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Carbon emission measurement and reduction analysis of typical campus buildings using BIM and LCA

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KEYWORDS

Carbon Emissions;
Campus Buildings;
Emission Intensity;
Building Information Model (BIM);
Life Cycle Assessment (LCA)

ABSTRACT

In the context of carbon peaking and carbon neutrality, the carbon emission issue in the construction sector has become increasingly salient. Campus buildings, being vital carriers of campus activities, significantly influence the sustainable development of the entire campus via their carbon emission profiles. To comprehensively evaluate the life cycle carbon emissions of typical campus public buildings, this study utilizes Building Information Models(BIM) to gather data on material and energy consumption at all stages, namely raw material procurement, construction, operation, and demolition of campus buildings. A life cycle carbon emission model for a building at a university in Hangzhou is constructed to calculate and analyze the carbon emission characteristics and intensities of each stage. The results indicate that the building in this project has a life cycle carbon emission of 15,718.97 tCO_2e. Through building material recycling and greening measures, a carbon emission reduction of 1,311.48 tCO_2e is attained. After accounting for carbon emission reduction, the life cycle carbon emission intensity of the project building is 1,884.74 $kgCO_2e/m^2$. The carbon emissions during the operation phase account for 85.01% of the total life cycle, primarily due to the high energy consumption of the HVAC system during operation. Moreover, the carbon emissions in the production stage of construction materials account for 18.36% of the total life cycle, which is mainly associated with the quantities of steel bars and concrete required for the project construction. This research offers a reference for the low-carbon development of campus buildings and facilitates the construction industry's shift towards green and low-carbon development.

INTRODUCTION

The construction industry holds a pivotal position in addressing global climate change. Statistical data indicates that in the greenhouse gas emissions of both developed and developing countries, the construction industry accounts for over 40% of the global energy consumption(Atmaca and Atmaca, 2022; Sun et al., 2022). In China, the construction industry contributes approximately 20% of the national carbon emissions(Gao et al., 2023; Hu et al., 2022). Unlike general consumer goods, buildings have a long lifespan and continuously consume energy while emitting carbon dioxide throughout their entire life cycle(Chen et al., 2022). It is of great significance to integrate carbon emission indicators of the life cycle with life cycle assessment during the early

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design phase(Huang et al., 2024). This integration enables the control of greenhouse gas emissions across the building's life cycle, providing a means to evaluate the total carbon emissions within the life cycle(Atmaca et al., 2021). This includes the impact of construction, demolition, and other stages on the carbon emissions of the entire building life cycle(Peng, 2016).

For public buildings, carbon emissions during the building operation phase are mainly associated with equipment usage time and energy consumption. Although it is challenging to control carbon emissions during building operation through design optimization, early-stage optimization can effectively reduce carbon emissions during the building's embodied stage(Kairies-Alvarado et al., 2021). Public buildings possess distinct characteristics such as publicness, complexity, and serviceability compared to residential buildings(Li et al., 2022). The calculation and control of carbon emissions in public buildings play a crucial role in achieving the carbon emission targets within the construction industry. Campus buildings, being areas with a high density of people, attract significant attention regarding their carbon emissions(Kairies-Alvarado et al., 2021; Li et al., 2022).

BIM(Building Information Modeling), a digital tool for architectural design and management, allows for the comprehensive and accurate recording of building geometric information, material details, and equipment data(Heydari and Heravi, 2023). Life cycle assessment (LCA) is a method for evaluating the environmental impact of products, processes, or activities across their entire life cycle, from raw material acquisition to disposal(Huang et al., 2024; Rabani et al., 2021). In recent years, LCA has been increasingly applied in building carbon emission calculations. The aim of LCA is to identify and quantify the environmental impact of products, processes, or activities throughout their life cycle, providing a scientific basis for decision-making(Chen et al., 2023; Huang et al., 2024). By constructing BIM models to obtain detailed information at each stage of the building, the carbon emissions of the building's entire life cycle can be quantitatively evaluated using the LCA method(Ding et al., 2024; Gao et al., 2024). BIM and LCA technologies offer powerful tools for building carbon emission research, and their application in building carbon emission calculations is of great significance(Huang et al., 2024; Li et al., 2022).

This study focuses on buildings of a certain university in Hangzhou, analyzes the energy-saving design characteristics at each design level, uses BIM and LCA technologies to calculate the carbon emissions of these public buildings, and proposes effective emission reduction strategies from multiple perspectives such as building carbon emission characteristics, material selection, and building operation. This provides a case reference for carbon emission control in campus buildings.

