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IOT-ENABLED FRAMEWORK FOR MONITORING CARBON EMISSIONS IN THE MATERIALIZATION PHASE OF MODULAR INTEGRATED CONSTRUCTION

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Abstract. The potential of Modular Integrated Construction (MiC) to reduce carbon emissions (CEs) has led to increased attention on developing rigorous monitoring systems. Existing methods predominantly capture CEs of isolated MiC stages, overlooking nuances of arrangeable and reusable activities, thus hindering effective CE control measures. To overcome this limitation, this study develops an Internet of Things (IoT)-enabled framework for monitoring CEs of MiC, specifically focusing on the materialization phase, integrating across various MiC stages and facilitating detailed monitoring of CEs associated with arrangeable and reusable activities. This study builds up a CE measurement model tailored to the MiC materialization phase, providing a computational basis for a subsequent monitoring framework. By leveraging IoT technology, the framework is evaluated through case studies to confirm its feasibility and efficacy. The results indicate that the framework enabled improved monitoring capabilities, and the CEs of many MiC activities are successfully integrated into the system. The case study analysis demonstrates that the system's feedback-driven adjustments achieved a CE reduction of 732.04 metric tons.

Keywords: MiC, materialization phase, IoT, monitoring framework, carbon emmisions.

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Abbreviations

MiC – Modular Integrated Construction;
CEs – Carbon Emissions;
IoT – Internet of Things;
IT – Information Technology;
RFID – Radio-frequency identification.

1. Introduction

The increasing global warming has prompted a growing number of countries to prioritize and enact measures aimed at conserving energy and reducing carbon emissions (CEs). According to the 2022 Global Status Report for Buildings and Construction (United Nations Environment Programme, 2022), the construction industry's energy usage in 2021 exceeded 34% of the world's energy consumption. Consequently, there is a growing focus on CEs reduction within the construction industry.

The potential of industrialized construction to achieve significant CE reductions has been widely acknowledged, positioning it as a focal point of interest (Hao et al., 2020). Contrasted with conventional cast-in-place methods, the industrialized construction encompasses the prefabrication and assembly of building components within a factory or controlled environment (Li et al., 2020). This yields benefits such as reduced material waste (Kedir & Hall, 2021), optimized energy usage (Qi et al., 2021), and minimized transportation emissions (Hao et al., 2020).

Modular integrated Construction (MiC) exemplifies the industrialized construction with an impressive 90% assembly rate (Zheng et al., 2020). MiC significantly streamlines the construction process by facilitating simultaneous on-site groundwork and off-site module assembly (laili Jabar et al., 2013). It has great potential to effectively reduce non-essential CEs as long as reasonable planning and arrangements of MiC-specific activities are implemented (Loo et al., 2023; Pan & Zhang, 2023). This study focuses on the "materialization phase" of MiC. The "materialization phase" in MiC refers to the period from the production of building materials to the completion of construction, encompassing all activities related to the actual construction of MiC projects. The CEs generated during materialization phase are concentrated within a short timeframe and is worth noting that most of the key MiC activities that impact CE reduction, such as component production, logistics, and installation, are integral to the materialization phase (Li et al., 2023; Pakdel et al., 2021). Therefore, monitoring CEs in MiC materialization phase can identify potential carbon overruns and achieve effective control of CEs (Miklautsch & Woschank, 2022), and is essential for the effective execution of such strategies (Tao et al., 2018). A number of existing studies have investigated CEs of buildings' materialization phase, from the aspects of CEs prediction in advance or CEs assessment after construction (Tao et al., 2018). Some studies have employed information technology (IT) to facilitate the monitoring of CEs from buildings. Although IT technologies, such as cyber-physical technologies have been employed for real-time monitoring of CEs of industrialized construction (Liu et al., 2023), a variety of MiC activities with high CEs are overlooked due to the limitations of cyber-physical technologies. To enable real-time monitoring of CE in MiC materialization phase, this study sought to Internet of Things (IoT) technologies to develop a specialized framework. Due to its capability for seamless connectivity, real-time data from diverse sources, IoT has become a key technology to monitor and control physical objects in various fields (Alsamhi et al., 2021; Jia et al., 2019; Manavalan & Jayakrishna, 2019; Tsang et al., 2018). IoT has demonstrated feasibility and distinct advantages in monitoring CEs in industrialized construction by capturing real-time data for enhanced carbon pattern sensing (Xu et al., 2023). Prior studies have employed a single type of sensor for real-time data collection, overlooking the integrated data transmission capabilities of IoT systems (Tao et al., 2018). Alternatively, existing studies have predominantly utilized IoT for monitoring CEs in fixed environments like factories or on-site locations, resulting in limited monitoring of equipment and materials (Liu et al., 2023; Xu et al., 2023). There is a deficiency for facilitating real-time monitoring of CEs of MiC materialization phase that encompasses various high-CE activities, necessitating an IoT framework that is interoperable, seamlessly integrating the diverse CE data across the extensive range of activities in MiC materialization phases.

This study aims to propose an IoT-based framework to monitor CEs of MiC materialization phase, enabling the real-time data collation and communication. The purpose of this study is mainly translated into the following research questions and solutions:

- How to quantify CEs of MiC materialization phase? In this study, MiC materialization phase is segmented into the module integration production stage, transportation stage, and module assembly stage. A comprehensive identification of carbon sources is conducted for each sub-stage, enabling the systematic classification of these sources. The CE factor method is then applied to develop a measurement model for assessing the CEs during MiC materialization phase. This model serves as the foundation for calculating and establishing a logical framework for CE monitoring.
- How to enable real-time CE data collection and communication during the MiC materialization phase? This study builds an IoT framework that contains a data collection layer, a data transmission layer, a data processing layer, and a data visualization platform. Within this framework, various advanced data collection techniques are utilized to collect real-time CE data. For example, Radio-frequency identification (RFID) has been utilized to track building assets, allowing for the automatic collection of carbon data on building materials (Zhong et al., 2017). As a location tracking tool, the GPS module can monitor the transportation distance of the vehicle in real time and collect the transportation carbon data (Liu et al., 2020). Acceleration sensors are used to sense the movement of devices and thus determine the operating time of these devices (Li et al., 2019). Pneumatic pressure sensors are widely used in equipment that senses changes in vertical distance, and can be placed in construction elevators during the building construction stage to collect carbon data from the construction elevator operation (Al-Kodmany, 2023). In addition, this study develops a data transmission layer and a data processing layer to facilitate the presentation of real-time monitoring results.
- How can the captured real-time data be utilized to enable effective management of CEs during MiC materialization phase? This study developed a data visualization platform to visualize CEs measured using real-time carbon data, and to understand both current and cumulative CEs over time through bar charts and other forms. By observing the current level, trends, and the peak value of CEs, managers can perceive whether the CEs are abnormal or not, and if there is a need for timely intervention.

Through this research, the authors have developed a cost-effective and widely applicable CEs monitoring platform for the MiC materialization phase. Case studies demonstrate the platform's feasibility and practicality, enabling a paradigm shift from post-hoc CEs accounting to real-time process control. This study is further structured as follows. Section 2 provides a review of relevant studies. Section 3.1 designs a model for measuring CEs in MiC materialization phase, which provides logical and calculation bases for the monitoring framework. Section 3.2 designs a CE monitoring framework for MiC materialization phase based on IoT technology. Then, Section 4 examines the monitoring framework, using the example of a high-rise MiC in Shenzhen, China. Finally, Section 5 concludes the study and proposes future research directions.

2. Literature review

2.1. Overview of carbon monitoring in buildings

It has been emphasized that optimizing the management of building CEs beyond relying solely on the inventory method to assess annual CEs and conducting overall CE accounting and monitoring (Sina, 2022). Among the current monitoring methods, one of the simplest, most cost-effective, and direct strategies is taking regular energy readings using meters, such as electricity meters, to gather energy consumption data and monitor CEs (Guerra-Santin & Tweed, 2015). This strategy requires frequent monitoring of energy data to manage CEs effectively, involving a considerable investment of time and labor. Moreover, this method captures only a portion of the CEs during the operational phase of a building. With the progression of information technology, Building Information Modeling (BIM) technology, known for its automation and visualization features, integrates carbon data within a building's information platform. BIM technology also promotes collaborative communication among stakeholders, reducing unnecessary time spent and enhancing building energy simulations. Based on BIM technology, technologies such as the cyber-physical system (CPS) (Hackmann et al., 2013; Xu et al., 2023), IoT (Tang et al., 2019), digital twins (He & Bai, 2020), and geographic information systems (Hajibabai et al., 2011), have expanded into the domain of building CEs monitoring. Sensors are used to collect data from the physical environment, which, alongside virtual information provided by BIM, allows for the merging of physical and digital data. This shift away from traditional manual monitoring enables automatic, real-time monitoring of building CEs (Huang et al., 2022). However, building CEs monitoring systems that utilize these advanced technologies can be expensive, labor-intensive, and have limited applicability, which poses challenges for their practical deployment (Wang et al., 2021).

