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Carbon emission monitoring technology driven by IoT sensor networks during the construction phase of buildings

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Abstract This paper utilizes wireless radio frequency identification (RFID) readers and IoT sensors to monitor and collect relevant data during the construction phase. Taking the construction process of prefabricated buildings as an example, by systematically organizing data on carbon footprint factors such as energy, building materials, transportation, machinery shifts, and labor days, a carbon emission calculation model for the materialization stage of prefabricated buildings and a projection tracing clustering analysis method were established. Subsequently, a carbon emission calculation model for the construction process, including two stages—building material transportation and on-site construction—was constructed to quantitatively analyze carbon emissions during the construction phase of building projects. The results indicate that carbon emissions vary significantly among different residential buildings, with the production stage of building materials accounting for the largest share of carbon emissions (approximately 90%) in all processes. Additionally, taking prefabricated buildings as an example, materials are the primary factor contributing to carbon emissions during the construction stage, also accounting for over 90%. Furthermore, during the entire construction phase, the main structure is the primary carbon emission factor, accounting for over 70% of carbon emissions. Based on the carbon emission calculation framework, the primary causes and main elements of carbon emissions during the construction phase can be calculated and analyzed. By optimizing construction processes and adjusting construction techniques, carbon reduction and control effects can be achieved.

Index Terms RFID, IoT sensors, construction, carbon emissions, projection-based tracking and clustering analysis

I. Introduction

Since the beginning of the 21st century, energy consumption has continued to rise, not only accelerating the pace of global climate change but also causing severe impacts on local ecosystems, including issues such as biodiversity loss [1], [2]. Today, the trend of global warming is intensifying, and this warming trend is not merely a short-term phenomenon; it is expected to continue to worsen. The rising global temperature trend has led to an increase in abnormal weather events, including extreme temperatures, heavy rainfall, droughts, and hurricanes. These events not only severely impact agricultural production and the food supply chain but also intensify the frequency and severity of natural disasters, posing a threat to people's lives and property safety [3]-[7]. In this context, people have recognized the need to take measures to reduce emissions of carbon dioxide and other gases, thereby mitigating the trend of global warming.

As an important economic sector, the construction industry is characterized by high energy consumption and low efficiency, not only wasting resources and energy but also causing severe environmental pollution and damage. According to relevant literature, approximately one-third of global carbon emissions originate from the construction industry [8]-[10]. Statistical data shows that in 2024, the construction industry accounted for as much as 37% of global carbon emissions. Among these, carbon emissions in the construction industry are primarily distributed across three stages: building material production, construction, and building operation. In terms of carbon emissions volume, the construction stage and building material production stage account for 57.48% of total emissions [11], [12]. Therefore, to achieve the goal of "low-carbon buildings," it is essential to thoroughly understand all aspects of carbon emissions in the construction industry and implement comprehensive measures to reduce their adverse environmental impacts, lower carbon emissions, protect the environment, and promote sustainable development [13]-[15].

The construction industry has actively responded to national policy initiatives and implemented a series of carbon reduction measures. For example, it has vigorously promoted the use of low-carbon and environmentally friendly building materials, such as new insulation materials and renewable resource materials, to reduce carbon emissions during construction processes [16], [17]. Additionally, it has adopted lean construction principles to optimize construction processes, improve resource

utilization efficiency, reduce construction waste generation, and thereby lower carbon emissions [18], [19]. With the development of society, the construction industry is entering a golden period for low-carbon development. To promote low-carbon development in the construction sector, related intelligent methods have emerged in the field of carbon emissions calculation and assessment, improving the efficiency of carbon emissions calculation while helping managers establish relevant management platforms [20], [21]. However, the calculation data obtained through consumption quotas differs significantly from actual on-site data, and consumption quotas are not sufficiently applicable to individual construction projects [22], [23]. Additionally, monitoring and visualizing carbon emissions across all stages of construction can help identify high-emission activities and reduce the idle time of related construction equipment. Therefore, conducting carbon emission monitoring research using appropriate digital technologies during the construction phase can help reduce carbon emissions in the construction industry.

Currently, Global Positioning System (GPS), Building Information Modeling (BIM), Radio Frequency Identification (RFID), and sensors are commonly used technologies for monitoring carbon emissions in the construction industry. Zhang et al. [24] utilized BIM and the net value method to establish a carbon monitoring system for the construction process, incorporating customized carbon loading planning technology to automate carbon planning, monitoring, and prediction throughout the construction process of building projects. Liu et al. [25] employed cyber-physical system technology to identify carbon sources during the implementation phase of modular integrated buildings and developed measurement models for carbon emissions monitoring. Mao et al. [26] employed an IoT framework to collect carbon emission data during the construction phase of prefabricated buildings and display emission status under distributed sensor networks and BIM virtual models, thereby achieving real-time carbon emission monitoring. However, Wu et al. [27] pointed out that current GPS, BIM, RFID, and sensor technologies in the construction, engineering, and construction industries face limitations in integration, making it difficult to achieve automated real-time monitoring.

As is well known, the core concept of IoT is to endow ordinary objects with sensing, connectivity, and intelligence capabilities, constructing a vast sensor network through wireless sensor nodes, and collecting, transmitting, and processing data via the internet. A sensor network consists of a group of wireless sensor nodes that can self-organize, self-configure, and self-heal [28]. In the IoT, sensor networks serve as a bridge between the physical and virtual worlds, enabling various real-world data to be transmitted wirelessly to the cloud for processing, thereby achieving functions such as big data analysis and monitoring [29]. Xu et al. [30] developed an IoT-supported carbon assessment and monitoring system for prefabricated buildings, capturing real-time carbon emission data through IoT sensors integrated with RFID, GPS, and accelerometers, and leveraging application programming interfaces, BIM, and carbon assessment software for efficient communication during the construction process. Ma et al. [31] developed an IoT-based online monitoring technology for carbon emissions in geological engineering construction in the construction industry. This technology relies on sensor technology and sensor node layout to integrate power data, thereby calculating carbon emissions during the construction phase and enabling online monitoring.

