Research on Carbon Emission Calculation in the Materialization Phase of Construction Engineering Based on Information Technology

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Abstract. Information technology, as the fundamental technology driving innovation in internal production and management activities across various industries and fields, has emerged as an essential tool, particularly under the influence of China's eco-friendly and green development concepts, to imbue these sectors with environmentally sustainable characteristics. In the construction industry specifically, the application of information technology enables the calculation of carbon emissions during the materialization phase, thereby precisely grasping the actual carbon footprint of construction projects during this stage. This, in turn, provides accurate data and guidance for energy conservation and emission reduction during the materialization phase, ultimately enhancing the overall energy efficiency and carbon reduction levels within the construction industry.

Keywords: Information Technology; Construction Engineering; Materialization Phase; Carbon Emission Calculation

1 Introduction

With the continuous deepening of the concept of green and environmentally friendly development, various industries and fields in society are continuously optimizing and innovating the environmental protection and recyclability of internal production under the influence of information technology, effectively reducing carbon emissions from internal production and management activities, and contributing to promoting the green and environmentally friendly development of society. As a pillar industry of the social economy, the construction sector's carbon emissions have been investigated and studied. In 2021, the total energy consumption throughout the entire lifecycle of residential buildings nationwide (excluding infrastructure construction) amounted to 1.91 billion tons of coal equivalent (tce), accounting for 36% of the country's total energy consump-

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tion. Similarly, the total carbon emissions throughout the lifecycle of residential buildings nationwide reached 4.07 billion tons of CO2, representing 38.2% of the country's total energy-related carbon emissions [1]. The full lifecycle of a building encompasses various stages, including the production of building materials, transportation of materials, construction, operation, and demolition [2]. Specifically, the production of building materials accounted for 2.82 billion tons of CO2 emissions, constituting 28.2% of the country's total carbon emissions; while the construction stage contributed 100 million tons of CO2 emissions, representing 1.0% of the national total.

2 Carbon Source Analysis

2.1 Carbon Sources in the Full Lifecycle of Buildings

Carbon sources in the full lifecycle of buildings are mainly divided into five stages: building material production and transportation, construction, operation, and demolition [3]. These include:

1. Production Stage of Building Materials: This stage primarily involves the production of construction materials according to the specific design and construction drawings of a building, to support the smooth progress of construction projects, ultimately resulting in tangible buildings. Therefore, the primary carbon sources generated during this stage stem from the raw material extraction, transportation, factory production, as well as the carbon emissions from human labor and energy inputs involved in the production process of building materials.
2. Building material transportation: This stage involves transporting the produced building materials from the production site to the construction site to ensure the orderly progress of construction. Therefore, the carbon sources generated in this stage mainly come from transportation energy consumption and carbon emissions from loading and unloading building materials.
3. Construction Stage: The construction stage primarily encompasses the production, transportation, and construction processes of building materials such as concrete, steel, and reinforcing steel bars. The carbon emissions generated from the energy consumption during these processes constitute the carbon sources for this stage.
4. Operation Stage: The operation stage primarily involves the normal functioning, maintenance, and repairs of buildings, where various types of energy and resource consumption activities take place. As such, the carbon sources during this stage stem from the consumption of other energy and resources, such as carbon emissions arising from energy consumption in the forms of gas, outsourced heating, and the like.
5. Demolition Stage: Due to the complexity and extensive workload of demolition, apart from conventional manual demolition without energy consumption, it also necessitates the use of specialized equipment for targeted demolition. Additionally, the demolished waste materials need to be transported. Therefore, the carbon sources during this stage are primarily determined by the energy consumption, which is influenced by factors such as the amount of building materials consumed, the average

transportation distance of building materials, and the carbon emission factor per unit weight transported, based on the transportation mode.

2.2 Carbon Sources in the Materialization Phase of Buildings

The method for accounting carbon emissions in the embodied phase of buildings aims to enable real-time and rapid quantitative calculation of carbon emissions during the early design stage of construction, thereby optimizing design schemes and guiding the design of low-carbon buildings. The formula for calculating carbon emissions in the embodied phase of buildings is:

$$QC_M = \sum_{i=1}^{n} CB_{ri} \times mi \tag{1}$$

In the formula, *QCM* represents the equivalent of greenhouse gas emissions embodied in buildings, with the unit of kg/CO2e; *CBri* is the carbon footprint factor for the *ith* type of building component, with the unit of kg/CO2e; and *mi* denotes the quantity of the *ith* type of building component used, with the unit of individual items.

