

A BLOCKCHAIN-BASED APPROACH FOR EMBODIED CARBON MANAGEMENT ALONG THE CONSTRUCTION SUPPLY CHAIN

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Abstract

Blockchain offers a potential solution to enhance transparency and trackability in carbon management, but limited research exists on its implementation in the construction industry. This study proposes a blockchain-based approach for transparent and trackable carbon management in the construction supply chain to address concerns regarding data quality and confidentiality. A system was developed comprising off-chain carbon management and on-chain (public blockchain) storage, with technical highlights of: role-based access control for functionality, hierarchical hashing strategy for validation, and selective data disclosure before on-chain. The research's contributions include enhancing data quality and traceability for carbon assessments.

Introduction

The construction industry significantly influences global carbon emissions due to its energy-intensive processes, use of materials, and the operation of buildings (Sizirici et al., 2021). Carbon emissions from the construction supply chain, referred to as upfront embodied carbon, are estimated to account for around 30% of construction projects' whole life cycle carbon emissions (Gan et al., 2017). Therefore, how to manage and reduce carbon emissions from construction supply chains has become an urgent task in the construction industry. Although many practices and studies have been implemented to manage carbon emissions at the specific stage of the construction supply chains, it is still difficult to track carbon footprints along the supply chain. For one thing, the fragmentation of supply chains makes it difficult to gather consistent and accurate data on carbon emissions from each stage of the supply chain among multiple tiers of suppliers and subcontractors (Hijazi et al., 2021). For another, considering the wide scope of carbon emission data required during carbon assessment and tracking, stakeholders may find it difficult to access (Lai et al., 2023). In that case, the data transparency is very limited both for internal carbon management along the construction supply chain and external supervision for sustainability disclosure, which hampers the ability to track carbon footprints effectively.

As a promising technology, blockchain offers a possible and effective solution for the insufficient transparency and low trackability problems during carbon management along the construction supply chain (Turk et al., 2017). Blockchain technology is a decentralized and distributed ledger system that allows multiple parties to maintain a shared database without the need for a central authority. It

is a chain of blocks, where each block contains a list of transactions or data (Hunhevicz et al., 2020). These blocks are linked together using cryptographic hashes, creating an immutable and transparent record of all transactions or data entries (Tao et al., 2022). With the help of blockchain, problems such as fragmentation, inefficient data-sharing, insufficient data transparency, and poor data trackability have been solved in many construction scenarios. Existing studies have explored blockchain's capability and feasibility in various construction scenarios, including construction payment transactions, construction information-sharing and collaboration during multiple project stages, and governmental supervision of construction work (Xu et al., 2023). However, there is limited research in the field of blockchain-based carbon management along the construction supply chain, especially focusing on the whole supply chain lifecycle and how to motivate all stakeholders to participate in such an innovative approach. During the interviews, it was noted that other challenges include concerns regarding data quality and sensitive information. Therefore, the two research questions in this research are:

- (1) How can blockchain technology integrate with carbon management along the whole construction supply chain?
- (2) How can carbon data quality and privacy be enhanced in the blockchain-based carbon management system?

This study aims to propose a blockchain-based approach for transparent and trackable carbon management along the construction supply chain for all stakeholders (suppliers, contractors, architects, and developers of the construction project) by developing a blockchain-based carbon management system. This approach covers all stages that will produce carbon emissions in construction supply chains (from material processing, transportation, and on-site construction activities), which is consistent with the A1 to A5 stages from the life cycle assessment identified in international standards.

Related work

Carbon management in the construction supply chain

Carbon emissions from the construction supply chain, referred to as upfront embodied carbon, are estimated to account for around 30% of construction projects' whole life cycle carbon emissions. Under the urgent trends of global carbon reduction, the importance of carbon management in construction supply chains is increasingly recognized.

A range of international standards have been developed and can be applied to assess and manage carbon emissions

in the construction industry, including carbon assessment and management in construction supply chains. The European standard, EN 15978, is commonly recognized for the assessment of the environmental performance of new and existing buildings based on a life cycle approach. This standard specifies the calculation method and multiple carbon calculation stages based on Life Cycle Assessment (LCA) and other quantified environmental information based on the building level. Especially, A1 to A5 stages of product sourcing and construction stage identified in EN 15978 help assess carbon emissions from the construction supply chains, including sourcing, transportation, fabrication, and construction of all materials and products (British Standards Institution, 2011).

