for the highest proportion at 33.82 percent, followed by concrete (18.76%), cement mortar (17.38%), and aerated concrete block B07 (13.03%). Collectively, these four materials represented over 83 percent of the production-phase emissions, indicating the primary sources. Structural materials such as reinforced concrete exhibit significantly higher carbon intensity compared to other building materials due to their energy-intensive manufacturing processes (Rabani *et al.*, 2021; Su *et al.*, 2023). Given that the consumption of such high-emission materials is closely associated with structural design, low-carbon material substitution and structural efficiency optimization should be considered during the design phase to achieve emission reduction at the source. Promoting green building materials, optimizing procurement strategies, and incorporating life-cycle cost analysis can enhance overall project benefits while controlling carbon emissions.

Based on the project's material list and the provisions of the *Standard for Building Carbon Emission Calculation*

Table 1. Results of carbon emissions in the building material production stage

Types of building materials	Usage quantity	Unit	Production factor (tCO_2e/unit quantity)	Carbon emission (tCO_2e)
Steel bars	417.00	t	2.34	975.78
Concrete	1,834.80	m^3	2.95×10^{-1}	541.27
Cement mortar	686.85	m^3	7.302×10^{-1}	501.53
Autoclaved aerated concrete blocks (B07)	1,504.06	m^3	2.5×10^{-1}	376.01
Rock wool boards	16.63	t	1.98	32.92
Thermal insulation metal-profile multi-cavity frames	353.60	sqm	2.54×10^{-1}	89.81
6 mm transparent+12 mm air+6 mm transparent	42.43	t	2.84	120.51
Wood (plastic) frame single-layer solid doors	513.77	sqm	2.54×10^{-1}	130.50
Fine stone concrete	222.17	m^3	2.95×10^{-1}	65.54
Extruded polystyrene foam boards	6.10	t	5.02	30.63
Lightweight aggregate concrete (for ramming)	148.17	t	1.26×10^{-1}	18.67
Compacted clay	953.59	t	2.51×10^{-3}	2.39
Total	-	-	-	2885.57

(GB/T 51366-2019), this study assessed the transportation modes and distances for various building materials. Road transport was the predominant mode, utilizing medium- and heavy-duty diesel trucks with different loading capacities (Hu *et al.*, 2022; Z. Huang *et al.*, 2024). Concrete was transported over a distance of 40 km, while all other materials were transported over 500 km. Where available, actual transportation data were prioritized—in cases of data gaps, default values from Appendix E of the GB/T 51366-2019 standard were applied.

As shown in Table S1, the total carbon emissions from the material transportation stage were 722.57 tCO_2e. Cement mortar accounted for the largest share at 28.57 percent, followed by aerated concrete block B07 (24.33%), compacted clay (22.04%), and steel reinforcement (9.64%). Together, these four materials constitute the main sources of transportation-related emissions. Transport emissions are primarily influenced by two factors: Transportation distance and material weight (Luo & Chen, 2020; Rabani *et al.*, 2021). Under the same transport mode, longer distances and heavier materials result in proportionally higher emissions. For bulk materials transported over long distances, such as cement mortar and aerated blocks, efforts should focus on developing localized supply chains or shifting to lower-carbon transport modes, such as rail or waterway, to effectively reduce transportation carbon intensity (H. Gao *et al.*, 2024; Z. Huang *et al.*, 2024).

According to Table S2, the carbon emissions from the material recycling stage—including transport—total 737.23 tCO_2e for steel reinforcement and 216.26 tCO_2e for aerated concrete block B07, making these the dominant sources in this phase. These results are closely associated with the high energy consumption for transporting these materials (Al-Obaidy *et al.*, 2022; A. Atmaca & Atmaca, 2022).

To assess recycling potential, this study adopted recovery rates based on local industry averages. Steel typically exhibits high recovery rates (90–95%), and recycled scrap steel can be directly used in new steel production, offering significant substitution benefits (Kairies-Alvarado *et al.*, 2021; Lai *et al.*, 2023). In addition, this study applied a conservative, lower-bound recovery rate for steel. Concrete recycling primarily targets the recovery of embedded steel reinforcement, and the resulting crushed concrete can be used as recycled aggregate to replace natural sand and gravel, with recovery rates generally ranging from 70 percent to 90 percent. The recycling factor, defined as the greenhouse gas emissions avoided per unit of recycled material replacing virgin material, was sourced mainly from the GB/T 51366-2019 standard.

