Integrating IoT and Blockchain to Monitor Embodied Carbon of Modular Buildings

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Abstract
The construction industry is the largest emitter of greenhouse gases, accounting for 37% of global emissions, among which embodied carbon of modular buildings cannot be ignored. Although many studies have been conducted on monitoring the embodied carbon of modular buildings, there are still limitations, such as a lack of real-time and transparent data, fragmented and isolated systems, and inconsistent measurement and reporting standards. Therefore, this study aims to develop a real-time embodied carbon monitoring system for modular buildings. The system consists of three essential parts: (1) Firstly, through the Internet of Things (IoT) sensors, the system can automatically monitor and collect data from equipment such as factory processing machines, transport vehicles, and on-site installation equipment, etc. (2) Secondly, the data from the isolated system and the data collected by IoT sensors are stored in blockchain, which can ensure the transparency and credibility of the data. (3) Thirdly, the system has a visual web platform that presents and reports the embodied carbon, which uses a uniform life cycle assessment (LCA) method using the collected data. The study developed a novel multi-technological embodied carbon monitoring system, which will be applied to the Kowloon Tong student hostel being constructed by the Hong Kong Polytechnic University to test its effectiveness. We anticipate that the system can help monitor and manage carbon emissions during construction. This system provides a valuable implication and practical demonstration for the embodied carbon monitoring of modular buildings.

Keywords**:** Internet of Things, blockchain, embodied carbon, modular building, web platform

1. INTRODUCTION

Global warming is a huge challenge for humanity, and carbon emissions (CEs) are recognized as a major cause of global climate change. The construction industry has a significant impact on global CEs. According to a recent report by the United Nations Environment Programme (UNEP), the construction field accounted for about 37% of global CEs in 2021, including CEs from energy consumption, as well as CEs from materials such as concrete, steel, aluminum, glass, and bricks (UNEP, 2022). CEs from buildings are categorized into operational carbon and embodied carbon. Operational carbon refers to the CEs produced during the use of a building, which can be reduced by implementing energy efficiency measures and using renewable energy sources and which can be adjusted flexibly over decades of use. In contrast, embodied carbon refers to CEs from the construction phase of a building, which is a one-time emission (Chen et al., 2023; Hu, 2023). Therefore, monitoring and reducing the one-time embodied carbon is crucial to reducing the overall CEs of buildings.

Modular construction has been acknowledged as a feasible approach for decreasing the embodied carbon of buildings (Lyu et al., 2022; Loo et al., 2023). It divides a building structure into multiple independent modules that are prefabricated in a factory and then delivered to the site for assembly to be a complete building. Therefore, the design and construction process is standardized and manageable. This means it’s possible to establish a standard monitoring scheme to monitor and calculate the embodied CEs and then achieve the goal of carbon reductions.

Many studies have adopted the life cycle assessment (LCA) method to calculate the embodied carbon of modular buildings. LCA divides the life cycle of a building into multiple phases and counts material and energy consumption at each stage of the construction process to calculate the building’s embodied CEs (Luo et al., 2022). However, there are limitations to the LCA method. First, there is a lack of real-time data. LCA is usually carried out before or after construction. Before construction, material and energy consumption amounts are estimated according to the designer’s drawings to calculate the embodied CEs, while after construction, embodied CEs are calculated from data recorded during the construction process. Suppose the calculated embodied carbon is significantly different from the previously estimated embodied carbon after construction; it is not easy to find the reasons for the difference, and adjustments cannot be made promptly. Besides, there is a lack of transparent data. The consumption amounts of materials and energy, usually obtained manually and stored in centralized databases, are often non-transparent, leading to doubtful results. Moreover, there is a deficiency in data integrity. Embodied carbon-related data often comes from multiple organizations that are usually reluctant to reveal their data. Thus, the data collected is frequently incomplete and fragmented, making it difficult to calculate accurate CEs.

The Internet of Things (IoT) and blockchain have the potential to solve these limitations. IoT is a network of connected sensing devices that can collect and share data over the internet in real-time (Whitmore et al., 2015; Chung et al., 2023). Blockchain technology enables data to be shared among multiple parties, allowing all participants to access and validate the data and solving the transparency and trust issues of the assessment process. Many researchers have adopted IoT or blockchain to monitor embodied carbon, but few studies integrate them together during the process of embodied carbon monitoring and calculation.

Thus, this study aims to develop a real-time monitoring system for embodied carbon of modular buildings based on blockchain and IoT. The IoT technology allows for automatic and real-time data collection at all stages of the construction process. Blockchain technology ensures the transparency and liquidity of the stored data. CEs are calculated at each stage using a unified LCA method and displayed on a web platform, where stakeholders can view the CEs during construction in real time, compare them with the expected plan, and make prompt adjustments. Finally, the developed system will be applied to monitor the embodied carbon of a student hostel under construction at the Hong Kong Polytechnic University, which will be used to test the effectiveness of the system.

The objectives of this study are:

(1) Formulate a solution to collect data automatically through IoT at all stages of the construction process;

(2) Create a blockchain network to store the data collected by IoT and uploaded by all stakeholders to ensure data transparency and liquidity.

(3) Develop a visualization web platform for stakeholders to view the CEs of the construction process in real-time.

The rest structure of this article is as follows: Section 2 systematically discusses the existing embodied carbon estimations and analyzes their merits and demerits, as well as the existing CEs monitoring system based on IoT or blockchain. Section 3 introduces the calculation process of the life cycle assessment method, the data collection, the data storage, and the design of the system architecture. Section 4 describes the blockchain creation process in detail, introduces the practical case that this study uses to examine the system's validity, presents the results, and discusses the advantages and limitations of the system. Finally, section 5 draws the main conclusions.

