BIM-Based Carbon Emission Measurement for Building Whole Life Cycle: Model Construction, Stage Analysis and Case Verification

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Abstract. Against the backdrop of global climate change, the construction industry accounts for ~40–50% of global greenhouse gas emissions, making low-carbon development an urgent priority. This study focuses on whole-life-cycle (WLC) carbon emission measurement of buildings and innovatively integrates BIM technology to address challenges such as inaccurate material quantification and fragmented data across stages. Taking a sports venue project in Xiqing District, Tianjin (total construction area 84,000 m², prefabrication rate 70.2%) as a case, a multi-disciplinary BIM model with LOD400 precision was constructed using Revit. For each WLC stage, targeted carbon emission measurement methods were developed:

Materialization stage: BIM visualization tools were used for prefabricated component design, BIM4D simulation optimized construction management, and a measurement model was built by linking BIM-derived material quantities to a carbon emission factor database (labor, materials, machinery).Operation and maintenance (O&M) stage: The BIM model (supplemented with component thermal/physical properties) was exported as a gbXML file to Green Building Studio, enabling quantitative calculation of annual energy consumption and carbon emissions.Demolition and renovation stage: “Waste” and “recyclable” attributes were assigned to BIM components to quantify waste/recyclables, and carbon emissions from demolition, transportation, and recycling were measured.

Case results show: (1) Total embodied carbon emissions of main building materials reached 25,470.5 tCO_2e, with steel structures (components + accessories) accounting for 62.6% (the largest share). (2) Among three O&M schemes, Scheme 3 (water chillers + geothermal energy + LED lighting) achieved the lowest carbon emission intensity (57.26 $kgCO_2e/m^2\cdot a$), a 16.7 $kgCO_2e/m^2\cdot a$ reduction compared to Scheme 1 (water chillers + gas-fired boilers). (3) The O&M stage contributed over 80% of WLC carbon emissions, remaining the core for emission reduction.

This study’s innovation lies in integrating BIM with stage-specific carbon measurement methods: LOD400 models ensure accurate material quantification, gbXML-Green Building Studio realizes O&M data visualization, and component attribute assignment enables demolition-stage quantification. The findings provide a replicable technical framework for low-carbon building practices, empowering the construction industry’s green transformation.

1. Introduction

Global climate change has become a critical threat to human survival, with the construction industry contributing ~30% of global energy consumption and 40–50% of greenhouse gas emissions annually. In China, building-related energy consumption (including building materials production) accounts for ~45% of total social energy consumption [1]. McKinsey Global Institute identifies four building-related measures (insulation, lighting, air-conditioning, hot water systems) as among the most cost-effective for emission reduction, highlighting the urgency of low-carbon development in construction.

BIM technology has emerged as a core driver for industrial transformation, as it endows building components with unique digital identities and enables data integration across stages. Combined with big data and cloud computing, BIM supports standardized design, refined construction, and information-based management—key to reducing resource consumption and carbon emissions. Unlike traditional high-energy-consuming “passive energy-saving” approaches, BIM enables simulation of natural ventilation, daylighting, and

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renewable energy utilization, fundamentally cutting emissions in building construction and operation [2].

This study takes an assembled steel structure sports venue in Tianjin as a case, constructs a BIM-based WLC carbon emission measurement system, and verifies its feasibility through quantitative analysis—aiming to provide a technical reference for low-carbon building practice.

2. Construction of Low-Carbon BIM Model for the Case Project

2.1 Selection of Case Projects

The project is located in Xiqing District, Tianjin, with a land area of 51,274 m² and total construction area of 84,000 m² (51,000 m² above ground, 33,000 m² underground). It includes an underground garage and two multi-story sports gymnasiums (1 underground floor, 3–5 above-ground floors). The structural system adopts reinforced concrete frames (underground) and steel frames + steel trusses (above ground), with autoclaved aerated concrete (ALC) wall panels for internal partitions. The prefabrication rate reaches 70.2%, representing a typical assembled steel structure project (Fig. 1).

