A BIM–IoT-Based Framework for Lifecycle Carbon Tracking in Modular Construction

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Abstract -
Modular construction (MC) has attracted increasing attention as a promising strategy for carbon emission reduction in the context of global low-carbon transitions. However, accurate estimation and continuous tracking of lifecycle carbon emissions in MC projects remain limited, as existing studies predominantly focus on individual stages and provide fragmented evidence. To address this gap, this study proposes a lifecycle-oriented carbon tracking approach for MC based on the integration of Building Information Modeling (BIM) and the Internet of Things (IoT). By combining BIM-based object representations with multi-source IoT-enabled sensing mechanisms, the proposed approach establishes a unified mechanism for carbon accounting and data integration at the module level, enabling consistent representation of carbon emissions within a unified framework. The approach is demonstrated through two real-world modular integrated construction (MiC) projects in Hong Kong, validated separately for the construction and operational stages. The results show that the approach supports continuous, time-resolved characterization of carbon emissions and effectively captures their dynamic patterns under different application contexts. Overall, this study provides a systematic methodological framework for lifecycle-oriented carbon tracking in modular construction, contributing to more data-driven carbon assessment practices.

Keywords -
Modular Construction, Lifecycle Carbon Monitoring, BIM, IoT

1 Introduction

The building sector contributes a substantial share of global energy-related carbon emissions, making it a key target for decarbonization strategies [1]. MC has been increasingly adopted to improve productivity and reduce environmental impacts, particularly in high-density cities such as Hong Kong [2]. However, existing studies have struggled to systematically characterize the carbon emission profile of MC at the lifecycle scale. This limitation is largely attributable to the lack of methods capable of supporting continuous lifecycle carbon data acquisition and tracking.

Existing MC carbon studies still rely predominantly on material-driven estimation approaches. Although BIM and IoT have been introduced to support carbon data acquisition and management, their applications are typically confined to individual stages or isolated systems. As a result, a lifecycle-wide data integration mechanism and unified accounting pathway have yet to be established, limiting further systematic analysis of carbon emission characteristics.

From the perspective of embodied carbon (EC), MC exhibits highly discrete and process-oriented characteristics. Conventional cast-in-situ construction is dominated by on-site activities, with carbon emissions largely localized in both spatial and temporal dimensions. Although prefabricated construction relocates part of component production to factories, substantial wet works remain on-site, and EC emissions are still primarily material-driven. MC adopts modules as highly integrated, standardized, and traceable construction units, resulting in EC emissions being distributed across multiple construction stages, including factory manufacturing, transportation, and on-site assembly. Due to highly dispersed production processes and a module-based object hierarchy, carbon emission data in MC are difficult to continuously acquire and consistently represent across construction stages, which weakens the applicability of traditional material-based estimation approaches at both module and building scales.

For operational carbon (OC), MC exhibits stronger early-stage coupling with EC. Module envelope design, connection configurations, and integrated building services are typically finalized during the manufacturing stage, thereby exerting persistent influences on building energy performance and operational carbon during long-term operation. However, existing OC studies in MC predominantly rely on design-stage energy simulations for independent estimation, which cannot capture dynamic variations during actual operation and lack effective linkage with construction-stage data, limiting deeper understanding of operational carbon behaviours.

To address these gaps, this study proposes a lifecycle-oriented BIM–IoT-based carbon tracking approach for MC. The proposed approach supports continuous carbon data acquisition and integration across lifecycle stages and enables unified carbon accounting across different stages, providing a systematic methodological framework for data-driven carbon assessment in modular construction. The remainder of this paper is organized as follows.

Section 2 reviews related literature, Section 3 introduces the proposed methodology, Section 4 presents the case studies and results, and Section 5 concludes the paper.

2 Literature review

In recent years, increasing research attention has been directed toward the use of digital technologies to address the complexities of lifecycle carbon assessment in MC [3]. Due to the fragmented nature of production processes and the hierarchical organization of building objects in MC, effective carbon assessment requires consistent object-level representation across different stages, and the capability to continuously capture time-resolved data from construction processes and building operation. In this context, BIM and IoT have emerged as key technological foundations for carbon data integration and analysis in modular construction.