2. LITERATURE REVIEW

2.1 Embodied carbon estimation

Process-based LCA is the most commonly used method for calculating embodied carbon. It involves detailed modeling of all processes involved in the life cycle of building materials, from raw material extraction to disposal. It provides detailed and specific results, allowing a thorough understanding of where emissions are generated. However, it has the drawbacks of being time-consuming and data-intensive, and it requires comprehensive and accurate data, which can be challenging to obtain (Crawford, 2011). The input-output (IO) method is also a common method, which uses economic input-output data to estimate the environmental impacts of various sectors. It links economic transactions to environmental emissions. It can cover entire economies and accounts for indirect emissions across supply chains. However, it is less specific than process-based LCA and typically uses more generalized data, which can lead to less accurate results for specific materials or processes (Mattila, 2017). Moreover, a hybrid method combines the process-based LCA with the input-output method to leverage the strengths of both methods, providing detailed results while covering broader economic interactions. However, implementation is complex and requires extensive data from process and economic input-output tables (Crawford et al., 2018).

This paper adopts a process-based LCA method to calculate the embodied carbon, and blockchain and IoT technologies are used to assist data collection and storage. This improves the accuracy and credibility of the calculation results and overcomes the challenges of consuming too much time and intensive labor.

2.2 IoT-empowered carbon monitoring system in the construction field

In the construction sector, stakeholders need to monitor the data in real time, whether in terms of consideration for safety issues during the construction process or convenience for management of CEs or energy consumption. IoT has been testified and identified as an effective and efficient solution for real-time data monitoring in diverse fields, especially in building and infrastructure. Tao et al. (2018) developed a system to monitor greenhouse gas emissions in real-time using IoT technology while the prefabricated building components were being manufactured. They utilized Radio Frequency Identification (RFID) sensors to identify each component and calculate material usage. They also installed laser sensors in the factory to monitor the machines' running time and calculate energy usage in real-time. After being applied to a program in China, they proved the system's validity in promptly controlling irregular emissions and realized CE reduction, possibly in construction. Besides, Mao et al. (2018) proposed an IoT-based system combining a sensor network and a BIM virtual model to help construction teams cut down excessive CEs. The network can collect data on CEs in real-time, and the model can display the status of CEs in diverse construction activities. The framework has proved promising in monitoring real-time CEs and reducing emissions in the construction field. What's more, by integrating the IoT, BIM, and AI technologies, Arsiwala et al. (2023) presented a digital twin framework to automatically monitor and control CEs of buildings that are put into use. Validating its feasibility through a real-life case analysis, they indicated that BIM and IoT play a significant part in visualizing crucial spatial information regarding facility management and monitoring indoor air quality in real-time.

Therefore, many researchers have examined the role of IoT in monitoring and identifying data in real-time. It can serve as a feasible solution for construction stakeholders to monitor the construction process in real-time and then make adjustments promptly if the calculated CEs deviate from the estimated plan.

2.3 Blockchain-empowered monitoring system in the construction field

Blockchain's features in ensuring data transparency, liquidity, security, and traceability have led to its increasing use in the construction sector to monitor CEs. In 1997, the Kyoto Protocol, whose aim was to control CEs by developing a system that monetizes CO2, was signed by nearly 200 countries. Nevertheless, the scheme failed to achieve its objective later due to a lack of data integrity, manipulation, and other obstacles. To solve the issue, Sadawi et al. (2021) presented a blockchain-based solution to monitor and decrease CEs. They presented a holistic three-stage blockchain framework that adopts smart contracts to guarantee collected data's security, transparency, immutability, trust, and traceability. The carbon trading system proved to be an optimized tool for re-achieving the CEs reduction goal. Besides, Shu et al. (2022) stated that the existing emissions-trading system is centralized by one authority, which means that the transaction of emissions is opaque and low-efficient. To deal with the issue, they developed an emissions-trading system based on blockchain technology to manage CEs in the construction industry. The blockchain-enhanced system can audit CEs in the construction phase and enhance the reliability and efficiency of data empowered by blockchain technology with smart contracts when it is processing large amounts of transactions. Moreover, to make it easier and more convenient to monitor, report, and verify embodied carbon in the construction sector in Hong Kong, Luo et al. (2024) proposed a novel system to audit CEs based on blockchain technology. With the aid of a consortium blockchain, the audit carbon tool could record the information on the building's life cycle at each stage. It could ensure that the recorded data is stored in a traceable, flowable, immutable, and transparent manner. The system was later put into use in Hong Kong's building sector in 2020 to test and verify its validity. It was proved to be a viable solution for monitoring, reporting, and verifying the CEs of a building's life cycle.

In a word, the role of blockchain in improving data transparency, liquidity, security, and traceability has been proven and acknowledged as a feasible tool for handling CEs, especially in the construction industry. However, despite the previous exploration of IoT and blockchain in collecting and storing data, there is limited study combining the two powerful tools to audit and manage the embodied CEs of modular buildings. Therefore, this study proposes an IoT-Blockchain integrated system to collect data automatically and promptly while ensuring the authenticity of data from modular buildings during the construction phase. With vibration and camera sensors to monitor the running time of equipment, GPS to identify the route of the transport vehicle, and consortium blockchain to share data across stakeholders, the system provides a visualization platform for monitoring the embodied carbon of modular buildings.