METHODOLOGY

Research Scope

Campuses, serving as the vanguard in economic and social development, are obliged to play a pivotal role in the pursuit of the dual-carbon objectives(Liu and Leng, 2022). Accurate quantification of carbon emissions from campus buildings lays the groundwork for the establishment of low-carbon campuses, with particular emphasis on the measurement during daily teaching activities(Liu and Leng, 2022; Liu et al., 2023). To formulate a comprehensive carbon emission measurement framework and define the boundaries for campus buildings demands a holistic consideration of multiple aspects(Kairies-Alvarado et al., 2021; Liu and Leng, 2022). Foremost among these is the precise demarcation of the measurement scope. This necessitates not only accounting for the carbon emissions generated during building operation but also incorporating those stemming from construction, demolition, and other relevant phases(Heydari and Heravi, 2023; Rabani et al., 2021). In the context of campus buildings, given their relatively straightforward energy consumption patterns, the principal sources of carbon emissions during the operational stage predominantly include fossil fuel combustion and electricity consumption(Min et al., 2022; Rabani et al., 2021). When delineating the boundaries for carbon emission measurement, due attention must be paid to both direct and indirect emissions induced by on-campus activities, either within the buildings or in their immediate vicinity(Hu et al., 2022; Kairies-Alvarado et al., 2021). In an endeavor to accurately appraise the carbon emissions of typical campus buildings across their entire lifecycle, this study, drawing upon the full lifecycle assessment theory and capitalizing on the unique characteristics of campus buildings, has devised a measurement framework for the full lifecycle carbon emissions of typical campus buildings, as illustrated in **Figure 1**.

Carbon Emission Calculation Methodology

To effectively manage carbon emissions in construction projects, it is essential to trace the carbon footprint across the entire life cycle of the project(Erdogan, 2021; Lai et al., 2023). This involves comprehensively understanding the impact of the carbon footprint at each stage of the life cycle on the ecosystem(Forth et al., 2023; Luo and Chen, 2020). Therefore, the first step is to identify the carbon footprint within the building's life cycle, followed by the adoption of an appropriate measurement system to calculate carbon emissions(Luo and Chen, 2020; Peng, 2016). Emissions generated during the material production and construction stages, including material manufacturing, material transportation, and building construction, are known as embodied emissions(Huang et al., 2024; Su et al., 2023). Additionally, emissions resulting from maintenance, demolition, and waste transportation are also considered significant(Min et al., 2022; Zhang et al., 2023).

During the operation phase of a construction project, aside from the energy consumption of building equipment, the carbon reduction contributions of renewable energy systems and green vegetation within the project area must be taken into account(Al-Obaidy et al., 2022; Huang et al., 2018). The carbon emission management during the building construction stage and the final building dismantling process is primarily focused on the scope of activities related to human resources, me-

