Efficient embodied carbon assessment and tracking using openBIM and blockchain

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Abstract
In light of the escalating emphasis on environmental stewardship, carbon management has emerged as a pivotal element in the construction industry. However, carbon emission information is often accompanied by cross-department information exchange needs, and the secure and accurate management of its data is still difficult. Therefore, this paper proposes an IFC-based embodied carbon assessment and tracking framework using blockchain to provide carbon management. This framework encompasses the IFC-based carbon emission information supplement and checking, coupled with developing a smart contract. It facilitates accurate collection of embodied carbon, grounded in BIM, across the Life Cycle Assessment (LCA) stages A1-A5, while simultaneously safeguarding model correctness and data traceability. The practicality of this framework has been substantiated through a designed derived scenario from OPARK2 in Hong Kong, with its utility corroborated by illustrating both the projected and actual embodied carbon emissions of the construction project in question.

Keywords: Embodied carbon, Life cycle assessment (LCA), Blockchain, Smart Contract, Industry Foundation Classes (IFC), Construction

1 Introduction
The urgency of managing carbon emissions in construction projects has intensified, particularly following the Paris Agreement and the enactment of carbon regulations by governmental bodies. The AEC industry is now recognized as a substantial contributor to carbon emissions, with the United Nations Environment Programme projecting that 34% of global greenhouse gas emissions in 2022 were originated from this sector (2024). As an important part of carbon emissions, the management of embodied carbon emissions from projects has also become one of the research priorities. According to Huang et al. (2018) 94% of carbon emissions from the construction sector in 2009 came from indirect carbon emissions. It comes from the carbon emissions generated

before the building is put into use. In order to manage and control the embodied carbon emission of buildings, extensive research was conducted (Pan and Teng, 2021). More refined assessment methods are analyzed. Meanwhile, the statistics and analysis of embodied carbon for infrastructures also provide policy recommendations for the government (Ge *et al.*, 2023). Despite these advancements, the construction industry still lacks a comprehensive and accurate carbon emission management system, with the complexity of emission sources and the inefficiency of manual calculations contributing to increased labor costs.

Building Information Modeling (BIM) is pivotal in the digital transformation of the construction industry, serving as a collaborative digital foundation across design, construction, and management phases. It enables interdisciplinary teams to work cohesively through BIM's structured data. Research has advanced BIM's utility in managing building information, exemplified by automated carbon emission management for prefabricated buildings (Xu *et al.*, 2022), and early design carbon emission analysis(Alwan and Ilhan Jones, 2022). Furthermore, BIM facilitates multi-party collaborative assessments of embodied carbon emissions in construction projects. These advancements bolster practitioners' comprehension of carbon management within construction. As carbon management policies evolve, so do the demands on design and construction teams' capabilities. Consequently, providing the carbon emission audit department with comprehensive, precise, and verifiable data remains a complex challenge.

In construction projects, the use of materials, operation of machinery, and personnel will produce carbon emissions. To reduce carbon emissions from construction, researchers have made efforts in many aspects, such as the development of low-carbon building materials (Lippiatt, Ling and Pan, 2020) and the control of carbon emission behaviors (Luo and Chen, 2020). Accurate statistics of carbon emissions from construction are a necessary condition for reducing them. The gap between the actual building materials usage in the construction site and the final carbon emissions sequestered by the building is inevitable. Accurate collection of this information can assist construction project managers in controlling material utilization and waste, further reducing the overall amount of embodied carbon produced. As a design, construction and information management platform in construction projects, BIM can provide the basis for carbon emission collection. However, existing BIM programs have barriers to non-related professional practitioners. Within the sphere of construction design, beyond the prevalent use of BIM platforms, Industry Foundation Classes (IFC) emerge as a streamlined and rapid collaborative format (Khudhair, Li and Ren, 2023). IFC's forte lies in its centralized repository for diverse engineering data, facilitating the exact alignment of information with BIM components and enhancing the efficacy of data retrieval. Moreover, its standardized and intuitive approach allows for swift data location and entry on-site for non-civil engineering professionals. These benefits position IFC as a straightforward mechanism for the authentic documentation of carbon emissions, including material transport and construction activities.