BIM provides structured building semantics and supports automated quantity take-off, enabling multi-level representation of carbon emissions from components to modules and buildings [4]. It also facilitates identification of dominant material- and process-related emission sources [5]. However, existing BIM-based approaches largely rely on static databases and ex post accounting mechanisms, which limits their ability to capture temporal dynamics of carbon emissions [6].

Meanwhile, IoT technologies enable distributed sensing and real-time data acquisition, allowing process-level information across construction and operation stages to be continuously recorded, which is particularly critical for fragmented production processes in MC [7, 8]. Nevertheless, recent review studies indicate that IoT-based carbon management in the construction sector still faces challenges related to limited interoperability, fragmented system deployment, and lack of standardized integration frameworks, which constrain scalability and applicability for cross-stage carbon tracking [9].

Building on the above studies, recent research has explored BIM–IoT integration to establish links between digital building models and physical process data [10]. Existing studies indicate that such approaches can support process-level tracking of embodied carbon at component and module scales and can also be applied to operational energy monitoring and data acquisition [11]. However, compared with existing BIM–IoT-based studies that primarily focus on embodied carbon tracking during the construction stage, most applications remain focused on specific processes, individual lifecycle stages, or localized use cases, and a unified framework that enables lifecycle-wide data integration and consistent carbon accounting has yet to be established [12, 13].

In summary, although BIM and IoT provide important capabilities for carbon data acquisition in modular construction, systematic methods that support lifecycle-wide data integration and unified carbon accounting across stages remain insufficient. To address this gap, this study proposes a BIM-IoT-based carbon tracking framework for modular construction to support continuous lifecycle carbon data acquisition and integrated carbon accounting.

3 Methodology

3.1 Research design

This study proposes a BIM–IoT-integrated framework for carbon tracking in modular construction, in which modules are defined as the primary analytical unit and buildings as the aggregation level. The overall research framework of the proposed BIM–IoT-integrated approach is illustrated in Figure 1. By linking module-level BIM semantics with process- and operation-level data acquired through IoT, the framework enables consistent module-scale attribution of carbon emissions across lifecycle stages, providing a basis for the integrated analysis of embodied and operational carbon.

3.2 Data acquisition and preprocessing

This study employs a data acquisition strategy targeting lifecycle stages of modular buildings to support the quantitative analysis of carbon emissions during both construction and operation. In accordance with EN 15978 [14], and considering the research scope and data availability, the system boundary includes construction-related stages A1–A5, representing embodied carbon (EC), and the use stage B6, representing operational carbon (OC). Other lifecycle stages, including maintenance and replacement (B2–B5), end-of-life processes (C1–C4), and benefits beyond the system boundary (D), are excluded. The corresponding carbon emission sources, data types, and acquisition approaches are summarised in Table 1. For construction-related stages (A1–A5), data acquisition is organised around process-level activities, focusing on energy use associated with module production, transportation, and installation. In contrast, for the operational stage (B6), data acquisition is structured by end-use energy consumption, capturing subsystem-level demand such as HVAC, lighting, and plug loads.

The proposed method integrates three categories of input data: BIM semantic data, IoT-derived sensing data, and carbon emission factors. BIM semantic data define a structured hierarchy linking components, modules, and buildings, enabling consistent carbon attribution across lifecycle stages. IoT-derived data capture time-resolved activity states and energy-use patterns associated with module production, transportation, installation, and building operation. Carbon emission factors are obtained from established life cycle assessment databases, including Ecoin-