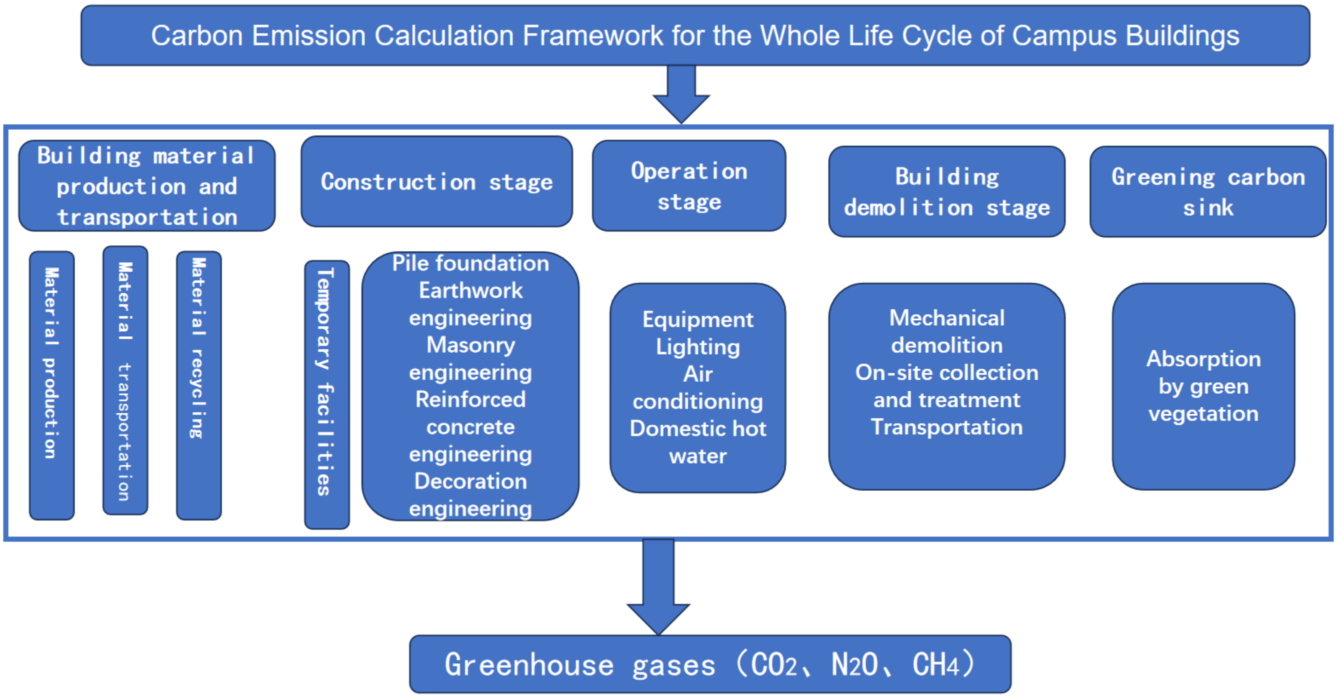

Figure 1 | Carbon emission activities of typical campus buildings

chanical equipment, and material losses during operations(Atmaca et al., 2021; Cai et al., 2022). The treatment of construction waste after building dismantling is also a crucial aspect to consider(Huang et al., 2024).

After determining the scope of building carbon emissions, starting from the building design indicators, the collected and organized design data of the construction project, such as building structure, materials, and operational energy consumption, are used to establish the carbon emissions and energy consumption during the building's use period as key indicators of the building's environmental impact(Sun et al., 2024; Zhao et al., 2024). In cases where energy meter data cannot be obtained throughout the year, the operational emissions can be simulated(Huang et al., 2018; Liu et al., 2023). By integrating LCA with digital design tools, the environmental hotspots of the building can be identified and the impacts can be mitigated(Gao et al., 2024; Luo and Chen, 2020). For instance, during the building material production stage, the BIM model can be used to obtain information on the types and quantities of building materials(Gao et al., 2024; Li et al., 2022). The construction process can be simulated using the BIM model to acquire information on energy consumption, material waste, etc. during the construction process(Ding et al., 2024; Li et al., 2022). By combining the LCA method, the carbon emissions during the building material production process and the construction process can be calculated(Huang et al., 2024; Kairies-Alvarado et al., 2021).

By meticulously recording the energy consumption and material consumption at each stage of the building, different types of energy consumption can be converted into building carbon emissions(Rabani et al., 2021; Su et al., 2023). These emissions are then multiplied by the corresponding carbon emission factors to calculate the carbon emissions, which are then accumulated to obtain the total carbon emissions of the building(Hu et al., 2022; Huang et al., 2024). Additionally, the optimization of carbon-saving, carbon-reducing, and carbon-neutral control measures, such as renewable energy and green vegetation (carbon sink), should be considered(Luo and Chen, 2020; Rabani et al., 2021).

Case Study

A campus engineering project of a university in Hangzhou, China is selected as the research object. As depicted in **Figure 2**, this project is situated in a region characterized by hot summers and cold winters. The building structure system is a shear - wall structure. The total building area amounts to 8,340.11 m² (above ground: 8,340.11 m²; underground: 0.00 m²). The total building volume is 33,362.86 m³ (above ground: 33,362.86 m³; underground: 0.00 m²). The total exterior surface area of the building is 8,313.70 m² (shape coefficient: 0.25). The building has 5 floors above ground and 0 floors underground, with a building height of 18.4 m. The building is designed for a service life of 50 years. The first three floors of this project are standard floors, featuring identical planar forms and identical building materials. Thus, the design of the standard floor is representative to a certain extent.

RESULTS AND DISCUSSION

Building Material Production and Transportation

The carbon emissions during the building material production stage are presented in Table S1. The total carbon emissions generated during the building material production phase of this project amount to 2,885.57 tCO_2e. In this stage, the carbon emissions of steel bars

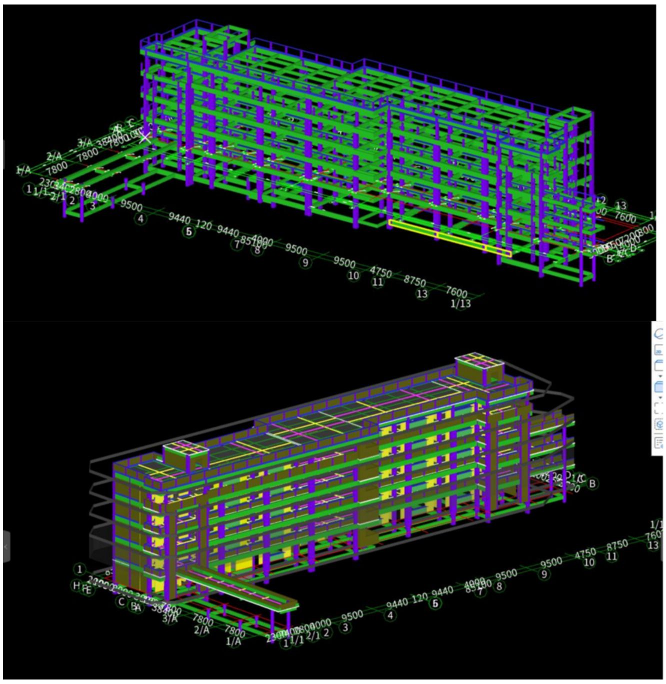

Figure 2 | Architectural appearance (BIM diagram in Glodon GTJ2021)