3. METHODS

3.1 Embodied carbon estimation model

We use the LCA method to estimate the embodied carbon. A building's life cycle is usually divided into the construction, use, and dismantling phases. This paper focuses on CEs in the construction phase. The construction phase of modular buildings can be separated into three phases: the factory production phase, the transportation phase, and the on-site installation phase. Furthermore, the primary source of embodied carbon comes from the materials, equipment, and vehicles (Xu et al., 2023).

We establish the calculation formulas for the three stages, as detailed in Table 1 (Zhou et al., 2023). In the factory production stage, the CEs include those from raw materials as well as equipment, such as cutting machines used for processing materials and producing prefabricated components. The CEs from materials can be calculated by multiplying the quantity of materials used in the factory and the carbon emission factor of the material. While the equipment's CEs are calculated by multiplying the equipment's running time and its carbon emission factor. The CEs during the transportation stage are primarily attributed to vehicles' fuel consumption when transporting materials and prefabricated components. The vehicles' CEs can be calculated by multiplying the transport distance, the weight of the goods, and the vehicles' carbon emission factor. The CEs in the on-site installation stage arise mainly from equipment, such as cranes used for installation, along with emissions from the materials used on the site. Understanding these sources of emissions is crucial for developing effective strategies to mitigate their impact, such as using green energy equipment and vehicles, and reducing transport distance.

TABLE 1. CEs estimation formulas for each stage

	CEs estimation formulas	Denotes interpretation
Factory production phase	$\sum_{k=1}^{n} Q_{M_k} \times CF_{M_k}$ $\sum_{j=1}^{m} T_{E_j} \times CF_{E_j}$	Q_{M_k} represents quantity of materials used in the factory CF_{M_k} represents CE factor of each material T_{E_j} represents running time of equipment in the factory CF_{E_j} represents CE factor of each equipment
Transportation phase	$\sum_{k=1}^{n} D_{T_k} \times W_{T_k} \times CF_{T_k}$	D_{T_k} represents distance of transportation vehicles W_{T_k} represents the weight of goods that transportation vehicles have transported CF_{T_k} represents CE factor of each transportation vehicles
On-site installation phase	$\sum_{k=1}^{n} Q_{M_k} \times CF_{M_k}$ $\sum_{j=1}^{m} T_{E_j} \times CF_{E_j}$	Q_{M_k} represents quantity of materials used on site CF_{M_k} represents CE factor of each material T_{E_j} represents running time of equipment on site CF_{E_j} represents CE factor of each equipment

3.2 Data collection

By utilizing a variety of IoT sensors, we can automatically obtain real-time data about equipment operation time in the factory and on-site, as well as the route of transport vehicles, to support CE calculation. We attach vibration sensors to equipment in the factory to monitor its operation time. These sensors are directly attached to the critical parts of the equipment and can monitor equipment vibration in real-time. Vibration data can accurately reflect the operating state of the equipment and help us record its running time. Besides, the on-site equipment is monitored by cameras. These cameras cover the work area and record the operation of each device. A pre-trained model will process the videos recorded by the cameras. The model is based on machine learning technology that automatically identifies and extracts the actual running time of the devices from the videos. GPS sensors record the route of all transport vehicles to acquire the distance they have transported.

3.3 Data storage

To store the data more securely, we introduce blockchain technology. There are usually three types of blockchain: public blockchain, consortium blockchain, and private blockchain (Wu et al., 2023; Yang et al., 2020). Public blockchain such as Ethereum, which allows anonymous users to participate, does not require licenses and can be joined by anyone, making it unsuitable for some practical applications with privacy needs. In addition, a private blockchain is more applicable for internal corporate use and maintenance than for systems with multiple stakeholders (Wang, 2017). Consortium blockchain links the features of public and private blockchain with access restrictions and privacy protection, while members of consortium blockchain can jointly manage and control the network. Moreover, consortium blockchain costs less energy while guaranteeing high performance. Compared with some high-consumption consensus mechanisms used in public blockchain, such as Proof of Work (PoW), consortium blockchain can choose lower energy-consumption consensus mechanisms such as PBFT (Practical Byzantine Fault Tolerance) (Huang et al., 2020).

Therefore, the author selects the Hyperledger Fabric (a consortium blockchain) as the blockchain platform for the system. The system stores all the data related to CE calculation during the construction phase of modular buildings, including data automatically acquired by IoT sensors and manually uploaded data. With the security and traceability of the blockchain, the results calculated from this reliably stored data thus have a high level of credibility.

3.4 System architecture

Figure 1 shows the system architecture. It consists of three layers: the application layer, the IoT layer, and the blockchain layer. In the application layer, stakeholders can view the CEs during construction in real time and compare them with the expected plan. If there is an irregular emission, they can make prompt adjustments. The IoT layer consists of various sensors, such as vibration sensors, GPS, and cameras. These sensors are responsible for collecting the related data used to calculate CEs. The blockchain layer is the pillar part of the system, including the contract, consensus, data, and network layers. In the contract layer, smart contracts for calculating embodied carbon are deployed, and operations such as upgrading smart contracts can be performed. The consensus layer includes leader peer election, transaction sequencing, transaction packaging, and block generation. The third blockchain layer is the data layer, where each new block is connected to the blockchain through cryptography and synchronized to each node's ledger. The network layer is the underlying layer of the blockchain. It supports peer-to-peer network communication as well as broadcast.

