A Comprehensive Framework for Evaluating Blockchain-Based Systems: Embodied Carbon Management in Construction Industry

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Abstract

Embodied carbon in the construction industry is a significant contributor to global carbon emissions. With growing emphasis on carbon neutrality and carbon pricing, the need for effective carbon accounting has become increasingly important. However, inefficient carbon information sharing, driven by the complex and fragmented nature of construction supply chains and the complicated quantification process, hinders carbon accounting. A blockchain-based system is believed to offer a potential solution, but limited research exists on its application. Additionally, existing blockchain-based studies often focus on computable metrics during evaluation, overlooking system design objectives and industry stakeholders' needs. To address these gaps, this study proposes a public blockchain-based carbon management system for embodied carbon information sharing and quantification in the construction industry. It also introduces a comprehensive evaluation framework to verify and validate the system. The research's contributions include: (i) exploring the application of blockchain for sharing and quantifying embodied carbon information in construction supply chains, and (ii) introducing a comprehensive evaluation framework to assess the functional suitability, performance efficiency, usability, system effectiveness, and industry impacts of a blockchain-based system.

Keywords –

Embodied carbon, Information Sharing, Blockchain, Evaluation, Verification, Validation

1 Introduction

According to the World Green Building Council, the construction industry accounts for 39% of global energy-related carbon emissions [1]. A building's life cycle comprises four phases: production, construction, operation, and demolition [2]. Among these, embodied carbon—which encompasses all emissions associated with materials and construction processes, from manufacturing to disposal—accounts for 11% of global carbon emissions [1].

During the 26th United Nations Climate Change Conference (COP26) in 2021, a call was made to achieve net-zero emissions for all new and existing assets by 2050 [3]. Additionally, the Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report, emphasized the significance of carbon pricing as a key tool for cost-effective climate change mitigation [4]. These developments highlight the rising importance of accounting for embodied carbon in the industry.

Many researchers agree that poor carbon information sharing is a significant issue, including inaccurate and insufficiently detailed carbon data [5], [6] and a lack of data transparency and traceability [6], often due to traditional database systems. Blockchain technology, with features such as immutability, traceability, and transparency, has been explored for applications in the construction industry, including information management [7], [8] and carbon management [9], [10]. Consequently, blockchain is believed to offer promising solutions for improving carbon information sharing. While blockchain-based approaches for embodied carbon management have improved data integrity and privacy [11], challenges remain in ensuring the traceability of carbon information sharing and the quantification process

Moreover, existing blockchain-based solutions for the construction industry primarily focus on computable performance metrics (e.g., network latency, system transactions per minute), neglecting usability, adaptability and effectiveness. There is a lack of comprehensive evaluation methods to verify and validate blockchain-based systems, particularly in assessing whether they meet their intended objectives, align with stakeholder needs, and have long-term adoption potential.

This research investigates how blockchain enhances carbon information sharing and quantification, and proposes a comprehensive evaluation framework for the blockchain-based system. Therefore, this research aims to address the following two research questions:

- How can a blockchain-based carbon management system enhance traceability in information sharing and the quantification process of embodied carbon in the construction supply chain?
- How can a comprehensive evaluation framework be developed to verify and validate a blockchain-based carbon management system?

2 Related Works

2.1 Blockchain applications in construction industry

Unlike traditional databases, where data is controlled and accessed by a central authority, which can lead to potential risks such as data tampering and reduced trust among participants [12] , blockchain is a decentralized ledger technology enabling secure, transparent transactions on a peer-to-peer network. Transactions are validated by consensus mechanisms and linked in blocks with unique hashes [13]. Therefore, the key characteristics of blockchain include transparency, immutability, traceability, and smart contracts executed by self-executing code [14]. Due to its capabilities and feasibility, researchers have begun exploring its potential applications in the construction industry since 2017. Two key areas of focus for blockchain in the construction industry are information management [7], [8] and supply chain management [15], [16]. Several studies have explored the application of blockchain to carbon management. For instance, blockchain has been integrated into certification and supply chains [9] [17], life cycle assessment [18], and embodied carbon estimation [10] and tracking [11]. However, while blockchain has been applied to carbon management in these contexts, existing studies tend to focus on simplified supply chain models. These models overlook the complexities involved in the carbon quantification process within the construction supply chain. This paper expands on previous research by incorporating smart contracts into the quantification process while maintaining data traceability.

