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Analysis of Carbon Emission Monitoring Technology in Building Construction Phase Driven by Internet of Things Sensor Networks

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SUMMARY: *Leveraging the information - physical framework of the Internet of Things (IoT) sensor network, this research paper develops a carbon emission monitoring system for the building construction phase. It devises various types of sensors to gather environmental data during building construction and incorporates a MySQL database to store the diverse data sets. The scope of carbon emission calculation for the building construction stage is re - delineated. A carbon emission calculation approach for the construction stage is formulated from three aspects: human resources, building materials, and construction machinery. The T project is selected as the case study. The carbon emissions during its construction phase are computed, and the functionality of the carbon emission monitoring system is validated. The findings indicate that the average relative deviation rate of the calculated carbon emissions from construction machinery is 8.43%. Moreover, the carbon emission monitoring system enhances the calculation efficiency by nearly 15 times when compared to the conventional manual calculation method. In conclusion, a comprehensive integration of IoT sensors with building construction can notably enhance the carbon emission monitoring capacity during the building construction stage and contribute to the advancement of green buildings.*

KEYWORDS: *information physical system; sensor network; carbon emission calculation; building construction stage*

1 Introduction

The building sector, which serves as a significant economic domain, possesses the industry characteristics of high energy consumption and low efficiency, which not only wastes resources and energy, but also causes serious pollution and damage to the environment [1, 2]. The research by Huang et al. and Chen et al. indicated that the proportion of carbon emissions contributed by the construction sector in the context of global emerging economies is close to 60%, Primarily, these emissions are indirect, stemming from hard coal, natural gas, and non - energy sources[3]. Carbon emissions within the construction industry are predominantly spread across three phases: building materials manufacturing, the construction process, and building operation. Notably, the construction phase and building materials production phase contribute over 50% of the total carbon emissions[4]. Kanafani and colleagues examined data from Danish construction sites. Their analysis showed that emissions from transportation and waste management during the construction stage make up a substantial portion, approximately 13.47% of the life - cycle baseline. This is followed by emissions from electricity, heat, and fuel [5].

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Therefore, the construction industry has actively adopted a series of carbon reduction measures. For example, It actively encourages the utilization of low - carbon and eco - friendly construction materials, like novel insulation substances and materials derived from renewable resources. This is done to curtail carbon emissions that occur during the building construction process [6, 7]. At the same time, concepts such as lean construction are adopted to optimize the construction process, Enhance the effectiveness of resource consumption and curtail the production of construction debris, thus minimizing carbon output [8, 9].

To foster the low - carbon advancement of the construction sector more effectively, various intelligent approaches have emerged within the realm of carbon emission computation and evaluation. These methods not only boost the efficiency of calculating carbon emissions but also assist managers in setting up relevant management platforms [10, 11]. However, there is a big difference between the relevant data obtained through consumption quotas and the actual data on the construction site, and the applicability of consumption quotas to individual projects is not strong enough [12]. At the same time, Continuous, on - the - spot surveillance and graphical representation of carbon emissions throughout every stage of building construction enable the pinpointing of activities that generate high levels of carbon emissions. Additionally, this process can minimize the periods during which relevant construction equipment remains inactive. Therefore, Employing suitable digital technology to conduct real - time monitoring of carbon emissions during the construction phase can contribute to a reduction in carbon emissions within the construction industry.

In the past few years, as the issue of global climate change has become more prominent, researchers have carried out initial investigations in the area of real - time carbon emissions monitoring. Li and Chen developed a separation - integration quantitative mathematical model grounded in life cycle assessment and green construction criteria, and took Shenzhen project as an example to quantitatively assess the unit emissions of different building types during the construction phase, which provided theoretical basis and methodological guidance for construction energy management and energy saving and carbon reduction [13]. Mao et al. integrated distributed sensor networks and building information modeling (BIM) to formulate an Internet of Things (IoT) framework to capture carbon emission data from three major activities of prefabricated buildings and use an online platform to visualize and dynamically manage the emissions [14]. Tao et al. Developed a monitoring system for greenhouse gas emissions that relies on the Internet of Things (IoT) and Radio - Frequency Identification (RFID) technology, It utilizes sensors to gather real - time data on the production of pre - assembled components. Then, it integrates this data with a visualization service platform. This integration enables real - time analysis of carbon emissions and issues risk warnings, and provide an effective strategy for the industry to reduce emissions [15]. Liu and colleagues integrated cyber - physical systems to put forward a real - time carbon emission monitoring system that encompasses the entire industrial chain of prefabricated buildings, which integrates multiple types of hardware and display platforms to realize effective real-time monitoring [16]. Zhang and Zhang creatively developed an automated carbon monitoring system that combines Building Information Modeling (BIM) and the earned value approach. which achieves dynamic tracking, prediction and visualization of carbon emissions by embedding customized plug-ins [17]. Zhao et al. created an integrated monitoring platform using IoT technology to realize real-time collection, calculation, analysis, multilevel visualization display and export of carbon emission data from projects of construction groups, and verified its good application value and promotion prospect in several projects [18]. Ding developed a multi-source data fusion system based on Kalman filter, which can effectively integrate satellite remote sensing and other data to realize high-precision, high-timeliness and low-carbon emission monitoring [19]. Sepanosian et al. used IoT to implement a customizable and scalable construction site real-time emissions monitoring architecture that monitors pollutant data through an integrated network of sensors to provide real-time insights for site management [20]. Liu et al. proposed an artificial intelligence monitoring and prediction framework based on self-coding neural networks for complex engineering construction such as highway bridges, and the model can realize accurate carbon emission prediction with small error and short training time, so as to clearly analyze the emission sources and support effective carbon emission reduction strategies [21]. Bai and colleagues devised a data - based framework that combines a wireless sensor network with a long - and short - term memory model for carbon emission data during the building industry's construction phase. This framework enables real - time, high - accuracy prediction of equipment - level carbon emissions, which is beneficial for carbon emission monitoring [22]. Through a case study, Li and others confirmed that an Internet of Things (IoT) - enabled framework for monitoring carbon material emissions across all activity phases in prefabricated buildings can attain a carbon reduction effect of 732.04 tons [23].