are the highest, accounting for 33.82% of the carbon emissions of all materials. Concrete (18.76%) ranks second, followed by mortar (17.38%) and autoclaved aerated concrete blocks B07 (13.03%), which are also significant sources of carbon emissions in this stage. As clearly evident from Table S2, the cumulative carbon emissions from the building materials transportation stage amount to 722.57 tCO_2e. Specifically, during transportation, cement mortar accounts for the highest carbon emissions (28.57%), followed by autoclaved aerated concrete block B07 (24.33%), rammed clay (22.04%), and steel bars (9.64%). The carbon emissions generated by building materials during transportation are closely associated with factors such as transportation distance and weight(Gao et al., 2024; Huang et al., 2024).

Reinforcing bars, concrete, and building equipment are all viable candidates for recycling initiatives(Al-Obaidy et al., 2022; Atmaca and Atmaca, 2022). As shown in Table S3, during the building materials recycling stage, the main source of carbon emissions lies in the transportation process. Even after accounting for the recycled portion, carbon emissions from reinforcing bars in building materials still amount to 737.23 tCO_2e, as shown in **Table 1**. Additionally, autoclaved aerated concrete block B07 also contributes significantly to carbon emissions in this stage, reaching 216.26 tCO_2e. This phenomenon can be mainly attributed to the high energy consumption during the transportation involved in the recycling and reuse of reinforcing bars and concrete blocks(Kairies-Alvarado et al., 2021; Lai et al., 2023). When compared to the carbon emissions during the building materials production stage of this project, if only considering the production and manufacturing aspects, the carbon emissions in the production stage of

Table 1 | Carbon emissions for the production and transportation of building materials

Name	Carbon Emission (tCO_2e)
Production stage	2885.57
Transportation stage	722.57
Recycling stage	-1003.98
Total	2604.15

the building materials required for this project amount to 2,885.57 tCO_2e. If the building in question successfully implements effective recycling and reuse of construction waste upon the expiration of its service life, the reduction in carbon emissions throughout the entire production and manufacturing stage could reach 34.79%.

From the above analysis, it is evident that the cumulative carbon emissions during the building materials stage of this project amount to 2,604.15 tCO_2e. Significantly, within this context, the carbon emissions generated during the production and manufacturing phase of building materials for this case-study building project are the most prominent, reaching 2,885.57 tCO_2e. Meanwhile, the carbon emissions during the transportation and logistics stage of the project's building materials are 722.57 tCO_2e A substantial reduction of 1,003.98 tCO_2e in emissions has been achieved through the recycling of building materials. This can be primarily attributed to the fact that the production of materials such as reinforced concrete requires substantial energy input, and the transportation process is also associated with high energy consumption(Li et al., 2022; Zhang et al., 2023).

Construction Stage

Carbon emission management throughout the building construction process is predominantly intertwined with activities related to the consumption of construction machinery and equipment, as well as human labor(Huang et al., 2024; Kairies-Alvarado et al., 2021). For the carbon emission quantification of this process, the bill of quantities-based method can be employed. Drawing on the project bill of quantities, we estimate the number of machine-shifts per national quota standards(Li et al., 2022; Liu and Leng, 2022). Based on the per-machine-shift energy consumption in "Calculation Standard for Building Carbon Emissions"(GB/T 51366-2019), along with the lower calorific value and carbon emission factors of fossil fuels, we estimate the carbon emissions of construction-stage machinery in sub-projects and sub-items(Liu et al., 2023; Rabani et al., 2021; Zhao et al., 2024).

As shown in Tables S4 and S5, the usage and energy consumption of mechanical equipment in sub-projects and measure items are first counted. According to the carbon emission factors of corresponding energy sources in **Table 2**, the carbon emissions of sub-projects and measure items are both 23,234 $kgCO_2e$. The carbon emissions during the entire construction process of the project amount to 250,828.37 $kgCO_2e$, with a carbon emission intensity of 30.07 $kgCO_2e/m^2$. To

Table 2 | 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 ($kgCO_2e$)
Diesel for Sub - projects and Sub - items	53.15	43.330 GJ/t	3.1453247	167.17
Electricity for Sub - projects and Sub - items	40446.84	/	0.57	23066.83
Diesel for Measure Items	211.90	43.330 GJ/t	3.1453247	666.49
Electricity for Measure Items	29398.88		0.57	16766.18
Construction Temporary Facilities	/	/	/	1161.70
Total				250828.37

