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Supporting building life cycle carbon monitoring, reporting and verification: A traceable and immutable blockchain-empowered information management system and application in Hong Kong

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ABSTRACT

The Hong Kong Green Building Council introduced the Climate Change Framework for the Built Environment, aimed at enhancing the monitoring and management of life cycle carbon emissions within the building industry. In response to this initiative, this paper presents a novel blockchain-based carbon audit tool designed to facilitate the monitoring, reporting, and verification (MRV) of embodied carbon in Hong Kong's building sector. Specifically, a consortium blockchain is utilized for system development in this study. The proposed blockchain system records the information pertaining to each stage of the building's life cycle, which is uploaded for storage. The system ensures the traceability, immutability, and transparency of the recorded information. To test and verify the system, it was initially applied to manage and audit the embodied carbon in Hong Kong's building sector in 2020. We anticipate our findings will provide a viable tool for MRV of building life cycle carbon emissions.

1. Introduction

Building sector is critical to realize the net zero strategy (Liang et al., 2023a; Schug et al., 2023; Wang et al., 2023b). As the latest statistics released by the United Nations Environment Program (UNEP) shows, the building sector accounted for 37 % of total global carbon emissions in 2021, which not only includes emissions from fossil fuels, but also incorporates carbon emissions from the production and use of building materials (e.g., concrete, steel, aluminum, glass, and bricks, etc.) (UNEP, 2022). Therefore, promoting the net zero building management is crucial to realize the net zero and carbon neutrality target, particularly for high-density cities like Hong Kong (Dombi et al., 2023; Liu et al., 2023; Yang et al., 2023), where, as a de-industrialized mega-city, more than half of the carbon emissions come from the building sector, as illustrated in Table S1 (Shen et al., 2021).

In line with other governments and international organizations, Hong Kong has also set the target of achieving "carbon neutrality" by 2050, which serves as a guideline for various sectors of the community to reduce carbon emissions (Liu et al., 2023). There is also a growing need for a referenceable framework adapted to the local characteristics of Hong Kong's building sector to achieve carbon neutrality and manage climate risks in response to the Hong Kong's Climate Action Plan 2050 (Biswas, 2014). With this background, for the better management on building sector's carbon emission, Hong Kong Green Building Council (HKGBC) has launched the "Climate Change Framework for Built Environment (CCFBE)" on June 2023, and one important content is to manage and reduce the "embodied carbon" in building sector (HKGBC, 2023).

This novel initiative is the first to focus on managing carbon emissions throughout the life cycle of buildings, and it clearly defines the scope of carbon audits, encompassing both operational carbon and embodied carbon, from buildings in Hong Kong (Chen et al., 2023; Hu, 2023). CCFBE serves as a guiding standard for the industry, with a focus on consistency in the scope and methodology of the monitoring, reporting, and verification (MRV) of the Hong Kong construction industry's carbon emissions. This framework will empower stakeholders

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in Hong Kong's building sector to establish net zero targets and develop a pragmatic and actionable carbon reduction roadmap. Additionally, it will actively contribute to assessing environmental, social, and governance (ESG) achievements of buildings, fostering green finance, and managing climate-related risks (Li et al., 2023; Wang et al., 2023a; Zhao et al., 2024).

The implementation of this initiative therefore raises two important scientific questions for the practical implementation of this novel framework: 1) for the stakeholders in the building supply chain, it is important to provide a solid accounting on the building embodied carbon, which is valuable benchmark information for science-based target setting in building sector; 2) for the supervisors, pinpointing to the accounting on building embodied carbon, to provide a tool for the MRV of carbon emissions in building life cycle is critical.