Fig.1 Renderings of case projects

2.2 Model Construction

Prior to modeling, component family files (containing geometric/non-geometric information, e.g., material type, size, thermal conductivity) were created in Revit to ensure data consistency [3]. The model achieved LOD400 precision (detailed manufacturing/installation information) and was built separately for architecture, structure, and MEP (Mechanical, Electrical, Plumbing) disciplines, followed by integration (Fig. 2). Key parameters (material price, carbon emission factor, thermal performance) were assigned to each component and numbered by discipline—laying the foundation for subsequent carbon emission calculation.

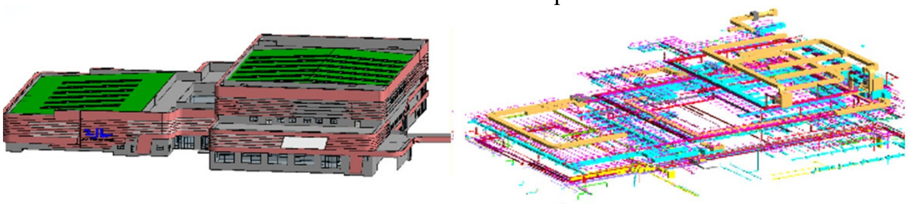

Fig.2 Case project building structure and MEP model drawing

3. Analysis of Carbon Emissions Throughout the Whole Life Cycle and Construction of the BIM Model

3.1 The Architectural Design Stage

The design stage accounts for only 0.5–1.0% of WLC carbon emissions (from personnel/office equipment) but determines core factors such as building shape, structure, and material selection [4]. BIM supports:

Precision design: BIM software (e.g., Revit) embeds design specifications to reduce errors and enable material substitution (e.g., replacing high-emission materials with low-carbon alternatives).

Performance simulation: BIM-based daylighting, sunlight, and energy consumption analysis (Fig. 3) optimizes the design scheme—for example, simulating natural lighting on floors 1–5 to maximize daylight utilization and reduce artificial lighting energy demand.

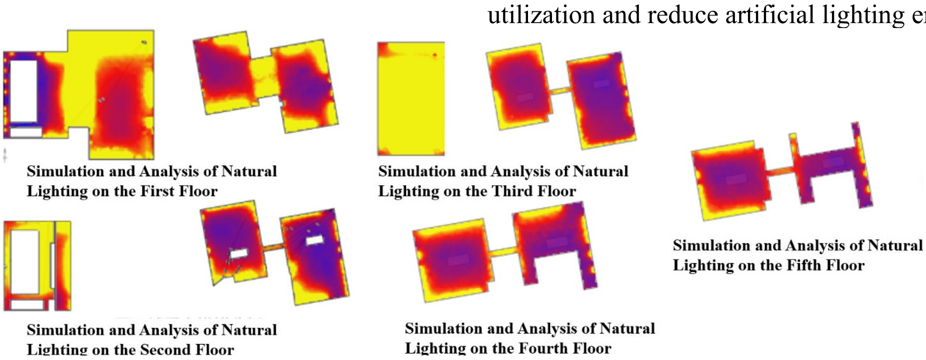

Fig.3 Case project daylighting simulation analysis

3.2 The Building Materialization Stage

The materialization stage (component production, transportation, construction) is a major source of embodied carbon emissions. Fig. 4 shows the BIM-based carbon emission measurement process for this stage:

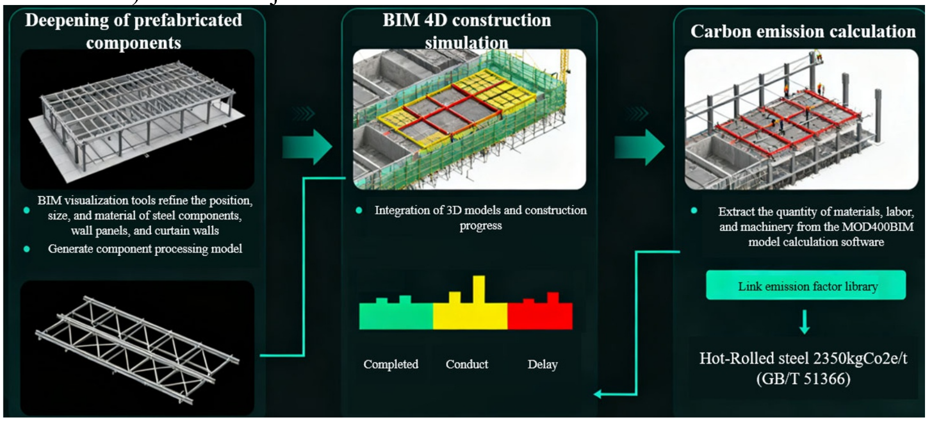

Fig.4 Flowchart of BIM-based carbon emission measurement in the materialization stage