This paper first uses radio frequency identification (RFID) collectors and Internet of Things sensors to monitor and collect carbon emission data during the construction phase, providing support for the implementation of refined management. Subsequently, starting from the carbon emissions of prefabricated buildings, we summarized the carbon footprint calculation method for the materialization stage of prefabricated buildings and constructed a carbon emission calculation model and cluster analysis model for this stage. To achieve the functionality of calculating carbon emission quotas for construction, we screened commonly used energy and resource data within the construction phase to obtain energy carbon emission coefficients applicable to this study. Based on this, we constructed a carbon emission calculation model for the construction process, including two stages: building material transportation and on-site construction, as well as a carbon emission calculation model for the construction waste treatment and resource utilization process. Finally, we analyzed carbon emissions during the construction phase based on two actual cases.

II. Carbon emission calculation model for the construction phase based on IoT sensors

II. A. Carbon emissions data collection during the construction phase

II. A. 1) RFID Collector Data Collection

Radio Frequency Identification (RFID) [32] data collectors are used for real-time monitoring and data collection in construction production lines. The collectors can collect and transmit data on equipment status, environmental conditions, and carbon emissions during the production process via wireless signals, providing a solid data foundation for achieving carbon emission targets. When selecting an RFID data collector, factors such as frequency range, data transmission capability, durability, and compatibility with other systems must be considered. High-frequency RFID readers are suitable for precise data collection at close range, while ultra-high-frequency RFID readers excel in long-distance data transmission.

II. A. 2) IoT Sensor Data Collection

In carbon emissions monitoring in manufacturing, the source of IoT sensor data is critical. IoT sensors can collect data in various ways, including environmental monitoring, equipment status monitoring, and production process data. This data forms

the foundation for carbon emissions monitoring and enables the optimization of production processes and reduction of carbon emissions. For environmental monitoring, sensors are primarily used to collect data such as temperature, humidity, air quality, and light intensity. This data helps companies adjust their production environments and improve energy efficiency. For example, by monitoring workshop temperatures in real time, air conditioning systems can be automatically adjusted to reduce unnecessary energy consumption. Such data typically originates from environmental sensors installed in different areas of the factory, which transmit data via wireless networks to a central system for analysis and processing. In terms of equipment condition monitoring, IoT sensors can collect real-time data on the operational status of machinery and equipment, including parameters such as vibration, noise, rotational speed, and current. This data not only aids in predicting equipment failures to prevent unexpected downtime but also enables the optimization of equipment operating parameters to reduce energy consumption and carbon emissions.

Production process data covers the entire process from raw material input to product output. Sensors can monitor energy consumption and carbon emissions at each stage, providing support for refined management. By analyzing this data, high-energy consumption stages can be identified and targeted improvements made, thereby achieving low-carbon goals in the production process. Data is typically collected via RFID tags and smart sensors, and processed using big data analysis technology.

II. B. Carbon emissions calculation and clustering analysis methods during the construction phase

The production of prefabricated components for prefabricated buildings [33] involves the precise manufacture of building components required for prefabricated buildings through standardized design, modular construction, and integrated installation. The carbon emissions life cycle assessment (LCA) calculation for prefabricated buildings includes three stages: the materialization stage, the operation stage, and the demolition stage. The formula for calculating the carbon emissions (C) of prefabricated buildings is as follows:

$$C = C_w + C_y + C_z \tag{1}$$

where C: Total LCA carbon emissions ($kgCO_2$), C_w: Carbon emissions during the materialization phase ($kgCO_2$), C_y: Carbon emissions during the operational phase ($kgCO_2$), C_z: Carbon emissions during the demolition phase ($kgCO_2$).

The carbon emissions during the materialization phase of prefabricated buildings (C_w) are equal to the sum of the carbon emissions from the prefabricated components (C_q) and the carbon emissions from the cast-in-place components (C_x), i.e.:

$$C_w = C_q + C_x \tag{2}$$

where, C_w: Carbon emissions during the materialization phase of prefabricated buildings ($kgCO_2$), C_q: Carbon emissions during the materialization phase of prefabricated components ($kgCO_2$), C_x: Carbon emissions during the materialization phase of cast-in-place components ($kgCO_2$).

II. B. 1) Formula for calculating carbon emissions from prefabricated components

Formula for calculating carbon emissions from prefabricated components Carbon emissions from the materialization process of prefabricated components are calculated based on the sum of five factors: material production process, material transportation process, prefabricated component production and transportation process, and construction process.

$$C_q = C_{q1} + C_{q2} + C_{q3} + C_{q4} + C_{q5} \tag{3}$$

where C_{q1}: Carbon emissions from the production stage of prefabricated components ($kgCO_2$), C_{q2}: Carbon emissions from the transportation process of materials ($kgCO_2$), C_{q3}: Carbon emissions from the production stage of prefabricated components ($kgCO_2$), C_{q4}: Carbon emissions during the transportation stage of prefabricated components ($kgCO_2$), C_{q5}: Carbon emissions during the construction stage of prefabricated components ($kgCO_2$).

(1) Material production stage

The building material production stage refers to the calculation of the energy consumption of materials used in the entire construction process combined with the corresponding carbon emission factors of the consumed materials. Therefore, the carbon emission calculation formula for the material production stage of the prefabricated part of prefabricated buildings is:

$$C_{q1} = \sum_{i=1}^{n} M_i \times F_i \times (1 + \lambda) \tag{4}$$

where M_i: Energy consumption of the i-th material, F_i: Carbon emission factor of the i-th material (kgCO_2/unit material consumption), λ: Material loss coefficient value, same below.

(2) Prefabricated material transportation phase

The prefabricated material transportation phase refers to the process of transporting materials such as concrete and reinforcing bars from the processing plant to the construction site, including carbon emissions generated by transportation machinery and equipment. Freight transportation distances are adjusted using the empty return coefficient (F_y) when considering empty return trips, where the transportation distance $D_h(D_i)$ equals the one-way transportation distance multiplied by F_y. That is:

$$C_{q2} = (\sum_{h=1}^{n} \frac{M_h}{W} \times D_h \times E_t \times EF_t + \sum_{i=1}^{n} M_{z,i} \times D_i \times T_i) \times (1+\lambda) \tag{5}$$

where, M_h: Concrete consumption for the hth strength grade (m^3), W: Concrete mixer truck capacity (m^3), D_h: Concrete transportation distance (km), E_t: Diesel consumption per kilometer for concrete mixer trucks (L/km), EF_t: Diesel carbon emission factor (kgCO_2/L), M_{zi}: Weight of the i-th type of material (t), D_i: Transportation distance of the i-th type of material (km), T_i: Carbon emission factor for the transportation of the i-th type of material per unit weight (kgCO_2/(t·km));

(3) Precast component production stage

Precast components are processed in a precast plant to become independent functional units. Carbon emissions during the precast component production stage are related to energy and material consumption during the production process. However, since material consumption is calculated during the material production stage, this process is not included in the calculation of carbon emissions for the relevant materials. The carbon emission calculation formula for this stage is:

$$C_{q3} = \sum_{j=1}^{n} P_j \times E_{sc.j} \times EF_j \times (1+\lambda) \tag{6}$$

where, P_j: Consumption of the jth type of prefabricated material, $E_{SC,J}$: Energy consumption per unit volume of the jth type of prefabricated component, EF_j: Energy carbon emission factor (kgCO_2/unit energy consumption).