These studies confirm the potential application of IoT technologies and sensors in building carbon emission monitoring. However, the monitoring data are mostly presented in the form of two-dimensional charts, the information gathered by sensors comes in multiple modalities, and the current data analysis efficacy is insufficient to comprehensively and effectively demonstrate the real-time changes in carbon emissions. In addition, Sandaruwan et al. systematic literature review showed that the existing system mostly combines IoT and BIM, but faces multidimensional challenges such as missing emission reduction targets and early decision-making, difficult to track the responsible parties in the supply chain, insufficient transparency in the validation process, data uncertainty, and limitations in system application [24]. The main goal of IoT sensor network technology is to establish a wireless, distributed organizational network to achieve comprehensive coverage of environmental sensing and data sharing, which in turn improves the monitoring and diagnostic capabilities of the environment,This research devises a carbon emission monitoring system for the building construction phase, relying on the Internet of Things sensor network.

It demarcates the calculation scope of carbon emissions during the building construction process and presents a detailed method for calculating carbon emissions. By utilizing this system for carbon emission monitoring in the building construction stage, it can address the existing issues of low - efficiency carbon emission calculation and large inaccuracies in the calculation results during the building construction period. Moreover, it can diminish the potential carbon emissions that may occur during the building construction phase and offer support for comprehensive carbon emission monitoring throughout the building's construction.

2 Development of a system for monitoring carbon emissions

With the environmental problems of globalization and the ecological awakening of mankind, green, ecological, low-carbon and sustainable development has become an inevitable trend. The current process of building construction in some areas does not pay enough attention to carbon emissions as well as the lack of corresponding measures and means, which leads to the emergence of a large number of pollution problems, causing great impacts on the neighboring residents. Therefore, the establishment of effective carbon emission monitoring methods for building construction is aimed at developing green buildings to curtail energy usage, diminish carbon discharges, and enhance the ecological setting.

2.1 Information Physical Networks

The Cyber - Physical System (CPS) is generally regarded as a networked physical device system that is controllable, reliable, and scalable. It integrates computation, communication, and control capabilities in a profound manner, based on environmental sensing. Through the mutual influence and feedback loop between computational and physical processes, new functions can be added or expanded, enabling deep integration and real - time interactions. This allows for the safe, reliable, efficient, and real - time monitoring and control of a physical entity.The overarching objective of CPS is to achieve a full - fledged integration of the information realm and the physical realm. By doing so, it aims to construct a CPS network that is controllable, reliable, scalable, safe, and efficient. Ultimately, this will bring about a fundamental transformation in the way humans construct engineering physical systems.In a CPS, the physical and computational processes form a closed - loop system via sensors, actuators, and network communications. This mechanism enables the deep - seated integration of computational and physical processes.

Generally speaking, CPS has the following distinctive features:

(1) Heterogeneous hybridization. On the one hand, it is the heterogeneous mixing of continuous physical processes and discrete computing processes, and on the other hand, it is the integration of heterogeneous computing platforms.

(2) Uncertainty of system dynamic behavior: physical processes in CPS have concurrency, physical behavior has uncertainty, the system has no global unified state, and network communication is uncertain.

(3) Spatio-temporal dependence: CPS has typical spatio-temporal characteristics, and the correct operation of the system is not only related to time, but also closely related to the spatial state.

(4) System openness: CPS has network diversity (including wireless network, wired network, domain-specific network, etc.), and system components diversity (physical components, computing components, control components, network components, etc.).

(5) Diversity of non-functional attribute requirements. Many CPSs have strict requirements for non-functional attributes such as security, reliability, and real-time performance.

2.2 Monitoring system framework

CPS is a highly integrated system of computation, In the context of the building construction phase's requirement for carbon emission monitoring, this paper integrates communication and physical processes to formulate a carbon emission monitoring system architecture, depicted in Fig. 1. This architecture comprises three distinct layers: the sensing layer, the network layer, and the control layer. The sensing layer primarily consists of sensors and other smart Internet of Things (IoT) devices, which are mainly used to collect physical data information from the construction site.The network layer, utilizing an established communication protocol, conveys the data gathered in the perception layer to the server via the edge gateway. This edge gateway serves as the crucial link that joins the physical realm and the information domain. The control layer receives the data transmitted from the network layer for storage, and transmits the analyzed and processed results to the front-end page to present them to the user in the form of a visualization page.