The carbon emissions in the building material production stage mainly originate from two types: on-site construction materials and component production. The formula is expressed as:

$$\begin{cases} C_p = C_{mp} + C_{ep} \\ C_{mp} = \sum_{i=1}^{n} M_{mp,i} EF_{mp,i} \\ C_{ep} = \sum_{i=1}^{n} E_{ep,i} C_{ucp,i} + \sum_{i=1}^{n} E_{ep,i} C_{uco,i} \end{cases} \tag{2}$$

In the formula, *Cp* represents the carbon emissions from building material production; *Cmp* is the carbon emissions from on-site building material production; *Cep* denotes the carbon emissions from component production; *i* stands for the type of building material on-site, *Mmp* is the quantity of materials used on-site; *EFmp* is the carbon emission factor for the quantity of building materials used on-site; *Eep* represents the number of components; *Cucp* is the carbon emissions from building material production per unit component; *Cuco* is the energy consumption for the production of per unit component; all the above units are in kg/CO2e. For example, if the CO2 emissions during the production stage of steel reinforcement are 2303.79 kg, but the recycling rate of this building material is >80%, then the carbon emissions of this material are calculated as:

$$2303.79 \times (1 - (2118.53 - 393.10) \times 0.8) = 923.45 \text{kg/CO2e} \tag{3}$$

Next, for building material transportation, the primary source of carbon emissions during this stage is the transportation equipment, which arises from the energy consumption incurred when transporting building materials and components from their production sites to the construction site. The formula can be expressed as:

$$\begin{cases} C_t = C_{mt} + C_{et} \\ C_{mt} = \sum_{i=1}^{n} M_{mt,i} D_{mt,i} EF_{mt,i} \\ C_{et} = \sum_{i=1}^{n} E_{et,i} D_{et,i} EF_{et,i} \end{cases} \quad (4)$$

In the formula, *Ct* represents the carbon emissions from building material transportation; *Cmt* is the carbon emissions from on-site construction material transportation; *Cet* denotes the carbon emissions from component transportation; all units are in kg/CO2e; *i* stands for the type of building material; *M* is the quantity of building materials used; *D* is the transportation distance, with the unit of km; and *EF* represents the mode of transportation, with the unit of kgCO2e/t·km.

Finally, for the construction phase, the main sources of carbon emissions include temporary but necessary carbon emissions from the energy consumption of equipment on the construction site, as well as the living consumption of personnel. The formula is expressed as:

$$C_{co} = \sum_{i=1}^{n} E_{co,i} EF_{e,i} \quad (5)$$

In the formula, C_{co} represents the carbon emissions from construction; i represents the type of energy; E_{co} represents the amount of energy used, measured in kWh; and EF_e represents the carbon emission factor, measured in $kgCO_2e/kWh$.

3 Calculation Method for Carbon Emissions during the Embodied Phase of Buildings

3.1 Boundaries for Carbon Emission Calculation

It is crucial to investigate the methods for calculating carbon emissions during the embodied phase of construction projects and to establish clear boundaries for such calculations. In the context of green and energy-efficient evaluations, the full life cycle of a building is typically divided into distinct phases based on time, including the production phase of building materials, transportation of building materials, construction phase, operation phase, and demolition phase [4]. The embodied phase of a building starts from the initial stages of a construction project and ends with its completion and acceptance. During this phase, the primary task is to transform the design outcomes into a physical building through a series of construction techniques. Therefore, in the embodied phase, construction techniques and methods determine the construction organization and management of the project, which further affects the selection, consumption, and regional planning of construction equipment, materials, and so on. These factors can directly reflect the capability and level of the construction unit. Consequently, during this phase, the construction unit plays a central role. The choice of construction techniques, management measures, and other aspects when developing a construction plan will all impact the carbon emissions during this phase. Therefore, the carbon emissions during the embodied phase of a building project are defined as those occurring during the construction process.