2.2. Existing CE monitoring in industrialized construction

In recent years, there has been an increasing amount of attention paid to industrialized buildings, in line with the low-carbon development goals of the construction industry. Initially, RFID technology has been used to collect carbon data, enabling real-time monitoring of carbon emissions (CEs) from prefabricated components (Tao et al., 2018). However, the complex and diverse production processes in industrialized buildings present challenges, as the limited capacity of a single sensor to capture carbon data can hinder the comprehensive collection and transmission of information. Additionally, CPS technology has been implemented for real-time monitoring of CEs in industrial parks, thus broadening the scope of CE monitoring across both temporal and spatial dimensions (Liu et al., 2023). Nonetheless, CPS may have inherent limitations that could result in missing certain high-CE activities within industrialized building production. IoT technologies have also been introduced for monitoring CEs in industrialized buildings (Xu et al., 2023; Zahid et al., 2021). However, current research tends to focus on using IoT to monitor CEs in static environments such as factories and construction sites, leading to limited monitoring of equipment and materials. Furthermore, the production phase of many high-carbon activities has not been sufficiently highlighted.

2.3. Advantages of IoT in energy consumption and CE monitoring

IoT combines various smart sensors and communication networks to facilitate real-time intelligent data sensing, collection, and analysis. Furthermore, IoT is recognized as a fundamental component of the Fourth Industrial Revolution due to its significant potential (Aheleroff et al., 2020) and has emerged as a pivotal technology in domains such as supply chain management (Zhou et al., 2015), facility management (Wu et al., 2022), and security management (Kamel & Hegazi, 2018). IoT also offers distinctive advantages in CEs monitoring. It can integrate many interconnected devices, allowing for the deployment of numerous sensors and meters in different locations (Georgakopoulos & Jayaraman, 2016), thus enabling comprehensive energy monitoring cost-effectively. IoT devices can seamlessly connect to the Internet, supporting real-time data transfer and remote monitoring (Perwej et al., 2019). This connectivity allows for centralized management and analysis of energy consumption data, even across geographically dispersed locations. Furthermore, IoT devices (such as smart meters and sensors) are often cost-effective and readily accessible (Avancini et al., 2019). They can be easily installed in existing infrastructure without the need for significant retrofitting or investment, broadening energy monitoring access to a wider range of users. Research has explored monitoring household electricity consumption by using IoT technology to predict future energy usage (Johannesen et al., 2019). However, much of the existing research focuses on using IoT technology to monitor CEs in the static environments of industrialized buildings (Liu et al., 2023). Notably, there is a significant lack of systems designed to monitor CEs of MiC materialization phase.

2.4. Research gaps

Through the literature review, three primary research gaps in monitoring CEs in buildings were identified.

1. **Cost and applicability issues:** Existing frameworks for carbon monitoring are expensive and lack universal applicability. The CE monitoring frameworks for buildings presented in previous studies are costly and have limited generalizability. In contrast, the monitoring framework proposed in this study is cost-effective and versatile, suitable for CEs monitoring during the materialization phase of various MiC projects.

2. **Overlooked monitoring of CEs associated with MiC activities:** The potential for reducing CEs in MiC significantly depends on optimizing its modular and reusable activities. However, the systematic assessment and monitoring of CEs related to these activities are not thoroughly addressed. Traditionally, the estimation of total CEs for a building or construction project depends on analyzing material and energy flows. In the realm of industrialized construction, current monitoring systems often focus narrowly on certain segments or processes, such as those in production lines or during transportation. This traditional approach to monitoring fails to fully capture the CEs associated with all MiC activities, which hinders the achievement of substantial optimizations that are crucial for maximizing the CE reduction potential of MiC methods. This study introduces a comprehensive framework for monitoring all CEs related to MiC activities.
3. **Lack of IoT monitoring in MiC materialization phase:** There is a lack of research on the use of IoT for monitoring CEs during the MiC materialization phase. While IoT technology is recognized for its benefits in carbon and energy monitoring, existing research has primarily focused on its application within the static environments of industrialized buildings, paying limited attention to the materialization phase where many high-carbon activities occur. This study aims to bridge this gap by developing an IoT-based framework for monitoring CEs throughout the MiC materialization phase.

3. Research methods

As depicted in Figure 1, this research centers on two crucial breakthroughs: (1) establishing a CE measurement model for the MiC materialization phase, serving as the foundational calculation and logical basis for the CE monitoring framework; (2) developing a CE monitoring framework for the MiC materialization phase, utilizing IoT for the seamless real-time automatic collection and analysis of carbon data.

3.1. Computational and logical basis of the CE monitoring framework for MiC materialization phase

3.1.1. System boundary definition

Researchers typically categorize a building's entire life cycle into distinct phases to manage the CEs across the building's entire life span. Similar to the life cycle of conventional prefabricated buildings, MiC projects are also segmented into the materialization phase, the operation and maintenance (O&M) phase, and the demolition phase (Hao et al., 2020). However, due to the unique production method of MiC, all activities related to the actual construction are concentrated in the materialization phase (Loo et al., 2023; Pakdel et al., 2021). During this phase, a variety of building materials are combined using diverse construction machinery and complex techniques within a short timeframe. Additionally, this phase is characterized by the generation of substantial CEs over a brief period. This phase possesses the greatest potential for achieving large-scale environmental sustainability and emission reduction (ES&ER) through the enhancement of industrialization. Accordingly, this study concentrates on the materialization phase, in which the majority of MiC's CEs are produced (Loo et al., 2023). In contrast to conventional prefabricated buildings, this study delineates the scope of the carbon monitoring research system for MiC materialization phase, encompassing the module integrated production stage, transportation stage, and module assembly stage, as illustrated in Figure 2.

3.1.2. Carbon source analysis

CEs during the MiC materialization phase primarily stem from two main sources: the procurement of construction materials and the energy consumed during the building

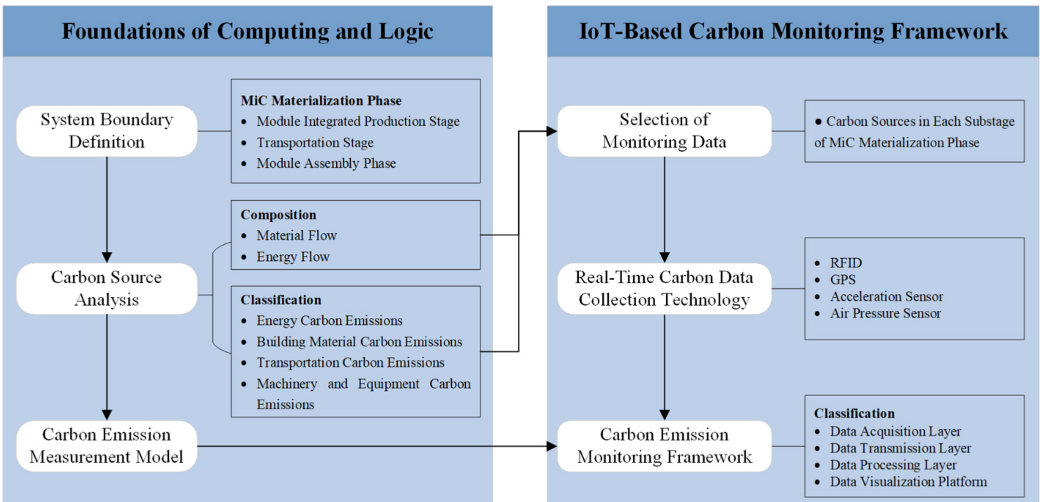

Figure 1. Framework of methods

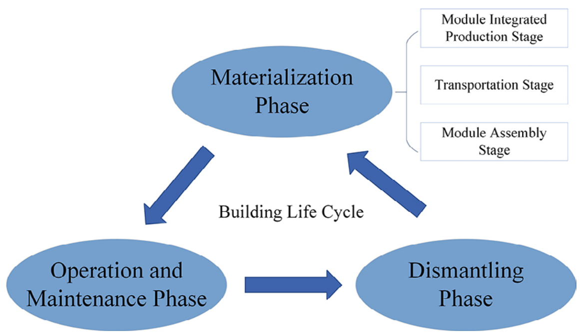

Figure 2. System boundaries for MiC

process. The term 'material flow' refers to the necessary material inputs for construction activities, while 'energy flow' denotes the energy expended in these processes. A thorough analysis of both material and energy flows at each sub-stage of the MiC materialization phase is crucial for accurate quantification and real-time monitoring of CEs.