Limited emerging and our previous studies have resolved the question 1 to some extent, via developing a novel approach with integrating remote sensing techniques, night-time light data (Peled and Fishman, 2021a; Schug et al., 2023), building material flows analysis (Dai et al., 2022; Tanikawa et al., 2022), and life cycle assessment (LCA) (Hu et al., 2018; Luo et al., 2022; Zhang et al., 2019, 2018), to estimate and spatialize the building material stocks (MS) (Liang et al., 2023b) and the related life cycle carbon emissions (i.e., embodied carbon) (Liang et al., 2023a). Yet, the MRV on building life cycle carbon emissions is an extremely complex process that needs to be supported by effective tools and techniques. First, building is an extremely complex industrial product consisting of thousands of materials and building products (e.g., steel, cement, glass, etc.) (Chau et al., 2007). Besides, buildings often have a lifespan of decades or even centuries. There are many participants over such a long-time span, including material suppliers, manufacturing companies, construction workers, managers, owners, maintainers, and so on (Geng et al., 2017; Sharma et al., 2011). In addition, the carbon emissions of a building life cycle will also include the interests of different groups such as the stakeholders mentioned above, supervisors and even international organizations. To date, many tools and software have been developed to facilitate the LCA of buildings, including the assessment of embodied carbon. However, the scope and boundaries of these tools vary considerably as they serve different frameworks respectively. When these tools are directly employed to perform CCFBE, the mismatch in scope will undoubtedly cause problems for the MRV of carbon emissions (Teng et al., 2023). More important, trusted MRV tools are also essential for building energy performance and emissions trading systems. Unfortunately, existing tools do not ensure the safety and accuracy of MRV. On the other hand, blockchain technology can alleviate the aforementioned problems in the MRV of the building life cycle carbon emissions by constructing a decentralized anti-tampering system to record information. It is a decentralized system based on cryptography, distributed consensus and smart contracts that provides a secure, traceable, and reliable data foundation for building life cycle carbon MRV.

For this consideration, our study introduces a blockchain-based building information management framework, designed to bolster the authenticity of carbon emission MRV. The tool has been developed specifically to align with the building life cycle scopes and stage divisions outlined in the CCFBE. We utilize Hyperledger Fabric as the underlying blockchain system platform, as it implements a modular architecture, offers pluggable components, maintains high performance, and fully guarantees privacy. Consequently, all information generated throughout the building life cycle is uploaded and recorded on the proposed blockchain system. Ultimately, to demonstrate its feasibility as a proof-of-concept, we validated the framework through a practical case study. Additionally, we applied the developed system as a pilot to manage and audit the embodied carbon emissions in Hong Kong's building sector during 2020. In summary, the carbon auditing tool we developed leverages the distributed structure, consensus mechanism, and other integral components of the blockchain system, fulfilling the need for transparent and traceable information. This tool offers a practical solution for carbon emissions MRV throughout the building life cycle. The system we developed not only enhances building carbon audits but also facilitates improved climate-related disclosures in corporate ESG reports, thereby benefiting stakeholders in the building supply chain.

The paper is organized as: after this introductory section, Section 2 systematically discusses existing LCA tools for building carbon MRV and analyzes the unique advantages and great potential of blockchain technology. Section 3 describes the blockchain based system development and the building life cycle carbon accounting approach. Section 4 presents the demonstration of the system with the estimated life cycle carbon emissions in building sector of Hong Kong in 2020, as well as discussing strengths and limitations of the system, feasibility of actual deployment and application scenarios. Finally, Section 5 draws the major conclusions and addresses the policy recommendations.

2. Literature review

Currently, a series of LCA tools with corresponding assessment methodologies and standards, scope and boundaries for different carbon regulatory frameworks or different target users have been developed and are playing an active role in the decarbonization of the construction industry. For instance, the Construction Industry Council has developed a harmonized carbon assessment tool for evaluating the carbon performance of construction projects "from cradle to site" (CIC, 2018). The embodied carbon in construction calculator tool has been designed to focus on the embodied carbon emissions of the up-front supply chain of building materials, supported by databases such as quantities of building materials in a building information modeling (BIM) model allowing owners, policy makers to evaluate supply chain data, thereby enabling the procurement of low carbon solutions. Tally® tool has been developed to quantify the specific environmental impacts of building materials for comparative analysis of building design options (Tally, 2021). eToolLCD tool allows building designers to model project scenarios by importing building components and systems to obtain life cycle costs and environmental impacts (eToolLCD, 2014). One Click LCA tool is a BIM-based LCA software that automates the assessment of a building's whole life cycle, which also focus on comparing building design scenarios to optimize carbon emissions and costs during the design process (One-Click-LCA, 2001). Despite this, if these tools are used to implement the CCFBE proposed by HKGBC, the mismatch and incompatibility will undoubtedly create confusion on carbon emissions MRV of buildings. In addition, as far as data quality is concerned, the above tools cannot ensure data reliability and authenticity. At the same time, the data management of building embodied carbon accounting by the existing tools mainly relies on centralized databases, which implies the need to completely trust the data provided by the institutions or the government. This centralized approach to data management exacerbates the problems of data accuracy, authenticity and transparency.