Meanwhile, because this carbon emission-related information contains a lot of content that needs to be securely recorded and traced, how to safely manage this content is also a research focus. Blockchain technology, as a decentralized transaction and data management technology, is a potential solution (Tao *et al.*, 2023). In the blockchain, this information is stored in each block, as shown in Figure 1. Each time (or several times) information is submitted or a transaction is performed, a new block will be generated. These blocks are linked in chronological order to form a chain. It is stored in all servers participating in the platform and this information can be mutually verified. Modifying any data will cause the block to be unable to be connected to other blocks, and tampering with the stored content will result in unacceptable computational costs. Overall, in the blockchain system, the consensus mechanism ensures the consistency of information, and the special structure makes the data difficult to tamper with. These characteristics give the blockchain system the advantages of data being difficult to tamper with and being decentralized. The AEC industry has also taken advantage of these advantages. For example, Tao et al. (2021) proposed a distributed data environment for secure collaboration of

BIM. In terms of file management, a secure blockchain management framework has also been proposed (Das *et al.*, 2022). Blockchain technology also helps in building sustainable development (Gong *et al.*, 2024). These studies demonstrate the benefits of blockchain for securely managing data in construction projects.

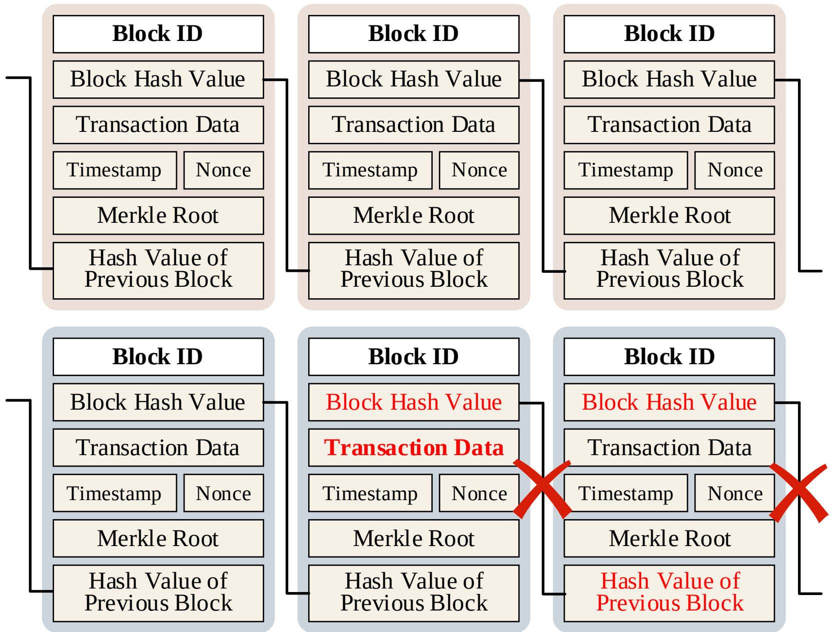


Figure 1. Blockchain Structure

Building embodied carbon information statistics and management based on blockchain can effectively provide secure and traceable data. Therefore, this paper designs an IFC-based construction embodied carbon emission assessment and tracking framework using blockchain to conduct comprehensive embodied carbon management of construction projects. Three objectives of the development in the framework are:

(1) **To propose a construction embodied carbon assessment and tracking framework.** Supplement carbon emission information to BIM through multiple departments to achieve the final carbon assessment. In this section the workflow of the framework will be designed.

(2) **To build an embodied carbon data enrichment and check approach for IFC.** In order to ensure that the uploaded IFC files can be used for final carbon emission data assessment, this paper will improve the BIM-based information supplement and inspection scheme. This step is to ensure the integrity of the information.

(3) **To develop smart contract to support the operation of blockchain system.** The blockchain system uploads and downloads information on the chain through smart contract. Technical component for the operation of the carbon emissions assessment framework will be developed.

The remainder of this paper is structured as follows: Section 2 introduces the framework for construction embodied carbon assessment and tracking. BIM data enrichment approach will be elaborated on in Section 3. Section 4 is the smart contract development, and Section 5 is the validation. Section 6 is the conclusion.

2 Construction Embodied Carbon Assessment and Tracking Framework

The proposed framework will be divided into four parts as shown in Figure 2. In the first part, information related to carbon emissions will be provided. Suppliers need to provide the types of materials used in construction and corresponding emission factors. This information will be directly used in the calculation of building carbon emissions. Supplier data and shipping warehouse locations also need to be provided, which can calculate the distance taken by the shipment through accurate data from openGIS. By identifying transportation methods and transportation distances, it becomes possible to accurately quantify the carbon emissions generated during transportation. On the other hand, contractors also need to provide information on energy usage within the construction site. It includes fuel, electricity and other related information.