(1) Carbon source composition

- Module integrated production stage

During the module integrated production phase, the primary factors influencing CEs are the consumption of materials and energy (Chen et al., 2022). The complete module production process was identified through literature analysis and on-site investigations. Figure 3 provides a comprehensive illustration of the cumulative material and energy requirements essential for the entire module production process, comprising 13 distinct procedures. Materials consumed in this stage can be classified into two primary categories. The first category includes permanent materials such as steel reinforcement, iron mesh, and concrete. Once utilized, these materials are incorporated into the final module product and are considered non-recoverable in terms of their CEs contributions. The second category encompasses reusable materials, exemplified by formworks (Dams et al., 2021). After the completion of module construction, the formwork is dismantled and reintegrated into the production cycle for future modules. The assessment of CEs associated with such recycled materials requires the application of material depreciation methods. This approach involves the spreading out of CEs contributions from the formwork, allocating them evenly over the lifespan of each production module.

The whole process of module production is accompanied by CEs from energy consumption. As depicted in Figure 3, these emissions mainly originate from the energy-intensive operations of production line equipment, encompassing electricity usage for activities such as steel cutting and concrete mixing, as well as diesel fuel consumption for equipment such as forklift trucks and kilns. Throughout the entire process of module generation, CEs are a byproduct of the utilization of secondary energy sources.

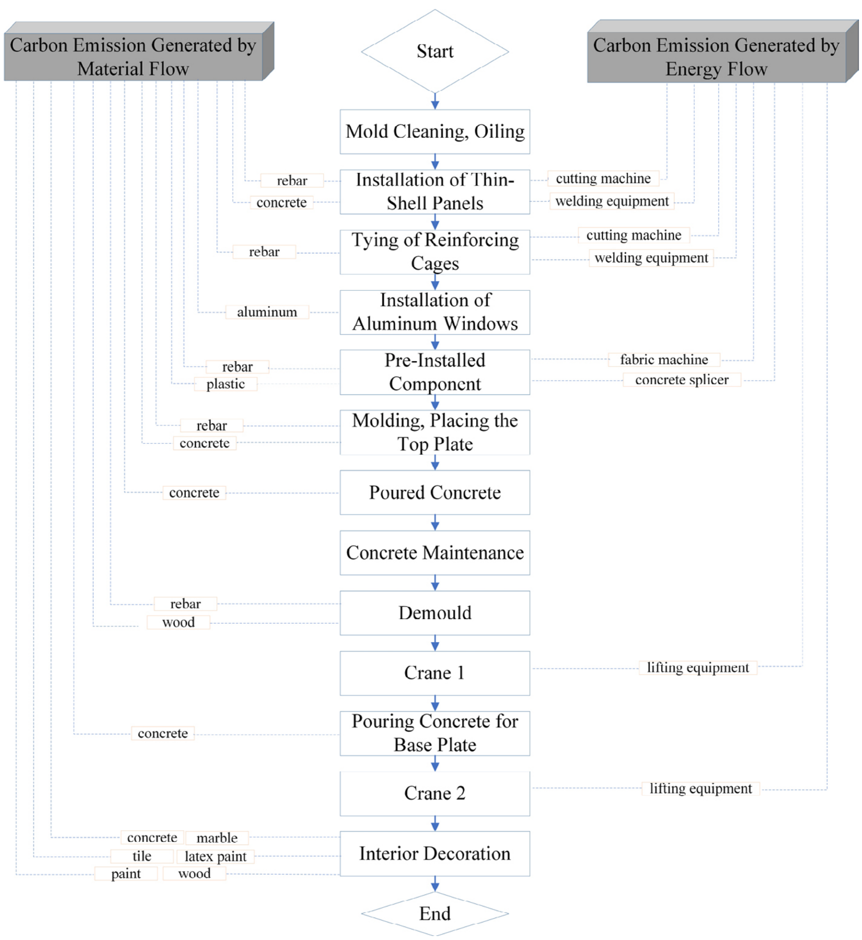

Figure 3. Material and energy inputs for modular production processes

- Transportation stage

CEs during the transportation stage mainly result from the energy consumption of transportation machinery. Within the MiC materialization phase, three primary types of transportation are evident: (1) Raw materials are conveyed to the processing plant; (2) Modules are transported to the construction site; (3) Construction waste is hauled to the landfill. During all three transport activities, CEs are produced due to the utilization of fossil fuels by transport machinery, regardless of the specific nature of the activity. Referencing Figure 4 provides insight into the energy consumption during the transportation stage. Different modes of transportation are utilized within the MiC materialization phase, mainly including road, water, and rail transport, all of which involve the consumption of secondary energy and subsequent CEs generation.

- Module assembly stage

CEs during the module assembly stage primarily arise from the consumption of materials and energy during assembly and cast-in-place activities. Assembly work involves positioning the module correctly within the building framework using mechanical equipment, while cast-in-place activities entail pouring nodes. Figure 5 depicts the material and energy consumed by each type of work in the module assembly stage.

Assembly work necessitates the deployment of diverse construction machinery, including cranes for lifting equipment and construction elevators for transporting materials and personnel. The operation of these devices consumes secondary energy, resulting in corresponding CEs.

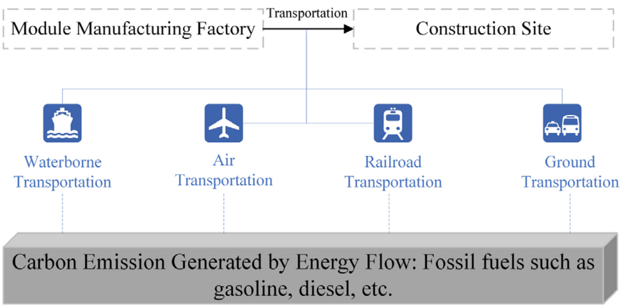

Figure 4. Energy consumption in the transportation stage

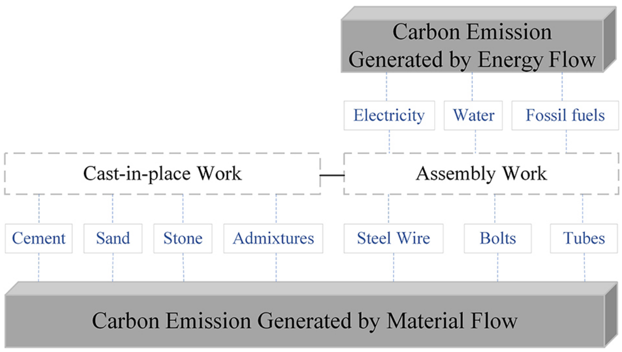

Figure 5. Material and energy inputs for the module assembly stage

Due to the distinctive process of MiC, wherein a substantial portion of work is accomplished in the module integrated production stage, less cast-in-place work is needed at the construction site. Consequently, the primary source of CEs stems from the energy consumption of construction machinery.

(2) Carbon source classification

Based on the analysis of carbon sources in MiC materialization phase, CEs primarily arise from two main sources: (1) indirect CEs generated during the production of building materials, and (2) direct CEs resulting from the production and operation of machinery and equipment, which consume secondary energy like electricity. By categorizing and organizing the carbon sources in each of the above stages, the types of CEs involved in each sub-stage are shown in Table 1.

3.1.3. CE measurement model

Drawing from the defined boundaries of the MiC materialization phase and the analysis of carbon sources in each stage, this study employs the CE factor method to develop a CE measurement model for the MiC materialization phase. The CE factors utilized are selected from the IPCC Carbon Emission Factor Inventory.