(4) Precast component transportation phase

The carbon emissions from precast component transportation primarily result from the energy consumption of transportation machinery and equipment used to transport completed building components from the manufacturing plant to the construction site. The transportation distance D_j for prefabricated components can be calculated as the one-way transportation distance multiplied by the coefficient F_y, where F_y is set to 1.665. Carbon emission calculation formula for the transportation phase of prefabricated components:

$$C_{q4} = \sum_{j=1}^{n} P_j \times D_j \times F_y \times T_j \tag{7}$$

where, D_j: Transportation distance (km) for precast components of type j, T_j: Transportation mode carbon emission factor (kgCO_2/(t·km)) for transporting unit weight of precast components of type j

(5) Construction phase

Carbon emissions during the construction phase of prefabricated components are mainly generated by the operation of construction machinery and equipment during the hoisting of prefabricated building components and by construction personnel. The formula for calculating carbon emissions during the construction phase of prefabricated components is:

$$C_{q5} = \sum_{j=1}^{n} P_j \times E_{zz,j} \times EF_j \times Q_r \times F_r \tag{8}$$

where, C_{q5}: Total carbon emissions during the construction phase of the prefabricated components (kgCO_2), E_{ZZj}: Energy consumption per unit mass of prefabricated components during lifting, Q_r: Labor consumption (man-days), F_r: Labor carbon emission factor (kgCO_2/man-day)

II. B. 2) Formula for calculating carbon emissions from cast-in-place concrete

The carbon emissions from the physical and chemical stages of the cast-in-place section include carbon emissions from three processes: the production process, the material transportation process, and the construction process, namely:

$$C_x = C_{x1} + C_{x2} + C_{x3} \tag{9}$$

where, C_{x1}: Carbon emissions from material production ($kgCO_2$), C_{x2}: Carbon emissions from material transportation ($kgCO_2$), C_{x3}: Carbon emissions from construction ($kgCO_2$).

(1) The formula for calculating carbon emissions from the material production stage of cast-in-place concrete is:

$$C_{x1} = \sum_{i=1}^{n} M_i \times F_i \times (1+\lambda) \tag{10}$$

where, M_i: Consumption of the i-th type of material, F_i: Carbon emission factor of the i-th type of material ($kgCO_2$/unit material consumption).

(2) Material transportation stage

Material transportation is an indispensable part of the construction process, referring to the process of transporting processed materials to the construction site. The material transportation distance $D_h(D_i)$ for the cast-in-place portion is calculated by multiplying the one-way transportation distance by the coefficient F_y, where F_y is set to 1.665. The carbon emission calculation formula for the material transportation stage of the cast-in-place portion is:

$$C_{x2} = (\sum_{h=1}^{n} \frac{M_h}{W} \times D_h \times E_t \times EF_t + \sum_{i=1}^{n} M_{z,j} \times D_i \times T_i) \times (1+\lambda) \tag{11}$$

where, M_h: Consumption of concrete of strength grade j (m^3), W: Concrete mixer truck capacity (m^3), D_h: Concrete transport distance (km), E_t: Diesel consumption per kilometer of concrete mixer truck (L/km), EF_t: Carbon emission factor of diesel ($kgCO_2$/L), M_{Zj}: Weight of the i-th type of material (t), D_i: Transportation distance of the i-th type of material (km), T_i: Carbon emission factor for transporting unit weight of material type i ($kgCO_2$/(t·km))

(3) Construction phase

Carbon emissions during the construction phase of cast-in-place sections mainly originate from the operation of construction machinery at the construction site and carbon emissions generated by personnel during labor. The carbon emission calculation formula for this phase is:

$$C_{x3} = \sum_{i=1}^{n} E_{jz,i} \times F_{jz,i} \times EF_{jZ,i} + Q_r \times F_r \times (1+\lambda) \tag{12}$$

where, $E_{jZ,i}$: Number of units (shift) of the i-th type of construction machinery, $F_{jZ,i}$: Unit energy consumption per shift of the i-th type of construction machinery, $EF_{jZ,i}$: Energy carbon emission factor ($kgCO_2$).

II. B. 3) Projection-based clustering analysis method

Projection Pursuit (PP) is a graphical exploration technique for visualizing high-dimensional data, as well as an exploratory data analysis method. Projection Pursuit identifies the optimal projection direction by searching for the projection direction that best reflects the internal structure or features of the original high-dimensional data, while minimizing (or maximizing) the projection metric function. This direction is then used to project the high-dimensional data onto a low-dimensional subspace, enabling analysis of the original data structure in the low-dimensional space. This method serves the purpose of studying and analyzing high-dimensional data and is a statistical approach for addressing complex problems involving multiple factors.

The projection pursuit algorithm utilizes projection pursuit to compress and extract the structure and features of high-dimensional data, followed by identification and classification. Projection pursuit is essentially an optimization problem conducted under relevant constraints based on the designed projection metric. This paper employs an accelerated genetic algorithm based on real number encoding to optimize the projection pursuit clustering model

The modeling process of the projection pursuit clustering model is as follows:

Step 1: Normalization of the sample evaluation indicator set. Let the sample set of each indicator value be $\{x^*(i,j) \mid i = 1,2\cdots n; j = 1,2\cdots p\}$, where $x^*(i,j)$ is the j th indicator value of the i th sample, n, p represent the number of samples and the number of indicators, respectively. To eliminate the dimensions of each indicator value and unify the range of changes in each indicator value, the original data must be normalized.