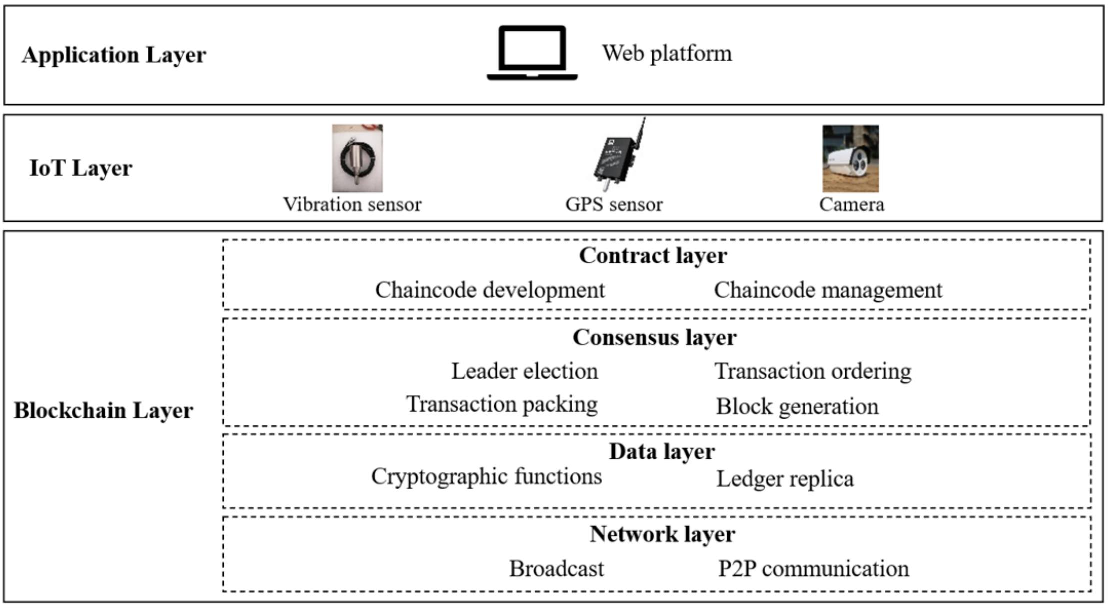

FIGURE 1. System architecture

4. SYSTEM IMPLEMENTATION AND RESULTS

4.1 Blockchain creation

Creating a Hyperledger Fabric network involves several steps, including setting up and configuring the network. Below is a detailed description of the process.

4.1.1 Download and installation

Install the following prerequisites:

- Docker: A container to run Hyperledger Fabric nodes, smart contracts, etc.
- Docker Compose: A platform to run and manage multiple docker containers.
- Go: A programming language used to develop smart contracts.
- Node.js: A programming language used to develop APIs (application programming interfaces) that interact with the blockchain.
- Hyperledger Fabric binary tools: The tools can generate cryptographic materials (such as private

and public keys), generate blockchain profiles, encode and decode blockchain profiles, deploy smart contracts, and manage the blockchain network.

- Hyperledger Fabric Docker images: The reliant environment of nodes, smart contracts, etc.

4.1.2 Configure and start network

Use the following steps to start the network.

(1) Use the 'cryptogen' tool to generate the cryptographic material for the network participants and their nodes.
(2) Use the 'configtxgen' tool to create the genesis block and blockchain profiles.
(3) Use Docker Compose commands to start the network.
(4) Use the 'peer' tool to deploy the chaincodes.

4.2 Case introduction

Our system will be applied to the Hong Kong Polytechnic University Kowloon Tong Student Hostel to monitor the CEs during the construction. It is located on the sloping site of Tat Hong Road. It contains four blocks. Figure 2 is the rendering of the hostel. The dormitory uses a modular construction method, and the prefabricated factory is in Zhaoqing City, Guangdong Province, China. The prefabricated modules will be transported to the site by lorries and ships.

FIGURE 2. The Hong Kong Polytechnic University, Kowloon Tong student hostel

4.3 Web platform design

We developed a web platform that allows stakeholders to visualize CEs directly. The homepage (Figure 3) and carbon calculation page (Figure 4) of the platform contain the real-time total CEs of the construction project, daily CEs, various types of charts, etc.

The carbon monitor page presents the accumulated CEs of the three phases: factory production, transportation, and on-site installation (Figure 5). In the interface of CE for the production site (Figure 6a and Figure 6b), users can click different devices to check the accumulated CEs of them in various factory areas. As for the interface of transportation (Figure 6c and Figure 6d), the routes of each vehicle and the corresponding daily CEs are recorded and displayed with line charts so that stakeholders can view the trend of CEs during the process and thus make timely adjustments. In light of the interface of on-site installation (Figure 6e and Figure 6f), the daily produced CEs by each device for assembling prefabricated modules are also presented on the web platform for monitoring and management.