3.2 Overview of Carbon Emission Calculation Methods

Measurement Method: This approach relies primarily on actual measurement data from emission sources to obtain relevant carbon emissions, which can be further divided into two types: on-site measurement and off-site measurement. On-site measurement typically involves the use of a continuous emission monitoring system equipped with a carbon emission monitoring module to continuously monitor and directly measure emission concentrations and flow rates. Off-site measurement involves collecting samples and sending them to relevant monitoring departments for quantitative analysis using specialized detection equipment and techniques [5].

Input-Output Method: This is a top-down estimation approach that primarily involves compiling input-output tables and constructing corresponding mathematical models to quantitatively calculate material usage. This method provides relatively high precision and detailed results, but acquiring the necessary data can be challenging, often resulting in incomplete data information.

Material Balance Method: This method calculates material balance based on the law of mass conservation. For any production process, the amount of raw materials consumed should equal the sum of the product quantity and material loss. It is primarily used for engineering analysis of polluting construction projects and is a conventional and fundamental method for calculating pollutant emissions. Its principle is that the total amount of material input into the system equals the sum of the total amount of product output and the total amount of material loss.

Emission Factor Method: This method is the most widely applicable and commonly used carbon accounting approach. Its calculation formula is expressed as: Greenhouse Gas (GHG) Emissions = Activity Data (AD) × Emission Factor (EF).

3.3 Determination of Carbon Emission Factors

In accordance with relevant standards and regulations such as GB/T51366-2019 and the "Announcement of the Ministry of Ecology and Environment and the National Bureau of Statistics on the Release of the Carbon Dioxide Emission Factor for Electricity in 2021," as well as the research content, the carbon emission factors were determined [6]. As shown in Table 1.

Table 1. Determination of Carbon Emission Factors

Type	Carbon Source	Carbon Emission Factor	Unit
Resource Category	Reinforced Concrete	295	$kgCO_2e/m^3$
	Molds	2400	$kgCO_2/t$
	Labor	19.49	kgCO2/(person·d)
Building Material Transportation	Equipment	295	$kgCO_2e/$ (t·km)
Energy Category	Electricity	0.942	$kgCO_2/$ (kW·h)
	Gasoline	2.031	$kgCO_2/kg$
	Diesel	2.171	$kgCO_2/$ (kW·h)
Mechanical Equipment	Tower Crane	266.04	kW·h/Machine Shift

3.4 Application of Information Technology

1) Blockchain Technology: Enhancing the Authenticity and Reliability of Carbon Emission Data

Firstly, blockchain technology, with its distributed, decentralized, and tamper-resistant characteristics, ensures high security and transparency of data information. Secondly, a carbon emission system based on blockchain technology can facilitate carbon trading, motivating enterprises to adopt a series of economic measures [6]. Lastly, the carbon emission system leveraging blockchain technology features intelligent management, assisting enterprises in comprehensively and accurately grasping their internal carbon emissions, proposing scientific and effective emission reduction measures, and optimizing their operational processes to achieve goals such as energy conservation, emission reduction, and meeting societal environmental protection requirements. However, applying blockchain technology in this context poses challenges, including how to personalize and address management issues specific to carbon emission systems, how to visually present internal carbon emission conditions within enterprises, and how to fully leverage the power of data analysis. Currently, these challenges are primarily addressed through human intervention, which, while lacking high precision to a certain extent, exhibits strong flexibility and personalization.

2)BIM Technology: Enhancing the Efficiency and Accuracy of Carbon Emission Calculation and Analysis

By directly acquiring the quantity of various building materials from the BIM model for carbon emission calculations, it is possible to effectively control carbon emissions during the architectural design process and provide a more precise estimation of carbon emissions from building components during the embodied phase. This approach effectively prevents additional carbon emissions or construction pollution during the construction process, thereby achieving the goals of energy conservation and emission reduction [7]. As shown in Figure 1.