Prefabricated component deepening: BIM visualization tools refine the position, size, and material of steel members, wall panels, and curtain walls, generating component processing models for manufacturers.

BIM4D construction simulation: Integrates 3D BIM models with construction schedules, using color coding (e.g., green = completed, yellow = in progress, red = delayed) to display component construction status. Simulation of key processes (concrete pouring, steel truss hoisting) clarifies management control points and reduces rework.

Carbon emission calculation: The LOD400 BIM model is imported into quantity-takeoff software to extract material/labor/machinery quantities, which are then linked to a carbon emission factor database (e.g., 2350 $kgCO_2e/t$ for hot-rolled steel [GB/T 51366]) to calculate total emissions [5].

3.3 The Building Operation and Maintenance Stage

The O&M stage has the longest duration (typically 50 years for buildings) and accounts for the largest share of WLC carbon emissions (mainly from HVAC, lighting, and equipment maintenance) [6]. Fig. 5 shows the BIM-based measurement process:

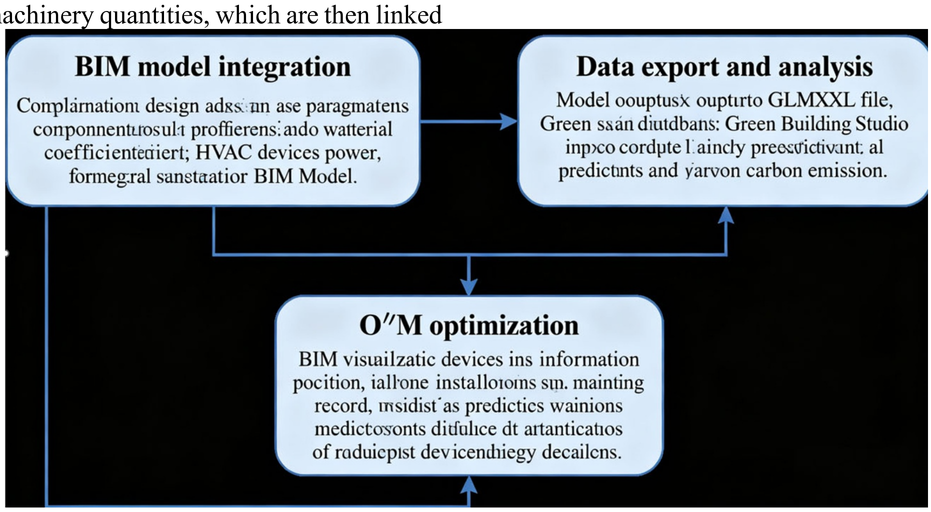

Fig.5 Flowchart of BIM-based carbon emission measurement in the O&M stage

BIM model integration: Merges design and materialization stage models, and supplements component attributes (e.g., thermal conductivity of insulation materials, power of HVAC equipment) to form a comprehensive O&M BIM model.

Data export and analysis: The model is exported as a gbXML file (a standard format for building energy analysis) and imported into Green Building Studio—a professional energy simulation tool—to calculate annual predicted energy consumption and carbon emissions [7].

O&M optimization: BIM visualizes equipment information (e.g., installation location, maintenance records) to support predictive maintenance, reducing energy waste from equipment failures.