Blockchain is a distributed ledger technology proposed by Satoshi Nakamoto to ensure the transparency and immutability of the information sharing process, which consists of a growing number of blocks storing transactions connected by cryptographic methods (Bitcoin, 2008). Each block consists of transactions and a block header, which contains timestamp, previous hash, Merkel root, and so on (Liang et al., 2017). This chain structure protects the immutability and security of information in the blockchain system, i.e., all transactions cannot be edited or deleted once they have been written to the ledger. If a transaction is recorded wrongly, a new transaction must be added for correction, and the old transaction will not be overwritten, which means both transactions will be visible to the entire blockchain network. In addition, compared to traditional control and decision-making models that rely on centralized entities such as individuals, organizations, or groups, blockchain is a peer-to-peer distributed network (Xiao et al., 2020). Each node involved in it keeps an identical ledger, suggesting that all transactions are transparently visible. This feature significantly mitigates the lack of trust among participants, thus enhancing the efficiency of cooperation. Furthermore, blockchain system establishes a consensus mechanism to enable the updating and maintenance of the ledger kept by the member nodes (Lashkari and Musilek, 2021; Sukhwani et al., 2017). Only if a majority of participants in the network agree, the new transaction can be considered valid and be recorded and stored in the blockchain system. The above unique properties of the blockchain system ensure that the transaction data generated and stored by each stakeholder in the life cycle is authentic and trustworthy, thus guaranteeing that the MRV is accurate and valid. Therefore, by utilizing the immutable and tamper-proof features of blockchain, building a CCFBE-compliant tool for MRV of carbon emissions in the building life cycle can effectively meet the needs of all stakeholders in Hong Kong building sector.

3. Methods and data

3.1. *Life cycle management on building emissions*

3.1.1. *Building life cycle*

The life cycle of a building can generally be divided into four stages: the product stage, the procure stage, the in use stage, and the end of life stage as illustrated in Fig. 1. Among them, the product stage mainly includes raw material mining, transportation, and building material manufacturing. The procure stage involves building material transportation and building construction. The in use stage refers to activities such as maintenance and repair. The end of life stage mainly includes building deconstruction, transportation, waste disposal and recycling.

From the life cycle perspective, the building sector contributes much higher embodied carbon emissions than its operational emissions due to embodied carbon over the life cycle of buildings, such as production of construction materials, transportation, and end of life products (Biswas, 2014; Monahan and Powell, 2011; Zhang and Wang, 2016; Zhu et al., 2022). Therefore, accounting (provide quantitative value), mapping (provide spatially explicit information) and auditing the embodied carbon in buildings would be helpful to decision makers and for urban policy promotion (Dong et al., 2018; Figueiredo et al., 2021; Too et al., 2022; Wu et al., 2022), for example, it would help to set a science-based target, update the existing green building certification system for management and supervision, conduct scenario simulations of the substitution of building materials, and support net zero district, city, and urban agglomeration (e.g., the Guangdong-Hong Kong-Macao Greater Bay Area) planning. However, the related urban level studies on building embodied carbon management had been still limited so far.

3.1.2. *Regulatory framework of HKGBC*

To better manage the "embodied carbon" in building sector, Hong Kong Green Building Council (HKGBC) has launched the "Climate Change Framework for Built Environment (CCFBE)". In the CCFBE, HKGBC defined the scope of carbon audits for buildings from a life-cycle perspective based on internationally adopted standards (i.e., ISO14000 and ISO14040) and the local situation.

As shown in Fig. S1 in *"Appendix"*, the management of a building's life cycle can be categorized into four stages according to CCFBE, which include the "Product" stage (A1-A3), the "Procure" stage (A4, A5), the "In use" stage (B1-B7) and the "End of life" stage (C1-C4). Over 4 stages of the life cycle, there are two main sources of carbon emissions from buildings. One is operational carbon emissions (CE_{oper}) from the "In use" stage of the building, which is mainly contributed by the operational energy (B6) and the operational water (B7). Another is the embodied carbon (CE_{emb}) emitted indirectly from the supply chain of a building, which continues throughout its life cycle. In the "Product" stage, the CE_{emb} should take the acquisition and handling of raw materials (A1), transportation (A2), and the following product manufacturing (A3) into consideration. The CE_{emb} of the "Procure" stage comes from transportation (A4) and on-site activities (A5). Moreover, the CE_{emb} is caused by in use (B1), maintenance(B2), repair(B3), replacement(B4), and refurbishment(B5) during the "In use" stage, while comes from the deconstruction (C1), transportation (C2), waste of processing (C3), and disposal (C4) processes in the "End of life" stage. Moreover, beyond the building life cycle, to further implement the concept of a "circular economy" and inform the decarbonization agenda of a wider range of industry stakeholders, the CE_{emb} from reuse, recycle and recover processes (D) is also within the scope of this framework. In a word, the system boundary of this framework is "Cradle to Cradle", which is set as the scope of the blockchain-based carbon audit developed for this work.