2.2 Evaluations of blockchain-based in construction industry

There are several studies related to blockchain-based systems that have been developed in various areas, such as supply chain management. Examples include blockchain-based systems for transforming personal protective equipment supply chain operations [19], facilitating inventory sharing between suppliers and retailers [20], and enhancing product traceability in the healthcare supply chain [21]. These systems are typically evaluated through smart contract validation, which focuses on functionality, error resolution, and transaction simulation, alongside additional assessments such as cost analysis and security evaluations. Security assessments often include factors such as confidentiality, data integrity, availability, non-repudiation, and protection against man-in-the-middle attacks.

In the construction industry, several blockchain-based systems have been proposed with distinct evaluation methods. For example, a study aimed at improving supply chain traceability and information sharing in precast construction focused its evaluation on information sharing management, real-time control of scheduling, information traceability (e.g., number of transactions per minute), and economic performance at a macro level [7]. Another study on cross-border logistics supervision and data sharing in modular construction evaluated product accountability, data traceability (e.g., time to record and trace information), and system security, including data immutability, authentication, and authorization [22]. Additionally, research linking permissioned blockchain to IoT and BIM platforms for off-site production management in modular construction assessed metrics such as storage cost, IoT data transaction integrity, authorization, and authentication [23]. Similarly, a blockchain-based framework for carbon management toward construction product certification was evaluated based on security, performance, blockchain network latency, and cost [17].

However, their evaluations often focus on computable metrics without addressing other important dimensions, such as the usability and effectiveness of the systems. This reliance on traditional metrics fails to capture the holistic value of blockchain systems and how they address industry-specific challenges inherent in their design. This study expands on previous research by adopting a more comprehensive evaluation approach for evaluating the performance and effectiveness of the proposed blockchain-based system.

3 Methodology

This study employs the Design Science Research (DSR) methodology [24], a structured approach that supports systematic problem-solving activities in research. The methodology begins with the identification of research problems and objectives, accomplished through a comprehensive literature review of existing studies on blockchain-based applications and their evaluation methodology, as identified in Section 2.

Following this, the system framework of the blockchain-based carbon management system and the comprehensive evaluation framework for blockchain-based systems were designed and developed. Subsequently, a system prototype will be created based on the designed framework and demonstrated through a real-life case study in the construction industry to validate its feasibility. The prototype will then be rigorously evaluated using the proposed comprehensive evaluation framework to verify and validate how well it meets its design objectives and addresses the identified challenges. Finally, both the system framework and the evaluation framework underwent practical assessment through structured communication with relevant stakeholders.

3.1 Design and Development

3.1.1 System Framework

Referring to the previous conference paper [11], the study focuses on the integration of blockchain technology with carbon management across the entire construction supply chain to enhance the quality and traceability of embodied carbon data. A system framework and operational workflow were proposed. In the framework, the system consists of traditional off-chain carbon management functions, encompassing user registration and data input, and a decentralized public database (on-chain) with self-executing smart contracts is utilized to store significant project information and carbon emissions data to make carbon footprints transparent, reliable, and trackable. The stakeholders involved are developers, architects, consultants, contractors, and product suppliers. Carbon data input parameters are divided into three groups based on the building life cycle: Materials in New Construction (A1–A3), Upstream Transportation (A4), and Construction Site Activities (A5). Besides, the study introduced three technical highlights: (i) Role-Based Access Control for Functionality, allowing every stakeholder to have a clearly defined role and functionality within the system, (ii) Hierarchical Hashing Strategy for Validation, enabling multiple validations by various parties to ensure data quality before data is stored on-chain, and (iii) Selective Data Disclosure Before On-chain, allowing input parties the right to select the data to be disclosed or protected before uploading it to the blockchain and sharing it with the public.

The proposed system framework improves carbon information sharing by enhancing data integrity, transparency, and privacy through recording carbon data on-chain. However, the embodied carbon quantification process, which is integral to information sharing, is a complex task that cannot be accomplished solely by a single recording smart contract. To address this challenge, the smart contract functionality has been advanced to incorporate both recording and quantification capabilities.