Table 3 | Carbon Emissions Calculated for Energy Consumption during Building Operation

Energy Consumption Type	Annual Equivalent Electricity Consumption （kwh/a）	Energy Usage (kwh or m³ or kg)	Carbon Emission Factor (tCO_2e/unit usage)	Carbon Emissions over the Life Cycle (tCO_2e)
Heating	97894.87	97894.87	5.81×10^-4	2843.85
Air-conditioning	176891.39	176891.39	5.81×10^-4	5138.69
Lighting	57532.31	57532.31	5.81×10^-4	1671.31
Equipment	127396.80	127396.80	5.81×10^-4	3700.88
Ventilator	265.63	265.63	5.81×10^-4	7.72
Total	459980.99	0.00	--	13362.45

actualize dynamic carbon emission management during the construction stage, a comprehensive and in-depth analysis predicated on construction drawings, construction organization design, and the bill of quantities is imperative(Huang et al., 2018; Sun et al., 2024).

Building Operation Stage

Table 3 shows that the total life - cycle CO_2 emissions of the case - project building during the operation phase amount to 13,362.45 tCO_2e, with a carbon emission intensity of 1,602.19 $kgCO_2e/m^2$. Notably, the energy consumption of air-conditioning systems during the operational period registers at 7,982.54 tCO_2e, constituting 59.74% of the total carbon dioxide emissions within the project's operation stage. This dominant proportion is primarily attributable to the heating capacity of the air-conditioning units(Liu et al., 2023; Peng, 2016). The carbon emissions stemming from lighting energy consumption tally 1,671.31 tCO_2e, accounting for 12.51% of the total carbon dioxide emissions at this stage. Meanwhile, the carbon emissions associated with equipment energy consumption amount to 3,700.88 tCO_2e, representing 27.70% of the overall carbon dioxide emissions during the building's operation stage. The carbon emissions resulting from the power system's energy consumption are measured at 7.72 tCO_2e, occupying a mere 0.06% of the total carbon dioxide emissions in the operation stage. The annual carbon emissions per unit area of the project during operation stand at 32.04 $kgCO_2e/m^2$. It is evident that the preponderant focus of energy consumption in the building operation stage lies in electricity utilization. Consequently, spurring the intensive development of low-carbon energy sources, such as solar energy, wind energy, and marine energy, holds the potential to curtail carbon dioxide emissions during the operation stage(Atmaca et al., 2021; Cai et al., 2022).

Demolition Stage

Carbon emissions in the demolition phase primarily stem from the energy consumption of demolition and transportation equipment during the disassembly of buildings, representing the inverse process of construction(Huang et al., 2018; Huang et al., 2024). Building demolition methods mainly consist of manual demolition, mechanical demolition, blasting demolition, and static-breaking demolition. In most demolition projects, manual and mechanical demolitions are employed(Luo and Chen, 2020; Peng, 2016).

Specialized demolition methods like blasting demolition, static-breaking demolition, and integral mechanical demolition are not factored into this estimation. Given that this building has not yet undergone actual demolition, the calculation approach for carbon emissions upon reaching its service-life end is identical to that for existing building demolitions(Huang et al., 2018; Lai et al., 2023). Thus, quota-based estimation is performed using the engineering quantity data from the building construction phase. As presented in **Table 4**, at the end

Table 4 | Carbon Emission Calculation Results in the Demolition Stage

Type of Energy Consumed	Energy Consumption	Lower Calorific Value of Fuel	Carbon Emission Factor	Carbon Emissions ($kgCO_2e$)
Dump Truck	Loading mass 8t	24542.35 kg diesel	3.1453247	77193.66
Rubber - tired Loader	Bucket capacity 0.5m³	16633.49 kg diesel	3.1453247	52317.73
Manual Labor Consumption	Man - days	19410.84	1.11	21546.04
Total				151057.43

Table 5 | Carbon emission reduction calculation outcomes in the green carbon sink

Greening Type	Annual CO_2 Fixation of Greening Type [$tCO_2e/(m^2\cdot a)$]	Proportion of the Type (%)	Greening Area (m²)	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

of the life-cycle of this case project, the carbon emission intensity in the building demolition phase is 18.11 $kgCO_2e/m^2$, with the total carbon emissions amounting to 151,057.43 $kgCO_2e$. Only the construction-process carbon footprint is considered during the demolition phase, while the carbon emissions management of construction waste has been accounted for in the building materials phase(Chen et al., 2023; Sun et al., 2022).