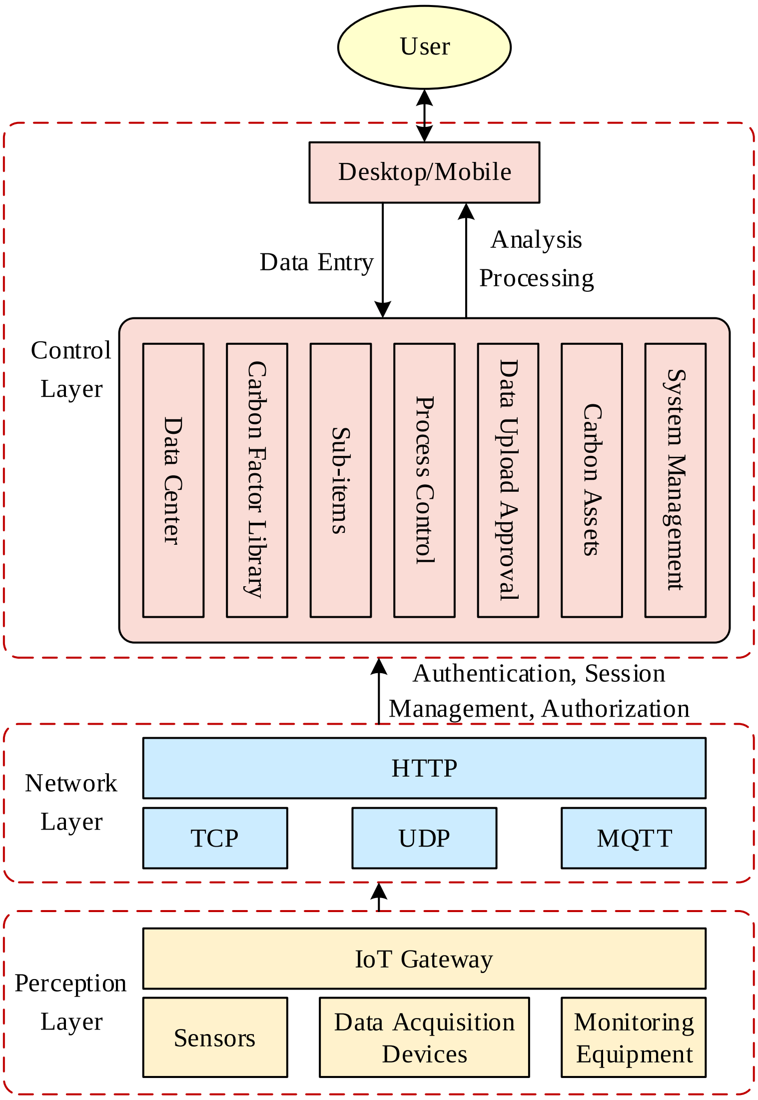

Figure 1: Architecture of carbon emission monitoring system

To meet the requirements for monitoring carbon emissions during the building construction stage, the platform backend is divided into seven management modules, including data center, carbon factor library, subsection, process control, data upload and approval, carbon asset and system management. The data center is the basic data maintenance module, including the types of emissions constituted by machinery, materials, transportation and energy, and the types of emission reduction required by the project. Users enter different types of basic data into the backend management system for storage, and the data center is directly linked to the carbon factor library and data uploading and approval. The web application is developed through the Vue framework, mainly including the data center, carbon factor library, sub-sections, process configuration, data uploading and approval, carbon assets, system management, and data overview pages. Users can directly add, delete and change the basic data through the browser, and upload and approve the data. From the data overview page, managers can directly view the total amount and distribution of carbon emissions from construction sites.

2.3 Physical sensing networks

The hardware system constitutes the physical layer of the carbon emission monitoring system. Sensors, a crucial component of this physical layer, play a vital role in gathering data from the physical environment and transforming it into electrical signals for transmission to the computing layer.In the carbon emission monitoring system designed for construction sites, appropriate environmental sensors must be installed. Given that greenhouse gases are highly responsive to fluctuations in temperature and humidity, it is essential to install sensors such as CO2 detectors, air quality monitors, temperature gauges, and humidity sensors. These sensors can collect a diverse range of environmental data from the site and transmit this information.

The carbon dioxide sensor stands out as the most crucial sensor. It functions as a tool for gauging the carbon dioxide concentration level, enabling direct measurement of the carbon emissions from a building construction site. In line with the requirements of the construction site, to achieve the multi - functionality of sensors and make rational use of resources, noise sensors and air quality sensors can be incorporated. These additional sensors are used to determine whether the tunnel environment complies with safety standards. Since a variety of sensors are needed to collect information, it can be designed as an integrated sensor, with a combination of multiple modules inside the integrated box, including CO2 sensor module, thermistor sensor module, power supply module, main board circuit module, etc., and adopting multi-button control.Beyond the integrated enclosure, a carbon fiber panel is employed to fabricate a fixture for mounting on the construction equipment. This fixture serves a dual purpose: safeguarding the internal sensors within the enclosure and shielding them from external disturbances.

2.4 Database design

In the carbon emission monitoring system of the construction site, the primary role of the database is to store diverse types of data. This data predominantly comprises readings from CO2 sensors, environmental data specific to the construction site, the electricity consumption of construction equipment, carbon emission coefficients associated with various resource and energy uses, and the computed carbon emission figures, as well as time data, cost data, and carbon emission data of the optimization management module, and so on.

MySQL database has a significant advantage over many relational databases, not only because of its open source nature that reduces costs, but also because of its good adaptability and reliability that makes it perform well in various application scenarios. In transactionless scenarios, MySQL databases are considered to be the best choice. This means that MySQL can perform data storage and retrieval functions efficiently and quickly without the need to perform complex operations on the data and ensure data consistency. In addition, due to its open source nature, MySQL has a large community support where users can easily find solutions and optimization tips to improve database performance and stability. Therefore, MySQL database is chosen as the data storage warehouse in this study, aiming to fully utilize its advantages and provide efficient and reliable data support for the study.

Integrating the surveillance management and enhancement management components within the carbon emission surveillance system designed for construction sites, the static model information and the dynamic monitoring data with the integrated management operation characteristics, the static information and the dynamic data generated by monitoring are summarized. And through the database management platform to realize the integrated management of the two, it is used to collect, analyze and store the monitoring data on the construction site and interoperate with the dynamic and static information in the BIM platform, in order to achieve the administration and retrieval of the data.

3 Calculation Scope and Method for Carbon Emissions

In the context of the worldwide drive for sustainable development, the construction sector is placing growing emphasis on achieving green construction management. The aim is to mitigate the adverse environmental effects and enhance the efficiency of resource utilization. Leveraging the data from the carbon emission monitoring system at the construction site, this chapter delineates the scope of carbon emission calculation during the construction stage. It also formulates the logic for carbon emission calculation and offers algorithmic backing for assessing the carbon emissions at the construction site.