The Smart Contract - Carbon Quantification & Recording functionality quantifies total carbon emissions while ensuring that key carbon information is accurately recorded and shared on the blockchain. It also allows stakeholders to protect sensitive information by recording only its corresponding hash value on-chain. The smart contract owners can be suppliers (responsible for permanent materials and upstream transportation emissions) or contractors (responsible for temporary materials and site activity emissions). To ensure accuracy and integrity, all data must be validated by designated parties, while input parties retain the ability to select which parameters are disclosed on-chain. Inputs to the system include, but are not limited to, product specifications, emission factors, quantities, and transportation distances. Outputs generated by the system encompass key carbon information (e.g., emission source information, emission factor, transportation distance), hash values of carbon and validation process data, and total project emissions. Both input and output data are combined to form a transaction that is recorded on the blockchain, ensuring immutability, traceability, and transparency for the project team and the public. Figure 1 presents the updated system framework.

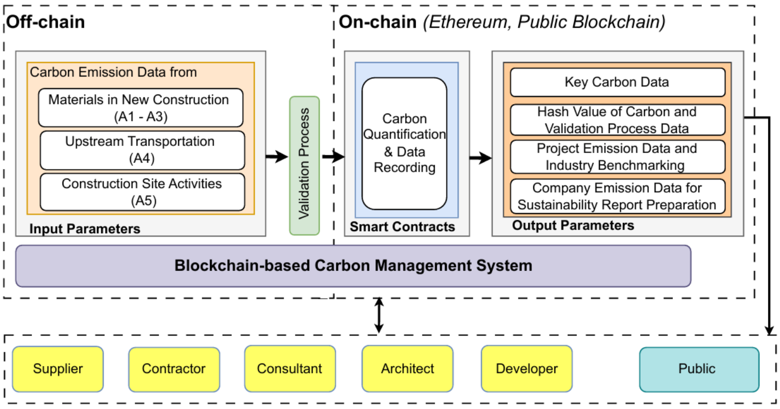

Figure 1: System framework

The updated operational workflow (Figure 2) begins with the architect creating a project account, inputting project details, and adding stakeholders. Suppliers and contractors then input carbon data, which senior staff review and validate before submitting it for further validation. Once validated, senior staff confirm the data for blockchain upload and select key data for public disclosure before invoking the smart contract. Finally, the developer quantifies and records the total project emissions, holding the final authority in the process.

In summary, the proposed blockchain-based carbon management system enhances embodied carbon information sharing by improving data integrity, traceability, and transparency while preserving privacy. It also leverages smart contracts to automate and streamline the quantification process, ensuring accurate and reliable carbon data management.