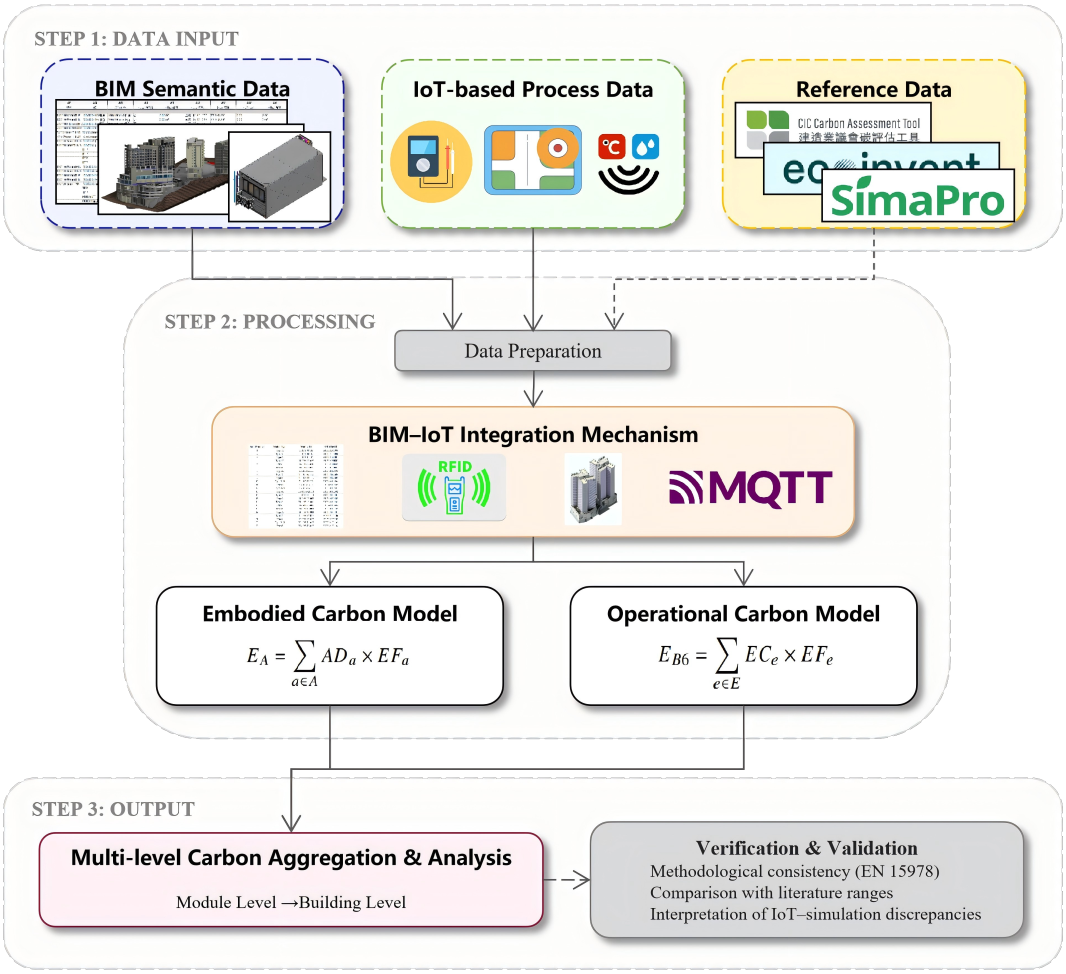

Figure 1. Research design of the proposed BIM-IoT integrated framework.

vent [15], SimaPro-integrated databases [16], ICE [17], and the CIC Carbon Assessment Toolkit [18].

Prior to integration, heterogeneous data from different lifecycle stages are preprocessed to improve temporal consistency and data reliability. This includes addressing differences in sampling frequency and temporal resolution, handling missing or incomplete data, and aligning time-resolved IoT data with BIM-defined modular objects and corresponding emission factors. These steps provide a reliable basis for subsequent module-level carbon quantification and lifecycle-scale analysis.

3.3 BIM–IoT integration mechanism

The integration of BIM and IoT introduces challenges related to object consistency and temporal alignment, as data collected from different lifecycle stages exhibit heterogeneity in structure, temporal resolution, and activity semantics. Without a unified reference framework, such data cannot be reliably linked to modular objects, thereby limiting the traceability of carbon emission quantification.

To address this issue, a module-oriented BIM–IoT integration mechanism is established, in which the module serves as the unified unit of analysis across lifecycle stages. Each module is assigned a unique identifier (Module ID) and linked to its corresponding BIM object, ensuring consistent identity representation within the defined system boundary. A one-to-one mapping between Module IDs and RFID tags enables physical identification of modules and supports the association of activity-related data during construction processes.