Moreover, multiple carbon certification schemes for construction materials and products have also been implemented in the construction industry, targeting to control and reduce carbon emissions at the start of construction supply chain management (A1 to A3 stages). For instance, the carbon reduction label managed by the Carbon Trust in the UK is one of the earliest certification schemes in the world. Under this scheme, organizations are required to report environmental claims and detailed carbon-proof data to get the certified label of products. Similar practices can also be found in The Singapore Green Building Product Certification (SGBPC), and the Construction Industry Council (CIC) Green Product Certification scheme in Hong Kong.

In academia, how to manage and reduce carbon emissions in construction supply chains to realize a green supply chain and improve its sustainability is also a hot topic. There are various research categories in the existing papers about carbon management in construction supply chains, including (1) green purchasing and procurement, (2) low-carbon design and manufacturing of construction materials and products, (3) green logistics, and (4) construction waste management. Green purchasing and procurement mainly focus on evaluation schemes and strategies for material and product selection along the construction supply chains. Bagul et al. developed a sustainable sourcing strategy for mega-construction projects using the analytic hierarchy process (AHP) technique and a multi-objective Goal Programming (GP) model, which has also been verified using a single construction megaproject case (Bagul et al., 2023). In the field of low-carbon design and manufacturing of construction materials and products, studies are focusing on how to design environmentally friendly construction materials and limit resource consumption during the production process of construction materials and products. For instance, Yang et al. developed a low-carbon design of an Ultra-High Performance Concrete (UHPC) by incorporating high-volume phosphorous slag (PS), which shows a promising approach to developing a cleaner building material with lower carbon footprints (Yang et al., 2019). Zheng et al. proposed a knowledge-based integrated product design framework to support low-carbon product development. Green logistics is another research field in carbon management

along the construction supply chains. It aims to reduce carbon emissions during the delivery process of construction materials and products (Zheng et al., 2021). Chen et al. integrated building information modeling (BIM) and web map service (WMS) for the source selection of sustainable construction materials to reduce carbon emissions during the delivery (Chen et al., 2019). The carbon management of the recycling process of the construction supply chain is also studied in existing studies. Wibowo et al. proposed a measurement model to analyze the carbon reduction performance of recycled materials to support sustainable construction (Wibowo et al., 2017).

Blockchain applications in the construction industry

Blockchain is one of the most prominent types of distributed ledger technology (DLT) that allows all transactions to broadcast and operate on a distributed peer-to-peer (P2P) network without a centralized administrator. It enables the secure and transparent recording of transactions and data. The blockchain transactions are first grouped together, validated by particular consensus mechanisms (e.g., Proof of Work, Proof of Stake) among all nodes, and finally added to a block in a specific order. Since the newly generated block links to the previous block by unique a hashing index, it is difficult to modify once a block is added (needs to modify all previous block indexes and value if want to change one block), which ensures the integrity and trackability of the recorded data (Scott et al., 2021). Currently, blockchain's capability and feasibility have been discussed and validated in various construction scenarios, including construction payment and procurement, information-sharing and collaboration, construction supply chain management (including construction carbon management), regulations and compliance, and contract management (Li et al., 2021 a).

For construction payment scenarios, blockchain-based payment systems can enable faster payments by eliminating intermediaries and self-executing smart contracts. A distributed blockchain-based framework that does not require trust to automatically enforce the terms and conditions related to interim payments was proposed by Das et al., aiming to facilitate payment transparency, enforce conditions of interim payments, and automatically record payment cycles (Das et al., 2020). Similarly, to avoid the risks and disputes caused by slow payments among construction stakeholders, an autonomous payment administration solution integrating blockchain-enabled smart contracts and robotic reality capture technologies was proposed by Hamledari et al., which can automatically transfer cryptocurrencies by smart contracts after finishing phased work (Hamledari et al., 2021).

Blockchain technology has also been applied in the single stage or multiple stages of construction projects, such as design, construction, and maintenance, for information sharing and stakeholder collaboration to enhance construction data transparency, reliability, and trackability. For example, a blockchain-based prototype system was

developed and evaluated to address the challenges of design liability control and information security during the construction design process (Pradeep et al., 2021). For the construction stage, a blockchain-based verification framework of adequate scaffolding was proposed for onsite inspections, aiming to make the onsite operations safer (Baek et al., 2020).