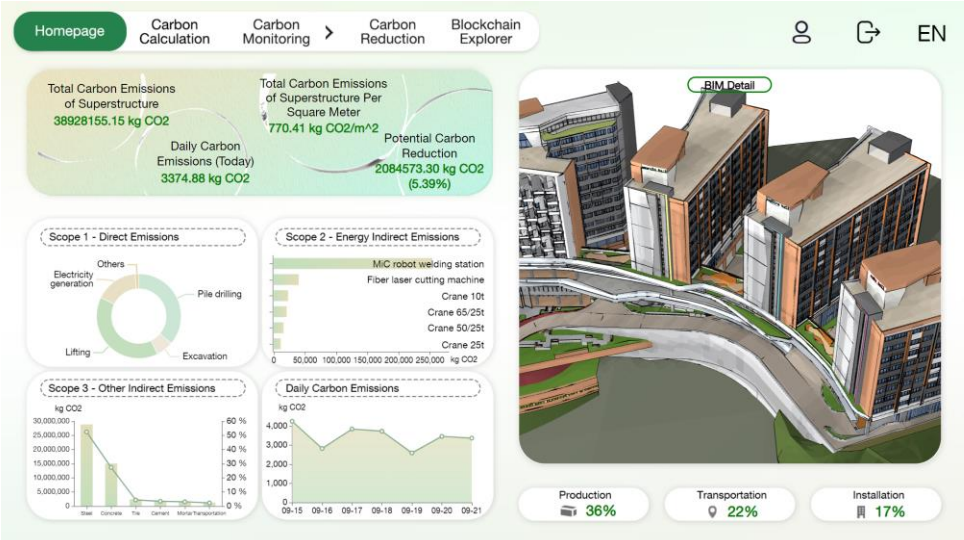

FIGURE 3. Homepage

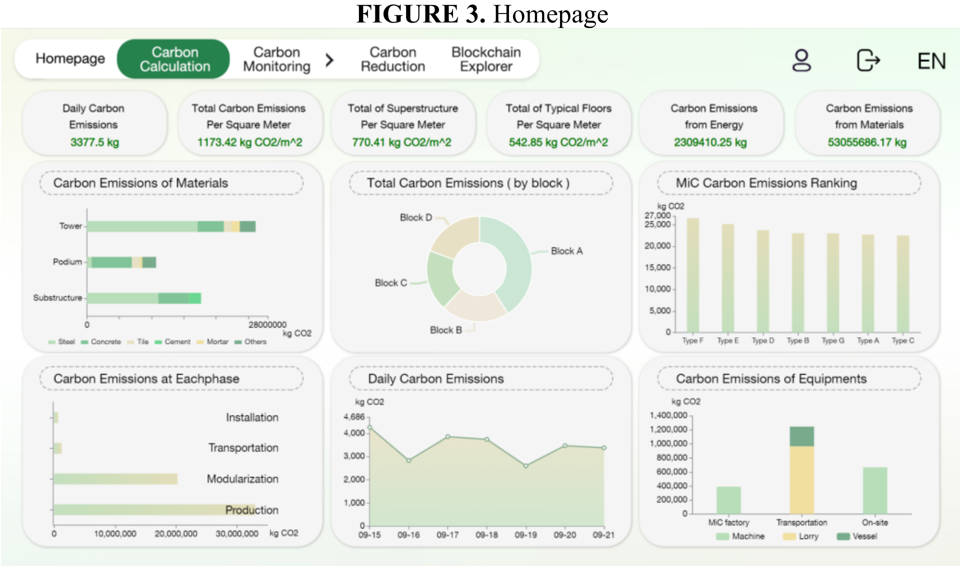

FIGURE 4. Carbon Calculation page

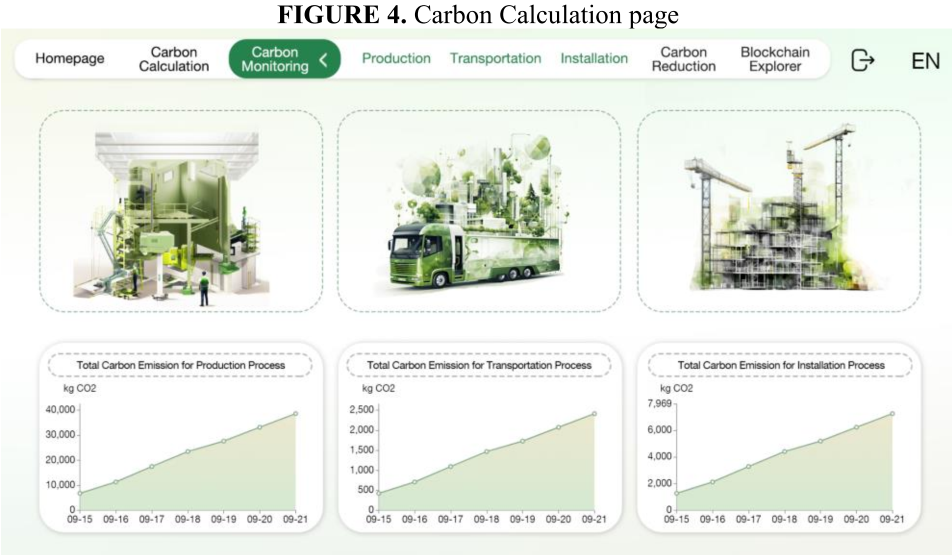

FIGURE 5. Carbon Monitoring page

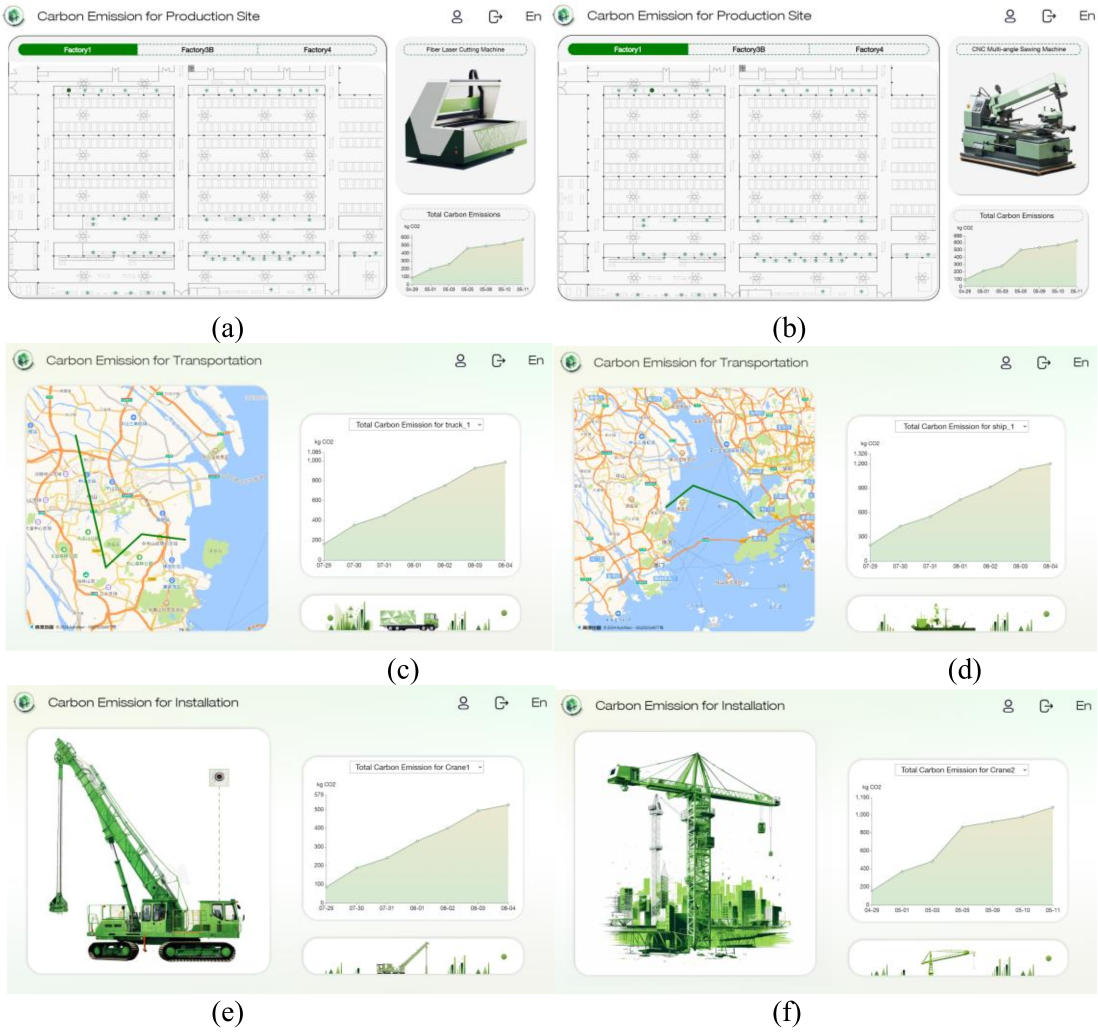

FIGURE 6. CEs of each equipment in the production, transportation, and installation stage

On the carbon reduction page (Figure 7), stakeholders can choose different carbon reduction measures and see the carbon reduction effect of the combination of various measures directly in the chart.