3.1 Definition of computational boundaries

In the exploration of carbon emission measurement approaches during the construction stage of a building project, the accurate delineation of the statistical boundary and scope is of paramount importance. According to the entire life - cycle concept, a construction endeavor can be segmented into five distinct phases: the manufacturing of building materials, logistics and shipping, the actual construction process, the operation and upkeep, and the demolition. Specifically, the construction phase commences when the project officially begins and concludes upon the successful completion and acceptance of the project, and the core task is to transform the design results into a physical building through construction technology. In this phase, the construction company as the main implementation body, its construction organization and management level through the selection of machinery, material loss control and site planning and other key elements directly reflect, Ultimately, ascertain the extent of the environmental influence exerted by the construction procedure. In particular, it should be pointed out that the construction program preparation, technology selection and on-site management decisions led by the construction company constitute the key control nodes affecting carbon emissions.

Therefore, this paper clearly limits the boundary of carbon emission accounting to the project implementation stage led by construction companies, focusing on the carbon emission sources directly generated by construction activities. This definition not only highlights the main responsibility of construction enterprises, but also efficiently zeroes in on the fundamental elements influencing carbon emissions throughout the construction phase., and lays a theoretical foundation for the construction of an accurate measurement model. The so - called carbon emissions in the construction phase refer to the situation where the engineering contracting entity considers all the processes associated with the project during the construction period as an integrated system, which will produce various energy transfer and resource loss, and finally converge to emit carbon dioxide to the outside. As for the definition of the construction stage, All the operations conducted throughout the time frame commencing from the design and pre - work arrangements of the building project to the ultimate hand - over and approval of the project, including the construction site leveling, earthwork, foundation works, equipment installation, main structural works, on-site management, etc., are all considered as the construction stage.

Based on the preceding discussion, the scope of carbon emission measurement during the construction phase has now been defined. At the construction stage, the design plan, technology and techniques and construction site management factors lead to resource consumption and energy use, and its carbon emissions mainly come from two aspects,one aspect is the wastage of building materials. Specifically, it pertains to the latent carbon emissions associated with the primary construction materials (such as timber, iron and steel, and cement) during their production, shipping, and building processes. The second aspect is the energy usage (for example, petrol, diesel, and coal) during the operation of equipment, construction machinery, and vehicle transport at the building site.The level of carbon emissions during the construction stage of a building project has a significant positive correlation with the rate of building material loss. It is also directly influenced by the energy efficiency of the machinery and the frequency of transportation.Consequently, to precisely measure carbon emissions, the construction site can be efficiently partitioned into a construction zone, a living zone, and an office zone. The carbon emissions of each of these partitions can then be calculated separately.

3.2 Calculation method establishment

(1) Carbon emission calculation process

Different standards focus on different boundaries and scopes of carbon emission accounting, applicable fields are also different. However, during the ultimate phase of carbon emission calculation, the basic principles and processes are the same, regardless of Regarding the various types of carbon emission accounting standards, when it comes to calculating the carbon emissions during the building construction phase, the underlying principles and procedures are largely similar. The process of calculating carbon emissions is presented in Figure 2. The first step is to determine the calculation process, clarify the scope of accounting, and identify the carbon source. The second step, collect data, calculate carbon emission data, and check the uncertainty. In the third step, the results are corrected, validated and verified, and a conclusion report is formed.

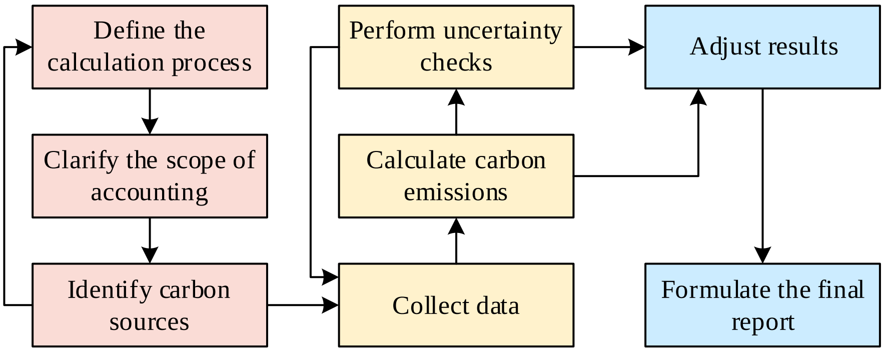

Figure 2: Procedure for calculating carbon emissions

The building project construction process typically encompasses three phases: the pre - preparation stage, the actual construction stage, and the completion and acceptance stage. This paper places its emphasis on the carbon emissions that occur during the construction period. Specifically, the boundaries and scope for carbon emission accounting are defined for the construction phase of the building project. The carbon emissions during the construction phase primarily stem from the utilization of materials, mechanical devices, and human activities involved in the construction process. which require carbon source identification and a greenhouse gas inventory according to standard requirements. After the inventory is determined, A system for monitoring carbon emissions is employed to gather data on greenhouse gas emissions and classify this data, with primary data collected directly and secondary data derived from simple extrapolations. After the data collection is completed, the calculation model is established, appropriate parameters are selected, and specific calculations are carried out using the data and calculation methods within the accounting scope, and the calculation results also need to be reviewed by experts.

(2) Carbon emission calculation method

During on-site construction, construction equipment and personnel activities will generate corresponding carbon emissions, calculated as:

$$C_{SG} = C_{SG,c} + C_{SG,j} + C_{SG,r} \tag{1}$$

where C_{SG} is the carbon emissions in the construction phase, $C_{SG,c}$ is the carbon emissions from materials in the construction phase, $C_{SG,j}$ is the carbon emissions from machinery in the construction phase, and $C_{SG,r}$ is the carbon emissions from personnel in the construction phase. That is:

$$C_{SG,j} = \sum_{i=1}^{n} Q_{SG,i} N_{SG,i} EF_{SG,i} \tag{2}$$

$$C_{SG,r} = Q_{SG,r} EF_{SG,r} \tag{3}$$

where $Q_{SG,i}$ is the energy consumption of the i th construction apparatus in a shift, $N_{SG,i}$ is the number of shifts of the i th construction apparatus, and $EF_{SG,i}$ is the carbon emission factor of the i th construction apparatus (or its energy type). $Q_{SG,r}$ is the man-days and $EF_{SG,r}$ is the carbon emission coefficient of the staff.