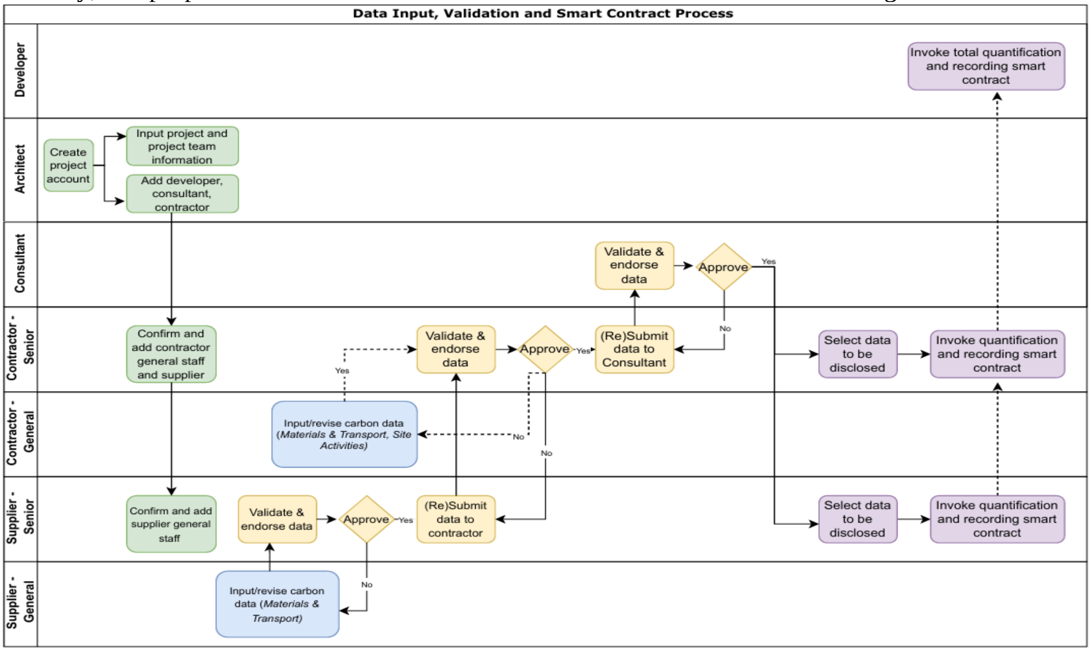

Figure 2: Operational workflow (Green - User/Project Initialization; Blue – Data Input; Orange – Validation Process; Purple - Smart Contracts)

3.1.2 Evaluation Framework

In DSR methodology, evaluation focuses on measuring performance, collecting feedback, and determining how closely the artifact aligns with its stated objectives. This typically includes verifying how well the artifact meets its specified design objectives (verification) and validating whether it effectively solves the identified problem and meets stakeholder needs (validation).

ISO 29119 [25] is a software testing standard that outlines key concepts of software testing, including test processes and techniques. It defines eight testing types: functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability. For the verification and validation of the proposed blockchain-based system, three testing types have been identified as priorities: functional suitability, performance efficiency, and usability. These testing types evaluate how well the system addresses its core functionalities, ensures efficient operation, and is practical for adoption by stakeholders. On the other hand, the proposed systems are usually a standalone solution specifically designed for blockchain-based deployment, making compatibility and portability testing less relevant at this stage. Furthermore, reliability testing and security may not prioritized in this phase of development due to the inherent resilience and cryptographic safeguards provided by the public blockchain platform, which inherently ensures data integrity and fault tolerance. Similarly, maintainability is not a focus, as the system remains in the prototype development phase.

For functional suitability testing, the functionality of the system should first be clearly identified. Blockchain-based systems are typically dual-systems, comprising a traditional management system (off-chain) and a decentralized database (on-chain). Each component serves distinct purposes with specific objectives and enhancements, making it essential to evaluate functionality across these two integrated parts. The functionality of the system can be broadly categorized into two areas: (i) Core System Functions and (ii) Functional Enhancement Features. Core System Functions include fundamental operations such as project and project team registration in the off-chain system, as well as data recording and the execution of smart contracts in the on-chain system. These functions are essential for the system's basic operation and compliance with its design objectives. Functional Enhancement Features encompass advanced strategies and mechanisms designed to address critical challenges, such as concerns related to data integrity, traceability, and privacy.

For Performance Efficiency, the testing attributes typically include scalability, cost, response time, and transaction latency. These attributes are critical for evaluating the system's ability to handle increasing workloads efficiently, maintain operational cost-effectiveness, and deliver acceptable performance under varying conditions. However, the relevance and emphasis of these attributes may vary depending on the specific characteristics and nature of the blockchain-based system being tested. For example, systems with concerns about response time and transaction latency would prioritize these attributes due to the need for immediate updates and decision-making.

Moreover, as noted earlier, the proposed blockchain-based systems often incorporate specific enhancement features aimed at addressing various challenges and achieving distinct objectives. These features, such as enhanced transparency, traceability, and data integrity, are designed to meet the unique demands of their application contexts. Consequently, system effectiveness should be one of the key metrics in the evaluation framework, as it is important for assessing whether the system successfully fulfills its intended objectives.

Table 1: Proposed evaluation framework for the blockchain-based system

Stage		Test attributes	Test Techniques	Test method	Participants
Verification: Meets design objectives		• Functional Completeness • Functional Correctness • Compliance and Non-Compliance Conditions	• Scenario testing	• Prototype Testing	• System designer
Validation: Solves problem and meets needs	(i) Performance Efficiency	• Scalability, cost, response time, and transaction latency (varies in relevance depending on the characteristics and nature of the system being tested)	• Worst-case Scenario Analysis	• Case-based simulation	• System designer
	(ii) Usability	• Functional Appropriateness • User Satisfaction • User Experience • Learnability • User Error Protection	• Use Case Testing	• Surveys (quantitative & qualitative)	• Testing parties
	(iii) System Effectiveness	• Subject to specific enhancement features of the system being tested	• Use Case Testing Comparison with Existing Tools	• Simulation • Sensitivity analysis • Surveys (quantitative & qualitative)	• System designer • Testing parties
	(iv) Industry impacts	• Adoption Challenges • Short-term and Long-term Benefits/Changes (which vary depending on the objectives of the system being tested)	• Impact Assessment • User acceptance testing	• Surveys (quantitative & qualitative) • Semi-structured interviews	• Testing parties • Stakeholders in industry