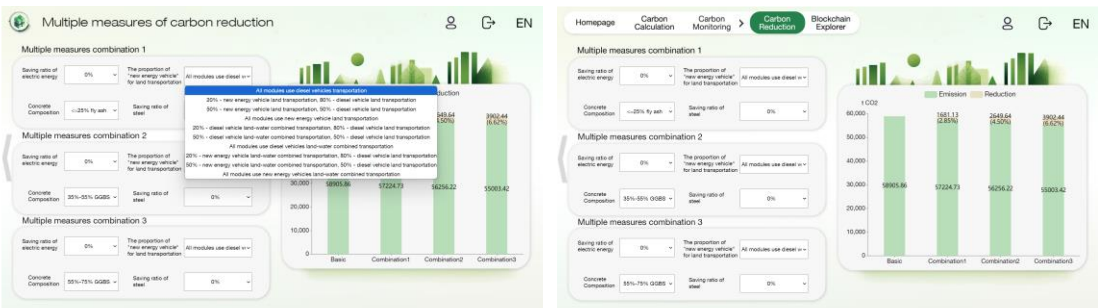

FIGURE 7. Carbon Reduction page

In addition, the platform has a blockchain explorer page to show the blockchain information (Figure 8). Users can view the details of each block and transaction.

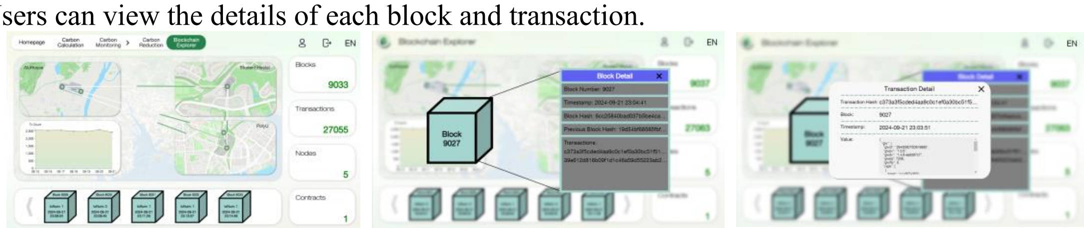

FIGURE 8. Blockchain Explorer page

4.4 Results

Through the web platform, stakeholders can analyze the CEs from different perspectives and get some inspiration for carbon reduction.