During module manufacturing, transportation, and on-site installation, RFID-based identification events are captured at key process nodes to link operational states and energy consumption data to individual modules. In this way, each construction activity can be directly associated with specific modules, allowing energy use to be traced back to corresponding processes. This activity-oriented integration approach establishes a clear connection between construction activities, energy consumption, and modu-

Table 1. Carbon emission sources and IoT sensors

Stage	Carbon Source Category	Representative Activities	Data Type	IoT Sensors
A1–A3	Material production; Module manufacturing	Raw material processing; Module manufacturing; Module decoration	Energy consumption; Equipment status	Smart meters; Accelerometers; Vibration sensors; etc.
A4	Module transportation	Off-site transportation	Travel distance; Transport status	GPS sensors
A5	On-site installation	Module lifting; Equipment operation	Energy consumption; Equipment status	Smart meters; Accelerometers; Vibration sensors; etc.
B6	HVAC systems	AC on/off switching; Temperature adjustment	Operating duration; Temp. & humidity	Environmental sensors; Current sensors
	Plug loads	Appliance usage; Device charging	Active power; Device status	Smart plugs; Smart switch
	Lighting	Light on/off switching; Active fixture count	Illuminance level; Operating status	Illuminance sensors; Smart switches
	Domestic water use	Water consumption; Usage patterns	Water volume; Flow rate	Smart water meters
	Gas consumption	Cooking; Hot water supply	Gas volume; Operating status	Smart gas meters

lar components, thereby enabling traceable module-level carbon quantification.

To ensure the temporal consistency and effective integration of multi-source IoT data, a publish–subscribe communication mechanism is adopted, with MQTT facilitating asynchronous data acquisition from distributed sensors. By linking module identifiers with activity types and corresponding data topics, heterogeneous operational data collected at different temporal resolutions can be systematically organized at the module level. This supports cross-stage data alignment and provides a coherent basis for subsequent carbon quantification.

3.4 Carbon emission accounting model

Based on the BIM–IoT data integration mechanism, carbon-related data generated at different lifecycle stages are consistently attributed at the module level. Within the defined system boundary, this study quantifies embodied carbon during the construction stages (A1–A5) and operational carbon during the use stage (B6) of modular buildings. All emissions are expressed in carbon dioxide equivalent (CO_2e), including major greenhouse gases such as CO_2, CH_4, and N_2O. Greenhouse gas emissions are converted into CO_2e using 100-year global warming potential factors (GWP100) from the IPCC Fifth Assessment Report (AR5) [19]. This choice ensures consistency with established LCA databases and prior studies commonly used in construction-related carbon assessment. Although updated characterization factors are provided in IPCC AR6 (2021), the differences are generally limited for the emission sources considered in this study and do not affect the methodological framework or comparative analysis.

For the construction stages (A1–A5), EC is quantified based on activity-related energy consumption captured through the IoT sensing system. Energy use associated with construction-related activities is converted into carbon emissions using corresponding emission factors, following an activity-based accounting logic. The general calculation form is expressed as:

$$E_A = \sum_{a \in A} AD_a \times EF_a \tag{1}$$

Where E_A denotes the total embodied carbon emissions of a module during the construction stages (A1–A5); AD_a represents the activity data associated with activity a, such as energy consumption, equipment operating time, or transportation distance; and EF_a refers to the emission factor corresponding to the activity and associated energy type.

For the operational stage (B6), OC covers emissions induced by energy use during normal building operation. Based on time-resolved energy consumption data collected by the IoT system, operational activities such as HVAC operation, lighting usage, and plug-load equipment operation are identified and aggregated over their operating periods. Operational carbon emissions are calculated as:

$$E_{B6} = \sum_{e \in E} EC_e \times EF_e \qquad (2)$$

Where E_{B6} represents the operational carbon emissions associated with energy use during the use stage (B6); EC_e denotes the consumption of energy type e; and EF_e is the emission factor corresponding to the specific energy type.

After module-level quantification, carbon emissions are further aggregated across different object levels using the hierarchical structure defined in BIM. At the component level, emissions can be disaggregated based on component–module relationships, while at the building level, module-level emissions are aggregated to derive overall carbon indicators. This hierarchical aggregation ensures consistency across object levels and supports lifecycle-scale carbon analysis.

3.5 Verification and validation

The reliability of the proposed lifecycle carbon assessment approach is examined through methodological consistency checks and comparative interpretation of results. Rather than aiming to establish absolute accuracy, the evaluation focuses on whether the framework produces reasonable and interpretable carbon estimates under real operating conditions.

Methodological consistency is ensured by adopting the lifecycle stage definitions of EN 15978 [14] and applying a unified activity-based accounting logic across construction and operational stages. This provides a coherent basis for cross-stage comparison and aggregation of carbon emissions.