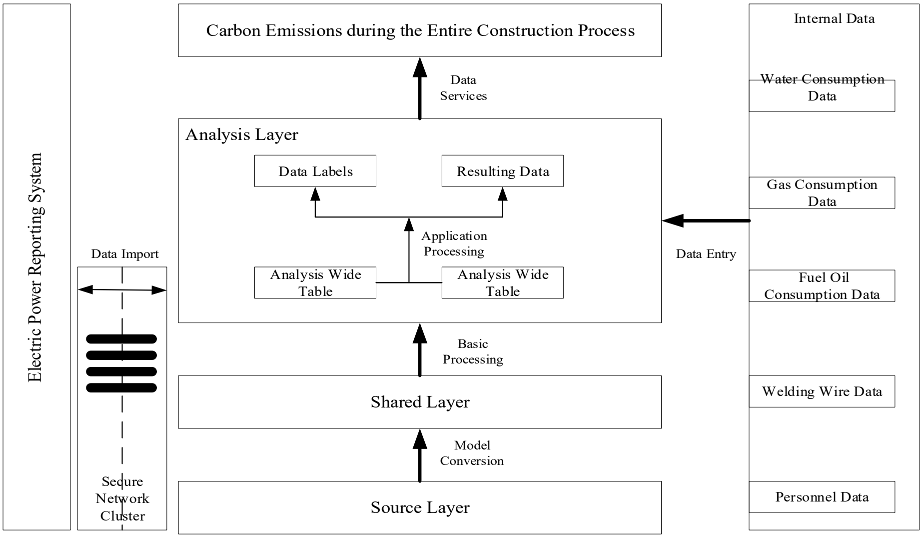

Fig. 1. Illustration of BIM Technology Application in Carbon Emission Calculations during the Embodied Phase of Construction

Furthermore, the primary challenges in utilizing BIM technology for carbon emission calculations related to building material usage lie in how to promptly calculate the carbon emissions based on the updated material usage following changes in model parameters and how to enhance the efficiency and impact of these calculations [7]. Currently, there is no optimal approach to address these issues, and they are primarily managed through real-time calculations and adjustments by relevant operators.

4 Development of a Carbon Emission Monitoring Platform for the Embodied Phase of Buildings

4.1 System Overview

In the information technology-based carbon emission monitoring platform for the embodied phase of construction projects, real-time carbon emission data is calculated by collecting consumption data of energy and resources during the construction phase, as well as inputting data on carbon emissions from building material production and transportation. This approach enables energy conservation and emission reduction at construction sites, enhances project management capabilities, and reduces construction costs. As shown in Figure 2.

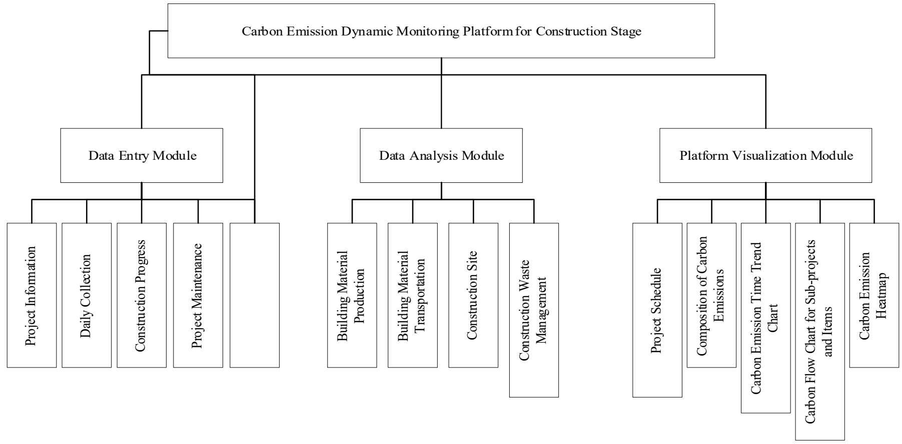

Fig. 2. System Architecture of the Information Technology-Based Carbon Emission Platform for the Embodied Phase of Construction Projects

4.2 System Architecture

The system architecture presented in this paper is service-oriented and primarily designed for the calculation of carbon emissions during the construction phase. It comprises four layers: the business application layer, analysis layer, shared layer, and data source layer [8]. The architecture supports the utilization of the B/S model, as illustrated in Figure 3.