For indicators where larger values are better:

$$x(i,j)=\frac{x^*(i,j)-x_{\min}(j)}{x_{\max}(j)-x_{\min}(j)} \tag{13}$$

For indicators where smaller is better:

$$x(i,j)=\frac{x_{\max}(i,j)-x^*(i,j)}{x_{\max}(j)-x_{\min}(j)} \tag{14}$$

where $x_{\max}(j)$ and $x_{\min}(j)$ are the maximum and minimum values of the j th indicator, respectively, and $x(i,j)$ is the normalized sequence of indicator feature values.

Step 2: Construct the projection indicator function $Q(a)$. The projection pursuit method combines the P-dimensional data $\{x^*(i,j)\,|\,i=1,2\cdots n;j=1,2\cdots p\}$ into a one-dimensional projection value $z(i)$ with projection direction $a=\{a(1),a(2),\cdots a(p)\}$:

$$Z(j)=\sum_{j=1}^{p}a(j)x(i,j),i=1,2\cdots,n \tag{15}$$

Then, classification is performed based on the one-dimensional scatter plot of $\{Z(i)\,|\,i=1,2\cdots n\}$. In the formula, a is the unit length vector. When combining the projection index values, the scatter characteristics of the projection values $Z(i)$ are required to be as follows: the local projection points should be as dense as possible, preferably clustered into several point clusters, while the projection point clusters should be as scattered as possible in the overall picture. Therefore, the projection index function can be expressed as:

$$Q(a)=S_zD_z \tag{16}$$

Among them, s_z is the standard deviation of the projection value $Z(i)$, and D_z is the local density of the projection value $Z(i)$, that is:

$$S_z=\sqrt{\frac{\sum_{i=1}^{n}(Z(i)-E(z))^2}{n-1}} \tag{17}$$

$$D_z=\sum_{i=1}^{n}\sum_{j=1}^{n}(R-r(i,j))\cdot u(R-r(i,j)) \tag{18}$$

Among them, $E(z)$ is the average value of the sequence $\{Z(i)\,|\,i=1,2\cdots n\}$; R is the window radius of the local density; $r(i,j)$ represents the distance between samples, $r(i,j)=|\,Z(i)-Z(j)\,|$; $u(t)$ is a unit step function.

Step 3: Optimize the projection indicator function. When the sample sets for each indicator value are given, the projection indicator function $Q(a)$ changes only with the projection direction a. Therefore, the optimal projection direction can be estimated by solving the maximum projection indicator function problem, i.e., the maximum objective function:

$$Max:Q(a)=S_zD_z \tag{19}$$

$$s.t.\sum_{j=1}^{p}a^2(j)=1 \tag{20}$$

Step 4: Substitute the optimal projection direction a obtained in Step 3 into $Z(i)=\sum^{P}a(j)x(i,j)$ to obtain the projection values $Z(i)$ of each sample point. Since the projection index of the projection tracking clustering model is obtained based on the clustering of projection eigenvalues, the most significant clustering analysis results are also obtained.

II. C. Construction phase carbon emission calculation model construction

II. C. 1) Commonly Used Energy Carbon Emission Coefficients

(1) Selection of carbon emission coefficients for electricity

In selecting carbon emission coefficients for electricity, this paper mainly refers to the calculation methods and results determined by the Climate Change Response Department of the Ministry of Ecology and Environment.

The marginal emission factor for electricity is calculated based on the total net grid-connected electricity generation, fuel types, and total fuel consumption of all power plants in the power system. That is:

$$EF_{oM,y} = \frac{\sum_{i}(FC_{i,y} \times NCV_{i,y} \times EF_{coz,i,y})}{EG_{y}} \tag{21}$$

In the formula, EFo_{My} — Simple electricity marginal emission factor in year y ($tCO_2MW{\cdot}h$), FC_{iy} — Fuel consumption of fuel i in the power system where the project is located in year y, $NCV_{i,y}$ — Net calorific value of fuel i in year y; $EF_{CO2,iy}$ — CO_2 emission factor for fuel i in year y (tCO_2/GJ), EG_{y} — Electricity supplied by the power system to the grid in year y (MW·h). The capacity marginal emission factor can be obtained by taking the weighted average of the emission factors of m sample units, as shown in the following formula:

$$EF_{BM,y} = \frac{\sum_{m} EG_{m,y} \times EF_{E,m,y}}{\sum_{m} EG_{m,y}} \tag{22}$$

In the formula, EF_{BMy} — Capacity marginal emission factor in year y ($tCO_2MW{\cdot}h$), $EF_{EL,m,y}$ — Emission factor of the mth sample unit in year y ($tCO_2/MW{\cdot}h$), $EG_{m,y}$ — Electricity supplied to the grid by the mth sample unit in the yth year (MW·h).

Considering the impacts of regional differences, energy structure, and timeliness, the electricity marginal emission coefficient is selected as the foundational research data for this paper.

(2) Selection of carbon emission coefficients for fossil fuels

In selecting carbon emission coefficients for fossil fuels, this paper comprehensively selected data that is relatively recent, relatively complete, and takes into account the characteristics of each province in China, based on authoritative research, existing literature, and carbon emission factor databases summarized in national standards

II. C. 2) Construction process carbon emission calculation model construction

(1) Carbon emission calculation model for building material transportation

The carbon emission coefficient for transportation was calculated based on the average energy consumption indicators in the gasoline and diesel vehicle shift consumption and mechanical shift cost quotas in the steel bar transportation sub-item:

$$C_i = W_{i,o} \times V_o \tag{23}$$

In the formula, C_i — Carbon emission coefficient for type i transportation vehicle, $W_{i,a}$ — Energy consumption of the a-th type of energy per unit of building material transported per unit distance when using type i transportation vehicle, V_a — Carbon emission coefficient of the a-th type of energy.