Compared to the total production-phase emissions of 2,885.57 tCO_2e, effective recycling of construction waste at the end of the building's service life could reduce production-phase emissions by approximately 34.79 percent. This underscores the significant potential of recycling in lowering the carbon footprint across the building's life cycle.

As summarized in Table 2, the total carbon emissions related to building materials across production, transport, and recycling amounted to 2,604.15 tCO_2e. The production phase is the largest contributor, accounting for 2,885.57 tCO_2e, followed by transport (722.57 tCO_2e). Material recycling resulted in a net reduction of 1,003.98 tCO_2e. This emission profile reflects the energy-intensive nature and high embodied carbon of key materials, such as reinforced concrete, in the current building supply chain. From an engineering economics perspective, the carbon offset achieved through recycling not only demonstrates a systematic improvement in the carbon footprint through circular utilization but also highlights the potential for dual environmental and economic benefits through optimized material cycling systems over the building's entire life cycle (X. Li *et al.*, 2022; Zhang *et al.*, 2023).

3.2. Construction stage

Based on the BOQ and BIM technology, this study systematically quantified carbon emissions during the construction phase of the building project (Z. Huang *et al.*, 2024; Kairies-Alvarado *et al.*, 2021). As presented in Tables S3 and S4, the BOQ generated through Glodon BIM—combined with machinery shift counts and energy consumption data—enabled carbon emission quantification for both work sections and provisional measures using corresponding emission factors.

As shown in Table 3, the total carbon emissions during the construction phase reached 250.828 tCO_2e, with work sections and provisional measures contributing 96.340 tCO_2e and 131.526 tCO_2e, respectively. The emission intensity per unit area was calculated at 30.07 $kgCO_2e$/sqm. Energy consumption by temporary construction facilities was estimated at 3.3 percent of work sections' energy use, further demonstrating its correlation with project scale and duration. The emission structure analysis revealed that construction machinery constitutes the primary emission source, with dump trucks, freight trucks, auger drilling rigs, concrete pumps, and butt welders identified as key contributing equipment (X. Li *et al.*, 2022; K. Liu & Leng, 2022).

To enhance carbon management efficiency during construction, contractors are recommended to integrate green construction principles into organizational planning. This can be achieved through optimizing construction sequences, rationalizing equipment selection and deployment, and implementing systematic site management strategies (Y. Liu *et al.*, 2023; Rabani *et al.*, 2021; Zhao *et al.*, 2024). The methodology employed illustrates how BIM-integrated quantity data can support precise carbon accounting in construction operations, thereby providing a foundation for targeted emission reduction measures in campus building projects (L. Huang *et al.*, 2018; Y. Sun *et al.*, 2024).

Table 2. Carbon emissions from the production and transportation of building materials

Stage	Carbon emission (tCO_2e)
Production stage	2,885.57
Transportation stage	722.57
Recycling stage	−1,003.98
Total	2,604.15

3.3. Building operation stage

Based on the results in Table 4, the total life-cycle carbon emissions during the operational phase of the case-study building amounted to 13,362.45 tCO_2e, with a carbon intensity of 1,602.19 $kgCO_2e$/sqm and an annual average of 0.03 tCO_2e/sqm. The energy consumption structure reveals that the HVAC system constitutes the largest emission source (59.74%), followed by equipment operation (27.70%) and lighting systems (12.51%), collectively representing the primary contributors to operational carbon emissions. The high concentration of emissions in the operational phase underscores the critical importance of systematic energy efficiency improvements in building energy management.

As the dominant emission source, the carbon reduction potential of HVAC systems is closely linked to the thermal performance of the building envelope. Research indicates that in hot-summer and cold-winter climates, increasing wall insulation thickness—while raising embodied carbon—can effectively reduce cooling demand during operation, although the marginal abatement effect declines with additional insulation (Y. Liu *et al.*, 2023; Peng, 2016). Notably, applying these findings to regions with higher heating demands (e.g., severe cold zones) or to continuously occupied building types (e.g., hospitals