Among the above blockchain applications in the construction industry, blockchain-integrated construction supply chain management is one of the most popular research directions across multiple project stages. Recent studies have illustrated blockchain-enabled construction supply chain management via case studies. Wang et al. proposed a blockchain-based information management framework for precast supply chain information-sharing, real-time controlling, and status tracking, and a case study was used to validate the performance of the proposed framework (Wang et al., 2020). Moreover, Lu et al. developed a smart construction objects-enabled blockchain oracles framework to bridge the on-chain and off-chain worlds, which was examined in the context of off-site logistics and on-site assembly services (Lu et al., 2021). Some studies in this field also integrated blockchain with other digital technologies such as BIM and IoT to improve the performance of construction supply chains. For example, Wu et al. linked a permissioned blockchain to the Internet of Things (IoT)-BIM platform for off-site production management in modular construction by providing better information visibility, traceability, and a more collaborative working environment (Wu et al., 2022). For construction carbon management, blockchain's potential to facilitate carbon data transparency and traceability has been examined in both carbon quantification and assessment. Rodrigo et al. explored the potential application of blockchain for accurate embodied carbon estimation in construction supply chains and developed a data model for the blockchain-based embodied carbon estimator for construction (Rodrigo et al., 2020). Recent literature has developed several theoretical frameworks for blockchain-enabled carbon management. For instance, Wang et al. proposed a conceptual framework integrating blockchain, supply chain, and environmental performance, which suggests using blockchain to enhance supply chain management and reduce carbon emissions (Wang et al., 2020). A blockchain-based identification and coordination framework was designed by Wang et al. based on a specific multi-tier supply chain for sustainable supply chain management, aiming to ensure compliance with sustainability standards in construction supply chains (Wang et al., 2023). Liu et al. proposed a conceptual framework integrating blockchain as a carbon management tool to achieve transparent carbon footprint disclosure during product certification and supply chain management (Liu et al., 2019). Moreover, Xu et al., developed a more detailed and implementable blockchain-based framework for the embodied carbon certification of construction materials and products, which was validated via real certification cases (Xu et al., 2024).

Some other blockchain-based applications in the construction field can also be found in construction supervision (Li et al., 2021 c), and contract management for solving contract disputes and claims (Li et al., 2021 b). In summary, blockchain technology has already been implemented in many construction cases with different objectives, such as increasing data transparency, enhancing mutual trust, and facilitating tracking functionalities. However, existing blockchain-integrated research mainly based on less decentralized solutions without transparency to the public, and there is limited research about sufficient transparency and traceability of upfront embodied carbon management among all stakeholders along construction supply chains.

Methodology

The research methodology employed in this study is based on the Design Science Research (DSR) method, which facilitates problem-solving activities as depicted in Figure 1. The research problems and objectives were identified through an extensive literature review of existing studies on carbon management in construction supply chains and blockchain-based applications, as well as through interviews conducted with stakeholders across the construction supply chain. Once the research problems were identified, the system framework and workflow of the blockchain-based system were developed. This entailed creating a model diagram that showcases the key components and a process diagram that illustrates the system workflows among different stakeholders. Subsequently, a system prototype was developed, tested, and demonstrated through a real-life case study, enabling the recording and tracking of carbon footprints along the construction supply chain. The final two steps of this study involve the evaluation of the system and its practical assessment through communication with relevant stakeholders.