Based on data such as building material usage from consumption quotas, the transportation volume of building materials is uniformly converted to building material weight and standardized units. This is then multiplied by the corresponding average transportation distance and transportation carbon emission coefficient for building materials to calculate the carbon emissions for the building material transportation phase quota sub-objective:

$$Q_1 = \sum_{i=1}^{t}\sum_{j=1}^{n} M_j \times D_j \times C_i \tag{24}$$

In the formula, Q_1 — Unit carbon emission coefficient for the building material transportation phase, M_j — Transportation volume of building material type j, D_j — Average transportation distance from the building material supply location to the construction site for building material type j, C_i — Carbon emission coefficient for the transportation of type i vehicles

(2) Carbon emission calculation model for the on-site construction phase

Based on the energy carbon emission coefficient, the corresponding carbon emission coefficient for on-site construction machinery is calculated as follows:

$$E_p = Z_{p,a} \times V_a \tag{25}$$

In the formula, E_p ——Mechanical carbon emission coefficient of p-class on-site construction machinery, $Z_{p,a}$ —— Energy consumption of the a-th type of p-class construction machinery per unit shift, V_a ——Carbon emission coefficient of the a-th type of energy.

By linking the machinery and equipment used in on-site construction processes to carbon emissions and replacing the unit price per machine shift in the consumption quota with the carbon emission coefficient of construction machinery, the carbon emissions generated by on-site construction machinery can be calculated:

$$Q_2 = \sum_{p=1}^{n} E_p \times X_p \tag{26}$$

In the formula, Q_2 — Unit carbon emission coefficient for on-site construction processes, E_p — Mechanical carbon emission coefficient for p-type on-site construction machinery, X_p — Number of machine hours worked by p-type on-site construction machinery.

(3) Carbon emissions calculation model for the construction process

This study divides the carbon emissions calculation for the construction process into two phases: material transportation and on-site construction. By summing the carbon emissions from each phase, the total carbon emissions for the entire construction process can be calculated:

$$G_k = \sum_{k=1}^{n} Q_k \times AD_k \tag{27}$$

In the formula, G_k ——Carbon emissions from each stage of the construction process, Q_k ——Unit carbon emission coefficient for sub-item k of the construction process quota, AD_k ——Engineering volume for sub-item k of the construction process quota

II. C. 3) Construction of carbon emission calculation model

(1) Carbon emission calculation model for construction waste disposal process

The amount of solid construction waste generated can be estimated using the following formula:

$$B = R \times b \times k \tag{28}$$

In the formula, B ——Amount of solid waste generated during the construction of the rice project, R ——Construction area of the project, b ——Base amount of construction waste generated per unit of construction area, k ——Construction waste generation correction coefficient.

Vertical transportation machinery is used to transport waste out of the building, and carbon emissions are calculated based on the on-site construction process:

$$P_1 = \sum_{q=1}^{n} E_q \times X_q + \sum_{m=1}^{n} \sum_{z=1}^{l} C_m \times B_z \times L_z \tag{29}$$

In the formula, P_1 — Unit carbon emission coefficient for construction waste not recycled, E_q — Mechanical carbon emission coefficient for q-type vertical transport machinery, X_q — Number of shifts worked by q-type vertical transport machinery, C_m — Carbon emission coefficient for m types of transportation vehicles, B_z — Transportation volume of z types of solid waste, L_z — Average transportation distance from the construction site to the waste treatment plant or landfill for z types of solid waste.

(2) Carbon emissions calculation model for construction waste recycling process

The method for calculating carbon emissions from the resource utilization of construction waste is the same as that for on-site construction processes. The difference between the carbon emissions generated by treating construction waste using energy-saving technologies and those generated by traditional construction waste treatment methods represents the carbon emissions reduced through energy-saving technologies:

$$P_2 = \sum_{q=1}^{n} E_q \times X_q + \sum_{j=1}^{m} S_j \times Y_j \tag{30}$$

In the formula, P_2 — Unit carbon emission coefficient for construction waste resource utilization measures, E_q — Mechanical carbon emission coefficient for q-type vertical transport machinery, X_q — Number of machine shifts for q-type vertical transportation machinery, S_j — Mechanical carbon emission coefficient for j-type waste treatment facilities, Y_j — Number of machine shifts for j-type waste treatment facilities.

(3) Carbon emissions calculation model for construction waste treatment and utilization processes

The construction area of a construction project is converted into the engineering volume for construction solid waste treatment, enabling the calculation of carbon emissions during the construction waste treatment and utilization process of the construction project:

$$H_i = \sum_{i=1}^{n} P_i \times AD_i \tag{31}$$

In the formula, H_i ——Carbon emissions from the construction waste treatment and utilization process, P_r ——Unit carbon emission coefficient of sub-item i in the waste treatment and utilization process, AD_i ——Engineering volume of sub-item i in the construction waste treatment and utilization process

III. Case Study

III. A. Case 1

III. A. 1) Introduction to the basic circumstances of the case

Case Study 1 selected two types of residential buildings: prefabricated concrete residential buildings and cast-in-place concrete residential buildings. The prefabricated concrete residential building project is located in Zaozhuang City, Shandong Province, featuring a prefabricated shear-wall structure, with a height of 53.10 m, a total floor area of 12,274.28 m^2, 18 above-ground floors, and 2 underground floors. The prefabricated components include prefabricated staircases and composite floor slabs, with the composite floor slabs used for living rooms, dining rooms, bedrooms, and elevator lobbies on floors 3 to 17, while the remaining floors use cast-in-place floor slabs. The cast-in-place concrete residential building project is located in Zaozhuang City, Shandong Province, featuring a shear-wall structure. The building has a height of 23.758 meters, a site area of 541.45 square meters, and a total floor area of 4,647.61 square meters, comprising 7 above-ground floors and 2 underground floors.

III. A. 2) Carbon emissions during the construction phase

(1) Carbon emissions during the material production stage

The PKPM model can be used to determine the consumption of building materials in each structural design plan. At the same time, this paper further determines the material consumption of each structural design plan in accordance with the relevant provisions of the "Consumption Quotas for Housing Construction and Decoration Projects." The carbon emissions during the production stage of brick-concrete structure building materials are shown in Table 1.