Table 3. Carbon emissions from sub-projects, sub-items, and measure items

Type of energy consumed	Energy consumption	Lower calorific value of fuel	Carbon emission factor	Carbon emissions (tCO_2e)
Diesel for sub-projects and sub-items (kg)	1,553.15 kg	43.330 GJ/t	3.1453247	4.885
Electricity for sub-projects and sub-items	160,446.84 kWh	-	0.57	91.455
Diesel for measure items	5,211.90 kg	43.330 GJ/t	3.1453247	16.393
Electricity for measure items	227,777.28 kWh	-	0.57	129.833
Construction temporary facilities	-	-	-	8.262
Total	-	-	-	250.828

or data centers) would likely result in significantly higher absolute operational emissions and emission shares (N. Atmaca *et al.*, 2021; Cai *et al.*, 2022). To decarbonize building operations, a two-tier approach is recommended: (i) integrating envelope performance and equipment efficiency considerations during the design phase to optimize thermal design and system configuration; and (ii) actively promoting the integration of solar, wind, and other low-carbon energy sources into building energy systems, thereby facilitating a gradual transition toward a renewable-dominated energy supply to achieve synergistic environmental and long-term economic benefits.

3.4. Demolition stage

As detailed in Table 5, the demolition phase of the case-study building generated total carbon emissions of 151.057 tCO_2e, corresponding to an intensity of 18.11 $kgCO_2e$/sqm. These emissions primarily resulted from diesel consumption by machinery—including dump trucks (77.194 tCO_2e) and wheeled loaders (52.318 tCO_2e)—as well as from manual labor operations (21.546 tCO_2e). Demolition, being the reverse process of construction, mainly produces carbon emissions through energy consumed by demolition and transport equipment (L. Huang *et al.*, 2018; Z. Huang *et al.*, 2024).

The present study considered both manual and mechanical demolition methods, excluding specialized techniques such as blasting (Luo & Chen, 2020; Peng, 2016). Since the building has not yet been demolished, emissions were estimated using a quota-based method based on material quantity data from the production phase—an approach consistent with common practices for estimating demolition-phase carbon emissions in existing buildings (L. Huang *et al.*, 2018; Lai *et al.*, 2023). It should be noted that emissions associated with construction waste treatment have been accounted for separately in the materials recycling phase and are not included in this stage. Although the demolition phase contributes a relatively small proportion of the building's total life-cycle carbon emissions, there remains potential for further emission reduction and process optimization (R. Chen *et al.*, 2023; Z. Sun *et al.*, 2022).

3.5. Effect of carbon emission reduction in the green carbon sink stage

As detailed in Table 6, the green carbon sink system achieved a total carbon reduction of 307.50 tCO_2e. With subtropical densely planted shrubs as the dominant vegetation type, their carbon reduction contribution reached 225.00 tCO_2e, representing 73.17 percent of the total. Subtropical small broad-leaved trees and coniferous species, which possess stronger carbon sequestration capabilities, accounted for 75.00 tCO_2e (24.39%), while herbaceous and aquatic plants exhibited relatively limited carbon sink potential, contributing merely 7.50 tCO_2e (2.44%). Functioning as a crucial component in the building's life-cycle carbon balance, the green carbon sink displayed distinct structural characteristics within the constrained greening area (site area: 10,000 sqm; greening ratio: 10%).

Based on the findings, although the annual carbon sequestration capacity per unit area of densely planted shrubs was lower than that of tree species, their substantial planting proportion (60% of the total greening area) positioned them as the primary carbon sink contributor.

Table 4. Results of carbon emissions during building operation

Type of energy consumption	Annual equivalent electricity consumption (kWh/a)	Energy usage (kWh or m^3 or kg)	Carbon emission factor (tCO_2e/unit usage)	Carbon emissions over the life cycle (tCO_2e)
Heating	97,894.87	97,894.87	5.81×10^{-4}	2,843.85
Air conditioning	176,891.39	176,891.39	5.81×10^{-4}	5,138.69
Lighting	57,532.31	57,532.31	5.81×10^{-4}	1,671.31
Equipment	127,396.80	127,396.80	5.81×10^{-4}	3,700.88
Ventilator	265.63	265.63	5.81×10^{-4}	7.72
Total	459,980.99	0.00	-	13,362.45

Table 5. Carbon emission calculation results for the demolition stage

Type of energy consumption	Energy consumption	Lower calorific value of fuel	Carbon emission factor	Carbon emissions (tCO_2e)
Dump truck	Loading capacity: 8 t	24,542.35 kg diesel	3.1453247	77.194
Rubber-tired loader	Bucket capacity: 0.5 m^3	16,633.49 kg diesel	3.1453247	52.318
Manual labor	Man-days	19,410.84	1.11	21.546
Total	-	-	-	151.057