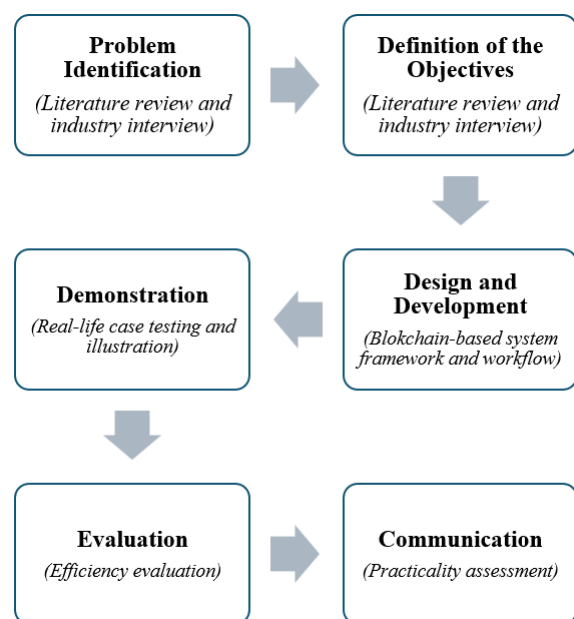


Figure 1: Research methodology in this study

System requirement analysis

Interview results for system requirements

We conducted interviews with one supplier, two contractors and one developer to gain insights into the industry practices related to embodied carbon practices. We also sought their opinions on the proposed blockchain-based carbon management system. The interview questions are provided below:

1. How does your company collect and store carbon-related information/data for a project? For instance, what types of data are collected, how is data collected from different parties, who is responsible for inputting the data, and how is the data stored?
2. Does your company have any concerns about using a blockchain-based carbon management system for tracking carbon-related data in the construction supply chain?

Based on the interviews, it is noted that only a few stakeholders have a practice of collecting and tracking embodied carbon data in their projects, such as having a

centralized procurement system and an online centralized database for storing data. The stakeholders also expressed concerns regarding data quality and sensitive information (e.g., the design formula of the product, total quantity and inventory sources). Besides, they expressed expectations for the system to support data sharing throughout the project and industry (e.g., project emission factor), and facilitate the establishment of industry benchmarks.

System design

The research primarily 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 for more accurate carbon assessments. In our blockchain-based carbon management system, the stakeholders involved are developers, architects, consultants (such as structural consultants and carbon consultants), contractors (such as foundation contractors and main contractors), and product suppliers (such as concrete and steel suppliers). The contractor and supplier are further categorized into general staff and senior staff for different roles in the system. The system framework is referenced in Figure 2.

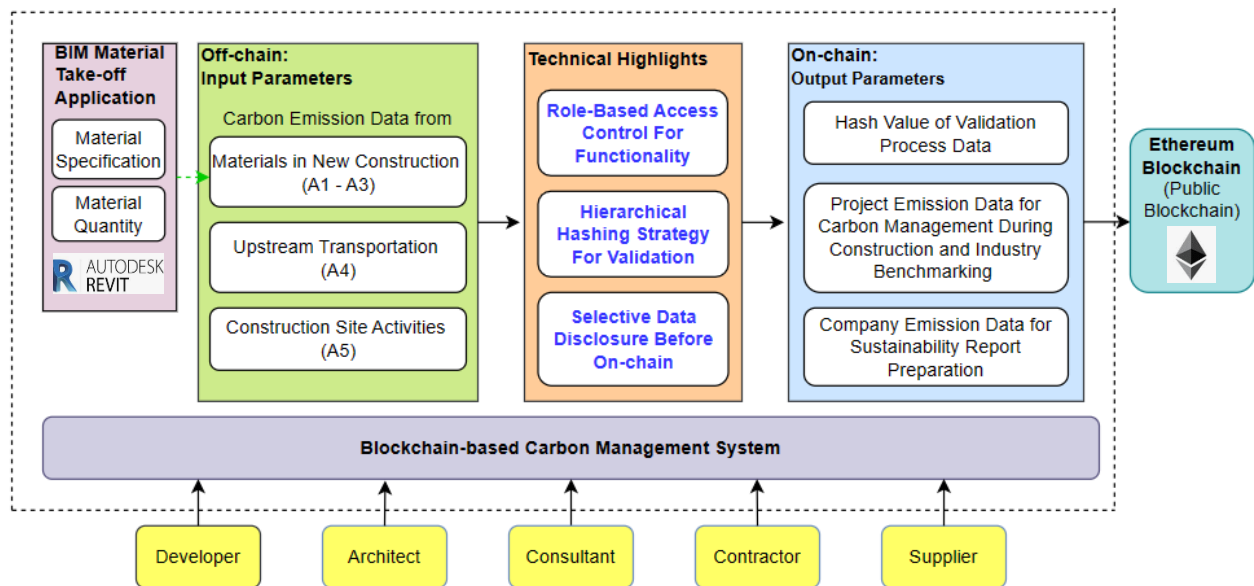


Figure 2: System framework

The proposed system framework provides the traditional off-chain carbon management functions, encompassing user registration and data input. Within this system, all stakeholders should register a unique account in the blockchain and carbon management system with their respective identities. Additionally, the architect creates a project account in the system. Under normal circumstances, the general staff of the contractors and product suppliers will be responsible for data input based on their respective roles in the project. 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). These parameters include raw materials, origin, emission factors, material quantities, and transportation modes and distances. The BIM material take-off function is utilized to extract information for the input of A1 - A3, which covers material specification and quantity.