Table 1: Carbon emissions from brick and mortar construction materials production

Name of building material	Dosage	Unit	Carbon emission factors	Carbon emissions (kg CO_{2e})
Concrete iron	1023.23	kg	2117kg CO_{2e}/t	2166.178
C30 concrete	26.25	m^3	316.5kg CO_{2e}/m^3	8308.125
Standard autoclaved gray sand brick	63.41	m^3	375.8kg CO_{2e}/m^3	23829.478
M10 masonry mortar	10.96	m^3	235kg CO_{2e}/m^3	2575.600

Table 2: The average transport distance of major building materials

Order number	Main building materials and their names	Unit	Mean transport distance (km)
1	Steel products	Kg	59.13
2	Cement	Kg	52.75
3	Concrete	m^3	10.92
4	Gas concrete masonry blocks	m^3	14.06
5	Mortar	m^3	54.71
6	Standard brick	Kg	27.2
7	Sand, gravel	Kg	40.24
8	Wood	m^3	33.16

(2) Carbon emissions during transportation

All building materials in this paper are transported by road using diesel trucks. The average transportation distance for major building materials is shown in Table 2. During the transportation phase, this study does not consider empty vehicle conditions. Instead, it uses heavy-duty diesel trucks with a load capacity of 10 tons to transport steel and cement products, while other building materials such as wall materials and formwork are transported via road diesel trucks. Specifically, the carbon emission factors are set at 0.175 kg CO_{2e}/t·km and 0.170 kg CO_{2e}/t·km, respectively. Additionally, when transporting materials, it is important to account for the conversion between volume and weight. In this case study, the national standard B05 grade is used to determine the absolute dry density of autoclaved aerated concrete blocks as 500 kg/m^3, the factory weight as 655 kg/m^3,

the density of wood as 530 kg/m³, and the density of autoclaved fly ash bricks as 16.5 kN/m³. These data can help us more accurately estimate the weight and volume of building materials and more reliably calculate the carbon emissions from their transportation.

Carbon emissions from building materials during transportation can be calculated based on the weight or volume of the materials and the distance traveled. Carbon emissions during the material transportation phase are shown in Table 3. During the material transportation phase, because concrete residential buildings are relatively heavy and bulky, the carbon emissions generated by the mechanical equipment used for transportation must be included in the calculation, whereas in traditional construction methods, the carbon emissions from the transportation of construction machinery can be ignored.

Table 3: Carbon emissions from material transportation

Transportation carbon emissions (kg CO_{2e})	Concrete masonry structure	Brick and mortar structure	Frame construction
Concrete, mortar	300.99	441.04	207.73
Mechanical equipment	48.78	—	—
Concrete iron	1.21	13.15	30.48
form work engineering	0	127.85	268.57
materials for wall	0	462.54	83.08
Amount to	350.98	1044.58	589.86

(3) Carbon emissions during the construction phase

This plan is suitable for using a carbon emission factor of 2.09 kgCO_2/person·day for light laborers as the carbon emission standard. It should be noted that because the production phase consumes a large amount of electricity, in order to make the comparison more intuitive, this article classifies the carbon dioxide generated during the production phase as carbon emissions from electricity. The carbon emissions during the construction phase for each structural form are shown in Table 4.

Table 4: Carbon emissions per structural form during construction

Carbon emissions (kg CO_{2e})	Concrete masonry structure	Brick and mortar structure	Frame construction
construction machinery	—	280.6	319.57
Electric energy	741.56	25.09	36.61
Man-made	69.44	344.04	415.01
Amount to	811	649.73	771.19

III. A. 3) Analysis of carbon emissions during the materialization phase

According to the carbon emissions calculation model formula, the carbon emissions per unit area during the construction phase can be calculated for two types of residential buildings. The comparison of carbon emissions per unit area between cast-in-place residential buildings and prefabricated residential buildings is shown in Table 5. Calculations indicate that the carbon emissions of prefabricated residential buildings are reduced by 28.59 kg CO_{2e}/m² compared to traditional cast-in-place residential buildings. Among these, during the building material production stage, prefabricated residential buildings reduce carbon emissions by 38.8 kg CO_{2e}/m² compared to traditional cast-in-place residential buildings. This is because, although prefabricated residential buildings involve an additional prefabricated component manufacturing process during the building material production stage, the standardized and large-scale production of prefabricated components in manufacturing plants reduces the consumption of concrete and reinforcing steel. Additionally, the high surface flatness of prefabricated components reduces the consumption of plastering mortar, thereby decreasing raw material carbon emissions.

During the building material transportation phase, the carbon emissions of prefabricated residential buildings are 13.23 kg CO_{2e}/m² higher than those of traditional cast-in-place residential buildings. This is because prefabricated residential buildings involve additional transportation of prefabricated components, thereby increasing energy-related carbon emissions; During the construction phase, the carbon emissions of prefabricated residential buildings are 3.02 kg CO_{2e}/m² higher than those of traditional cast-in-place residential buildings. This is because the installation process of prefabricated components in prefabricated residential buildings increases energy and electricity consumption, thereby increasing carbon emissions.

Table 5: Carbon emissions per unit area of on-site housing and prefabricated housing

Stage	Carbon emissions per unit area of existing housing	Carbon emissions per unit area of prefabricated housing
Production phase	439.32	400.52
Haulage stage	11.94	25.17
Construction stage	33.8	30.78
Amount to	485.06	456.47

The carbon emissions distribution across the various stages of residential construction is shown in Table 6. It can be observed that the carbon emissions from the materialization stage of prefabricated residential buildings and cast-in-place residential buildings are similar, with the production of building materials being the primary source of carbon emissions, accounting for 85% and 92% of the total carbon emissions in the materialization stage, respectively. The construction stage follows (8.5% and 6.5%), while the transportation of building materials has the lowest carbon emissions (6.5% and 1.5%).

Results of carbon emissions from various building materials during the production phase it can be seen that the primary sources of carbon emissions during the production phase for prefabricated residential buildings and traditional cast-in-place buildings are concrete and reinforcing steel. Among these, during the production phase of prefabricated residential buildings, concrete and reinforcing steel account for the largest proportions of carbon emissions, at 37% and 34.5%, respectively, together comprising 72.15% of total carbon emissions from primary materials. Next are cement, mortar, and bamboo plywood, accounting for 6%, 4.5%, and 4%, respectively. The combined carbon emissions from other materials account for 14%.