(1) Calculation formula for the total CEs in MiC materialization phase:

$$C = C_p + C_t + C_a, \tag{1}$$

where C – the total CEs from MiC materialization phase ($kgCO_2e$); C_p – CEs in the module integrated production stage ($kgCO_2e$); C_t – CEs from the transportation stage ($kgCO_2e$); C_a – CEs from module assembly stage ($kgCO_2e$).

(2) Calculation formula for CEs in the module integrated production stage:

$$C_p = \sum_{i=1}^{n} Q_i K_i + \sum_{j=1}^{m} E_{p,j} K_j, \tag{2}$$

where C_p – CEs in the module integrated production stage ($kgCO_2e$); Q_i – consumption of the ith major building material (kg); K_i – CE factor for the ith major building material ($kgCO_2e$/quantity of building materials per unit); $E_{p,j}$ – total energy use of jth type in the module integrated production stage (kWh or kg); K_j – CE factor for energy source jth ($kgCO_2e$/kWh or $kgCO_2e$/kg).

(3) Calculation formula for CEs in the transportation stage:

$$C_t = \sum_{i=1}^{n} Q_i D_i K_i, \tag{3}$$

where C_t – CEs in the transportation stage ($kgCO_2e$); Q_i – consumption of ith major building material (kg); D_i – average transportation distance of ith major building material (km); K_i – CE factor per unit weight of transportation distance for the ith mode of transportation of building materials [$kgCO_2e/(t*km)$].

Table 1. Types of carbon emissions involved in each sub-stage of MiC materialization phase

Research stage	Activities in MiC materialization phase	CE sources		Flow types	CE categories
Module-integrated production stage	Installation of thin-shell panels	Rebar use		Material flow	Indirect CEs
		Concrete use	Cement use	Material flow	Indirect CEs
			Sandstone use	Material flow	Indirect CEs
			Water use	Material flow	Indirect CEs
			Feeder truck consumes electricity	Energy flow	Direct CEs
			Spreading machine consume electricity	Energy flow	Direct CEs
		Cutting machine consume electricity		Energy flow	Direct CEs
		Welding equipment consumes electricity		Energy flow	Direct CEs
	Tying of reinforcing cages	Rebar use		Material flow	Indirect CEs
		Cutting machine consumes electricity		Energy flow	Direct CEs
		Welding equipment consumes electricity		Energy flow	Direct CEs
	Installation of aluminum windows	Aluminum use		Material flow	Indirect CEs
	Pre-installed component	Rebar use		Material flow	Indirect CEs
		Plastic use		Material flow	Indirect CEs
		Fabric machine consumes electricity		Energy flow	Direct CEs
		Concrete splicer consumes electricity		Energy flow	Direct CEs
	Molding, placing the top plate	Rebar use		Material flow	Indirect CEs
		Concrete use		Material flow/ Energy flow	Direct CEs/ Indirect CEs
	Poured concrete	Concrete use		Material flow/ Energy flow	Direct CEs/ Indirect CEs
	Demould	Rebar use		Material flow	Indirect CEs
		Wood use		Material flow	Indirect CEs
	Crane	Lifting equipment consume fossil fuel		Energy flow	Direct CEs
	Pouring concrete for base plate	Concrete use		Material flow/ Energy flow	Direct CEs/ Indirect CEs
	Interior decoration	Concrete use		Material flow/ Energy flow	Direct CEs/ Indirect CEs
		Marble use		Material flow	Indirect CEs
		Tile use		Material flow	Indirect CEs
		Latex paint use		Material flow	Indirect CEs
		Paint use		Material flow	Indirect CEs
		Wood use		Material flow	Indirect CEs
Transportation stage	Building materials transportation	Combustion of fossil fuels in transportation equipment		Energy flow	Direct CEs
	Module transportation	Combustion of fossil fuels in transportation equipment		Energy flow	Direct CEs
	Construction waste transportation	Combustion of fossil fuels in transportation equipment		Energy flow	Direct CEs
Module assembly stage	Cast-in-place operation	Cement use		Material flow	Indirect CEs
		Sandstone use		Material flow	Indirect CEs
		Additive use		Material flow	Indirect CEs
		Water use		Material flow	Indirect CEs
	Assembly operation	Cranes consume fossil fuel		Energy flow	Direct CEs
		Construction elevators consume electricity		Energy flow	Direct CEs
		Connecting structures use		Material flow	Indirect CEs

(4) Calculation formula for CEs in the module assembly stage:

$$C_a = \sum_{i=1}^{n} E_{a,i} K_i, \quad (4)$$

where C_a – CEs in the module assembly stage ($kgCO_2e$); $E_{a,\,i}$ – total energy use of ith type in the assembly stage (kWh or kg); K_i – CE factor for energy source ith ($kgCO_2e$/kWh or $kgCO_2e$/kg).

3.2. IoT-based CE monitoring framework in MiC materialization phase

3.2.1. Selection of monitoring data

Since CEs cannot be directly monitored, indirect methods are utilized, such as obtaining real-time CE data and calculating emissions using a CE measurement model. Consequently, the accurate selection of monitoring targets and obtaining real-time CE data are essential for monitoring emissions during the MiC materialization phase. The preceding context identifies carbon sources during this phase and establishes a CE measurement model. Thus, the focus of this study lies in monitoring the specific values necessary for the measurement model.

(1) Selection of monitoring data in the module integrated production stage

According to Eqn (2), given that K_i and K_j are known, monitoring CEs during the module integrated production stage merely involves acquiring the usage quantities of different building materials (Q_i) and energy consumption data ($E_{p,\,j}$). Given the time-consuming and labor-intensive nature of collecting data from electricity and fuel meters at high frequencies, this study employs an indirect approach to obtain energy consumption data, expressed as $E_{p,\,j} = p$ (equipment rated power) × t (equipment operating time). Consequently, during this stage, it is essential only to monitor the usage quantities of building materials (Q_i) and equipment operating time (t).

(2) Selection of monitoring data in the transportation stage

According to Eqn (3), with K_i known, monitoring CEs during the transportation phase simply involves acquiring the quantity of consumed building materials (Q_i) and the transportation distance (D_i). In this study, the quantity of building materials consumed (Q_i) is defined as the rated payload of the transportation vehicle. Therefore, during this phase, it is essential only to monitor transportation distance data (D_i).

(3) Selection of monitoring data in the module assembly stage

According to Eqn (4), given that K_i is known, monitoring CEs during the module assembly stage simply involves acquiring energy consumption data ($E_{a,\,i}$). Similarly, by employing an indirect method to obtain energy consumption data, expressed as $E_{a,\,i} = p$ (equipment rated power) × t (equipment operating time). Therefore, in this phase, it is essential only to monitor equipment operating time (t).

In summary, the realization of CE monitoring in the MiC materialization phase requires only the monitoring of data as shown in Table 2.

Table 2. Summary of monitored objects

Research stage	Monitoring object
Module integrated production stage	The usage quantities of building materials
	Equipment operating time
Transportation stage	Transportation distance data
Module assembly stage	Equipment operating time

3.2.2. Real-time carbon data collection technology

(1) Carbon data collection in the module integrated production stage

The primary sources of CEs during the module integrated production stage stem from the utilization of building materials and the operation of equipment within the component production line. The intricacies of production line processes, combined with the abundance of operating equipment, present challenges in directly monitoring equipment operational hours. Consequently, this study opts to utilize the processing duration of prefabricated components at each station by the equipment as the carbon data representative of that equipment.

In this study, RFID sensors are employed to capture real-time carbon data during the module integrated production stage. Each component is assigned a unique ID, and RFID readers are stationed with workers at each production line station. When a component begins or completes production at a station, the worker scans its ID with the RFID reader, recording the time difference between start and end times of the process. This time span represents the duration the component was processed at that station, serving as real-time carbon data for the equipment's operation. Simultaneously, the component's ID includes material usage data, allowing scanning with the RFID reader to obtain carbon data on building materials usage.

(2) Carbon data collection in the transportation stage

The transportation stage primarily focuses on monitoring the distance traveled to acquire real-time transportation carbon data. In this study, the GPS system integrated into the mobile devices of transporters is utilized for this purpose. At the commencement of transportation, the transporter accesses the carbon monitoring system and initiates tracking by clicking the order departure button. Subsequently, the system records the departure location and transportation details. Upon completion of transportation, the transporter re-engages with the system, confirming arrival by clicking the order end button. Real-time monitoring of transportation distance is facilitated by accessing GPS system data.