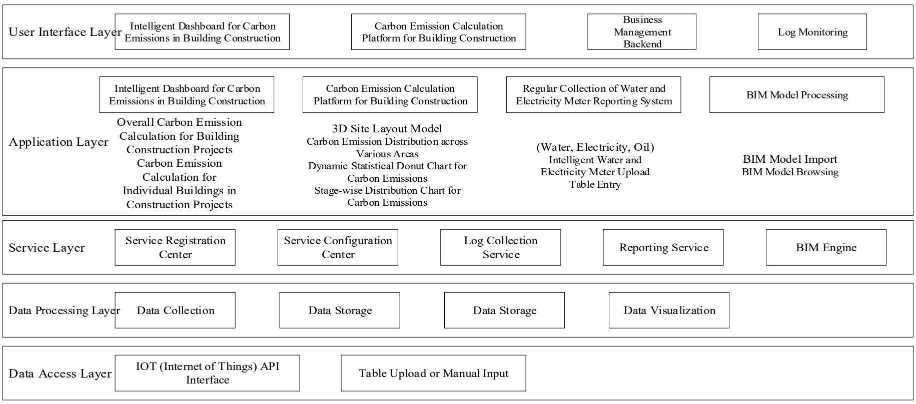

Fig. 3. System Architecture Design of the Information Technology-Based Carbon Emission Platform for the Embodied Phase of Construction Projects

1. Business Application Layer: Primarily interfaces with clients through a browser, providing users with different functional interfaces in a GUI (Graphical User Interface). Administrators have the authority to review and set permissions for the data

submitted daily by reporting personnel, while ordinary users can only browse the data dashboard.

2. Analysis Layer: Primarily responsible for front-end and back-end data analysis, which is an essential component of the architecture. It comprises three aspects: service bus, service registry, and service discovery and invocation. Additionally, the carbon emission calculation formula is integrated into the platform based on the "Standard for Calculation of Carbon Emissions from Buildings," and its unified data format enhances the efficiency of platform data analysis.
3. Shared Layer: As the level for implementing business logic, its main purpose is to transform different business logics into service forms.
4. Data Source Layer: Primarily serves as a storage function, processing carbon emission data during the construction phase. It achieves efficient data storage and retrieval through databases such as Oracle and SQL Server.

4.3 Functional Modules

In the system's functional design, the carbon emission system platform analysis for the construction phase of buildings needs to possess the following functions:

1) User Management: To ensure system security, users need to create passwords, and maintain their own information through the establishment of usernames.

2) Permission Management: Permission groups are the carriers used by the system platform to manage user behavior. The system manages permissions by granting access to permission groups. By classifying system users and matching them with corresponding permissions, it not only simplifies the system process but also improves the efficiency of authorization management [9].

3) Menu Permission Configuration: Access rights can be configured based on job positions, primarily to facilitate permission management for administrators and operators. Unlike operators, administrators can also create new accounts and delete unnecessary ones at any time, maintaining the efficient operation of the system.

4) Log Management: Allows administrators to review user-uploaded logs.

5) Report Management: The primary function is to collect data on equipment energy consumption, including daily, monthly, and annual reports. For example, it can statistically record the carbon emissions during the construction phase, laying the groundwork for calculating the carbon emissions of subsequent sub-projects [10].

Compared to existing carbon emission calculation models, the model proposed in this study, though unable to achieve 100% accuracy, can still reach over 85% accuracy, which fully meets the requirements of practical applications. In terms of efficiency, the carbon emission calculation model presented in this research demonstrates strong logic and comprehensiveness in its structure and architecture, thereby ensuring efficiency. Compared to other existing carbon emission calculation models, it exhibits higher applicability, value, and efficiency [11].

5 Application Case of Carbon Emission Monitoring Platform

5.1 Project Overview

This project is a construction engineering project located in Shaoxing City, Zhejiang Province. The total gross floor area of the building project is approximately 147,700 square meters, with a design service life of 50 years. The project is currently in the construction phase, and the relevant content of the carbon emission management platform for this phase is implemented in accordance with national standards such as GB/T 51366-2019 and GB 55015-2021. The monitored information of individual buildings is shown in Table 2.

Table 2. Monitoring Information of Individual Buildings

Serial Number	Individual Unit Name	Building Type	Area: m^2	Structural Type	Number of Floors
1	2#High School Section	Public Building	13445.16	Frame Structure	1 Underground Floor 5 Aboveground Floors
2	4#Training Center		5867.99	Frame Structure	1 Underground Floor 4 Aboveground Floors

5.2 Carbon Emission Monitoring and Calculation Boundaries

Monitoring Scope: The primary focus of carbon emission monitoring during building construction is on the embodied phase of the building, encompassing the total greenhouse gas emissions generated during the production and transportation of building materials as well as the construction phase. These emissions are expressed in terms of carbon dioxide equivalents.