To make carbon footprints transparent, reliable, and trackable, the proposed blockchain-based system framework entails an on-chain smart contract and public blockchain storage for data recording and output. A decentralized database with self-executing smart contracts is utilized to store significant project information and carbon emissions data. In addition to the previously

mentioned hash value of validation process data, the system also records and generates output data on a project basis and company basis. This includes details such as the project address, product emission factor, product quantity, monthly carbon emissions, total emissions in Materials in New Construction (A1 - A3), Upstream Transportation (A4), Construction Site Activities (A5), and the overall project emissions. These data serve various purposes, such as facilitating carbon management throughout the construction period, preparing sustainability reports, and establishing benchmarks. By storing data on the blockchain, it becomes immutable and can be easily shared with the project team and the public for enhanced traceability and transparency.

Technical Specification

There are three technical highlights of this carbon management system:

- Role-Based Access Control For Functionality:** Every stakeholder has a clearly defined role and functionality within the carbon management system. The levels of power within the system, listed in descending order, are as follows: The Developer holds the highest level, followed by the Architect, Consultant, Contractor, and Supplier, while within each level, the Senior Staff holds a higher position than the General Staff. For example, in the context of the carbon management system being applicable to the industry rather than a single company, ensuring proper access control for individual and project accounts becomes crucial. Therefore, during user registration and project initialization, only the Architect has the authority to create projects in the system and to add, edit, or delete the accounts of Developers, Contractors, and Consultants. The Senior

Staff, on the other hand, can add, edit, or delete the accounts of General Staff members. Furthermore, in the system view, the Contractor has the right to create and view all inputted carbon information, while the Developer is limited to viewing only the total carbon emissions data.

- Hierarchical Hashing Strategy For Validation:** Data quality is a significant concern for stakeholders. In order to enhance the quality of carbon data, a validation process consisting of three hash values is implemented within both a company and a project team. The first value represents the original carbon data, the second value corresponds to the validation process executed by the first designated stakeholder (e.g., senior staff of the supplier reviewing and validating the input data provided by the general staff of the supplier), and the third value represents the validation process executed by the second designated stakeholder (e.g., after the senior staff of the supplier validates the input, the senior staff of the contractor further reviews and endorses the data). These three hash values, associated with the validation process data, are then stored in the blockchain.
- Selective Data Disclosure Before On-chain:** Once the data has been validated, stakeholders who are concerned about sensitive data disclosure have the right to choose whether to disclose or encrypt the data before uploading it to the blockchain and sharing it with the public. For example, if the supplier has reservations about disclosing the product design formula, the senior staff of the supplier can opt to encrypt this information while disclosing other carbon data such as product specifications and emission factors.