(3) Carbon data collection in the module assembly stage

Based on the previous analysis of carbon sources in the MiC materialization phase, CEs during the module assembly stage primarily originate from the energy consumption of construction machinery. Considering the diverse array of construction machines employed on-site, this study predominantly focuses on monitoring CEs generated by large-scale machinery and equipment, such as tower cranes and construction elevators.

In this study, an acceleration sensor is deployed to assess the motion status of equipment, enabling the monitoring of tower crane operation duration. Positioned on the tower crane's hook, the acceleration sensor detects movement in six directions – lifting, lowering, lateral shifts, among others – to capture real-time operational data. Additionally, the monitoring system can promptly display corresponding real-time CEs. To address the unique vertical distance fluctuations of construction elevators, an air pressure sensor is selected for real-time carbon data collection. Leveraging their proficiency in detecting vertical shifts, barometric pressure sensors are installed within the construction elevator to record its operational status and duration.

In summary, the collection techniques for each carbon data are shown in Table 3.

3.2.3. CE monitoring framework

To furnish a technical roadmap and foundational rationale for the forthcoming CE monitoring system, this study devises a framework grounded in the IoT for the MiC materialization phase. Illustrated in Figure 6, the framework encompasses four pivotal layers necessitating system development: the data acquisition layer, data transmission layer, data processing layer, and data visualization platform.

(1) Data acquisition layer

The precision of data directly impacts the reliability of monitoring outcomes relayed to managers by the monitoring system. This study meticulously delineates CE boundaries, conducts a thorough analysis of carbon sources in the MiC materialization phase, identifies the pertinent carbon data for monitoring, and implements automated real-time carbon data collection through distributed sensors. Specifically, RFID sensors are employed to gather building material information and monitor equipment operation times in the component production line, while GPS modules track the transportation distances of vehicles utilized during the transportation stage. Additionally, acceleration sensors capture operational statuses and durations of tower cranes, and barometric pressure sensors record operational statuses and durations of construction elevators.

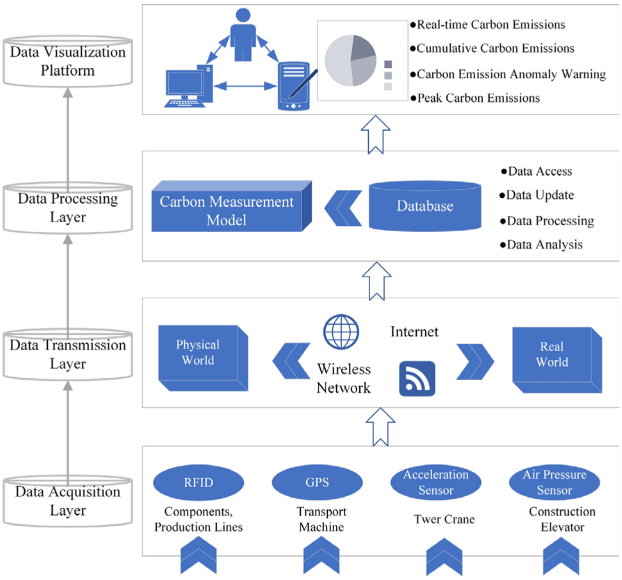

Figure 6. Carbon emission monitoring framework for MiC materialization phase

(2) Data transmission layer

The carbon data collected by sensors must be transmitted in real time to servers for subsequent processing and analysis, serving as a pivotal bridge between the physical and virtual realms. When integrating devices into IoT services, a high-speed and stable network is essential. Commonly utilized communication systems in the building industry encompass the Internet, wireless LANs, and restricted LANs, facilitating data transfer among various devices and between devices and cloud servers.

(3) Data processing layer

The data processing layer plays a crucial role in managing the received real-time carbon data, tailored to the user's objectives. Within the CE monitoring framework for the MiC materialization phase, processing real-time carbon

Table 3. Summary of carbon data collection technologies

Research stage	Monitoring object	Data acquisition technology	Technical description
Module integrated production stage	The usage quantities of building materials	RFID Sensor	RFID reader scanning ID to get the quantity of material used
	Equipment operating time	RFID sensor	At the beginning and end of production, RFID readers are used to scan the ID and automatically record the time difference between the start time and the end time of the process as the equipment running time.
Transportation stage	Transportation distance data	GPS module	GPS module to monitor transportation distances
Module assembly stage	Tower crane operating time	Acceleration sensor	Accelerometer sensors sense device operating status and time
	Construction elevator operating time	Barometric pressure sensor	Barometric pressure sensors sense device operating status and time

data can be summarized into four types: data access, data updating, data processing, and data analysis. This structure allows participants to conveniently access real-time carbon data from various locations and times, aligning with their specific needs.

(4) Data visualization platform

The data visualization platform is linked to the cloud server to ensure the synchronous updating of real-time CEs during the MiC materialization phase. This visualization platform serves three primary functions: (1) Displaying real-time CEs through bar graphs, depicting current stage emissions and cumulative emissions over the past ten minutes, ten hours, and seven days. (2) Issuing alerts when CEs surpass predefined thresholds, prompting management personnel to implement CE control measures. (3) Forecasting future CE trends based on historical carbon data and current CE line graphs, aiding management personnel in proactively addressing potential issues.

4. Learning case

This study aims to provide a preliminary exploration of CE monitoring in MiC materialization phase, with a focus on a high-rise MiC project situated in Shenzhen, China. The project was designed, procured, and constructed by China Construction Hilong Technology and China Shipping Construction, a subsidiary of China Construction International Group. The modular production line at CSCEC Hilong's Zhuhai base was selected as the monitoring environment. This project was selected for two primary reasons: (1) The implementing company is an industry leader with extensive experience, having completed design work for over 200 MiC projects in mainland China. (2) As mainland China's first high-rise MiC project, it serves as a highly representative case study. Furthermore, the project receives strong government support for related research, ensuring smooth implementation of the study. The project comprises two phases (I and II), both employing modular concrete construction with shear wall structural systems. With a total construction area of 229,500 m², Phase I includes 157,800 m² of floor area across five residential buildings, while Phase II covers 71,800 m² with four residential buildings. The site occupies 35,500 m², featuring structures reaching 90 meters in height (29 stories above ground) with two basement levels. The building layout is illustrated in Figure 7.

Figure 7 illustrates the building layout, where MiC represents modular units and YTB denotes balcony plates. The standard floor plan comprises three distinct zones: (1) modular zone containing primary living spaces; (2) prefabricated zone incorporating fully prefabricated balcony plates and staircases; and (3) cast-in-situ zone encompassing elevator rooms and corridors. The modular zone features two unit configurations: a 35 m² type combining YTB-1, MiC-1, MiC-2, and MiC-2R modules, and a 70 m² type comprising YTB-2, MiC-3, and MiC-4 modules. Table 4 details the standard-level application of single-story modules in this project.

4.1. Initial development of a CE monitoring system

Expanding on the previously established framework, this study commences the preliminary development of a CEs monitoring system specifically designed for the MiC ma-