This pattern highlights the critical role of vegetation configuration in determining overall carbon sequestration effectiveness under predefined spatial constraints (L. Huang *et al.*, 2018; Y. Sun *et al.*, 2024; Z. Sun *et al.*, 2022). For enhanced project performance, it is recommended to integrate carbon sink metrics into the landscape assessment framework during campus building planning and design phases. Through a holistic evaluation that balances plant growth cycles, maintenance requirements, and carbon sequestration potential, optimized greening configurations can be developed to maximize ecological and economic benefits across the project's life cycle.

4. Carbon emission evaluation and emission-reduction analysis within campus buildings

This study employed an integrated BIM–LCA framework to conduct a systematic, quantitative analysis of carbon emissions throughout the life cycle of a campus building. As shown in Figure 3, the project's total carbon emissions amounted to 15,718.97 tCO_2e, with an intensity of 1,884.74 $kgCO_2e$/sqm. Through material recycling and green carbon sink implementation, a total reduction of 1,311.48 tCO_2e was achieved, highlighting the synergistic value of circular economy principles and ecological compensation in building carbon management (Bayer & Pruckner, 2024; Cang *et al.*, 2020; Mostafavi *et al.*, 2021).

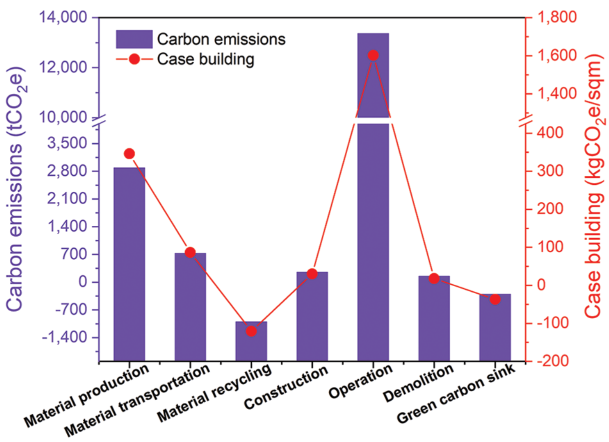

Figure 3. Life-cycle assessment of carbon emissions for the building
Source: Diagram by the authors.

The emission-structure analysis (Figure 4) revealed that the operational phase was the dominant contributor, accounting for 85.01 percent of total emissions (13,362.45 tCO_2e), with an intensity of 1,602.19 kgCO2e/sqm. The material production phase followed at 18.36 percent (2,885.57 tCO_2e), exhibiting an intensity of 345.99 $kgCO_2e$/sqm. Other phases, including material transportation, construction, and demolition, each contribute >5 percent, indicating their relatively limited impact on the overall life-cycle carbon footprint.

Comparative analysis with a similar office building (Figure 5) revealed that the operational carbon intensity of the case-study teaching building exceeded that of the office building by a factor of 2.3. This significant disparity primarily results from its functional characteristics: As a teaching facility, it features higher occupant density, stricter indoor environmental requirements, and consequently, substantially greater HVAC operational loads and duration compared with conventional office buildings.

In the embodied carbon phase (material production, transportation, and construction), the case-study building also exhibited consistently higher emission intensities (Z. Huang *et al.*, 2024; Kairies-Alvarado *et al.*, 2021). In particular, during the transportation and construction phases, the intensities were 16.3 and 6.0 times higher than those of the office building, respectively. This can be attributed to both the adoption of shear wall structures, which require larger quantities of steel and concrete, and the amplification effect of project scale on logistics and construction organization-related emissions.

During the operational phase, emission reduction efforts should prioritize enhancing HVAC system efficiency, promoting renewable energy integration, and reducing environmental control loads through optimized building envelope thermal performance and orientation

Table 6. Carbon emission reduction calculation results for the green carbon sink

Greening type	Annual CO_2 fixation of greening type (tCO_2e/[sqm·a])	Proportion of the type (%)	Greening area (sqm)	Planting duration (years)	Emission reduction (tCO_2e)
Sub-tropical broad-leaved small trees, coniferous trees, thinly leaved trees	0.015000	10.00	100.00	50.00	75.00
Sub-tropical densely-planted shrubs	0.007500	60.00	600.00	50.00	225.00
Sub-tropical flower nurseries, natural wild grasses, lawns, aquatic plants	0.000500	30.00	300.00	50.00	7.50
Total	-	-	-	-	307.50

Abbreviation: CO_2: Carbon dioxide.