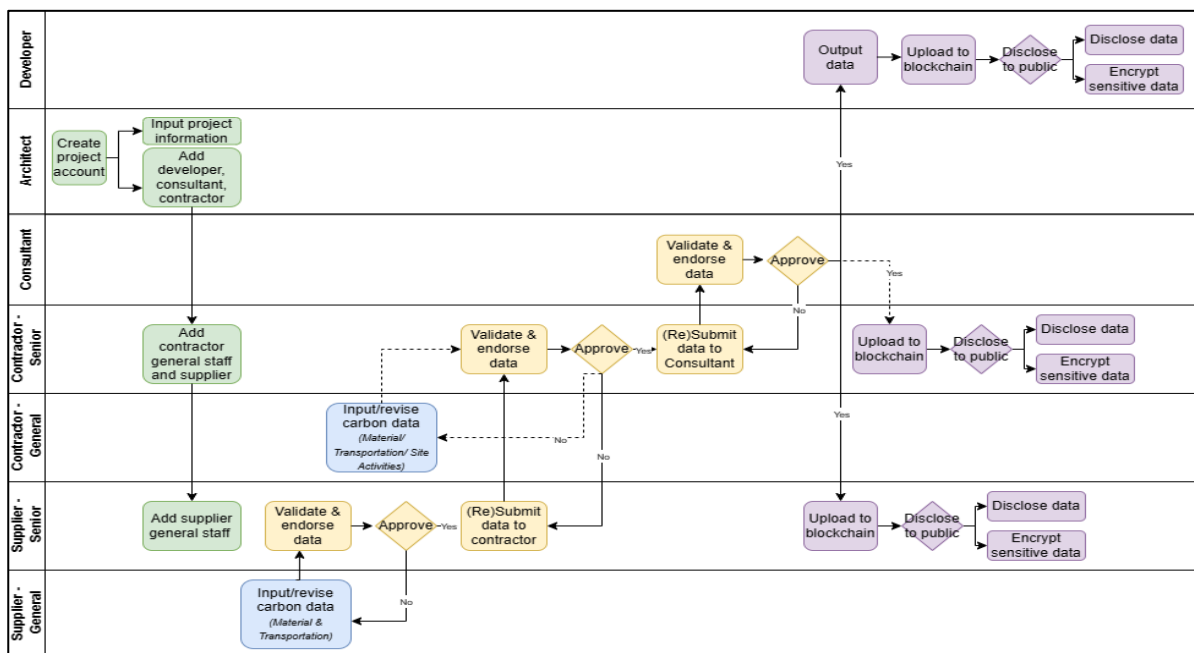


Figure 3: Operational Workflow (Green - User/Project Initialization; Blue – Data Input; Orange – Validation Process; Purple - Smart Contracts and Public Blockchain)

Operational Flow

In order to have a comprehensive understanding of the system, an operational workflow process is presented in Figure 3. Firstly, the architect initiates the creation of a project account and inputs the project information, as well as adds the relevant stakeholders (e.g., developers and contractors) within the project account. Additionally, the contractor adds the product suppliers, while the senior staff of the supplier/contractor includes their respective general staff in the project. Secondly, the general staff of product supplier and/or contractor input the carbon data into the information management system. Once the data is ready, their senior staff will review and validate the data before submitting it to the upper-level party for further validation. Thirdly, following the data validation process, the senior staff of the product supplier/contractor can choose specific data for encryption and subsequently upload it to the blockchain. This upload includes the three hash values associated with the validation process data, as elaborated in the previous section. Lastly, the developer possesses the final authority to select data pertaining to the total project and company emission for encryption and subsequently uploads it to the blockchain.

Implementation and results

System development

Figure 4 shows the system development details. First, a front end was developed for different users to collect carbon emission data via the web browser. A blockchain wallet tool called Metamask was used in this study to manage user blockchain accounts and provide methods to sign blockchain transactions during token transfer. At the backend, we use Alchemy to build the blockchain environment and provide the blockchain infrastructure. Considering this study aims to make carbon management along construction supply chains more transparent and directly assist with carbon data disclosure, Ethereum, a public blockchain platform, is thus used in this study to realize blockchain functions with smart contracts. For data storage, we use the integration of traditional databases and blockchain databases for safety and transparency. The traditional database is used to store original carbon emission data provided by all users. The blockchain transactions store and disclose all public carbon data transparently. At the same time, confidential carbon data for each party will also be stored on the blockchain after hash processing to satisfy the user's need to track their own carbon data through the blockchain-based carbon management system.