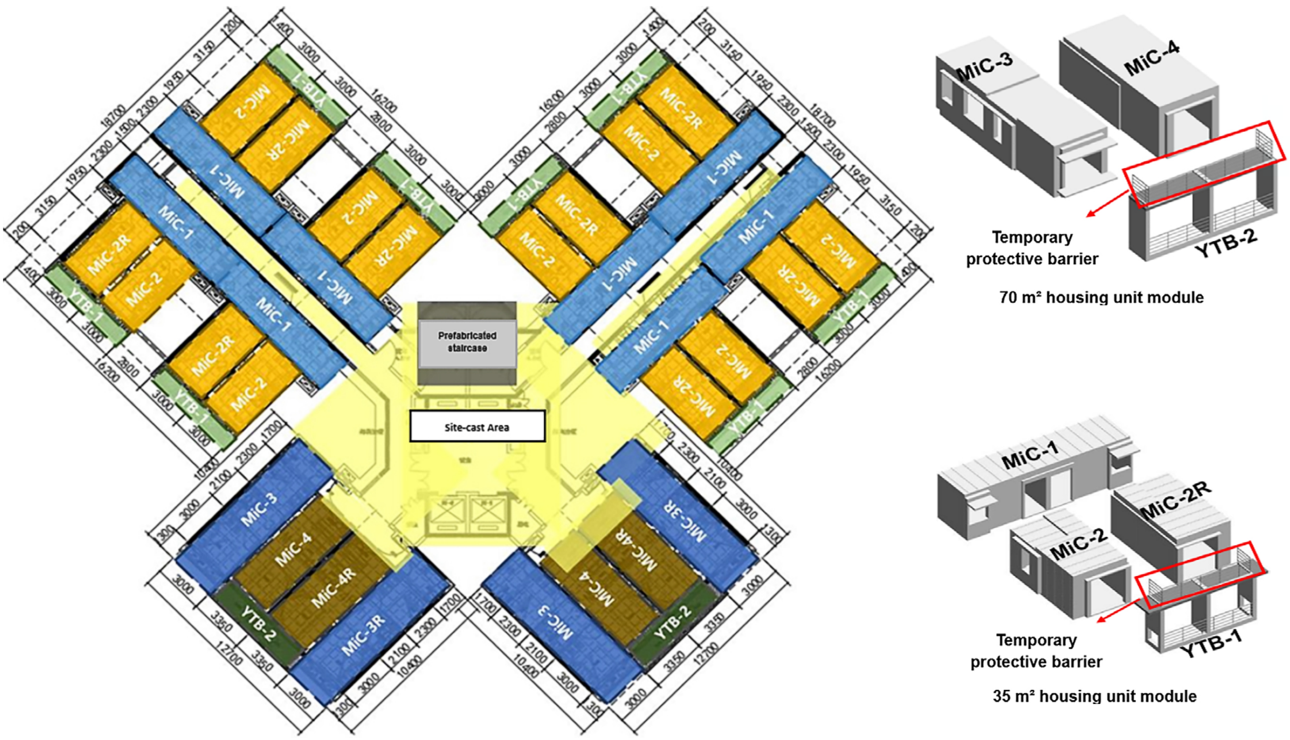

Figure 7. Carbon emission monitoring framework for MiC materialization phase

Table 4. Project standard layer single layer module application basics

Component No.	Number of single layers (unit: pcs)	Individual weights (in tons)
MiC-1	8	20.1
MiC-2(R)	16	13.2
MiC-3(R)	4	20.1
MiC-4(R)	4	16
YTB-1	8	5.5
YTB-2	2	8.3

terialization phase, intended for implementation in a pilot study. This endeavor aims to assess the effectiveness and feasibility of the IoT-based CEs monitoring framework. For this study, commercially available sensors with verified accuracy were primarily utilized; therefore, only the development of the RFID-based data acquisition system and visualization platform is presented herein. The total development cost of the monitoring system amounted to 146,000 RMB, comprising: 32,000 RMB for multi-type sensor procurement, 23,000 RMB for RFID system enhancement, 76,000 RMB for visualization platform development, and 15,000 RMB for ancillary expenditures. This cost structure demonstrates a significant reduction compared to existing monitoring systems reported in prior studies.

4.1.1. Data services platform development

In a CE monitoring system designed for MiC materialization phase, distributed sensors play a crucial role in collecting real-time carbon data. To achieve high-frequency data acquisition requirements unmet by commercial RFID sensors, this study conducted secondary development of RFID. Specifically, customized software was developed to enable rapid, high-volume data collection and transmission throughout the prefabricated component and module production process for CEs monitoring purposes. Ensuring the reliability of carbon data transmission is paramount alongside real-time data collection. The software interface encompasses five primary functional areas, as delineated in Figure 8.

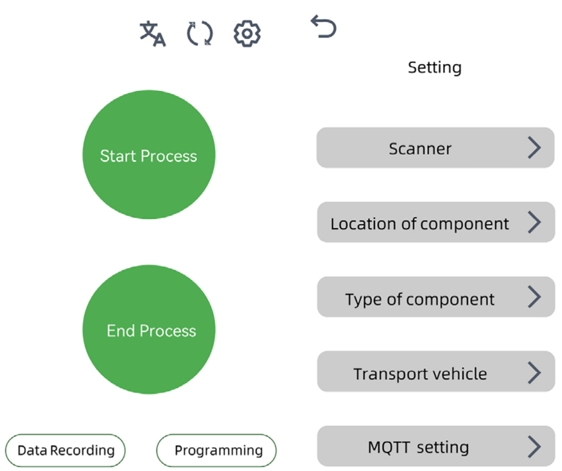

Figure 8. RFID secondary development software interface

(1) Setup

This function allows for the customization of collector worker names for both building materials and production line carbon data. Collection workers utilize RFID readers to scan QR codes on components on the production line, thereby collecting carbon data from equipment and building materials. Each piece of carbon data is associated with its corresponding collection worker on the platform. Additionally, this area facilitates the setup of the MQTT protocol to modify component location, type, and process. These adjustments are essential for subsequent carbon data calibration, ensuring data accuracy.

(2) Start reading

The start reading area comprises two sections: start inventory and tag status. The start inventory section displays tag information, enabling the modification of specific details based on real-time requirements. For instance, collector worker information, component ID, component status, component location, and reading time can be adjusted as needed. Upon initiation of the reading process by the collector worker, the platform gathers real-time carbon data accordingly. The tag status section offers managers a convenient overview of the corresponding component's status, facilitating efficient monitoring.

(3) End reading

When the equipment on the production line finishes processing the components, the collector worker clicks "end reading". Subsequently, the platform records the time interval between the start and end readings, enabling determination of the equipment's working time.

(4) Data logging and building block burning

After the reading process is completed, the different types of carbon data collected initially are summarized and transmitted wirelessly to the data visualization platform using the MQTT protocol.

(5) Server connection status

Personnel can easily verify the server status, indicating whether it is connected or disconnected.

4.1.2. Data visualization platform development

As shown in Figure 9, the data visualization platform integrates the CE measurement model for the MiC materialization phase. It presents quantified CEs from the MiC materialization phase in chart format, aiding management personnel in decision-making. The data visualization platform encompasses three functional areas.

(1) Real-time location of the module

Upon the module's initiation into the initial production process and its recognition by the RFID system, its location information is promptly displayed within the designated functional area. Additionally, the implied CEs of the module are automatically computed. Subsequently, as the module progresses to the next stage, team members conduct a re-scan to log the process's production time, triggering an upload of the module's location information.

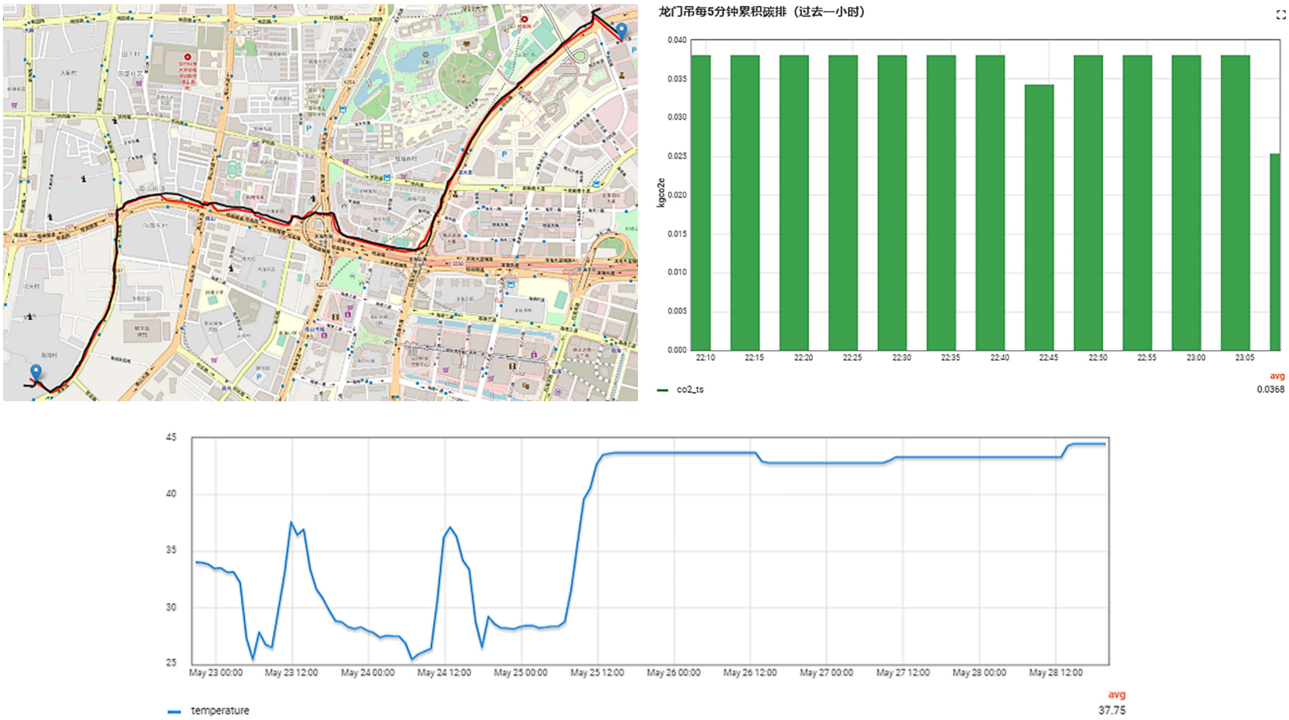

Figure 9. Demonstration of the three functional areas of the data visualization platform

Consequently, the module's location seamlessly transitions within the functional area to the succeeding process. As the module completes production and advances to the transportation phase, the GPS module actively tracks its real-time location, which is reflected in the designated area. This comprehensive system enables managers not only to monitor the implied CEs of each process component but also to gain insights into the real-time operational status of the production line, facilitated by the module's dynamic location tracking.