3.2. *Overall framework of the building carbon MRV system*

Currently, the operational energy use and carbon emissions of buildings in the "in use stage" have been well understood and investigated, accompanied by the implementation of many energy saving and emission reduction strategies, which can provide reference for carbon audits in Hong Kong's building sector. However, embodied carbon, as an

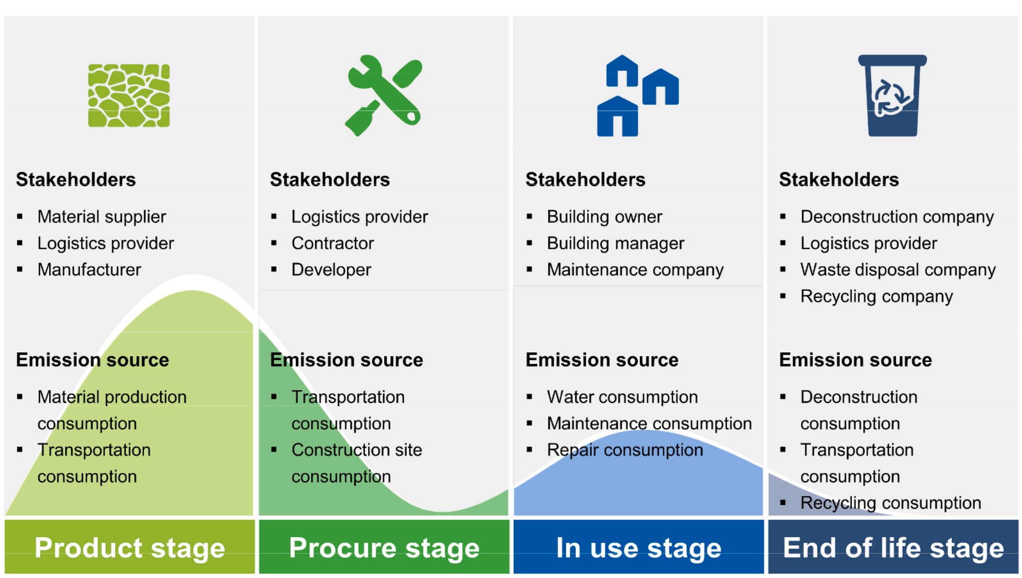

Fig. 1. Illustration of the building life cycle.

important indirect contribution to the carbon emissions and environmental impacts of buildings, lacks an effective assessment methodology. To address this critical issue and to fulfill the requirement of MRV for building life cycle carbon emissions, this work designs a blockchain-based MRV framework according to the embodied carbon standards of the building life cycle (A1-B5, C1-C4, and D) as mentioned in the CCFBE.

According to the building embodied carbon concept and matching to the regulatory framework of CCFBE by HKGBC, this paper developed a blockchain-based building embodied carbon MRV framework for managing the information generated by each participating stakeholders of the building life cycle, as shown in Fig. 2. The stakeholders in each stage of the building life cycle, such as material suppliers (A1), logistics (A2), manufacturers (A3) in the “Product stage”, constructors (A5) in the “Procure stage” and other participants involved in other stages, form a peer-to-peer permission network. Authorized stakeholders in the permissioned blockchain, which ensure the sensitive data is only shared by trusted subjects, can upload information to the blockchain network for recording. Contrary to traditional centralized databases, blockchain systems store data across all participating nodes, ensuring that every stakeholder maintains an identical ledger. Consequently, should the sensitive information of any node be compromised, the anomaly is quickly identified by the remaining nodes. This inherent feature significantly mitigates risks, including single-point attacks that often lead to data breaches, thereby safeguarding data confidentiality. Such robust security enhances trust among stakeholders and bolsters the efficiency of inter-organizational collaboration, underpinned by the transparent records maintained within the blockchain system. Benefited from the immutability and traceability of the information stored in the blockchain system, all the data generated and recorded by the stakeholders in each stage of the building life cycle cannot be tampered with, which can guarantee the authenticity of the information and help the regulators to track and audit the carbon emissions in a good way.