3.4 Building Demolition and Renovation Stage

Carbon emissions in this stage come from demolition energy consumption, waste transportation/disposal, and recycling of materials (steel, wood) [8]. Fig. 6 shows the BIM-based measurement process:

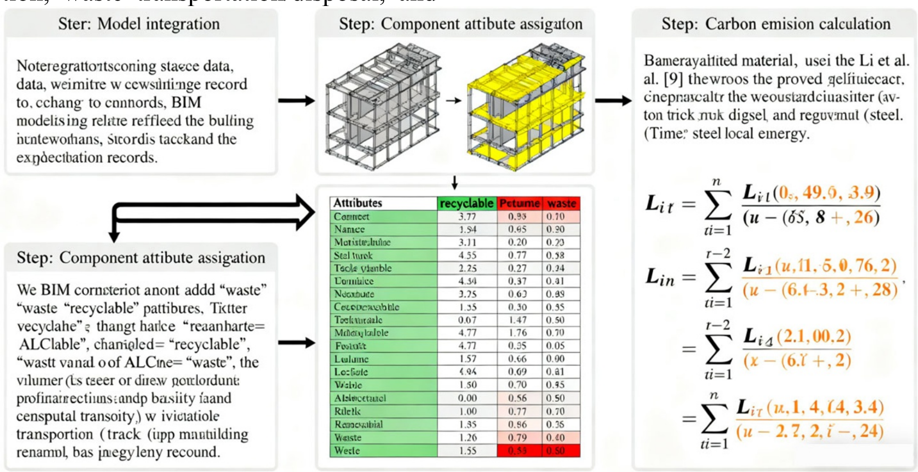

Fig.6 Flowchart of BIM-based carbon emission measurement in the demolition stage

Model integration: Incorporates O&M stage data (e.g., component wear status, replacement records) into the BIM model to reflect the actual condition of the building.

Component attribute assignment: Adds “waste” and “recyclable” attributes to the BIM component family library (e.g., steel trusses = “recyclable,” damaged ALC panels = “waste”) to quantify the volume of waste and recyclables.

Carbon emission calculation: Uses the method proposed by Li et al. [9] to calculate emissions from demolition (e.g., energy consumption of excavators), waste transportation (e.g., diesel consumption of trucks), and recycling (e.g., energy for steel melting), based on quantified material volumes.

3.5 Analysis of Carbon Emission Factors

The carbon emission factors for this project are as follows:

Steel components and steel component accessories: Hot-rolled carbon steel H-section steel (GB/T 51366); Steel reinforcement: Hot-rolled carbon steel reinforcement (GB/T 51366); Concrete: C30 grade concrete (GB/T 51366); ALC and concrete blocks: Concrete bricks (GB/T 51366); Cushion material: Sand (f=1.6-3.0) (GB/T 51366); Windows: Average value of 6 types of windows specified in GB/T 51366; Profiled steel sheets: The carbon emission factor of carbon steel electrogalvanized coil specified in GB/T 51366 is 3020 kgCO2e/t. It is converted based on a steel plate density of 7.85 t/m³ and a thickness of 0.9 mm, resulting in a carbon emission factor of 21.34 kgCO2e/m² for profiled steel sheets; Aluminum-magnesium-manganese sheets: The carbon emission factor of electrolytic aluminum is 20300 kgCO2e/t. It is converted based on a plate density of 2.7 t/m³ and a thickness of 0.9 mm, resulting in a carbon emission factor of 49.33 kgCO2e/m² for aluminum-magnesium-manganese sheets; Thermal insulation material: The carbon emission factor of polystyrene foam plastic board is 5020 kgCO2e/t. It is converted based on a density of 24 kg/m³, resulting in a carbon emission factor of 120.5 kgCO2e/m³ for thermal insulation material; Electricity and natural gas: Refer to Guidelines for the Compilation of Low-Carbon (Near-Zero Carbon Emission) Demonstration Construction Implementation Plans (Trial) of Tianjin Municipality, 2021.

4. Case Study

4.1 Carbon Emissions from Main Building Materials

Based on the BIM-extracted material quantities and GB/T 51366 carbon emission factors, the total embodied carbon emissions of main building materials were 25,470.5 tCO_2e, with a unit area emission of 499.5 $kgCO_2e/m^2$ (amortized to 9.99 $kgCO_2e/m^2 \cdot a$ over the 50-year design life).