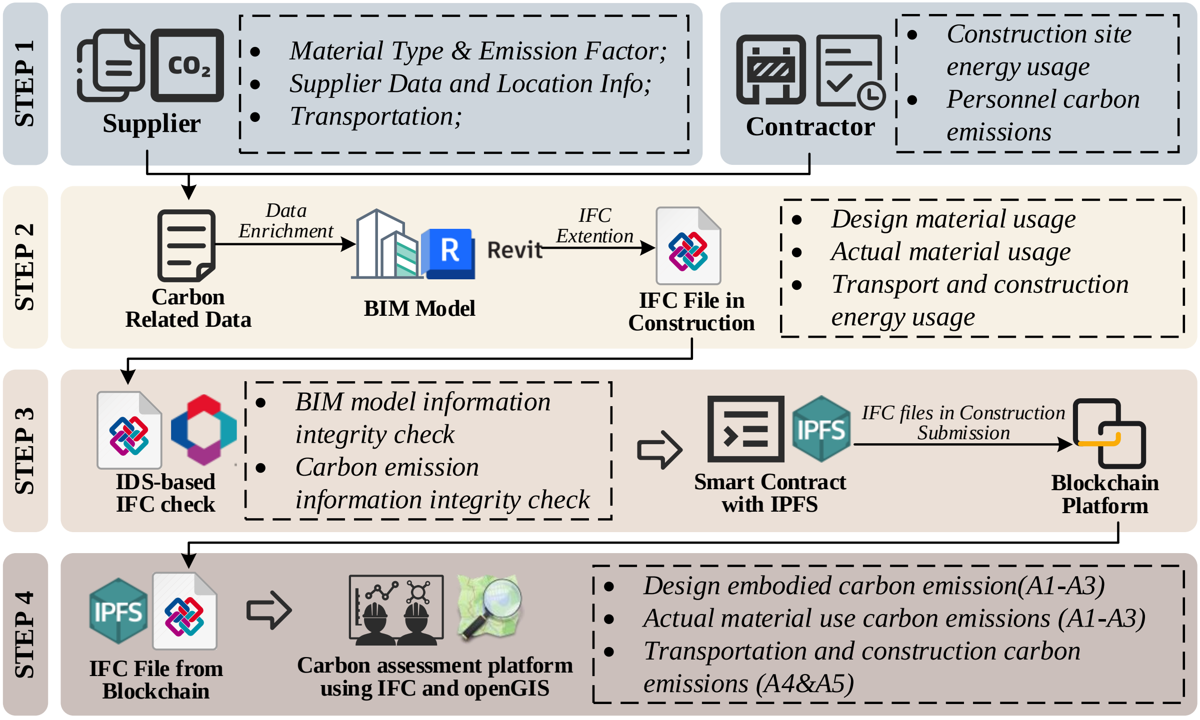
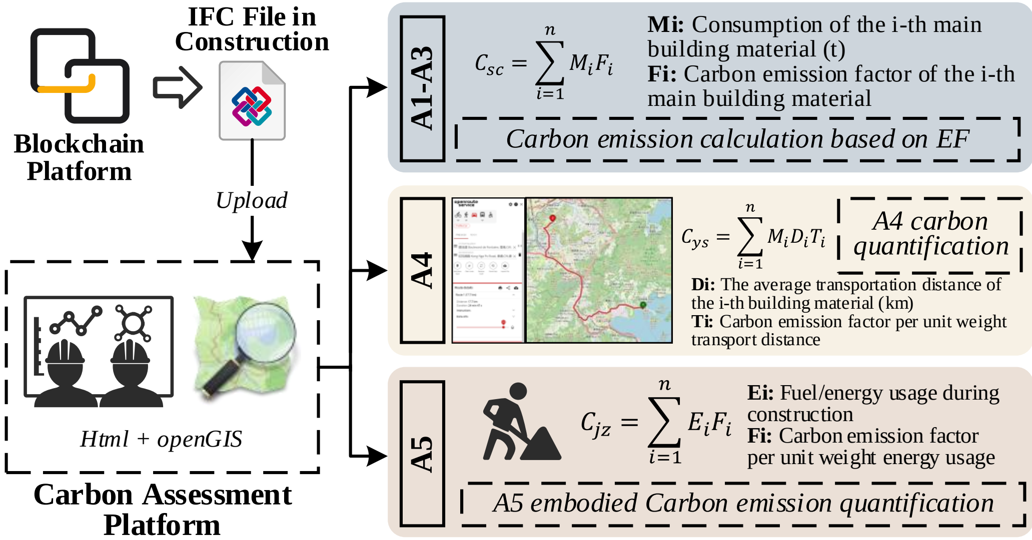