3.3. The blockchain-based building life cycle carbon audit information management system

For blockchain applications, the first thing we should do is to identify the type of blockchain (Wu et al., 2023; Yang et al., 2020). Due to the commercially sensitive data that may exist in the life cycle of buildings, public blockchains such as Ethereum, which allow anonymous users to participate in, might be permissionless and less suitable for application in practice. Besides, private blockchains (Dinh et al., 2017) are more suitable for the internal production and maintenance of enterprises. Consortium blockchain combines the characteristic elements of the public blockchain and the private blockchain, with a certain access restriction and security protection, provides a way to protect the interaction among organizations that have common goals but do not fully trust each other. In addition, consortium blockchain is more energy-efficient while ensuring high operational performance. Lower energy consumption consensus such as Practical Byzantine Fault Tolerance can be chosen for the consortium blockchain, comparing to some high-consumptive consensus used in public blockchain like Proof-of-Work (Huang et al., 2020; Jakobsson and Juels, 1999). This is also compatible with the main purpose of this work to audit carbon footprints and reduce the carbon emission of enterprises. Thus, it is more suitable for the application scenario in this study.

Hyperledger Fabric, which is a pluggable and validated enterprise-level distributed ledger platform that allows authorized participants to establish decentralized trust in the network, was selected as the underlying consortium blockchain platform for this work (Androulaki et al., 2018; Baliga et al., 2018; Sankar et al., 2017). It provides the service of creating separate channels among different stakeholders, thus enabling certain confidential information to be accessed only by the stakeholders in this channel, which ensures the privacy and safety of the information. This feature is particularly beneficial as different organizations may

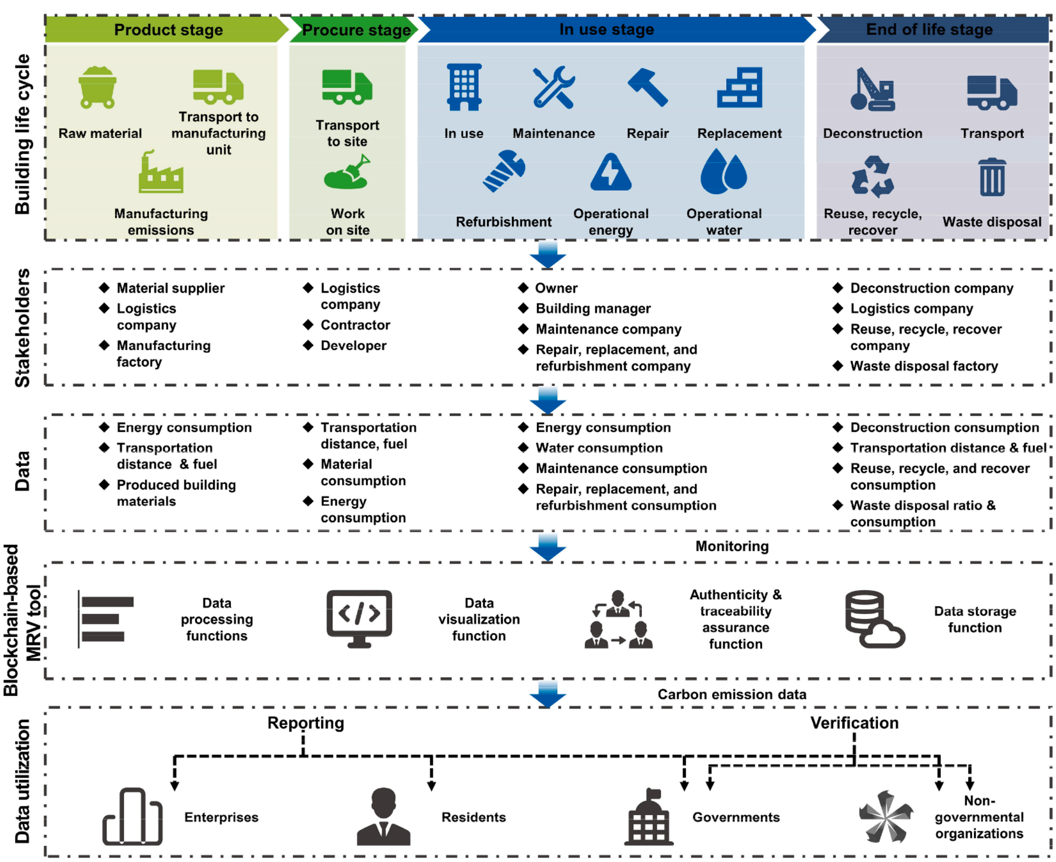

Fig. 2. The proposed framework for the building carbon MRV system based on the life cycle management on building sector.

have varying requirements for information-sharing permissions throughout the building life cycle. For instance, information can be shared among material suppliers, manufacturers, and logistics providers in the product stage of the building life cycle, while being restricted from maintenance company or stakeholders involved in other stages. For the above reasons, Hyperledger Fabric is selected as the underlying blockchain platform for the building life cycle in this study.