The plausibility of the results is assessed through two complementary perspectives. First, the magnitude of estimated carbon emissions is compared with ranges reported in existing modular construction studies, providing a reference for overall emission levels. Second, IoT-based monitoring results are interpreted in relation to simulation outputs, not as a direct validation benchmark, but as a means of examining deviations between assumed and actual conditions. In particular, discrepancies in temporal patterns are analysed to identify behaviour-driven variations, such as occupant-induced fluctuations in energy use, which are not captured by schedule-based simulations.

Given the absence of fully observed lifecycle carbon data, these comparisons remain indirect and do not constitute validation against ground truth. Instead, they provide supporting evidence on the interpretability and practical relevance of the proposed approach. This limitation reflects the inherent challenges of lifecycle carbon assessment under real-world conditions.

4 Case study

4.1 Embodied carbon emissions in the construction stage

Case I is a MiC student dormitory project in Kowloon Tong, Hong Kong, selected to evaluate the proposed BIM–IoT method for monitoring construction-stage embodied carbon (A1–A5). The project is a 15-storey steel-structured dormitory consisting of 867 prefabricated modules, with a gross floor area of approximately 50,200 m^2. A cast-in-situ portion of the project contributes about 33,042.82 tCO_2e during construction. As these emissions cannot be reliably attributed at the module level, they are excluded from the analysis. It should be noted that this exclusion represents a substantial portion of the total construction-stage emissions and therefore constitutes an important limitation of the module-level analysis. Within this scope, on-site emissions are limited to crane operations for module lifting, while other equipment energy use without consistent module-level attribution is omitted, in accordance with the defined module-based accounting boundary.

Figure 2 illustrates the composition of module-level embodied carbon emissions. Material-related emissions dominate across all module types, accounting for approximately 94.3% of the total, while contributions from production equipment, transportation, and on-site lifting remain relatively small. As summarised in Table 2, embodied carbon per module ranges from approximately 11.0 to 11.9 tCO_2e across different module types. This consistency, together with the dominant contribution of material-related emissions observed in Figure 2, indicates that, in a highly standardised MiC system, module-level embodied carbon is primarily governed by shared material compositions and uniform production arrangements, with limited influence from functional or spatial differences. These patterns are consistent with previous studies on modular construction [20, 21, 22]. Overall, Case I demonstrates that the BIM-IoT-based monitoring approach enables attributable and interpretable embodied carbon analysis during construction, particularly in scenarios where conventional inventory-based methods cannot provide traceable module-level attribution.

4.2 Operational carbon emissions in the operational stage

Case II investigates a MiC student dormitory project in Wong Chuk Hang, Hong Kong, to evaluate the proposed BIM–IoT-based approach for operational-stage carbon monitoring (B6). The project has been in operation since September 2023 and comprises two 17-storey MiC residential towers with 952 prefabricated modules. This case serves as an operational-stage validation of the proposed framework, complementing the construction-stage