Effect of Carbon Emission Reduction in the Green Carbon-Sink Stage

The site area of this campus building project is 10,000.00 m², with a greening rate of 10.00%. The computation of carbon emission reduction within the greening carbon sink is presented in **Table 5**. The carbon emission reduction quantum of the greening carbon sink for this project is 307.50 tCO_2e. Specifically, the carbon emission reduction achieved through the planting of subtropical broad-leaved small trees, coniferous trees, and sparse-leaved trees in this project amounts to 75.00 tCO_2e, accounting for 24.39% of the total. The carbon emission reduction effected by planting subtropical densely planted shrubs totals 225.00 tCO_2e, with a proportion reaching 73.17%. Additionally, the carbon emission reduction engendered by planting subtropical flower beds, natural wild grass, lawns, and aquatic plants is 7.50 tCO_2e, accounting for 2.44%. It is thus manifest that the extensive planting of subtropical densely planted shrubs in this project can make a substantial and positive contribution to the carbon emission reduction of the greening carbon sink(Huang et al., 2018; Sun et al., 2024; Sun et al., 2022).

CARBON EMISSION EVALUATION AND EMISSION-REDUCTION ANALYSIS WITHIN CAMPUS BUILDINGS

As depicted in **Figure 3**, the life-cycle carbon emissions of the campus buildings in this project total 15,718.97 tCO_2e. Carbon emission reductions of 1,311.48 tCO_2e are achieved through building material recycling and greening initiatives. Post-implementation of effective carbon-reducing measures, the per-unit-area carbon emissions of the project buildings stand at 1,884.74 $kgCO_2e/m^2$. During the building material production phase, carbon emissions reach 2,885.57 tCO_2e, with a per-unit-area emission of 345.99 $kgCO_2e/m^2$. In the building material transportation and logistics stage, emissions amount to 722.57 tCO_2e, corresponding to 86.64 $kgCO_2e/m^2$ per unit area. For the construction stage of the case-project buildings, carbon emissions are 250.83 tCO_2e, with a per-unit-area value of 30.08 $kgCO_2e/m^2$. In the operation stage of the case - project buildings, carbon emissions peak at 13,362.45 tCO_2e, equating to 1,602.19 $kgCO_2e/m^2$ per unit area. In the initial design phase of the project, strategies such as selecting green building materials, harnessing renewable energy, and applying suitable energy-saving and efficiency-boosting technologies can significantly curtail the energy requirements during subsequent

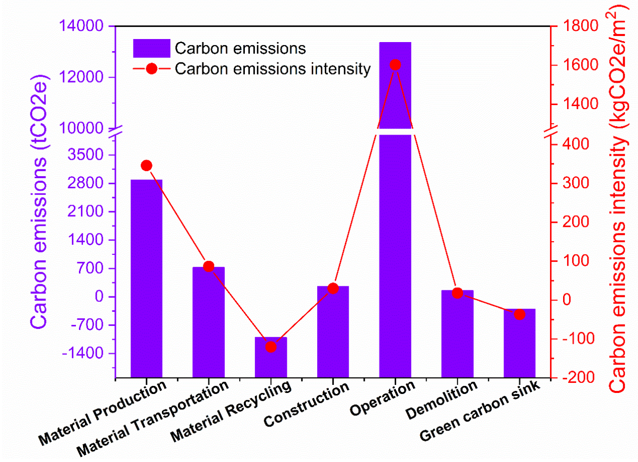

Figure 3 | Assessment of carbon emissions over the building's life cycle

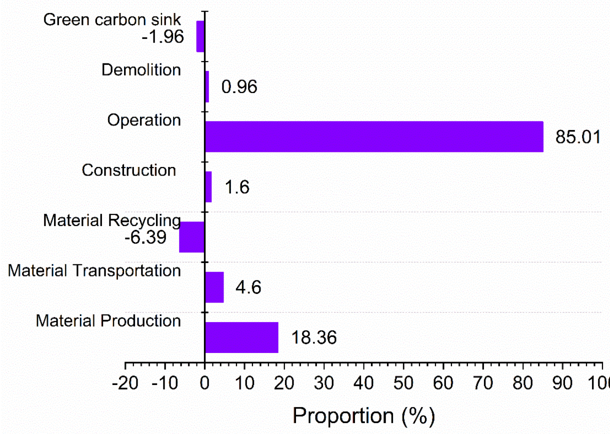

Figure 4 | Proportion of carbon emissions in each stage

operation(Bayer and Pruckner, 2024; Cang et al., 2020; Mostafavi et al., 2021).