The proposed blockchain system accounts for storing the data generated in the building life cycle. All data collected from the product stage to the final recycling stage will be recorded in the blockchain ledger. With the unique characteristics of immutability and traceability of the blockchain, all these reliable data can be used for the follow-up calculation of carbon emissions and for a truthful and visible MRV process, as well as helping regulators and users to analyze the impact of building embodied carbon on the environment.

As shown in Fig. 3(a), the blockchain-based building carbon emission MRV functionality is realized by the MRV calculator, database, distributed network and system interface, respectively. The proposed blockchain system architecture for information management is shown in Fig. 3(b). It contains two main layers, the application layer and the blockchain network layer. The topmost layer is the application layer where each stakeholder has a corresponding client application. Stakeholders can perform data uploading, information querying and other operations through their own user interfaces. The supervisor can also regulate the activity information generated in each stage through the explorer. The blockchain layer is the core component of the architecture, which includes the contract layer, consensus layer, data layer and the network layer. The first and second layers in the blockchain network are the contract layer and the consensus layer respectively. In contract layer, smart contract written for realizing various functions in the system are packaged and deployed into channel. The consensus layer includes leader election, transaction ordering, transaction packing and block generating. The third layer in the blockchain network is the data layer, where the transactions in the block are represented after encrypting and the increasing blocks are linked by cryptographic techniques. Network layer is the bottom layer of the blockchain component. It enables the network communication, including the propagation and synchronization of the transactions and blocks.

3.4. Building embodied carbon estimation methodology

Fig. 4 shows the method for calculating embodied carbon in buildings. Based on the life cycle perspective, this study calculated the embodied carbon emissions at each stage of the building life cycle.

The estimation and mapping of building MS lay the groundwork for quantifying carbon emissions embodied in buildings. Our estimations of building material stocks relied on a previously established approach that combined the methodology of mapping building MS within urban built-up areas, as described by (Peled and Fishman, 2021b). Minor adjustments were made, as outlined in our previous study (Liang et al., 2023b). The findings are summarized in Table S2 in "Appendix". We divided the built-up areas within cities into multiple micro-units in detail. Subsequently, we employed night-time light data, along with an enhanced clustering technique for built-up areas and a building volume estimation model, calibrated using local data, is proposed for estimating and mapping building material stocks, such as cement, gravel, steel, wood, sand, and brick. This estimation process incorporates updated and localized material intensity data.

With material stock inventory, the embodied carbon in buildings was able to be estimated and mapped according to the building life cycle and emission factors obtained from China Building Carbon Emission Calculation Standard. Tables S3–5 in "Appendix" summarize the carbon emission factors of different building materials, energy consumption, and transportation distance, respectively. The "cradle" to "grave" emissions are calculated based on our previous study (Liang et al., 2023a). Table S6 in "Appendix" describes the equations and parameters for calculation.

4. System implementation and results

By capturing transparent, tamper-resistant, and traceable data on material consumption throughout the building life cycle, it enables precise calculation and analysis of energy consumption at each stage. This facilitates the identification of carbon emission sources and the strategic targeting of carbon footprint reduction initiatives. To paint a clearer picture of the carbon emissions throughout a building's life cycle, we select new buildings constructed in Hong Kong in 2020 as demonstrators, assuming a uniform lifecycle starting point to negate the impact of varying building ages. In this section, we first introduce the implementation details of the blockchain prototype. We then present the calculated results of embodied carbon emissions throughout the building life cycle. Lastly, the MRV of embodied carbon in the building life cycle is demonstrated, leveraging the proposed blockchain-based information management system.