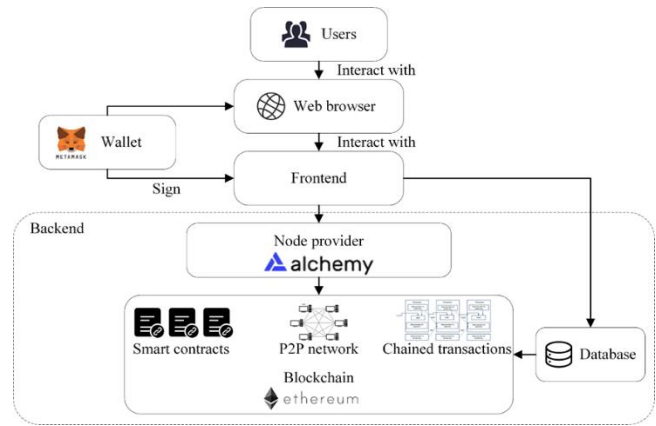


Figure 4: System development details

Result demonstration – User interface of input parameters

As mentioned previously, the DSR method is used as the research methodology in this study, consisting of six steps covering 1) problem identification, 2) definition of objectives, 3) design and development, 4) demonstration, 5) evaluation, and 6) communication. Based on the research progress, the study is currently at the stage of system design and development, with the user interface of input parameters being presented in this section. The input parameters consist of two main categories. The first category is the project information (e.g., site address, construction floor area) and project team information (e.g., names of stakeholders and their corresponding blockchain accounts), which are input by the architect. The second category is the upfront embodied carbon-related data, which covers the A1 - A5 modules of the building life cycle (from raw material extraction to the construction stage). This category is further divided into three groups based on the building life cycle and the parties responsible for inputting the data (i.e., product suppliers and contractors) for the substructure and superstructure stages. Figure 5 displays the extracted user interface of the input parameters.

Upfront EC - Substructure > Materials (Permanent) > Raw materials and transportation emission

Product Category: Ready-mixed concrete

Project Specification: [Dropdown]

Raw Material Emission

Materials: Cement

Supplier: [Text]

Material Emission Factor: [Dropdown] (tCO2e/t)

Material Consumption: [Dropdown] (tCO2e/year)

CO2e from Raw Material per Product: [Dropdown] (tCO2e/year)

Transportation Emission

Origin: [Text]

Calculation Method: Distance-based

Transportation Mode: Ship

Distance: [Text] (km)

Evidence for Distance: Select a file

Transportation Emission Factor: [Dropdown] (hgCO2e/hg/km)

Transportation Emission Factor per Product: [Text]

Submit Add a Material

Figure 5: User interface diagram – carbon data related to raw materials and transportation emission

1. **Materials for constructing new buildings (permanent and temporary):** This group includes emissions from raw material extraction (A1), transport to manufacturing (A2), and manufacturing (A3). The data includes product

information (e.g., product category and specifications), raw material emission data (e.g., emission factors, material consumption), transportation emission data (e.g., origin, transportation mode, fuel emission factors, and consumption), and manufacturing emission data (e.g., manufacturing process type and the fuel used).

2. *Upstream transportation and distribution*: This group includes emissions from A4 (transport to site) only, which refers to emissions from transporting products and materials from manufacturing plants to the project site. The input data is similar to the transportation emissions data in group 1 (e.g., transportation mode and distance).
3. *Construction site activities*: This group covers emissions during the construction of the building(s). The data includes emissions from fuel and energy-related activities (e.g., electricity, town gas, refrigerant, welding, and flame cutting) and waste generated during operations (e.g., landfill, public fill, metal, and timber recycling).

Conclusions

Carbon footprint management, especially carbon tracking, is complex along the construction supply chain due to the lack of accurate data collection and sufficient data transparency. Blockchain provides a potential and effective solution to enhance transparency and trackability issues in carbon management across the construction supply chain. However, there is limited research in the field of blockchain-based carbon management along the construction supply chain, especially focusing on the whole supply chain lifecycle and how to motivate all stakeholders to participate in such an innovative approach. Therefore, this study proposes a blockchain-based approach for transparent and trackable carbon management along the construction supply chain for all stakeholders by developing a blockchain-based carbon management system. The research methodology employed in this study is based on the Design Science Research (DSR) method based on (1) the literature review results of existing research about carbon management in construction supply chains and blockchain-based applications and (2) industry interview feedback from stakeholders along the construction supply chain. Based on the system requirement analysis results, a blockchain-based carbon management system is designed and developed, which consists of an off-chain traditional carbon management method and an on-chain (public blockchain) storage. There are three technical highlights of this carbon management system: role-based access control for functionality, hierarchical hashing strategy for validation, and selective data disclosure before on-chain. This research mainly contributes to enhancing the quality and traceability of embodied carbon data for more

accurate carbon assessments by using blockchain during construction supply chain management. In the future, we intend to improve the system development and test the system by inviting more industry stakeholders to provide feedback.

Acknowledgments

The authors would like to thank Gammon Construction and Limited, China State Hong Kong for their support during the interviews. Also, the work described in this paper was substantially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region (Project No. T31-603/21-N). Any opinions and findings are those of the authors and do not necessarily reflect the views of the Research Grants Council of the Hong Kong Special Administrative Region.

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