(2) Real-time data display

Drawing upon data transmitted by the data service platform, this functional area offers a line graph representation of CEs data collected from individual pieces of equipment. It effectively presents both the real-time CEs data of each equipment (updated within 5 minutes) and its historical CEs data. This setup empowers managers to effortlessly monitor the real-time operational status of each equipment and promptly detect any potential issues. To ensure data reliability, the system incorporates a "data verification" function with dedicated modules for data reception and transmission (Asif et al., 2025). Each data transmission undergoes automated verification within these modules, generating a "verification successful" notification to administrators upon completion. This dual-layer validation mechanism minimizes transmission errors while ensuring data integrity.

(3) CEs visualization

Upon receipt of data uploaded by the data service platform, the CE measurement model integrated into the MiC materialization phase within the data visualization platform automatically computes the CEs for each equipment and stage. This information is then presented in a bar chart format, categorizing CEs into real-time emissions and cumulative emissions. Through this visualization, managers can dynamically monitor the current level, trends, peaks, and any anomalies in CEs in real-time.

4.2. Preparations for monitoring

4.2.1. Selection of monitoring targets

The CE measurement model for the MiC materialization phase necessitates the acquisition of corresponding carbon data for each stage to enable CE monitoring. This study primarily focuses on monitoring MiC-1, MiC-2 modules, information of which is shown in Table 5, as well as concrete conveyors, placing machines, and traversing vehicles on the production line. Transportation machinery comprises large trucks, while construction machinery includes tower cranes, excavators, loaders, and construction elevators. Table 6 provides specific information regarding the monitoring machinery.

Table 5. Production information for MiC-1 and MiC-2

Component number	Concrete consumption	Reinforcing steel consumption
MiC-1	14.94 t	670.69 kg
MiC-2	12.63 t	410.70 kg

4.2.2. Selection of monitoring points and installation of sensors

Firstly, relevant information pertaining to the component, such as concrete consumption, rebar quality, and steel content, is inputted into the RFID tag. This tag is then

Table 6. Specific information on monitoring machinery

	Name	Model	Type of energy consumption	Rated power/fuel consumption
Construction machinery	Tower crane	W600-32U	Electricity	62.3 kw
	Excavator	Carter 320C	Diesel	16.44 L/h
	Loader	CLG365B	Diesel	14 L/h
	Construction elevator	SC200/200	Electricity	66 kw
Transportation machinery	Trucks		Diesel	12L/100 km
Production machinery	Concrete conveyor		Electricity	7.7 kw
	Placing machine		Electricity	22 kw
	Traversing vehicle		Electricity	10 kw

affixed to the component's surface, serving as its identity plate, streamlining subsequent RFID reader scans to retrieve component information. Secondly, as the component undergoes processing by the equipment at the workstation, the tag is initially scanned. Subsequently, it is scanned again at process completion, with the data service platform recording the time difference between the two scans (Δt) as the equipment's working time at the workstation. Additionally, the RFID reader records positional information of the component during scanning, effectively integrating the virtual and real worlds within the visualization platform.

For transportation monitoring, the GPS module on the transporter's mobile device tracks the vehicle's precise location in real-time. At the commencement and conclusion of transportation, the transporter activates the GPS module, transmitting real-time transportation carbon data and specific location information to facilitate transportation stage monitoring.

Tower cranes utilize acceleration sensors to monitor operational time. These sensors, affixed to the tower crane hook, detect hook movement, thus determining the crane's working time. Similarly, air pressure sensors installed in construction elevators collect carbon data during elevator operation. Water and electricity consumption are monitored via water meters and electricity meters, respectively.

4.3. Monitoring results

The carbon data collected by the data visualization platform is primarily presented through current CEs and cumulative CEs. In Figure 10, the CE results for the building factory plant are depicted, with the data visualization platform showcasing the current CEs of the plant alongside the hourly and daily cumulative CEs. Cumulative CEs denote that with the generation of each new component, the CEs produced by the new component are aggregated with those generated in the past. This cumulative CE value increases over time, facilitating management in conducting component material analysis and identifying potential optimization opportunities for hidden CEs. Moreover, cumulative CEs can also reflect the cumulative direct CEs during the operational lifespan of production line equipment and construction site equipment. This aids management in comprehending the total energy consumption of equipment operation and the upward trend in total CEs, thus enabling exploration of methods to mitigate direct CEs.

As shown in Figure 11, the visualization results of CEs during the transportation phase are displayed. From this, one can clearly understand the position of the transport vehicles as well as the historical locations and route information of the target vehicles for the past 3 hours and 24 hours. The cumulative CEs for each vehicle in the past half-hour are also included.