4.1. Implementation details

The current system was developed under Hyperledger Fabric v1.4, Go was used for writing the smart contracts, and the deployment of nodes was realized through Docker container. For a better demonstration of the details of our system implementation, the product stage of building life cycle was chosen to be presented. There are three main

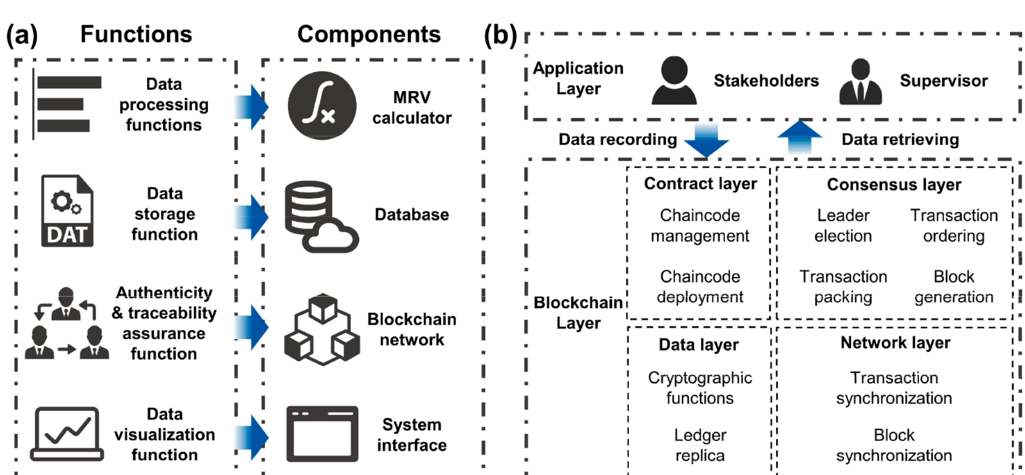

Fig. 3. (a) The functions of blockchain-based building carbon emission MRV, and (b) the blockchain system architecture.

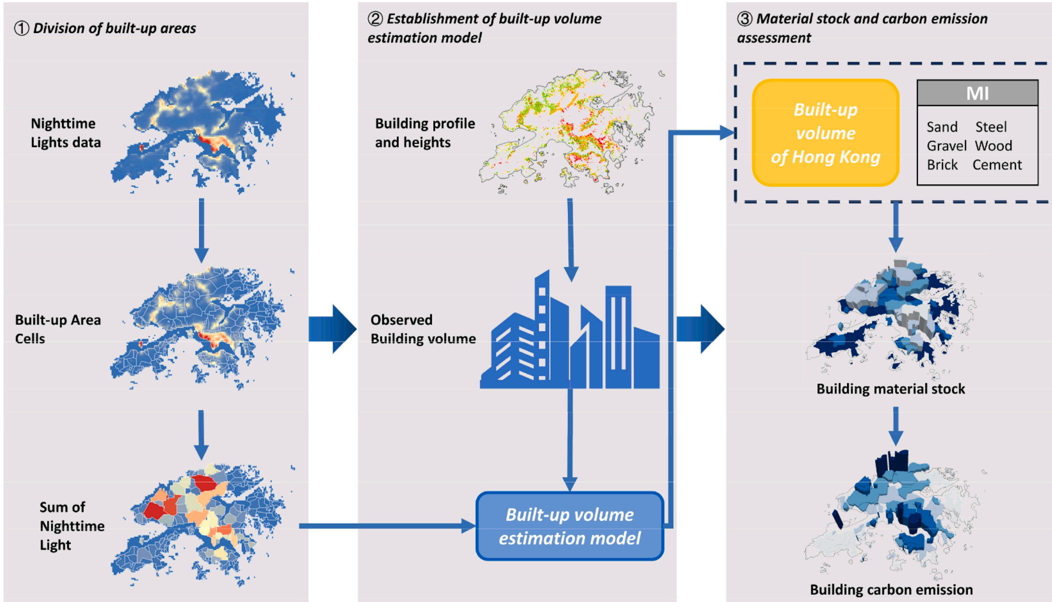

Fig. 4. Overall methodology for calculating embodied carbon in buildings.

stakeholders included in the product stage, material suppliers (R1), manufacturers (R2), and logistics (R3). The configuration information of the organization and the ordering service of the blockchain prototype is presented in the Fig. S2(a). Each organization was configured with two peer nodes, Peer0 and Peer1. Among them, Peer0 of each organization was set as an endorser node and an anchor node, which was responsible for executing the endorsement policy and communicating with other organizations. Fig. S2(b) demonstrates the configuration of Peer0 of the manufacturer organization as a sample and Fig. S2(c) presents the configuration of the genesis block and the channel. In addition, Hyperledger Explorer was deployed in this system to monitor the blockchain network, such as viewing the details in the blocks and transactions, which enables the visualization of the blockchain network and makes it easier to the regulators for querying and auditing.