Figure 2. Construction Embodied Carbon Emission Assessment and Tracking Framework

In the second part the information related to embodied carbon will be enriched in the BIM model. Using component data in the model, precise material usage can be calculated. In addition, the actual consumed material data can be called in the model. Through such steps, a data basis is provided for comparison and management of the theoretical solidified carbon emissions of buildings and the carbon emissions of actual materials. In the third part, the enriched IFC files will be checked by the designed Information Delivery Specification (IDS) rules. The purpose of this inspection is to ensure the integrity of the carbon emission information of the construction project so that the final carbon emission assessment is accurate. The IFC files that pass the inspection will be uploaded to the blockchain system by the smart contract. The blockchain framework used in this article is Hyperledger Fabric 1.4. As a stable blockchain platform, in addition to maintaining a distributed structure, it ensures that data is shared only with the relevant parties with whom the user wants to share data. At the same time, it is very convenient for customization according to different needs.

In the final step, the BIM model downloaded through the smart contract will be processed by the developed carbon assessment platform, as shown in Figure 3. It mainly quantifies three aspects of information: (1) Designed embodied carbon emission in A1-A3 stage, which comes from the material itself, the process from raw materials to building materials; (2) Actual embodied carbon emission in A1-A3, this information comes from The total number of building materials provided to the construction site by the supply chain; (3) A4 transportation and A5 construction, this information comes from the GIS data provided by the supplier and the energy consumption information provided by the contractor respectively.



$$C_{sc} = \sum_{i=1}^{n} M_i F_i$$

$$C_{ys} = \sum_{i=1}^{n} M_i D_i T_i$$

$$C_{jz} = \sum_{i=1}^{n} E_i F_i$$

Figure 3. Embodied Carbon Emission Quantification Method

3 Embodied Carbon Data Enrichment and Check Approach

In order to ensure the integrity of the BIM model information and adapt it to the requirements of the carbon emission management framework, we designed an information supplement method for embodied carbon. As shown in Figure 4, it consists of two parts. The first is the supplement of information, which is implemented in two data supplement methods, namely based on Dynamo method and based on IFC extension algorithm. Depending on the situation on site, different methods can be adopted on site.