- From the material perspective, the percentage and specific quantity of CEs generated by each material can be observed clearly and respectively from the chart when a computer mouse is put on the pillars. Steel and concrete are the main contributors to the CEs among the calculated materials, accounting for nearly three times the amount produced by other supplies, especially regarding the building parts of the tower and substructure. The data could imply that contractors can utilize lower-carbon steel and concrete to achieve CE reduction (Figure 9).
- From the equipment perspective, the CEs of devices are displayed in three phases: factory production, transportation, and on-site installation. As for the transportation phase, CEs are generated by vehicles such as lorries and vessels. It would be an effective solution if more green energy vehicles could be used to transport materials and modules. In terms of the remaining two phases, machines such as cutting, bending, and cranes account for the total CEs calculated. Therefore, it is possible to reduce CEs if lower-power and lower-pollution machines are used on the prerequisite that average work efficiency is satisfied (Figure 10).
- From the perspective of the construction process, the author mentioned before that the whole process could be divided into factory production, transportation, and on-site installation. It is worth stating that factory production could be further separated into two phases, production and modularization, both undertaken in the factory. Between the two parts, the former refers to materials production and processing, and the latter means assembling the components into a module. Given that the above two phases are the main embodied carbon contributors, it is essential to improve factories' capacity to capture and process CEs (Figure 11).

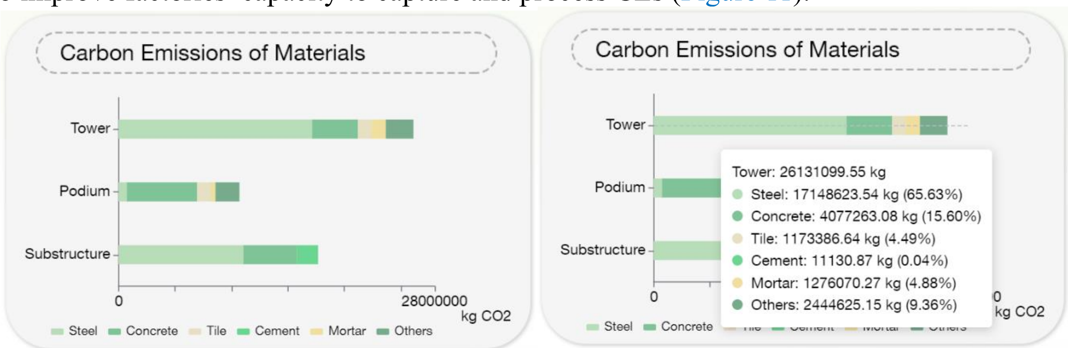

FIGURE 9. CEs of materials

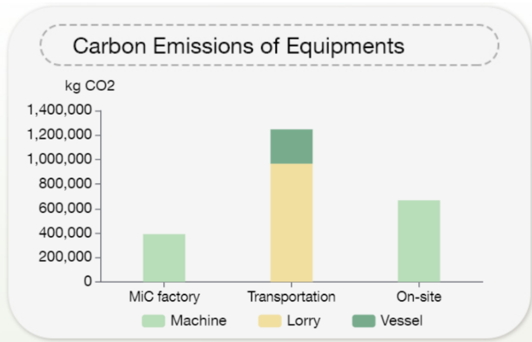

FIGURE 10. CEs of equipment

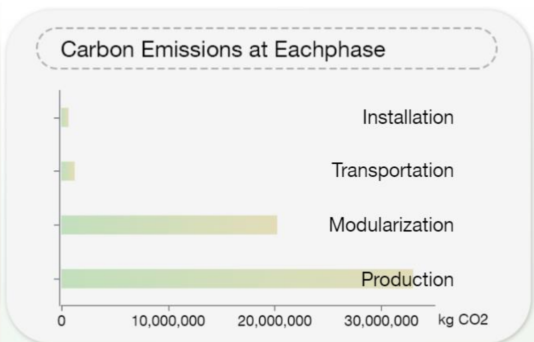

FIGURE 11. CEs at each phase

4.5 Discussion

This paper has proposed a novel system to monitor the embodied carbon of modular buildings based on IoT and blockchain, offering several advantages over existing methods. Traditional methods often rely on manual data collection, which is labor-intensive, error-prone, and lacks real-time accuracy. In contrast, our proposed system integrates IoT to automatically gather data, reducing inefficient labor work and significantly improving data accuracy and authenticity. Unlike conventional approaches, where data is collected intermittently, IoT sensors continuously monitor real-time parameters such as energy consumption, emission levels, and equipment operating status throughout construction. This continuous data stream enables stakeholders to proactively adjust ongoing activities if any deviation from the original plans occurs, a feature that traditional systems lack. Moreover, in existing systems, data storage and sharing often pose data security and integrity issues. Our system addresses these concerns by leveraging blockchain technology, ensuring data is securely stored, verified, and immutable. This adds a layer of transparency and trust often missing in conventional methods. The blockchain's decentralized nature also reduces the risk of data tampering, further enhancing system reliability.

Despite some of the merits mentioned above, some challenges and limitations remain. Firstly, any new approach waits for time to prove its validity. Thus, testing the novel system and presenting its fruits to stakeholders takes time. Additionally, such a complex IoT-blockchain integrated system will be opposed by interested parties who are used to the traditional ways of monitoring. Therefore, bringing about change and ensuring that users adopt it involves much change management and heavy training and communication with all users. Secondly, the investment costs in implementing an integrated IoT and blockchain system for monitoring CEs are high, ranging from hardware, IoT sensors, network infrastructure, blockchain platforms, and software development. This also means that there will be a significant cost associated with maintenance, data storage, and updating, which again will work against smaller construction companies. Thirdly, it is essential to clarify the ownership, governance, and access to the data within a blockchain network for trust and transparency to be well established among stakeholders. The issue of who controls, shares, and uses data becomes complicated, further complicating the system's governance framework. Despite the above challenges, the system still throws light on monitoring embodied CEs more efficiently and accurately.