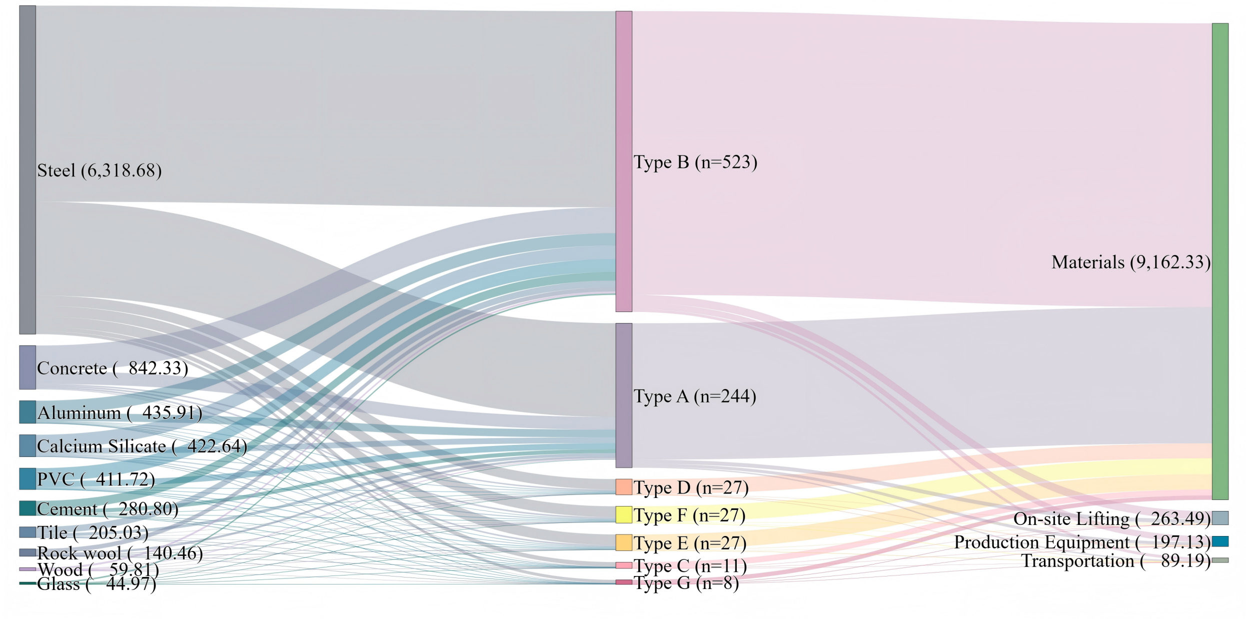

Figure 2. Carbon flow of module-related embodied carbon (tCO_2e)

Table 2. Carbon emission inventory of MiC modules by stage and type (kg CO_2e)

Module Type	**Quantity**	**Production Equipment**	**Material**	**Transport**	**On-site Lifting**	**Total per Module**	**Total Emission by Type**
Type A	244	230.04	10,744.96	104.17	306.32	11,385.49	2,778,060.18
Type B	523	224.73	10,431.34	101.12	300.62	11,057.81	5,783,235.75
Type C	11	220.51	10,430.61	98.52	300.08	11,049.72	121,546.93
Type D	27	228.89	10,638.78	104.91	309.77	11,282.36	304,623.65
Type E	27	237.47	10,959.92	110.92	318.42	11,626.72	313,921.57
Type F	27	246.20	11,250.80	117.02	327.64	11,941.67	322,425.02
Type G	8	224.73	10,412.25	101.37	302.11	11,040.46	88,323.72

analysis in Case I. Given the standardised layout and function of dormitory rooms, room-level energy use is primarily electricity-based. Multi-source IoT data, including HVAC energy consumption, plug loads, and lighting electricity use, were collected at the module level (room level) over a one-month period. These data provide time-resolved carbon emission profiles across different end-use categories and are compared with EnergyPlus simulation results.

Figure 3 presents the comparison between IoT-based monitoring and simulation at both total and end-use levels, based on a representative room selected from the monitored dataset. At the aggregate level, monitored carbon emissions exhibit pronounced temporal variability and noticeable deviations from simulation results. At the end-use level, lighting emissions show intermittent peaks associated with occupant-driven usage, plug-load emissions display irregular fluctuations not captured by simulation, and HVAC-related emissions deviate from simulated trends due to differences between assumed control conditions and actual indoor operation.

Overall, while simulation captures general trends, it fails to represent short-term variability and peak emissions observed in monitoring data. These results highlight the strong dependence of operational carbon emissions on occupant behaviour and demonstrate the advantage of the BIM–IoT-based approach in capturing dynamic, time-resolved carbon characteristics in modular residential buildings.

A combined view of Case I and Case II shows that the proposed BIM–IoT-based approach enables detailed module-level carbon analysis across both construction (A1–A5) and operational (B6) stages. Together, these results further indicate the broad applicability and versatility of the proposed framework across different lifecycle stages.