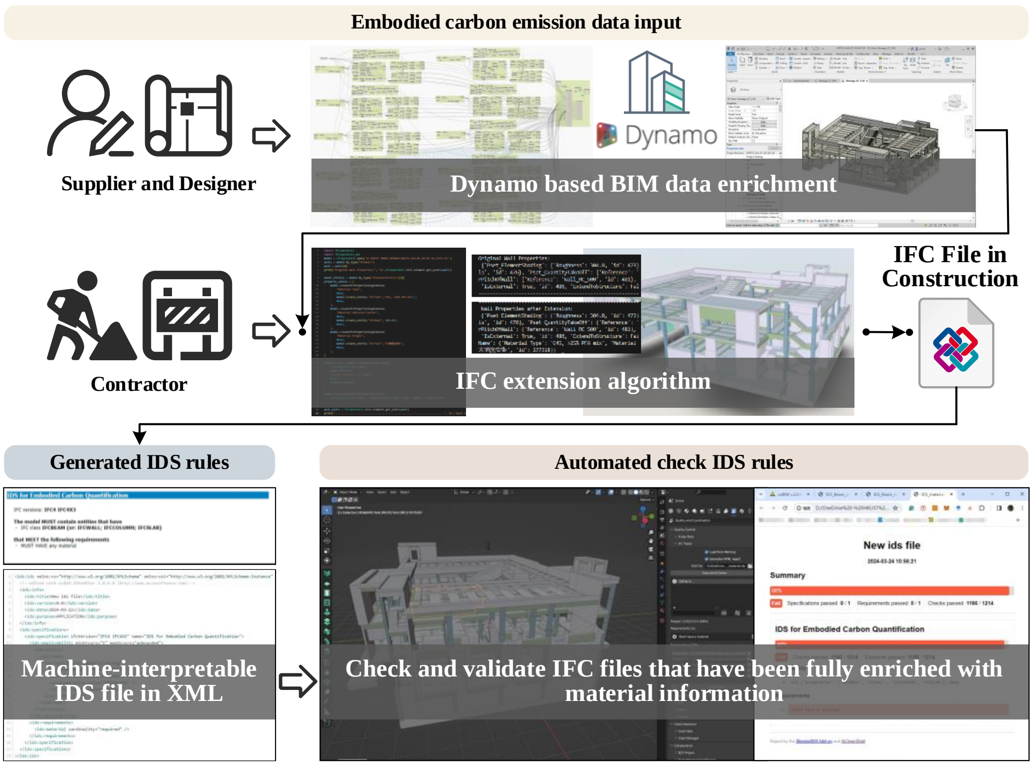


Figure 4. Embodied Carbon Data Enrichment Approach for IFC

The second part is the inspection of the integrity of BIM information. ISO 29481 IDM defines how to use things such as exchange requirements and process maps to clarify the information required for BIM (Jeon *et al.*, 2021). This paper designs two rules for checking IFC files: (1) model basic information integrity, and (2) carbon emission information integrity. Through the IDS rules generated by this paper, the missing information of the model can be highlighted in the HTML interface. Models that pass the inspection will be placed in the blockchain system for future management and analysis.

4 Smart Contract for Blockchain Development

In order to implement the information upload and query functions in the framework, this paper designed a smart contract based on the GO language. It can query all information uploaded to the blockchain system. Due to the limitations of the blockchain structure, each block cannot store large data. Therefore, before the smart contract is run, the IFC files that need to be uploaded will be uploaded to the InterPlanetary File System (IPFS). IPFS is a distributed web, point-to-point hypermedia protocol. It can store files distributedly on the network and only need to obtain them through a hash value (CID in IPFS). This allows the blockchain system to store only a hash value, allowing users to obtain large files that would not otherwise be stored.