In addition, industry impacts should be incorporated into the evaluation framework, encompassing both short-term and long-term effects, as well as the adoption of the blockchain-based system within the industry. Since the proposed blockchain-based systems often represent significant innovations, immediate evaluation results from functional, performance, and usability testing may not fully capture their overall value. Assessing industry impacts provides valuable insights into how the system contributes to broader industry goals over time. This dimension is particularly important for understanding the system's potential to influence industry standards and practices, especially regarding long-term development.

Based on the above, a comprehensive evaluation framework for the blockchain-based system has been developed and is divided into two primary stages, as outlined in Table 1: verification and validation. The verification stage focuses on ensuring that the system meets its design specifications and objectives by evaluating attributes such as functional completeness, functional correctness, and compliance through scenario-based prototype testing. The system designer, who possesses the most in-depth knowledge of the system's architecture, functionality, and expected outcomes, serves as the participant in this process.

The validation stage assesses the system's ability to address the identified problem and fulfill stakeholder needs. It is divided into four dimensions: (i) performance efficiency, which evaluates scalability, cost, response time, and transaction latency through worst-case scenario analysis and case-based simulation, varies in relevance depending on the characteristics and nature of the blockchain-based system; (ii) usability, which tests functional appropriateness, user satisfaction, user experience, learnability, and error protection through case testing and surveys with participants ; (iii) system effectiveness, which is evaluated based on specific enhancement features using use case testing and comparisons with existing tools, both in quantitative approaches (e.g., simulation models and sensitivity analysis) and qualitative approaches (e.g., surveys); and (iv) industry impacts, which assess adoption challenges as well as short-term and long-term benefits, are evaluated through impact assessments, user acceptance testing, surveys, and semi-structured interviews. Testing parties and industry stakeholders should be included in the interviews to ensure more representative results and enhance the potential for practical implementation.

This comprehensive framework provides a robust evaluation of blockchain-based systems by assessing both technical performance and practical usability to ensure the systems meet their design objectives, deliver short-term changes and long-term value to stakeholders.

4 Implementation and results

4.1 System Framework

A prototype was developed using Ethereum for blockchain deployment and Etherscan for monitoring transactions. Figure 3 shows the prototype's user interface, and Figure 4 displays an example of data uploaded in the blockchain transaction.

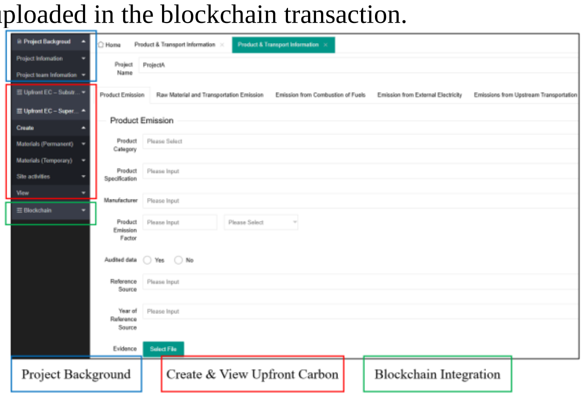

Figure 3: User interface of the prototype

- *Project Background:* This module captures key project information, including project details and team member information.
- *Create and View Upfront Carbon:* This module supports the input and visualization of data related to the substructure and superstructure phases, managing materials, specifications, transportation, quantities, emissions, and site activities to ensure accurate upfront carbon recording.
- *Blockchain Integration:* This module manages the blockchain-related aspects of the system, including transaction execution, the recording of hash values, and ensuring data traceability, linking off-chain data while preserving carbon information integrity.