In traditional cast-in-place residential buildings, concrete and reinforcing steel account for the largest share of carbon emissions during the building material production stage, at 45.5% and 32.2% respectively, together accounting for 77.7% of total carbon emissions from primary materials. Next are aerated concrete blocks, cement, and extruded polystyrene boards, accounting for 10.2%, 4.1%, and 3% respectively; other materials account for a combined 5% of total carbon emissions

Table 6: Carbon emission proportion of each stage of housing

Residential category	Stage	Prefabricated housing	Stage	Existing residential buildings
The proportion of carbon emissions in the residential materialization stage(%)	Production phase	85%	Production phase	92%
	Haulage stage	6.5%	Haulage stage	1.5%
	Construction stage	8.5%	Construction stage	6.5%
Carbon emission proportion of various building materials in residential building production stage(%)	All kinds of building materials	Prefabricated housing	All kinds of building materials	Existing residential buildings
	Concrete	37%	Concrete	45.5%
	Concrete iron	34.5%	Concrete iron	32.2%
	Cement	6%	Gas concrete masonry blocks	10.2%
	Bamboo plywood	4.5%	Cement	4.1%
	Mortar	4%	Extruded polystyrene board	3%
	Electric welding rod	3%	Mortar	1.3%
	Ironwork	2.5%	Lime	0.9%
	Polyurethane board	2%	Wood	0.5%
	Wood	1.5%	Electric welding rod	0.3%
	Other	5%	Other	2%

III. B. Case 2

III. B. 1) Project Overview

The M Construction Project is located in Jinniu District, M City, and is a comprehensive medical facility. The project primarily consists of an outpatient building and an inpatient tower, along with a four-story basement. The main structure of the inpatient tower stands at 20 stories above ground, with a building height of approximately 85 meters, qualifying it as a Class I high-rise medical building with a height exceeding 100 meters. The total building area of the hospital is 45,849.275 square meters, with an above-ground building area of approximately 35,000 square meters. This section calculates the carbon emissions of the construction and decoration projects of the M Project, and through analysis and management of each project, provides reasonable suggestions for carbon reduction during the construction phase.

III. B. 2) Calculation of project carbon emissions data

According to the carbon emission calculation model, the carbon emissions of each production factor for the foundation replacement work of Project M are calculated as shown in Table 7.

Table 7: Carbon emission calculation of M project foundation replacement work

Number of projects	850.26	
Measurement unit	m^3	
Man-made	Unit consumption	0.35
	Total consumption	316.22
	Carbon emission(kg CO_2)	495.37
Material	Name of material	The product is concrete C15; water
	Unit	m^3
	Total consumption	861.33; 205.15
	Carbon emissions per unit	226.37; 0.18
	Carbon emission(kg CO_2)	195564.72; 35.28
Machinery	Type of energy consumption	Electricity
	Energy consumption per unit shift	0.24
	Carbon emissions per unit	0.31
	Carbon emission(kg CO_2)	57.43

After calculating, summarizing, and standardizing the quantities listed in the bill of quantities for the M project, the carbon emissions for the civil engineering and decoration works of the M project are shown in Table 8.

Table 8: Standardize M project carbon emission treatment data

Number	Partitioned project	Standardize data processing		
		Man-made	Material	Machinery
1	Foundation treatment	0.72	0.06	0.98
2	Slope support engineering	0.12	0.12	0.06
3	Earth and rock works	0.12	0.02	0.25
4	Reinforced concrete works	0.97	1.02	0.07
5	Form work engineering	0.96	0.06	0.01
6	Concrete work	0.34	0.86	0
7	Structural steelwork	0.37	0.3	0.04
8	Masonry works	0.15	0.1	0
9	Plastering works	0.28	0.04	0.01
10	Lightweight partition wall and partition engineering	0.22	0.31	0.02
11	Painting works	0.15	0.02	0
12	Ceilings	0.02	0.02	0.01
13	Doors and Windows engineering	0.02	0.01	0.02
14	Insulation work	0.2	0.12	0.02
15	Waterproofing work	0.25	0.12	0.01
16	Surface works	0.18	0.05	0.02
17	Wall and column decoration works	0.03	0	0
18	Handrail, balustrade	0.02	0.02	0
19	Scaffolding work	0.77	0.04	0
20	Vertical transportation engineering	0.42	0.03	0.14

After standardizing the material, machinery, and labor data in the M project management items, values greater than or equal to 0.2 are included in the corresponding production factor dataset. In summary, the carbon emission management clustering items of the M project can be grouped into five of the eight types. The preliminary classification of the data is as follows:

(1) Material single-factor management item dataset X = {None}

(2) Equipment single-factor management item dataset Y = {Earthwork Engineering}

(3) Labor single-factor management item dataset:

Z = {{Formwork Engineering}, {Plastering Engineering}, {Insulation Engineering}, {Waterproofing Engineering}, {Scaffolding Engineering, Vertical Transportation Engineering}}.

(4) Material and machinery dual-factor management item dataset XY = {None}

(5) Material and labor dual-factor management item dataset

XZ = {{Reinforcement engineering, concrete engineering, steel structure engineering, lightweight partition walls and partitions engineering}}

(6) Machinery and labor dual-factor management item dataset YZ = {{Foundation treatment engineering}}

(7) Material, machinery, and labor three-factor management item dataset XYZ = {None}

(8) Non-management item dataset:

XYZ^{*} = {Slope Support Engineering, Masonry Engineering, Painting Engineering, Ceiling Engineering, Door and Window Engineering, Floor Engineering, Wall and Column Surface Decoration Engineering, Railings and Handrails}

III. B. 3) Project Carbon Emissions Management Analysis

According to the initial classification principle, the carbon emission management of Project M is divided into five categories. The arithmetic mean values of each normalized data set are calculated and used as the initial centers for the projection tracing cluster analysis method. The initial cluster center results are shown in Table 9.

Table 9: Results of initial cluster centers

Number	Management item classification	Standardize data processing		
		Man-made	Material	Machinery
1	Mechanical single-factor management items	0.18	0.04	0.22
2	Manual single-factor management items	0.46	0.04	0.01
3	Material manual two-factor management item	0.5	0.61	0.04
4	Mechanical and artificial two-factor management items	0.73	0.06	1.02
5	No management items required	0.06	0.06	0.04

Import the computational data into SPSS Statistics software and perform K-means clustering analysis. The clustering results for the carbon emission management items of Project M are shown in Table 10; the final clustering centers are shown in Table 11; and the carbon emission proportions of various production factors and some engineering components of the project are shown in Table 12. By using computational models and projection tracing clustering, the carbon emission management items of Project M were calculated, analyzed, and clustered to provide reasonable recommendations for emissions reduction during the construction phase. Based on the comprehensive results, the following conclusions can be drawn.