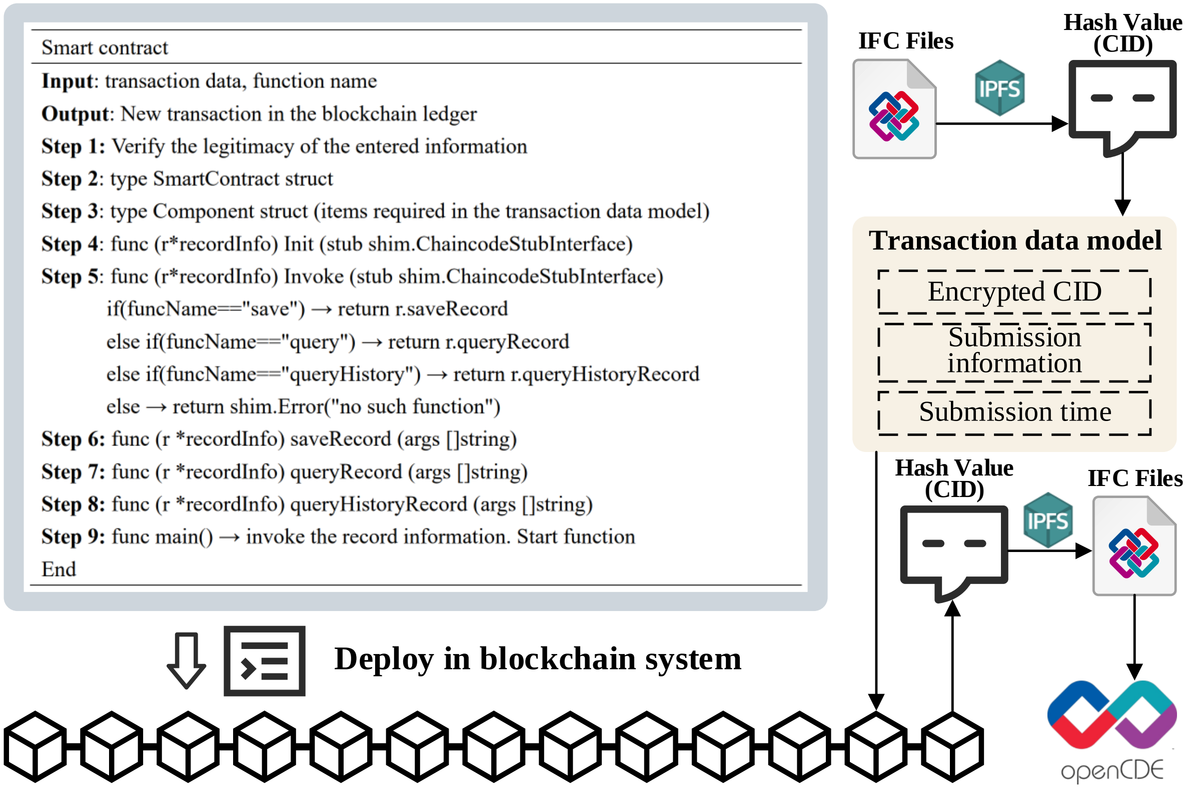


Figure 5. Smart Contract Development

In addition to uploading the hash value of the IFC file, the user will also be asked to enter other information, such as the construction time period of the model, the name of the project manager and the upload time. This information will not be directly used in the final carbon emissions assessment, but it will help users more quickly confirm the construction part represented by the IFC file, especially after it is displayed as a hash value in the blockchain.

5 Proof of concept

After completing the establishment of the entire framework, we evaluated the embodied carbon assessment method proposed in this paper. The designed verification scenario is based on the Hong Kong organic resources recovery center phase 2 (O·PARK2), an organic resource recovery center project covering an area of two hectares. First, the supplier provides material information and openGIS-based material transportation information to the construction site. In this design scenario, the concrete materials are C45 30% PFA and C20 45% GGBS, the steel bars are general rebar, and reused formwork is used. The emission factors of these materials come from the Hong Kong local database (2024). For the transportation of construction materials, the coordinates of the transportation origin of the material are provided. Through the openGIS platform, an automatic material transportation route was calculated, with a transportation distance of 17.7

kilometers. Contractors also provide mechanical operation information at the construction site into the BIM model. After completing the enrichment of all information, the file is checked by the developed IDS. BIM files that pass the inspection are uploaded to the blockchain system. The carbon emission management department obtains these files through the blockchain integrated with IPFS and submits the content to the developed platform.

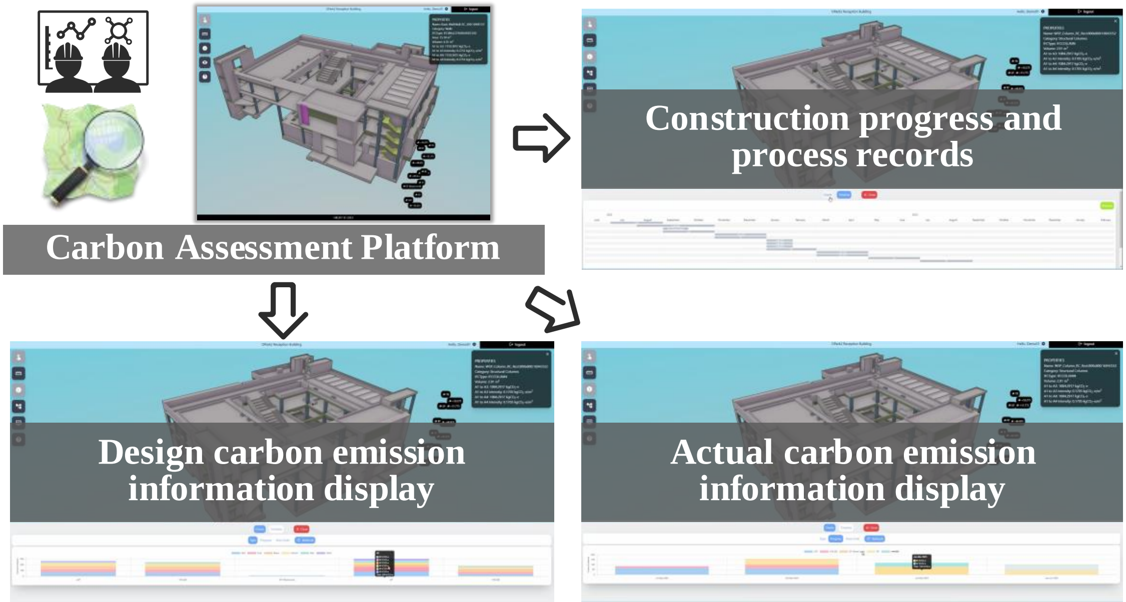


Figure 6. Framework Verification Result

As shown in Figure 6, the developed framework can display three parts: (1) Construction progress, which is the information display contained in IFCs submitted at different frequencies; (2) Design carbon emission, this part is extracted from the BIM model The component information is calculated, and the coefficient of the corresponding material is calculated to show the part of carbon emission solidification; (3) Actual carbon emission, this part counts the actual construction site material usage information submitted by contractors and suppliers, and calculates the corresponding carbon emissions. The carbon emission results of this design scenario are shown in Table 1. The carbon emission visualization results are shown in Figure 7.