(3) Calculation method of carbon emissions from machinery

Based on the aforementioned carbon emission calculation approach, this paper proceeds to formulate the quantitative carbon emission calculation formula for three kinds of machinery, namely tower cranes, construction elevators, and on - site transfer vehicles, in construction sites. The details are as follows:

Tower cranes belong to power-consuming machinery, different types of cranes often have different rated power, the use of wireless sensors to count their running time, By integrating the rated electrical capacity and the carbon emission coefficient associated with electric power, one can carry out the computation of carbon emissions, the calculation process is:

$$C_1 = \sum_{i=1}^{m} P_{1,i} \times \left(\frac{T_{1,i}}{3600} \right) \times f_e \tag{4}$$

where m is the number of tower cranes at the construction site, $P_{1,i}$ is the rated power of the i th tower crane, $T_{1,i}$ is the operating time of the i th tower crane, f_e is the carbon emission factor of electricity, m and $P_{1,i}$ can be obtained from the engineering information, $T_{1,i}$ is obtained from the construction site by the carbon monitoring system of CPS, and f_e can be obtained by collation.

Similar to tower cranes, the procedure for calculating the carbon emissions generated by construction elevators is as follows:

$$C_2 = \sum_{i=1}^{n} P_{2,i} \times \left(\frac{T_{2,i}}{3600} \right) \times f_e \tag{5}$$

where n is the number of construction elevators at the construction site, $P_{2,i}$ is the rated power of the ith construction elevator, and $T_{2,i}$ is the running time of the ith construction elevator, n and $P_{2,i}$ can be obtained from the engineering data, and $T_{2,i}$ is obtained from the construction site by the CPS carbon emission monitoring system.

On-site transfer trucks are fuel-consuming machines, and their carbon emission calculation is slightly different from the former. The transfer truck has a corresponding fuel consumption per unit work shift T_0, and its carbon emission calculation formula is:

$$C_3 = \sum_{i=1}^{k} \left(\frac{T_{3,i}}{T_0 \times 3600} \right) \times E_{3,i} \times f_i \tag{6}$$

where k is the number of construction site transfer trucks, $T_{3,i}$ is the working time of the ith on-site transfer truck, $E_{3,i}$ is the fuel consumption per unit shift of the ith on-site transfer truck, f_f is the carbon emission factor of fuel, and T_0 is the shift.

(4)Carbon Emission Factor of Frequently Utilized Construction Equipment

Table 1 presents the carbon emission factors of typical construction machinery and fossil fuels. These factors are determined according to the relevant data regarding the energy consumption per work - shift of common construction machinery, as specified in the construction carbon emission calculation standard.

Table 1: Emission factors of carbon for frequently utilized construction equipment

Fossil fuel				
No.	Type	CO_2 emission factor per unit calorific value	Average lower calorific value	Carbon emission factor
1	Kerosene	$70.43tCO_2 \cdot Tj^{-1}$	43070kJ/kg	$3.03kgCO_2/kg$
2	Fuel oil	$75.82tCO_2 \cdot Tj^{-1}$	41816kJ/kg	$3.17kgCO_2/kg$
3	Gasoline	$67.91tCO_2 \cdot Tj^{-1}$	43070kJ/kg	$2.92kgCO_2/kg$
4	Diesel	$72.59tCO_2 \cdot Tj^{-1}$	42652kJ/kg	$3.10kgCO_2/kg$
Construction machinery				
No.	Type	Diesel	Electricity	Carbon emission factor
1	Tower crane	$28.43kg \cdot Shift^{-1}$	$166.29kWh \cdot Shift^{-1}$	$78.34kgCO_2 \cdot Shift^{-1}$
2	Double-cage construction elevator		$81.86kWh \cdot Shift^{-1}$	$38.56kgCO_2 \cdot Shift^{-1}$
3	On-site transfer vehicle		$60.27kWh \cdot Shift^{-1}$	$28.39kgCO_2 \cdot Shift^{-1}$

4 Utilization of Carbon Emission Surveillance Systems

As the initiatives for achieving carbon peak and carbon neutrality progress, the construction market has also gradually emphasized the transformation of the model, with more emphasis on the unity of project economy and environmental protection. The construction part,as the central connection within the production process throughout the entire life - cycle, it represents the crucial aspect of energy conservation and carbon emission management. Hence, the creation of a carbon emission monitoring system founded on an Internet of Things (IoT) sensor network is advantageous for achieving a more sustainable building construction. This system can minimize energy usage to the greatest extent while ensuring construction quality and mitigate the influence of the construction process on the nearby natural environment. .

4.1 Construction Project Overview

Project T represents a dwelling structure for residential purposes. The construction work includes architecture, structure, electrical specialty, water supply and drainage specialty, heating specialty, fire protection specialty and so on. The number of floors of the building is 1 underground and 9 above ground, and the main function of the building is 1 underground floor, and 1 to 9 floors above ground are residential, with 2 residential units. The building height is 42m, the building area is 5428.36 square meters, covering an area of 331.54 square meters, and the green building grade is basic. The structural configuration consists of cast - in - situ concrete shear walls. As for the foundation setup, it combines pile foundations and raft slab foundations. the concrete and masonry mortar are ready-mixed commercial concrete and ready-mixed commercial mortar. Figure 3 depicts the operational sequence during the construction stage of a cast - in - place structural building.