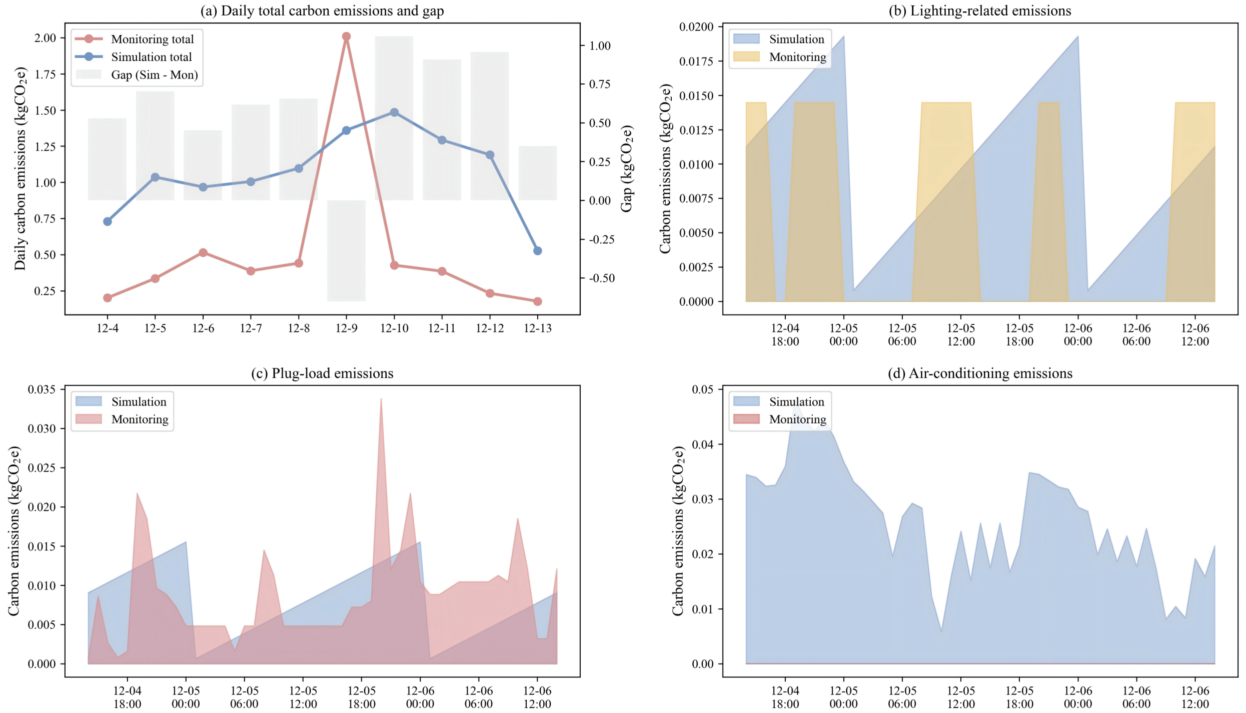

Figure 3. Operational carbon tracking using BIM–IoT integration at total and end-use levels.

5 Conclusion and discussion

Accurate and continuous lifecycle carbon monitoring in MC remains challenging, primarily due to fragmented production processes, heterogeneous data sources, and the lack of reliable mechanisms. To address these challenges, this study proposes a BIM–IoT-integrated approach in which modules serve as the fundamental analytical unit for carbon accounting, enabling consistent lifecycle carbon tracking at the module scale.

The results show that the approach supports consistent module-level representation of carbon emissions across both construction (A1–A5) and operational (B6) stages. By integrating BIM-based structural information with time-resolved IoT data, it enables attributable and traceable carbon analysis, providing clearer insights into carbon emission dynamics across activities and processes.

The findings also reveal key differences between simulation-based and measurement-based estimation of operational carbon. While simulation captures general trends, it overlooks short-term variability and peak emissions driven by occupant behaviour and operating conditions, potentially introducing systematic bias at finer temporal and spatial scales, particularly in highly standardised modular buildings.

Despite these contributions, several limitations should be acknowledged. The lifecycle scope is confined to stages A1–A5 and B6, excluding other stages, such as maintenance, and end-of-life processes, due to data constraints. Emissions from cast-in-situ components are also excluded as they cannot be reliably attributed at the module level, limiting completeness. In addition, embodied and operational carbon are demonstrated using separate projects rather than a single integrated case, due to the difficulty of obtaining continuous lifecycle data. Data uncertainty is also insufficiently addressed, including sensor noise, missing data, and their propagation in carbon accounting.

Future work will focus on implementing the framework within a single project to enable continuous data collection across construction and operational phases, extending coverage to additional lifecycle stages (e.g., maintenance and end-of-life) as data become available, and incorporating uncertainty-aware data processing and validation methods. These efforts are expected to enhance the robustness and practical applicability of data-driven lifecycle carbon management in MC.

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