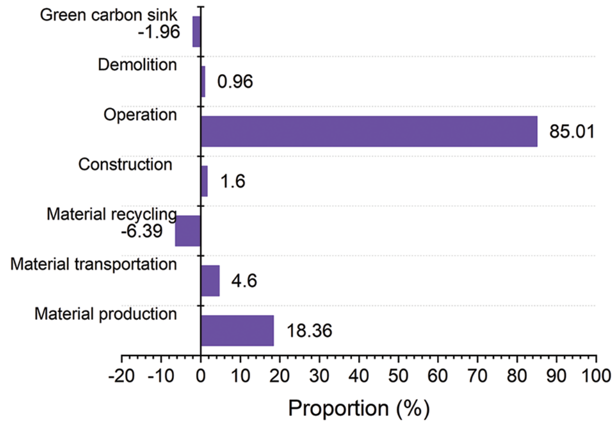

Figure 4. Proportion of carbon emissions in each stage
Source: Diagram by the authors.

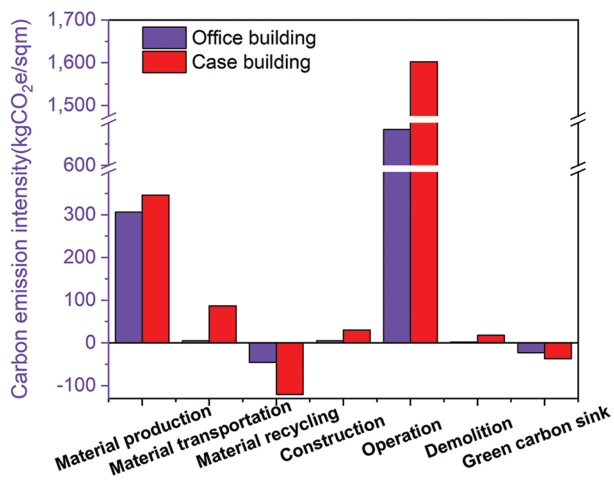

Figure 5. Carbon emission intensity between the case-study building and the office building
Source: Diagram by the authors.

(Hu *et al.*, 2022; Mostafavi *et al.*, 2021). For the embodied carbon phase, the focus should be on structural system optimization and low-carbon material substitution, emphasizing recycled concrete and other green building materials while establishing localized supply chains to minimize transportation-related emissions (Cai *et al.*, 2022; Cang *et al.*, 2020). In the demolition phase, the adoption of precision disassembly techniques and graded material recovery systems is recommended to improve the recycling rates of waste concrete and non-metallic materials.

5. Conclusion

In this study, an integrated BIM–LCA framework was developed for assessing life-cycle carbon emissions in campus buildings, systematically quantifying the carbon footprint across the material production, construction, operation, and demolition phases. Analysis of the case building revealed total emissions of 15,718.97 tCO_2e and a carbon intensity of 1,884.74 $kgCO_2e$/sqm, while recycling and greening initiatives achieved a net reduction of 1,311.48 tCO_2e. The emission profile indicated a high concentration of emissions in specific phases: the operational phase accounted for 85.01 percent of total emissions, followed by material production at 18.36 percent, suggesting that operational energy use and structural material selection represent the primary emission sources. These findings underscore that carbon reduction strategies for campus buildings should focus on improving HVAC system efficiency, optimizing the thermal performance of building envelopes, promoting the use of renewable electricity, and expanding the adoption of low-carbon building materials. This study demonstrates the effectiveness of the BIM–LCA framework in building carbon accounting and low-carbon decision support, providing a methodological foundation and practical reference for whole-life carbon management in campus and similar public buildings. Future research should further explore carbon emission characteristics under different climatic conditions and usage patterns to enhance the generalizability and applicability of the findings.

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Conflict of interest

The authors declare that they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The datasets generated and/or analyzed during the current study are not publicly available due to ethical reasons, but are available from the corresponding author on reasonable request. Supplementary data are provided in the Supplementary File.

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