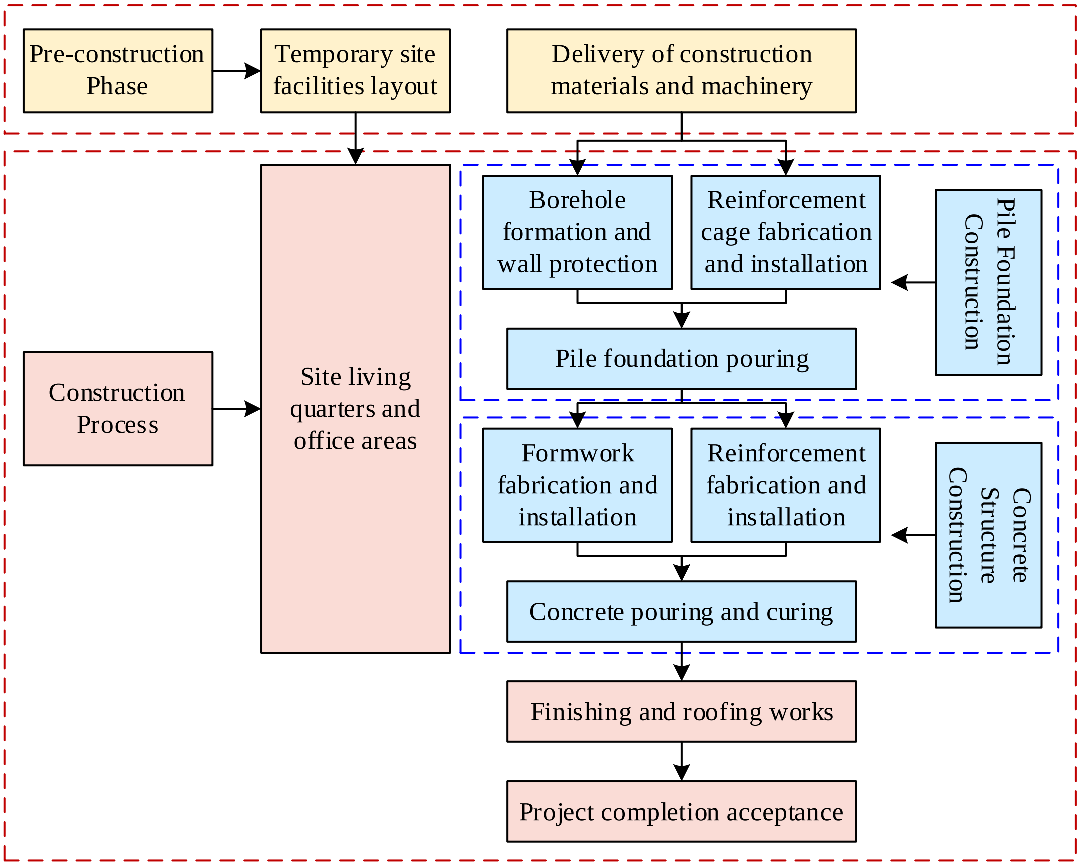

Figure 3: The procedure of operations during the construction phase of in-situ cast structures

The building is designed to have a service life of 60 years. It falls into two classifications of high - rise residential buildings for fire - safety purposes. The fire - resistance rating of the building is Class II for above - ground parts and Class I for below - ground parts. The structural safety grade of the building is Grade II, with a structural importance coefficient of 1.0. The seismic fortification intensity of the building is 7 degrees. For the columns and walls, from the foundation up to an elevation of 5.82m, the concrete is of strength grade C40. Above 5.82m, the concrete strength grade for columns and walls is changed to C35. The main building employs a pile - raft foundation. The elevation of the foundation bottom is - 6.8m. The design grade of the pile foundation is Grade A, and the type of pile used is the end - bearing friction pile,the length of piles is not less than 16m, and the pile foundation is mud shielded in-situ cast-in-place concrete cast-in-pile.

The pile foundation construction adopts rotary drilling rig to form holes, set up mud pool, equipped with cranes and dump trucks to cooperate with the construction. Two tower cranes and a single-cage construction elevator are arranged on the south side of the building, and steel reinforcement and carpentry processing areas are set up near the steel reinforcement and template stacking areas, and steel reinforcement processing machinery and carpentry processing machinery are configured. On-site set up machinery parking area, maintenance and repair of machinery. Office area is set up on site, which is a containerized two-story structure, and the living area is for construction workers to live.

The data of construction activities mainly come from the project pricing standards such as “S Province Building and Decoration Project Pricing Quotas”, “S Province Installation Project Pricing Quotas” and the project cost documents of this project, and the data of environmental impacts mainly come from the data obtained from the system for monitoring carbon emissions.

4.2 Computation of carbon emissions

(1) Examination of carbon emissions stemming from divisional operations

The tasks related to calculating carbon emissions for the research project handled by the department are segmented based on the construction order, including earthwork, foundation pit support works, pile foundation works, underground civil works, aboveground civil works and installation works, which are noted as GC1~GC6. The earthwork works include foundation elements such as digging general earth, digging foundation pit earth, gray soil backfill and backfill square, etc. The foundation elements are divided according to the construction sequence, which are noted as GC1~GC6. Foundation pit support works include shotcrete, cement mortar, high-pressure rotary piling, steel pipe piling, grouting piling and other base elements. Pile foundation works include reinforcing cage, bedding, foundation beam, reinforced concrete support and other base elements. Underground works include block wall, pile bearing foundation, full slab foundation, independent foundation and other foundation elements. Above-ground works include rectangular columns, rectangular beams, girder slabs, straight staircases and other primitives. Installation works include such primitives as protective railings, glass balustrades, window guard rails, stair railings, etc. Based on the carbon emission calculation formula put forward in this research, the carbon emissions of each sub - task can be computed, as presented in Table 2.