As illustrated in **Figure 4**, within the life-cycle carbon emissions of the campus buildings in this project, the building operation stage contributes approximately 85.01%. The HVAC system stands as a dominant source of building energy consumption(Huang et al., 2024; Kairies-Alvarado et al., 2021). Carbon emissions from the building material production stage account for roughly 18.36%. These two stages not only register the highest carbon emissions but also hold the most significant potential for emission abatement, making them pivotal aspects for future architectural design considerations. Over the building's life-cycle, the carbon emissions from the remaining stages are negligible, exerting minimal influence. To reach carbon peak and neutrality during the building operation stage, it is essential to initiate with elevating the building's energy-efficiency(Cai et al., 2022; Cang et al., 2020). This can be achieved through large-scale implementation of renewable energy throughout the building's life-cycle, thus augmenting the building's "energy-generation capacity". Moreover, expanding the area of green vegetation serves as an effective means of curtailing carbon emissions(Hu et al., 2022; Mostafavi et al., 2021).

CONCLUSION

This study utilizes BIM and LCA technologies to measure the cradle-to-grave life cycle carbon emissions of typical campus building projects. The project's total life cycle carbon emissions are 15,718.97 tCO_2e, with a carbon reduction of 1,311.48 tCO_2e and a carbon emission intensity of 1,884.74 $kgCO_2e/m^2$. In tracking the carbon footprint of campus buildings' life cycle, around 85.01% of the emissions originate from the operation stage, and approximately 18.36% from the material production stage. Through the analysis of campus building carbon emissions, appropriate energy-saving, carbon reduction, and carbon neutrality measures can be implemented for campus building projects. These measures, combined with those of renewable energy and green vegetation(carbon sinks), enable energy control and emission reduction. A comprehensive calculation and analysis of the carbon emissions of campus public buildings throughout their life cycle can provide a scientific foundation for low - carbon design, construction, and management, thus facilitating the sustainable development of green campuses.

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Appendix A. Supporting information Supplementary data related to this article can be found at supplementary materials.

Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information fle).

CRediT authorship contribution statement Xianquan Cai:Writing-original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Project administration. Xuejiao Zheng: Writing–original draft, Validation, Supervision.

Conflict of interest The author declares no conflict of interest.

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Supplementary Materials

Table S1 | Results of Carbon Emission Calculation in the Building Materials Production Stage

	Building material types	Usage quantity	Unit	Production factor (tCO_2e/unit quantity)	Carbon emission (tCO_2e)
1	Steel bars	417.00	t	2.34	975.78
2	Concrete	1834.80	m^3	2.95×10^-1	541.27
3	Cement mortar	686.85	m^3	7.302×10^-1	501.53
4	Autoclaved aerated Concrete blocks B07	1504.06	m^3	2.5×10^-1	376.01
5	Rock wool boards	16.63	t	1.98	32.92
6	Thermal insulation metal Profile multi-cavity frames	353.60	m^2	2.54×10^-1	89.81
7	6 Transparent + 12 air + 6 transparent	42.43	t	2.84	120.51
8	Wood (Plastic) frame Single-layer solid doors	513.77	m^2	2.54×10^-1	130.50
9	Fine stone concrete	222.17	m^3	2.95×10^-1	65.54
10	Extruded polystyrene foam boards	6.10	t	5.02	30.63
11	Lightweight aggregate Concrete for ramming	148.17	t	1.26×10^-1	18.67
12	Compacted clay (ρ = 1800)	953.59	t	2.51×10^-3	2.39
13	Total	--	--	--	2885.57

Table S2 | Results of carbon emission calculation in the building materials transportation stage

Building material types	Transportation Mode	Transportation Factor [tCO_2e/(t*km)]	Transportation Distance (km)	Carbon Emission (tCO_2e)
Steel bars	2t light-duty gasoline truck	3.34×10^-4	500.00	69.64
Concrete		3.34×10^-4	40.00	63.73
Cement mortar		3.34×10^-4	500.00	206.47
Autoclaved aerated Concrete blocks B07		3.34×10^-4	500.00	175.82
Rock wool boards		3.34×10^-4	500.00	2.78
Thermal insulation metal Profile multi-cavity frames		3.34×10^-4	500.00	11.16
6 Transparent + 12 air + 6 transparent		3.34×10^-4	500.00	7.09
Wood (Plastic) frame Single-layer solid doors		3.34×10^-4	500.00	16.22
Fine stone concrete		3.34×10^-4	40.00	7.42
Extruded polystyrene foam boards		3.34×10^-4	500.00	1.02
Lightweight aggregate Concrete for ramming		3.34×10^-4	40.00	1.98
Compacted clay (ρ = 1800)		3.34×10^-4	500.00	159.25
Total	--	--	--	722.57

Table S3 | Results of carbon emission calculation in the building materials recycling stage