Steel structures dominate emissions: Carbon emissions from steel components (6434 t) and their accessories (347 t) reached 15,119.9 + 815.5 = 15,935.4 tCO_2e, accounting for 62.6% of total material emissions (Fig.7, Fig.8). This is because steel has a high carbon emission factor (2350 $kgCO_2e/t$) and large usage (accounting for ~70% of structural materials).

Other major contributors: The floor system (profiled steel sheets, rebars, concrete) accounted for 15.3% (3895.6 tCO_2e), and wall materials (ALC panels, blocks) accounted for 11.0% (2800.8 tCO_2e). Roofing, insulation, and doors/windows contributed only 11.1% in total.

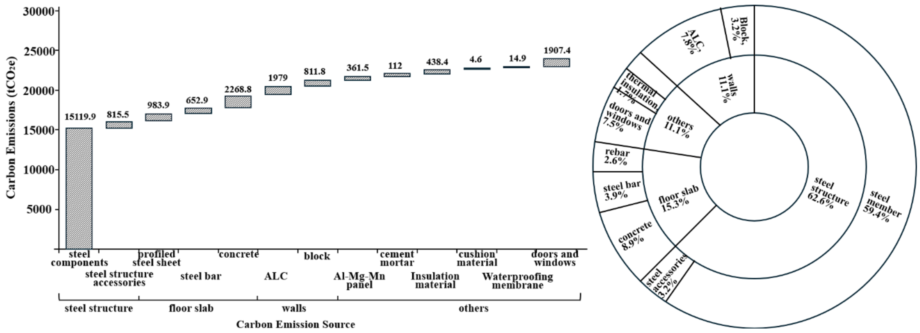

Fig.7 Calculation results of embodied carbon emissions of main building materials in Case project

4.2 Carbon Emissions from Building Operation

Three O&M schemes were designed for the air-conditioning cold/heat sources (the largest O&M energy consumer), and their carbon emissions were calculated using Green Building Studio (Table 1).

Scheme Design: Scheme 1: Water chillers + gas-fired boilers (traditional energy sources) + conventional lighting. Scheme 2: Magnetic levitation chillers (higher efficiency) + gas-fired boilers + LED lighting. Scheme 3: Water chillers + geothermal energy (renewable) + LED lighting.

Key Findings: Scheme 3 achieves the highest emission reduction: Annual O&M carbon emissions for Scheme 1 were 3771.52 tCO_2e (73.96 $kgCO_2e/m^2{\cdot}a$). Scheme 2 reduced emissions by 8.27 $kgCO_2e/m^2{\cdot}a$ (to 65.69 $kgCO_2e/m^2{\cdot}a$) due to magnetic levitation chillers (COP = 6.0 vs. 4.0 for traditional chillers). Scheme 3 further reduced emissions by 16.7 $kgCO_2e/m^2{\cdot}a$ (to 57.26 $kgCO_2e/m^2{\cdot}a$) because geothermal energy replaces gas-fired boilers (no fossil fuel consumption).

Lighting optimization contributes significantly: LED lighting reduced annual electricity consumption by ~200,000 kWh, cutting emissions by ~1.77 tCO_2e/a (0.03 $kgCO_2e/m^2{\cdot}a$) [calculated using Tianjin's 2021 electricity emission factor: 8.843 tCO_2/10,000 kWh [10]].

Renewable energy (geothermal, solar) and high-efficiency equipment (magnetic levitation chillers, LEDs) are key to O&M emission reduction. For sports venues (with long operating hours), Scheme 3 could reduce total WLC emissions by ~695,000 tCO_2e over 50 years.

Table 1 Annual O&M carbon emissions of different schemes

Scheme	Cold/Heat Source	Lighting	Annual Emissions (tCO_2e/a)	Unit Emissions ($kgCO_2e/m^2{\cdot}a$)	Emission Reduction vs. Scheme 1
Scheme 1	Water chillers + gas-fired boilers	Conventional	3771.52	73.96	0
Scheme 2	Magnetic levitation chillers + gas-fired boilers	LED	3356.88	65.69	8.27 $kgCO_2e/m^2{\cdot}a$ (11.2%)
Scheme 3	Water chillers + geothermal energy	LED	2926.56	57.26	16.7 $kgCO_2e/m^2{\cdot}a$ (22.6%)

4.3 Proportion of WLC Carbon Emissions

As O&M schemes were optimized, the proportion of O&M emissions decreased, while material and construction emissions increased relatively (Fig. 8).