As is evident from the table, in the earthwork (GC1), the carbon emissions of the entities such as excavation of general earthworks and excavation of foundation pit earthworks were added together to obtain a total of 2262023.8449 $kgCO_{2^e}$ generated by this division of the project. By analogy,it is possible to compute the carbon emissions of every division within the construction stage of this building project. Subsequently, the carbon emissions from each sub - project are aggregated to obtain the overall emissions of the construction phase of the building project as 183656996.2577 $kgCO_{2^e}$ .Based on the carbon emission calculation outcomes presented in the table, it is evident that there are significant disparities in the carbon emissions among the diverse divisional works of the project, which are, in descending order, above-ground civil construction works, underground civil construction works, foundation pit support works, piling works, earthwork works and installation works.Within this group, the aggregate carbon emissions of the above ground civil works of this project have exceeded 100 million

$kgCO_{2^e}$. Moreover, due consideration must be given to the carbon emission reduction efforts within this work segment. The carbon emissions of the project's different sub - sections consist of carbon emissions from labor, carbon emissions from materials, and carbon emissions from machinery. The composition of carbon emissions varies among different types of works. The earthwork project has a small demand for materials and is mostly carried out by construction machinery and personnel, consequently, the carbon emissions associated with labor and those related to energy from the two entities make up a comparatively significant proportion.On the contrary, a substantial quantity of building materials is needed for foundation pit support works, piling works, underground civil construction works, above ground civil construction works and installation works, which make the material carbon emissions account for a higher percentage.

Table 2: Carbon emissions of sub-projects

Type	Carbon emissions ($kgCO_2^e$)			
	Artificial	Materials	Mechanical	Total
GC1	261764.6143	14516.3348	1985742.8958	2262023.8449
GC2	1653031.7593	9951479.7185	2163592.1464	13768103.6242
GC3	591628.9375	7120638.8856	535796.5648	8248064.3879
GC4	3856192.7142	52179631.5938	745191.3289	56781015.6369
GC5	1342895.1078	98276314.8453	982532.1614	100601742.1143
GC6	16832.5731	1941698.4281	37515.6483	1996046.6495

(2) Percentage difference in machinery carbon emissions from the norm

For every construction project during the earthwork stage, the carbon emissions resulting from the operation of machinery are computed, pit support works, pile foundation works, underground civil works, above ground civil works and installation works, and the relative deviation rate between the calculated results and the actual measurement results as depicted in Figure 4.

As is evident from the graph, the relative deviation percentages of carbon emissions from construction equipment across all construction undertakings are positive, which indicates that the carbon emissions calculation method significantly underestimates the carbon emissions generated by the operation of each construction machinery under the actual building construction stage due to the assumptions of theoretical bench quota and ideal working conditions. It is worth noting that the deviation rate of some unusual construction projects is significantly higher than the average, mainly because the construction phase of these projects involves the lifting of bulky steel structures and the construction of underground structures by reverse engineering method, and the frequency of the operation of heavy machinery with high loads is much higher than that of the conventional projects, and the level of energy consumption is also significantly higher. For construction scenarios such as multi-process coordinated operation and frequent dispatching of heavy equipment, the actual dynamic losses such as idle standby and inefficient operation are larger, and the calculation structure of the dynamic model is more significant than that of conventional working conditions. At the same time, refined construction organization and management can also inhibit the dispersion of carbon emission deviation to a certain extent. Based on the calculation results of the carbon emissions of machinery in the construction stage, the average value of the relative deviation rate is 8.43%, and the carbon emissions results obtained by the calculation method are generally lower than the measured carbon emissions by about 2% to 18%. A few construction projects appear to be doubled, and the distribution of the deviation rate shows significant inter-project heterogeneity and high volatility.

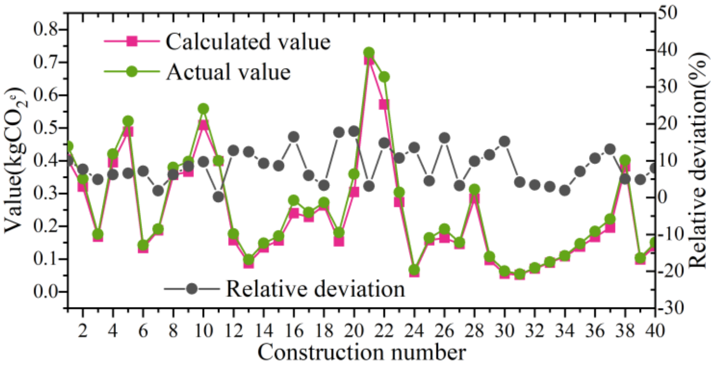

Figure 4: Relative deviation rate of mechanical carbon emissions

(3) Carbon intensity analysis

The aim of the carbon emission intensity assessment is to measure the carbon emissions of the pile foundation project during the construction stage of the primary engineering process, with the intention of putting forward relevant strategies for carbon emission reduction. This article presents the carbon emission intensity per unit cost based on the engineering cost quota standard, i.e., U=W/G, where U is the carbon emission intensity per unit cost of piling foundation in the construction stage (CO_2/yuan), W is the carbon emission of each component of piling foundation in the construction stage (CO_2/yuan), and G is the cost of each component of piling foundation in the construction stage (CO_2/yuan).

In the piling project, it includes rotary drilling rig drilling - drilling soil holes (within 600), rotary drilling rig drilling - drilling soil holes (within 900), rotary drilling rig drilling - drilling soil holes (above 1200), rotary drilling rig drilling - drilling rock holes (within 600), rotary drilling rig drilling - drilling rock holes (within 900), rotary drilling rig drilling - drilling rock holes (above 1200), rotary drilling rig drilling (within 600), rotary drilling rig drilling (within 900), rotary drilling rig drilling (within 1,200), rotary drilling rig drilling (within 1,500) and rotary drilling rig drilling (within 1,800), totaling 11 items, i.e. ZJ1~ZJ11. Based on the above formulae, the calculation of the fixed list of piles results in the carbon intensity of the various types of items, as shown in Figure 5. From the perspective of construction process of grouted piles, the intensity of carbon emissions for the same type of pile, regardless of varying pile diameters, remains approximately consistent, with little difference, but the difference between different construction processes is up to nearly 4 times or so. This is because the construction process selection of the grouted pile drilling rig drilling, making the selected construction machinery is different, rotary drilling rig drilling construction process of the construction machinery, which greatly reduces carbon emissions.