Building material types	Recycling Factor (tCO_2e/Unit)	Recyclability Rate	Transportation Mode	Transportation Factor [tCO_2e/(t*km)]	Carbon Emission (tCO_2e)
Steel bars	0.90	1.967709	2t light-duty gasoline truck	0.000334	737.23
Concrete	0.70	0.014984		0.000334	8.09
Cement mortar	--	--		0.000334	--
Autoclaved aerated Concrete blocks B07	0.70	0.207745		0.000334	216.26
Rock wool boards	--	--		0.000334	--
Thermal insulation metal Profile multi-cavity frames	0.80	0.059797		0.000334	16.74
6 Transparent + 12 air + 6 transparent	--	--		0.000334	--
Wood (Plastic) frame Single-layer solid doors	0.80	0.059797		0.000334	24.32
Fine stone concrete	0.70	0.014984		0.000334	1.03
Extruded polystyrene foam boards	--	--		0.000334	--
Lightweight aggregate Concrete for ramming	0.70	0.006400		0.000334	0.32
Compacted clay (ρ = 1800)	--	--		0.000334	--
Total	--	--		--	1003.98

** Note: The transportation distance is calculated as 10 km.*

Table S4 | Energy Consumption List in the Construction Stage

Construction Machinery	Specification	Energy Consumption per Machine-shift	Consumption of machine - shifts	Energy Consumption of Construction Machinery
Mortar Mixer	Mixing barrel capacity 200L	8.60 kWh/machine-shift	1.85	15.89 kWh
Electrode Drying Oven	Capacity 453545(cm^3)	6.70 kWh/machine-shift	9.67	64.77 kWh
Truck-mounted Crane	Lifting mass 12t	30.60 kg diesel/machine-shift	0.44	13.49 kg diesel
Tapered Thread Lathe	Diameter 45mm	9.20 kWh/machine-shift	85.50	786.60 kWh
Electric Air Compressor	Exhaust volume 6m^3/min	215.00 kWh/machine-shift	102.60	22058.20 kWh
Rubber-tired Crane	Lifting mass 16t	30.00 kg diesel/machine-shift	0.57	17.13 kg diesel
Concrete Troweling Machine	Power 5.5kW	23.10 kWh/machine-shift	14.34	331.24 kWh
Motorized Dump Truck	Loading mass 1t	6.00 kg diesel/machine-shift	3.75	22.53 kg diesel
Steel Bar Straightening Machine	40mm	30.00 kWh/machine-shift	26.19	785.59 kWh
Dry - mixed Mortar Tank Mixer	Nominal storage 20000L	28.50 kWh/machine-shift	44.29	1262.13 kWh
Argon Arc Welder	Current 500A	70.70 kWh/machine-shift	10.15	717.75 kWh
Butt Welder	Capacity 75kV·A	122.00 kWh/machine-shift	24.60	3000.75 kWh
DC Arc Welder	32kV·A	100.00 kWh/machine-shift	94.80	9480.28 kWh
Metal Surface Polishing Machine	Metal Surface Polishing Machine	0.00 kWh/machine-shift	10.15	0.00 kWh
Plate Cutting Machine	Plate width 1300mm	0.00 kWh/machine-shift	20.53	0.00 kWh
Spot Welder	Capacity 75kV·A	154.60 kWh/machine-shift	0.35	53.94 kWh
Steel Bar Bending Machine	Diameter 40mm	12.80 kWh/machine-shift	61.59	788.36 kWh
Pipe Cutting Machine	Pipe diameter 150mm	12.90 kWh/machine-shift	16.92	218.27 kWh
Steel Bar Cutting Machine	Diameter 40mm	32.10 kWh/machine-shift	27.51	883.07 kWh

Table S5 | Energy Consumption List of Measure Items

Construction Machinery	Specification	Energy Consumption per Machine-shift	Consumption of machine - shifts	Energy Consumption of Construction Machinery
Single - cage Construction Elevator	Lifting mass 1t, lifting height 75m	42.30 kWh/machine - shift	122.05	5162.60 kWh
Electric Rammer	Ramming energy 250N·m	16.60 kWh/machine - shift	0.22	3.59 kWh
Self - climbing Tower Crane	Lifting mass 400t	164.30 kWh/machine - shift	146.48	24066.93 kWh
Steel Bar Bending Machine	Diameter 40mm	12.80 kWh/machine - shift	0.28	3.58 kWh
Steel Bar Straightening Machine	14mm	15.10 kWh/machine - shift	0.21	3.17 kWh
Truck - mounted Crane	Lifting mass 8t	28.40 kg diesel/machine - shift	0.02	0.45 kg diesel
Motorized Dump Truck	Loading mass 1t	6.00 kg diesel/machine - shift	0.43	2.58 kg diesel
Steel Bar Cutting Machine	Diameter 40mm	32.10 kWh/machine - shift	0.10	3.21 kWh
Truck	Loading mass 6t	33.20 kg diesel/machine - shift	6.29	208.87 kg diesel
Woodworking Circular Saw Machine	Diameter 500mm	24.00 kWh/machine - shift	6.49	155.80 kWh