O&M remains the dominant stage: Even in Scheme 3 (the most optimized), O&M emissions accounted for 83.81% of WLC emissions—far higher than materials (14.62%) and construction (1.57%). In Scheme 1, O&M emissions reached 86.99%.

Material proportion rises moderately: Material emissions increased from 11.75% (Scheme 1) to 14.62% (Scheme 3), but this was due to O&M emission reduction (not increased material usage). Total WLC emissions still decreased by ~845 tCO_2e/a in Scheme 3 vs. Scheme 1.

The O&M stage is the core of WLC emission reduction, but intervention should start in the design and materialization stages: (1) Design: Select high-insulation materials (e.g., low-thermal-conductivity insulation) to reduce HVAC load; (2) Materialization: Adopt energy-efficient equipment (e.g., variable-frequency pumps) to lay the foundation for O&M optimization.

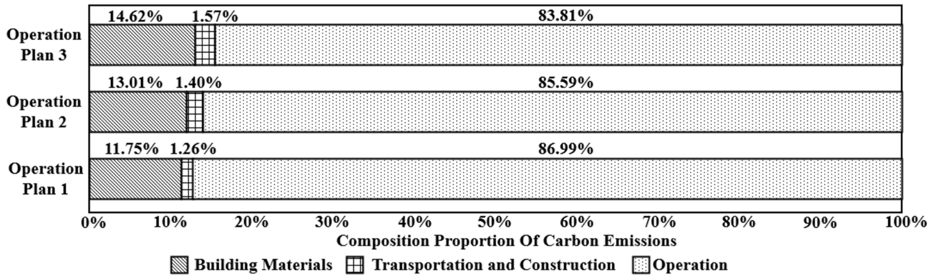

Fig.8 The proportion of carbon emissions from building materials, construction and operation in Case project

5. Conclusion and Analysis

BIM enables precise and efficient carbon measurement: By constructing LOD400 multi-disciplinary models and assigning component attributes (e.g., carbon emission factors, "waste/recyclable" labels), BIM accurately extracts material/labor/machinery quantities, solving the problem of fragmented data across stages.

Stage-specific methods improve measurement accuracy: The materialization stage uses BIM4D + factor databases, the O&M stage uses gbXML + Green Building Studio, and the demolition stage uses component attribute assignment—forming a closed-loop WLC measurement system.

Core emission reduction paths are clarified: Steel structures dominate material emissions (62.6%), and renewable energy + high-efficiency equipment (Scheme 3) achieves the largest O&M emission reduction. The O&M stage (83.81% of WLC emissions) is the key, requiring early intervention in design and materialization.

This study also has certain limitations that should be noted. First, regarding model assumptions: The carbon emission calculation relies on the assumption that building components maintain stable thermal and physical properties throughout the life cycle, while actual performance may degrade due to wear, environmental erosion, or improper maintenance—this could lead to deviations between simulated and actual O&M carbon emissions. Second, data availability constraints exist: Carbon emission factors are mainly derived from national standards (GB/T 51366) and local guidelines, lacking personalized data for specific material suppliers or regional production processes. Third, case study specificity: The research object is a high-prefabrication-rate steel structure sports venue in Tianjin, with unique characteristics such as large steel usage and long operating hours. These features limit the direct generalization of the conclusions to residential buildings, low-rise public buildings, or projects in regions with distinct climate conditions (e.g., extreme cold or hot areas).

This study provides a replicable technical framework for low-carbon buildings, especially assembled steel structure projects. Future research could integrate real-time monitoring (e.g., IoT sensors) with BIM to realize dynamic carbon emission management.

Acknowledgments

This study was funded by the research and application of the key technology of electromechanical rapid modeling of the homemade aecmate series BIM (grant number: CSCEC-2024-Z-3), the research on the key technology of rapid modeling based on the independent and controllable three-dimensional graphics platform, and the R&D of series products (grant number: CSCECTC-2024-Z-2).

Disclosure of Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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