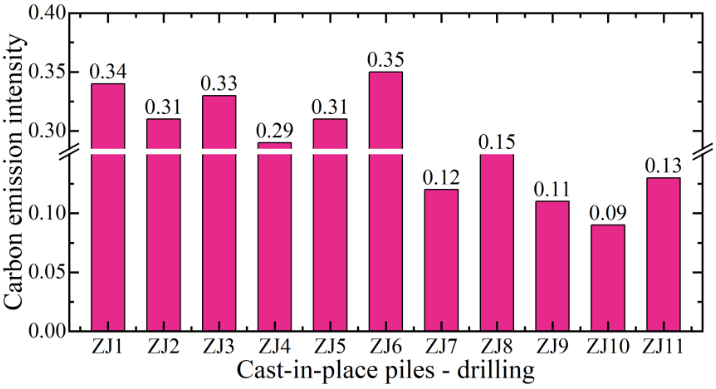

Figure 5: Carbon emission intensity of various projects

In this paper, the variation of carbon strength of piles with different pile lengths is carried out by taking square piles and square piles delivered piles as examples, and their specific conditions are shown in Fig. 6. In the figure, FZ1~FZ4 denote precast concrete square piles within 10m, within 20m, within 35m and above 35m respectively, and FZ5~FZ8 denote precast concrete square piles delivered within 10m, within 20m, within 35m and above 35m respectively. As is evident from the illustration, Within the same type of pile, the intensity of carbon emissions from the pile exhibits an inverse relationship with the increase in pile length. As the pile length grows, the carbon emission intensity gradually decreases. This finding further validates the statement in the previous text that carbon emissions will decline as the pile length increases. The source is attributed to the change of construction machinery, from small power construction machinery to high power, but at the same time reduce the working shift of construction machinery, to a certain extent, it is going to exert a favorable influence on the carbon emissions during the construction stage.

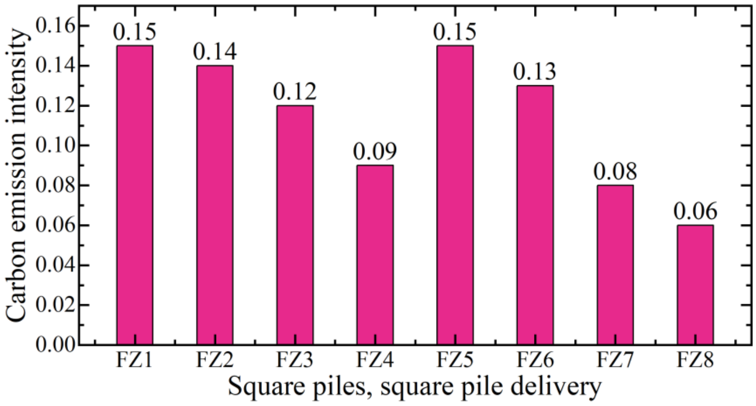

Figure 6: Carbon emission intensity of square piles and square pile delivery

4.3 System performance errors

To validate the functionality of the carbon emission monitoring system during the building's construction stage, this paper applies the system according to the building floor segments of the T project by comparing the traditional manual calculation method, and records the system in terms of the calculation efficiency and the calculation results. Tables 3 and 4 show the comparison of the efficiency and results of the system and manual calculation, respectively.

It can be concluded from the comparison that the carbon emission monitoring system developed by this paper in conjunction with the IoT sensor network in the construction phase of the building has improved the calculation efficiency by nearly 15 times compared with the traditional manual calculation method, and the difference between the calculated results and the manual calculation results is within 1.5%, which is within the acceptable range of error. This shows that the carbon emission monitoring system designed based on CPS in the construction phase of the building has excellent performance and is suitable for the accurate calculation of building carbon emissions. According to the comparison results, it can be seen that the manually calculated values of carbon emissions in the construction phase are slightly higher than the system calculated values. The reason for this is that the system ignores the problems of material loss and waste caused by irresistible factors in the actual construction phase, which leads to the calculation results of the carbon emission monitoring system being smaller than the actual values. However, because the error is within the acceptable range, and the carbon emission system integrates data collection, data analysis and other functions, the overall calculation is more convenient and less prone to calculation errors, which is more suitable for the calculation of carbon emissions during the construction phase of the building.

Table 3: Comparative analysis of computational efficiency

Calculation scope	Manual computing time (min)	System computing time (min)	Efficiency improvement
Foundation construction	33.78	2.13	1585.92%
The first basement floor	39.51	3.06	1291.17%
Floors 1~3	41.94	3.25	1290.46%
Floors 4~6	36.37	2.47	1472.47%
Floors 6~9	48.62	3.18	1528.93%
Total	200.22	14.09	1585.92%

Table 4: Comparative analysis of calculation results

Calculation scope	Manual computing time (*10^4t)	System computing time (*10^4t)	Efficiency improvement
Foundation construction	9.73	9.61	1.25%
The first basement floor	8.68	8.59	1.05%
Floors 1~3	15.04	14.94	0.67%
Floors 4~6	15.81	15.72	0.57%
Floors 6~9	19.12	18.85	1.43%
Total	68.38	67.75	1.25%

5 Conclusion

Supported by the Cyber - Physical System (CPS), the paper develops a carbon emission monitoring system for the construction phase. It delineates the scope of carbon emission calculation from three aspects: materials, machinery, and labor, and presents a detailed method for calculating carbon emissions during construction. The T project is selected as the research subject to examine the carbon emission calculation approach and the variation in carbon emission intensity. Additionally, the performance of the carbon emission monitoring system is evaluated through comparison.The findings indicate that among the various sub - projects of the T project, the above - ground civil construction works generate the highest carbon emissions. The average relative deviation rate of machinery carbon emission calculations during the construction stage is 8.43%. When compared with manual calculation results, the outcomes from the carbon emission monitoring system have an error within 1.5%. Consequently, the carbon emission system for the construction phase can be effectively utilized in the actual calculation of construction - phase carbon emissions. This demonstrates the significant value of the carbon emission monitoring system based on the Internet of Things sensor network in construction carbon emission calculations.

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