Table 1. OPark2 Construction Project Embodied Carbon Emission Result

Material Type	Design Carbon A1-A3 (kgCO2)	Actual Carbon A1-A3 (kgCO2)	A4 Carbon (kgCO2e)	A5 Carbon (kgCO2e)
Concrete	2583941.34	4181134.85	342379.54	
Rebar	4017733.86	9073473.04	532361.11	453951.13
Formwork	78972.21	164530.44	10464.04	
Summary	6680647.41	13419133.30	885204.69	453951.13
Design Embodied Carbon Emission	A1-A4 (kgCO2e)			7565852.10
	A1-A5 (kgCO2e)			8019803.23
Actual Embodied Carbon Emission	A1-A4 (kgCO2e)			14304338.01
	A1-A5 (kgCO2e)			14758289.12

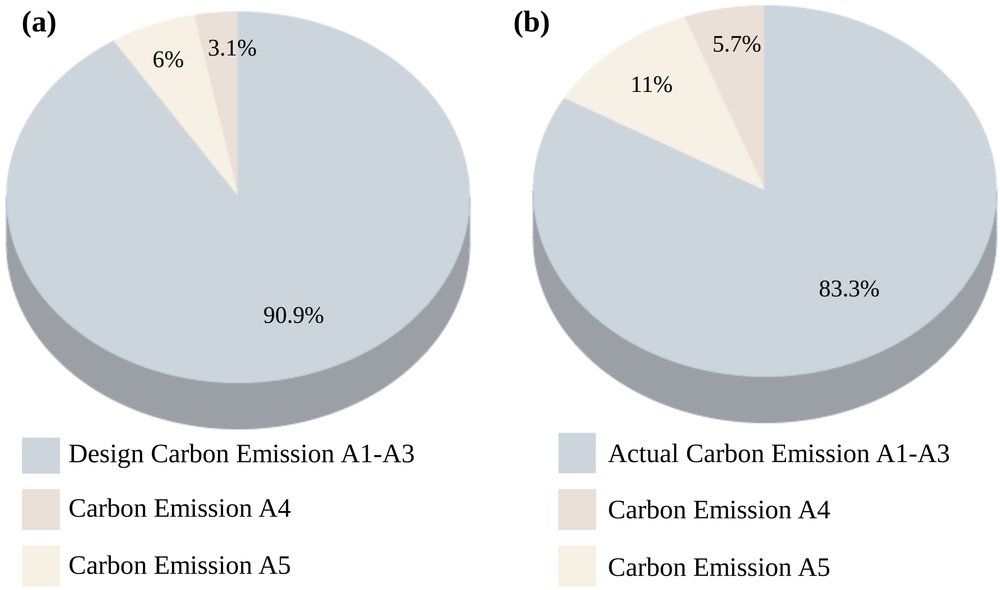


Figure 7. Visualization of Embodied Carbon Results of OPark2 Construction Project: (a) Embodied Carbon of Design Stage; and (b) Embodied Carbon of Actual Construction

The amounts of LCA A1-A3, A4 and A5 of the project's embodied carbon emission are counted. The actual carbon emission part is constructed from the data in the BIM model, and its value comes from the material procurement and usage during part of the actual construction process. According to the statistics of the platform, the material itself (A1-A3) accounts for 83.3% of the total embodied carbon emission. The carbon emissions in the A4 and A5 stages account for 11.03% and 5.6% of the total carbon emissions respectively. According to the data displayed on the platform, construction project managers can control the carbon emission information of the building. The operation of the framework has been verified through simulation scenarios.