5. CONCLUSION

This study proposes an embodied carbon monitoring system for modular buildings based on IoT and blockchain technologies to realize real-time monitoring of CEs during construction. This enables managers to observe CEs in real-time, compare them with the plan, and promptly control the CEs of the construction process. Specifically, IoT sensors are utilized to automatically obtain data related to equipment operation, vehicle transportation, and other relevant data to calculate CEs through the LCA method. The underlying blockchain deploys the Hyperledger Fabric framework to record the data and calculation results at each stage of the construction process, ensuring data transparency, security, and traceability. In addition, a web platform is developed to display the real-time CEs at each stage of the construction process so that managers can compare the actual CEs with the expected plan, identify problems, and make adjustments promptly. The feasibility of the system will also be verified by using the student hostel construction project of the Hong Kong Polytechnic University as a real case study. The results show that the system can effectively and automatically collect data on equipment operation and vehicle transportation at various stages of the building construction process and fully satisfy the diversified data needs of different users (e.g., contractors and managers). In summary, the modular building embodied carbon monitoring system developed in this study utilizes the automated data collection function of IoT sensors and the distributed structure and consensus mechanism of blockchain to satisfy the demand for real-time, transparent, and traceable information, which can practically help stakeholders to monitor and manage CEs during the construction process. The system provides valuable theoretical and practical demonstrations for embodied carbon monitoring in construction.

REFERENCES

Arsiwala, A. et al. (2023) Digital twin with Machine learning for predictive monitoring of CO2 equivalent from existing buildings. *Energy and buildings*. [Online] 284112851-.

Chen, L. et al. (2023) Green construction for low-carbon cities: a review. *Environmental chemistry letters*. [Online] 21 (3), 1627–1657.

Chung, W. et al. (2023) *IoT-based application for construction site safety monitoring*. Taylor & Francis.

Crawford, R. (2011) *Life cycle assessment in the built environment*. London; Spon Press.

Crawford, R. H. et al. (2018) Hybrid life cycle inventory methods – A review. *Journal of cleaner production*. [Online] 1721273–1288.

Hu, M. (2023) A look at residential building stock in the United States - mapping life cycle embodied carbon emissions and other environmental impact. *Sustainable cities and society*. [Online] 89104333-.

Huang, D. et al. (2020) Performance Analysis of the Raft Consensus Algorithm for Private Blockchains. *IEEE transactions on systems, man, and cybernetics. Systems*. [Online] 50 (1), 172–181.

Loo, B. P. Y. et al. (2023) Environmental comparative case studies on modular integrated construction and cast-in-situ construction methods. *Journal of cleaner production*. [Online] 428139303-.

Luo, X. et al. (2022) Life cycle assessment for carbon emission impact analysis for the renovation of old residential areas. *Journal of cleaner production*. [Online] 367132930-.

Luo, Y. et al. (2024) Supporting building life cycle carbon monitoring, reporting and verification: A traceable and immutable blockchain-empowered information management system and application in Hong Kong. *Resources, conservation and recycling*. [Online] 208107736-.

Lyu, F. et al. (2022) Comparative analysis about carbon emission of precast pile and cast-in-situ pile. *Energy reports*. [Online] 8514–525.

Shen Geoffrey Q. P et al. (2018) 'Real-Time Carbon Emissions Monitoring Tool for Prefabricated Construction: An IoT-Based System Framework', in *ICCREM 2018 - Sustainable Construction and Prefabrication*. American Society of Civil Engineers (ASCE). pp. 1–1.

Mattila, T. J. (2017) 'Use of Input–Output Analysis in LCA', in *Life Cycle Assessment*. [Online]. Switzerland: Springer International Publishing AG. pp. 349–372.

Rodrigo, M. et al. (2020) Potential Application of Blockchain Technology for Embodied Carbon Estimating in Construction Supply Chains. *Buildings (Basel)*. [Online] 10 (8), 140-.

Sadawi, A. A. et al. (2021) A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. *Technological forecasting & social change*. [Online] 173121124-.

Shu, Z. et al. (2022) Blockchain-enhanced trading systems for construction industry to control carbon emissions. *Clean technologies and environmental policy*. [Online] 24 (6), 1851–1870.

Tao, X. et al. (2018) Greenhouse gas emission monitoring system for manufacturing prefabricated components. *Automation in construction*. [Online] 93361–374.

UNEP. (2022). *2022 Global Status Report for Buildings and Construction*.

Wang, J. (2017) *BLOCKBENCH: A Framework for Analyzing Private Blockchains*. ProQuest Dissertations & Theses.

Whitmore, A. et al. (2015) The Internet of Things—A survey of topics and trends. *Information systems frontiers*. [Online] 17 (2), 261–274.

Wu, H. et al. (2023) Blockchain-Based On-Site Activity Management for Smart Construction Process Quality Traceability. *IEEE internet of things journal*. [Online] 1–1.

Xu, J. et al. (2023) Integrating IoT and BIM for tracking and visualising embodied carbon of prefabricated buildings. *Building and environment*. [Online] 242110492-.

Yang, R. et al. (2020) Public and private blockchain in construction business process and information integration. *Automation in construction*. [Online] 118103276-.

Zhou, F. et al. (2023) Analyze Differences in Carbon Emissions from Traditional and Prefabricated Buildings Combining the Life Cycle. *Buildings (Basel)*. [Online] 13 (4), 874-.