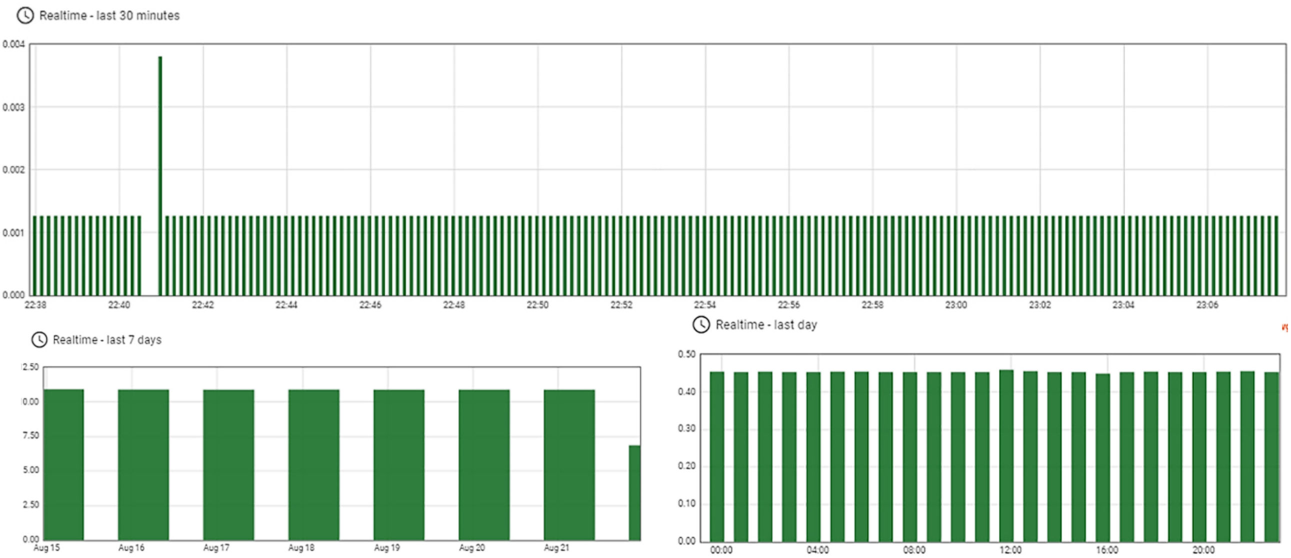

Figure 10. Carbon emission visualization for building factory plant

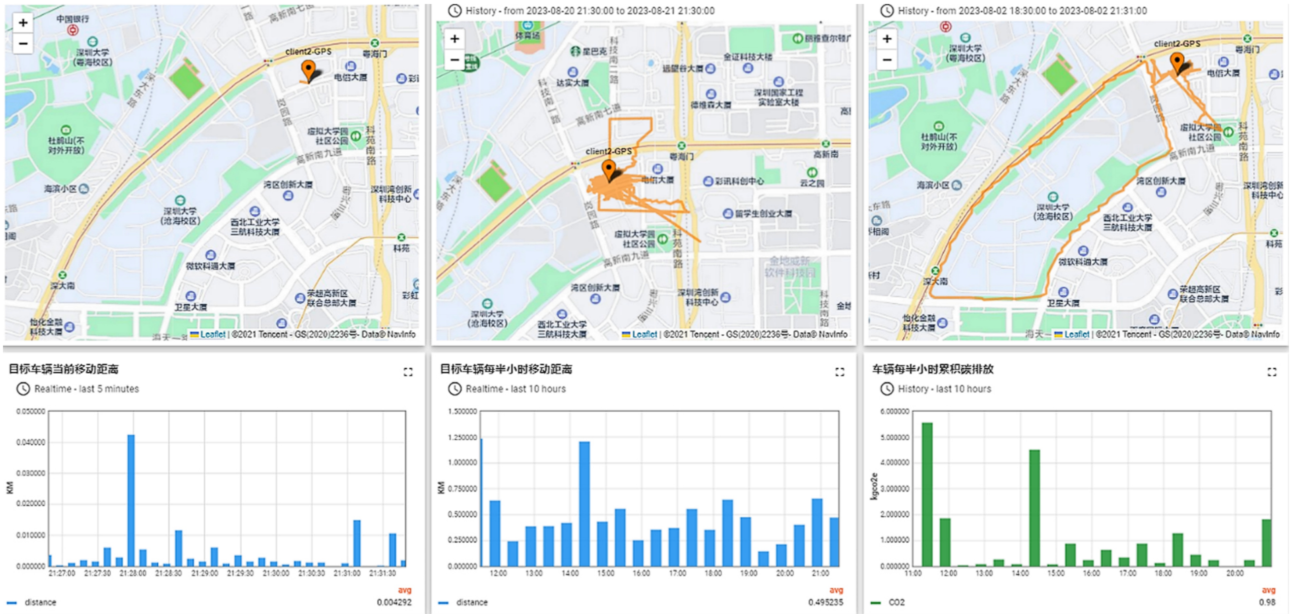

Figure 11. Carbon emission visualization at the transportation stage

4.4. Discussion

The data visualization platform provides a clear display of CEs changes across various modules, phases, and equipment over time and presents specific CEs. As shown in Table 7, in this study, the actual CEs of the monitored modules MiC-1 and MiC-2 are selected and compared and analyzed with the CEs of MiC-1 and MiC-2 that are not subject to real-time monitoring, in order to test the practicability and validity of the IoT-based monitoring of MiC materialization phases in terms of emission reduction. The CEs of MiC-1 and MiC-2 without real-time monitoring were calculated from the bill of quantities provided on site.

As shown in Table 6, a single MiC-1 module, when controlled by the monitoring platform, can reduce CEs by 126.04 kg, while a single MiC-2 module can achieve a reduction of 97.87 kg. In the case study, 44 modules are used per floor, with a total of 5,808 modules across 132 floors in five buildings. Based on MiC-1, it can be calculated that the monitoring platform can reduce CEs from the production and transportation of the modules by 732.04 tons. This demonstrates that the IoT-based CE monitoring framework proposed for the MiC materialization phase not only enables real-time and dynamic tracking of the operational status of the monitored objects but also provides immediate feedback on CE overruns. This facilitates timely intervention by management, reducing unnecessary resource waste and lowering the project's overall CEs.

5. Conclusions

This study endeavors to develop a framework for monitoring CEs during the MiC materialization phase utilizing the IoT. To attain this objective, the study has achieved the following:

(1) Through on-site investigations and literature analysis, this study has defined the system boundaries, comprehensively identified carbon sources during the MiC materialization phase, and classified and organized these carbon sources.

(2) The study has developed a measurement model for CEs during the MiC materialization phase, utilizing the CE factor method. This model offers a computational framework for effectively monitoring CEs.

(3) The study initially identifies the monitoring targets, specifies the data requiring monitoring, and designs the implementation of distributed sensors

Table 7. Individual module carbon emissions comparison results

Component number	Carbon emission activities	Carbon emissions (kg)		
		Monitored component	Non-monitored component	Carbon emissions changes
MiC-1	Production of single modules	7592.14	7707.06	114.92
	Machines for the production of single modules	52.48	60.23	7.75
	Transportation of single modules	50.64	54.01	3.37
MiC-2	Production of single modules	4461.72	4554.38	92.66
	Machines for the production of single modules	32.49	35.01	2.52
	Transportation of single modules	28.12	30.81	2.69

to gather real-time carbon data of diverse types. Building upon IoT, this study establishes a CE monitoring framework for the MiC materialization phase, offering a technical roadmap and foundational logic for the monitoring system's development. This framework outlines four essential levels for the monitoring system's evolution: the data acquisition layer, data transmission layer, data processing layer, and data visualization platform.

(4) Finally, to validate the feasibility and practicality of this framework, the study developed an initial IoT-based CE monitoring system for the MiC materialization phase, built upon the framework. A high-rise MiC project in Shenzhen, China, was chosen for real-time monitoring of CEs during its materialization phase. The research findings indicate that this monitoring framework adeptly facilitates real-time data collection, transmission, analysis, and visualization of CEs throughout the MiC materialization phase.

In comparison to extant studies, the CE monitoring framework developed in this research achieves comprehensive automatic real-time collection of carbon data during the MiC materialization phase. It further processes and analyzes the real-time carbon data, visualizes the monitoring outcomes, and triggers alerts in instances of abnormal CEs. Such functionalities facilitate the management of CEs in the MiC materialization phase by administrative personnel. This study demonstrates that the IoT-based framework for monitoring CEs during the MiC materialization phase exhibits the following advantages:

(1) Low cost and wide applicability. Throughout the study, IoT devices were effortlessly integrated into pre-existing infrastructure without necessitating substantial retrofitting or investment, and were readily accessible. Conversely, the resultant cost savings were considerable, rendering them applicable to various types of modular buildings.

(2) Comprehensive consideration of MiC's high carbon-emitting activities. The study's findings demonstrate that the established monitoring framework systematically assesses and monitors the CEs generated by all schedulable and reusable activities within the MiC system.

(3) Monitoring CEs in the MiC materialization phase using IoT. In this study, IoT technology is employed to develop a framework for monitoring CEs during the MiC materialization phase. Its feasibility and applicability are validated, addressing a gap in the literature where few existing studies have utilized IoT for monitoring the materialization phase of numerous high-carbon-emitting activities.

Due to project constraints, this study only undertook initial development of the CE monitoring system for the MiC materialization phase. The system requires further refinement in subsequent research. Future research endeavors will primarily concentrate on the following two aspects:

(1) Expand the monitoring scope. In addition to monitoring CEs during the materialization phase, the framework can be extended to encompass monitoring of CEs throughout the entire lifecycle of MiC. The MiC O&M phase significantly contributes to CEs across the building's lifecycle. Implementing lifecycle monitoring of buildings is advantageous for enhancing the monitoring system for MiC and promoting the sustainable development of the construction industry.

(2) Strengthen the analysis of carbon data. The current monitoring framework can collect carbon data, quantify the CE values at each stage, and display the peak CEs at the materialization phase, including cumulative CEs. In subsequent studies, the monitoring framework will further explore the analysis of real-time carbon data, use the platform to visualize the results of the comparison between the actual CEs in MiC materialization phase and the estimated value of CEs in the design phase, and predict the subsequent trend of CEs, to assist project managers in the efficient management of CEs.

(3) System-wide supervision enhancement. The currently developed CE monitoring system has incorporated preliminary data verification modules for both data reception and transmission, establishing basic data credibility. Future research will implement an integrated blockchain-dynamic calibration framework to: (a) complete the fundamental regulatory infrastructure, and (b) establish a closed-loop management mechanism encompassing monitoring, early warning, traceability, and continuous improvement.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Clyde Zhengdao Li: Conceptualization; Yiqian Deng: Writing – original draft, Methodology; Hengqin Wu: Data curation, Writing – review & editing; Vivian W. Y. Tam: Supervision; Khoa N. Le, Shan Guo: Validation.

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