6 Conclusion

The AEC industry's embodied carbon emission management has garnered significant attention. however, the integration of data and accurate information collection within the intricate construction process has seen limited advancement. Additionally, the data security management for the complex sources of carbon emission data remains underexplored. Addressing these gaps, this paper proposed an IFC-based construction embodied carbon assessment and tracking framework using blockchain. Three of these objectives have been implemented. First, the workflow of the developed framework is proposed, and the source and key content of the information are identified. Secondly, an embodied carbon data enrichment and check approach for IFC is built. Thirdly, a smart contract is developed to facilitate the blockchain system's operations. The framework was verified and evaluated in design scenarios. And reasonable results were obtained in terms of feasibility. One limitation is that the design's rules are not comprehensive enough for complex real-world construction. Future work will focus on designing a carbon emission management system based on digital twins, enhancing carbon emission analysis to adapt to complex construction environments and diverse project scenarios, and realizing a collaborative update mechanism between BIM models and actual project progress.

References

Alwan, Z. and Ilhan Jones, B. (2022) 'IFC-based embodied carbon benchmarking for early design analysis', *Automation in Construction*, 142, p. 104505. Available at: https://doi.org/10.1016/j.autcon.2022.104505.

Construction Industry Council Hong Kong (2024) 'CIC Carbon Assessment Tool'. Available at: https://cat.cic.hk/.

Das, M. *et al.* (2022) 'A blockchain-based integrated document management framework for construction applications', *Automation in Construction*, 133, p. 104001. Available at: https://doi.org/10.1016/j.autcon.2021.104001.

Ge, Z. *et al.* (2023) 'Embodied carbon emissions induced by the construction of hydropower infrastructure in China', *Energy Policy*, 173, p. 113404. Available at: https://doi.org/10.1016/j.enpol.2022.113404.

Gong, X. *et al.* (2024) 'Secure Environmental, Social, and Governance (ESG) Data Management for Construction Projects Using Blockchain', *Sustainable Cities and Society*, p. 105582. Available at: https://doi.org/10.1016/j.scs.2024.105582.

Huang, L. *et al.* (2018) 'Carbon emission of global construction sector', *Renewable and Sustainable Energy Reviews*, 81, pp. 1906–1916. Available at: https://doi.org/10.1016/j.rser.2017.06.001.

Jeon, K. *et al.* (2021) 'A relational framework for smart information delivery manual (IDM) specifications', *Advanced Engineering Informatics*, 49, p. 101319. Available at: https://doi.org/10.1016/j.aei.2021.101319.

Khudhair, A., Li, H. and Ren, G. (2023) 'Knowledge-based OpenBIM data exchange for building design', *Automation in Construction*, 156, p. 105144. Available at: https://doi.org/10.1016/j.autcon.2023.105144.

Lippiatt, N., Ling, T.-C. and Pan, S.-Y. (2020) 'Towards carbon-neutral construction materials: Carbonation of cement-based materials and the future perspective', *Journal of Building Engineering*, 28, p. 101062. Available at: https://doi.org/10.1016/j.jobe.2019.101062.

Luo, L. and Chen, Y. (2020) 'Carbon emission energy management analysis of LCA-Based fabricated building construction', *Sustainable Computing: Informatics and Systems*, 27, p. 100405. Available at: https://doi.org/10.1016/j.suscom.2020.100405.

Pan, W. and Teng, Y. (2021) 'A systematic investigation into the methodological variables of embodied carbon assessment of buildings', *Renewable and Sustainable Energy Reviews*, 141, p. 110840. Available at: https://doi.org/10.1016/j.rser.2021.110840.

Tao, X. *et al.* (2021) 'Distributed common data environment using blockchain and Interplanetary File System for secure BIM-based collaborative design', *Automation in Construction*, 130, p. 103851. Available at: https://doi.org/10.1016/j.autcon.2021.103851.

Tao, X. *et al.* (2023) 'Enhancing BIM security in emergency construction projects using lightweight blockchain-as-a-service', *Automation in Construction*, 150, p. 104846. Available at: https://doi.org/10.1016/j.autcon.2023.104846.

United Nations Environment Programme (2024) *2023 Global Status Report for Buildings and Construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector*. United Nations Environment Programme. Available at: https://doi.org/10.59117/20.500.11822/45095.

Xu, J. *et al.* (2022) 'BIM-integrated LCA to automate embodied carbon assessment of prefabricated buildings', *Journal of Cleaner Production*, 374, p. 133894. Available at: https://doi.org/10.1016/j.jclepro.2022.133894.