Calculation Method: To effectively monitor and accurately quantify the carbon emissions during construction, a combination of the actual site conditions, monitoring data collection methods, and relevant standard documents is utilized to select the appropriate carbon emission monitoring and calculation method.

5.3 Carbon Emission Data Analysis for the Embodied Phase of the Building

Utilizing the Donghe Building Carbon Emission Calculation and Analysis Software, the project's construction drawing budget material list and construction drawing budget machinery list are imported to calculate the carbon emissions of the project's overall and monitored individual units during the embodied phase. These calculated values serve as the target carbon emission values for the embodied phase of the project, as shown in Table 3.

Table 3. Comparison of Carbon Emissions in the Embodied Phase of the Project with the Target Value

Unit Name	Activity Phase	Actual Measured Value: $kgCO_2e/m^2$		Target Value: $kgCO_2e/m^2$		Progress Percentage: %
		Carbon Emission per Unit Area	Total Carbon Emission	Carbon Emission per Unit Area	Total Carbon Emission	
Project	Building Material Production	1141.17	168550.72	1241.94	183434.11	91.89
	Building Material Transportation	56.88	8401.66	62.10	9171.71	91.60
	Building Material Construction	15.72	2321.57	32.51	4801.76	48.35
	Total	1213.77	179273.96	1336.54	197407.58	90.81
2#	Building Material Production	450.92	6062.67	594.75	7996.54	75.82
	Building Material Transportation	22.45	301.90	29.74	399.83	75.51
	Building Material Construction	5.97	80.23	35.68	479.79	16.72
	Total	479.34	6444.81	660.18	8876.16	72.61
4#	Building Material Production	388.34	2278.78	581.46	3412.01	66.79
	Building Material Transportation	19.42	113.95	29.07	170.6	66.79
	Building Material Construction	3.43	20.13	34.89	204.72	9.84
	Total	411.19	2412.86	645.42	3787.33	63.71

As shown in Table 3, by comparing the carbon emissions per unit area and total carbon emissions between the measured values and target values, it is observed that for Projects 2# and 4#, the measured values of carbon emissions per unit area and total carbon emissions are lower than the target values. Further prediction and analysis based on the above research content indicate that the actual total carbon emissions of this construction project have not reached the target value and are in fact lower, demonstrating the project's excellent energy-saving and emission-reduction performance.

6 Conclusion

In summary, the research on carbon emission calculations during the embodied phase of construction projects based on information technology, with information technology as the foundation, can effectively enhance the accuracy, comprehensiveness, effectiveness, and scientific rigor of carbon emission calculations during this phase. This enables a thorough analysis and understanding of the specific carbon emissions during the embodied phase of construction projects, providing clear directions and data for subsequent energy-saving and emission-reduction measures. Moreover, in the embodied phase of construction, carbon emission information technology plays a role in promoting and optimizing construction management, effectively enhancing the environmental protection level and efficiency of construction management, thereby contributing to the overall green and environmentally friendly characteristics of construction projects. Therefore, by further promoting the green and environmentally friendly development and construction of the construction industry, while ensuring construction quality and standards, the specific application value of information technology can be fully leveraged.

7 Discussion

Method Clarity: How can the clarity of the carbon emission calculation method during the embodied phase be further enhanced, especially in terms of practical application within construction projects? What strategies or approaches can be employed to ensure that the methodology is more straightforward and easily understandable for practitioners? Technological Integration: What are the specific challenges or limitations encountered in integrating blockchain and BIM technologies for carbon emission monitoring? Furthermore, how can these challenges or limitations be addressed or mitigated to ensure effective and reliable carbon emission tracking? Comparative Analysis: How does the proposed carbon emission calculation model compare to existing models in terms of accuracy and efficiency? What insights does this comparison provide, and does the inclusion of a comparative analysis with other models strengthen the contribution of this paper? Case Study Details: Can the case study be expanded to incorporate more detailed data or additional examples? Would such an expansion better illustrate the effectiveness of the carbon emission monitoring platform across various construction scenarios? What specific data points or examples would be most valuable in this regard? Contributions and Implications: What are the practical implications of this research for the construction industry? How can the findings inform future research or policy-making related to carbon emission reduction in construction projects? Lastly, how does this work contribute to the existing body of knowledge in this field, and what gaps in knowledge does it help to address?

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