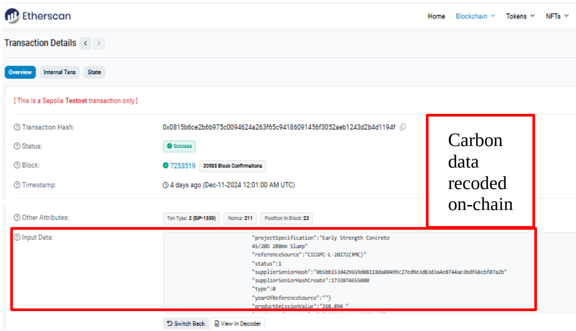

Figure 4: An example of Etherscan transaction

4.2 Evaluation Framework

Referring to Section 3.1, the proposed blockchain-based carbon management system consists of both off-chain and on-chain components. Its objective is to support embodied carbon information sharing and the quantification process in the construction industry, with enhancements in data integrity, transparency, traceability, and privacy achieved through three highlighted approaches and strategies. Based on the characteristics and nature of the proposed system, corresponding verification items based on its functionalities have been identified and summarized in Table 2, while the framework for validation is summarized as follows.

- *Performance Efficiency*: Scalability, cost estimation and transaction latency are considered. Scalability is a critical issue for the application and adoption of blockchain-based systems, ensuring the system can handle increasing data volumes and transaction loads effectively. Cost estimation addresses stakeholder concerns and ensures the system's long-term feasibility, while latency is a key factor in real-time performance.
- *Usability*: The testing parties are divided into three groups: stakeholders involved in the input and validation process (e.g., suppliers, contractors, and consultants), stakeholders responsible for the total project carbon quantification process (e.g., developers), and other stakeholders (e.g., architects and the public). These groups are assessed using data collection methods such as the System Usability Scale, task completion times, and error rates in surveys.
- *System Effectiveness*: This focuses on evaluating

the system's ability to meet its objectives, particularly in enhancing data integrity, transparency, traceability, and privacy, both through quantitative approaches (e.g., simulation models and sensitivity analysis) and qualitative approaches (e.g., surveys).

- *Industry Impacts*: This evaluates adoption challenges, as well as the short- and long-term impacts of the proposed system on carbon management practices in the construction industry. The impact assessment may include performance indicators related to short-term impacts (e.g., behavior change scales, level of stakeholder collaboration and data accessibility) and long-term industry impact (e.g., sustainability impact, adoption motivations and barriers at the project, company, and industry levels). The interviews will include testing parties and key stakeholders directly affected by the system (e.g., contractors and developers), as well as industry policy bodies (e.g., councils). This approach ensures representative results, enhances practical implementation potential, and provides a roadmap for long-term adoption.

Table 2: Verification Framework Summary for the Proposed Blockchain-Based Carbon Management System

		Verification items		Off-chain	On-chain
Core System Functions	i)	Information Sharing and Reporting	Data Collection (input parameters)	✓	
			Data Reporting (output parameters)		✓
	ii)	User Authentication and Authorization	Role-based Access Control Approach	✓	
			Authentication and Authorization	✓	✓
	iii)	Smart Contract	Quantification and Recording		✓
Functional Enhancement Features	i)	Data Integrity	Hierarchical Hashing Validation Strategy	✓	
			Immutable Records of Validation Process Data		✓
	ii)	Transparency	Open Access to Data		✓
	iii)	Traceability	Transaction Logs		✓
			Hashed Detailed Data and Validation Records		✓
	iv)	Privacy	Selective Data Disclosure before Chain		✓

5 Conclusion

Embodied carbon in construction significantly contributes to global emissions, but poor information sharing hinders its accounting. Blockchain offers a solution, but is underexplored. Also, most studies focus on computable metrics during evaluation, neglecting critical aspects of how blockchain systems align with their design objectives. This study proposes a public blockchain-based system to enhance carbon information sharing in construction supply chains and develops a comprehensive evaluation framework. This study uses the DSR approach, including the identification of problems and research objectives, the design and development of the system, and its comprehensive evaluation framework .

The contributions of this study: First, it explores how a public blockchain-based carbon management system supports the embodied carbon information sharing and quantification process in the construction industry. Second, it introduces a novel evaluation framework that extends beyond traditional metrics, offering a holistic approach to assess functional suitability, performance efficiency, usability, system effectiveness, and industry impacts. A key research limitation is the reliance on stakeholder participation, which is essential for successful system implementation and evaluation but requires additional time and resources, restricting adoption without incentive mechanisms. Future research will focus on developing a framework to utilize the proposed system to support green finance and incentivize adoption within the construction industry.

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