(1) Based on the carbon emissions proportions of each production factor, it is clear that materials are the largest contributor to carbon emissions, accounting for 91.27% of total carbon emissions, making them the primary factor in carbon emissions management; machinery and equipment account for 8.51% of carbon emissions, making them a secondary factor in carbon emissions management; while labor accounts for only 0.22% of carbon emissions throughout the entire construction process.

(2) Based on the calculation data for Project M, it can be seen that the main structure is the component with the highest carbon emissions during the entire construction phase, accounting for 73.24%, while decoration and finishing, and foundation and base components account for 19.23% and 7.58%, respectively

Table 10: Cluster results of carbon emission management items in M project

Number	Partitioned project	Clustering	Distance from the cluster center	Correspond to the management item category
1	Foundation treatment	3	0.01	Mechanical and artificial dual-factor management items
2	Slope support engineering	4	0.14	No management items required
3	Earth and rock works	1	0.02	Mechanical single-factor management items
4	Reinforced concrete works	2	0.35	Material manual two-factor management item
5	Form work engineering	5	0.26	Manual single-factor management items
6	Concrete work	2	0.36	Material manual two-factor management item
7	Structural steelwork	5	0.23	Manual single-factor management items
8	Masonry works	4	0.04	No management items required
9	Plastering works	5	0.25	No management items required
10	Lightweight partition wall and partition engineering	5	0.23	No management items required
11	Painting works	4	0.11	No management items required
12	Ceilings	4	0.12	No management items required
13	Doors and Windows engineering	4	0.11	No management items required
14	Insulation work	4	0.07	No management items required
15	Waterproofing work	4	0.15	No management items required
16	Surface works	4	0.09	No management items required
17	Wall and column decoration works	4	0.12	No management items required
18	Handrail, balustrade	4	0.12	No management items required
19	Scaffolding work	3	0.17	Manual single-factor management items
20	Vertical transportation engineering	5	0.26	Manual single-factor management

Table 11: Final cluster centers

Number	Management item classification	Standardize data processing		
		Man-made	Material	Machinery
1	Mechanical single-factor management items	0.18	0.04	0.22
2	Manual single-factor management items	0.66	0.14	0.02
3	Material manual two-factor management item	0.75	0.96	0.05
4	Mechanical and artificial two-factor management items	0.73	0.06	1.02
5	No management items required	0.16	0.08	0.02

Table 12: Carbon emissions of various factors of production and some projects

M project	All factors of production	Carbon emission share
Carbon emission ratio of each factor of production in the project	Man-made	91.27%
	Material	8.51%
	Machinery	0.22%
Carbon emission ratio of each sub-project	Main work	73.24%
	Decoration and renovation and other	19.23%
	Foundation and base	7.58%

III. B. 4) Project Carbon Emissions Clustering Results and Recommendations

The higher the variability, the clearer the focus of control for that production factor. The results for each production factor in the carbon emissions management items of the M project are shown in Figure 1. The variability in mechanical carbon emissions is significant across all management items, particularly in reinforcing steel engineering, where control strategies should be prioritized to minimize carbon emissions. The variability in material carbon emissions is also significant across all management items, particularly in masonry and plastering engineering, where control strategies should be prioritized to reduce material carbon emissions. The dispersion of carbon emissions from labor is relatively small across all management items. Therefore, control strategies should be prioritized for door and window engineering, lightweight partition walls and partitions, and reinforcing steel engineering to reduce carbon emissions from labor.

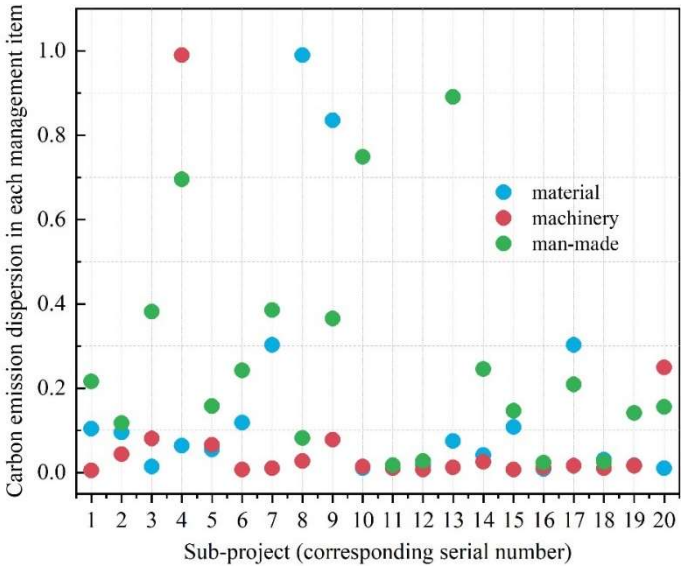

Figure 1: Results of various factors of production in carbon emission management

IV. Conclusion

This paper is based on the management needs for carbon emissions during the construction phase of buildings. Through research on calculation methods, it quantifies and analyzes carbon emissions during the construction phase. By combining engineering construction standards, it identifies key points that are easy to calculate and analyze, enabling enterprises to scientifically monitor and reduce carbon emissions during construction.

During the materialization phase, prefabricated residential buildings using composite slabs and precast staircases reduce

total carbon emissions by approximately 28.59 kg/m² compared to cast-in-place residential buildings. Carbon emissions during the materialization phase of prefabricated and cast-in-place residential buildings are relatively similar, with the majority of emissions originating from the building material production phase (85% and 92%, respectively); carbon emissions from the construction phase and building material transportation phase are both less than 10%. Different assembly rates in prefabricated buildings yield varying analysis results, but overall, prefabricated residential buildings have lower carbon emissions than traditional cast-in-place residential buildings. Materials are the primary source of carbon emissions among production factors, accounting for over 90% of total carbon emissions; mechanical equipment and labor have a relatively low impact on carbon emissions during construction. Additionally, the main structure accounts for over 70% of carbon emissions during the entire construction phase, making it the primary carbon emission factor. Overall, prefabricated residential buildings offer greater advantages in terms of environmental sustainability, low-carbon development, and long-term sustainability

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