Fig. S3 in "Appendix" provides a detailed view of the main components of the blockchain prototype, further describing the implementation details mentioned above. The manufacturer (R2) was designated as the network initiator, which defined the network configuration and created both the consortium and the Product Channel. Organizations (R1, R2, R3) belonging to the consortium joined the Product Channel through their respective peer node Peer0 in their organization, which had the smart contract S1 installed to enable communication among clients. Each peer node belonging to this consortium keep the same ledger L1. Additionally, as the initiator of the network, R2 configured and initiated the ordering service, which sorted all the transactions submitted to Product Channel, packed them into blocks after verifying, and finally distributed them to the peer nodes.

In the information recording process, endorsers of each authorized organization can invoke the smart contract to send the details of the order to the system. As shown in Fig. S4, every operation generates a transaction, and the details of each transaction can be check in the Hyperledger Explorer, including the creator, channel name, transaction hash and timestamp of this transaction. Fig. S4(a) presents the transaction information generated by one of the use cases. After the consensus was reached by multiple organizations, this transaction was packaged into block. The block contained the following types of information, which included block number, channel name, block hash, previous hash, and transaction hash (Fig. S4(b)). Besides, the transaction list is also demonstrated in the Fig. S4(c). All these information contributes to achieve traceability and immutability of the records generated during the life cycle of buildings.

4.2. Building embodied carbon emissions in Hong Kong in 2020

Leveraging nighttime light data, the study categorized various urbanized regions in Hong Kong and formulated an estimation model for the stock of building materials. By incorporating the carbon emission factors of various materials, the spatial distribution of MS, carbon emissions, and their densities were determined, as illustrated in Fig. 5 (a). In 2020, Hong Kong's MS comprised 2.27 Tg of steel, 0.16 Tg of sand, 0.16 Tg of gravel, 0.14 Tg of wood, 2.08 Tg of bricks, and 2.96 Tg of cement. Respectively, the embodied carbon emissions were 0.74 Tg for steel, 10.60 Tg for sand, 10.51 Tg for gravel, 0.44 Tg for wood, 6.42 Tg for bricks, and 3.94 Tg for cement. Utilizing life cycle analysis, it becomes evident that the stock of building materials and carbon emissions in Hong Kong Island and Kowloon surpass those in most other regions.

The contribution of various materials, including steel, brick, etc., to the embodied carbon emissions throughout the building's life cycle is evident in Fig. 5(b). Furthermore, the detailed breakdown of total carbon emissions at each stage is clearly visible. During the product stage, the embodied carbon emissions total 6.67 Tg, with cement, brick, and steel being the primary contributors, accounting for 2.00 Tg, 1.87 Tg, and 1.76 Tg, respectively. Additionally, wood, sand, and gravel contribute 0.09 Tg, 0.02 Tg, and 0.03 Tg of carbon emissions, respectively. During the procurement phase, the building materials that emit the highest embodied carbon emissions are brick (0.14 Tg), gravel (0.10 Tg), and sand (0.09 Tg), accounting for 35.9 %, 26.4 %, and 24.9 % of the total carbon emissions in this phase, respectively. Additionally, cement, wood, and steel contributed 0.03 Tg, 0.01 Tg, and 0.01 Tg of carbon emissions, respectively. During the in use stage, the carbon emissions total 2.47 Tg, with various materials contributing 0.62 Tg (steel), 0.71 Tg (brick), 1.02 Tg (cement), 0.04 Tg (sand), 0.04 Tg (gravel), and 0.03 Tg (wood), respectively. At the end of life stage, the embodied carbon emissions total 0.72 Tg, with respective materials contributing 0.50 Tg (steel), 0.06 Tg (brick), 0.04 Tg (cement), 0.04 Tg (sand), 0.04 Tg (gravel), and 0.04 Tg (wood).

Fig. S5 in "Appendix" depicts the spatial distribution of various MSs obtained in this study. Cement and steel exhibit the largest stocks, specifically 3.98 Tg and 2.00 Tg, respectively. Bricks rank third with a stock of 2.79 Tg. These three products alone constitute 94.3 % of the total MS. Sand, gravel, and wood exhibit significantly smaller stocks of 0.21 Tg, 0.21 Tg, and 0.17 Tg, respectively. The spatial distribution

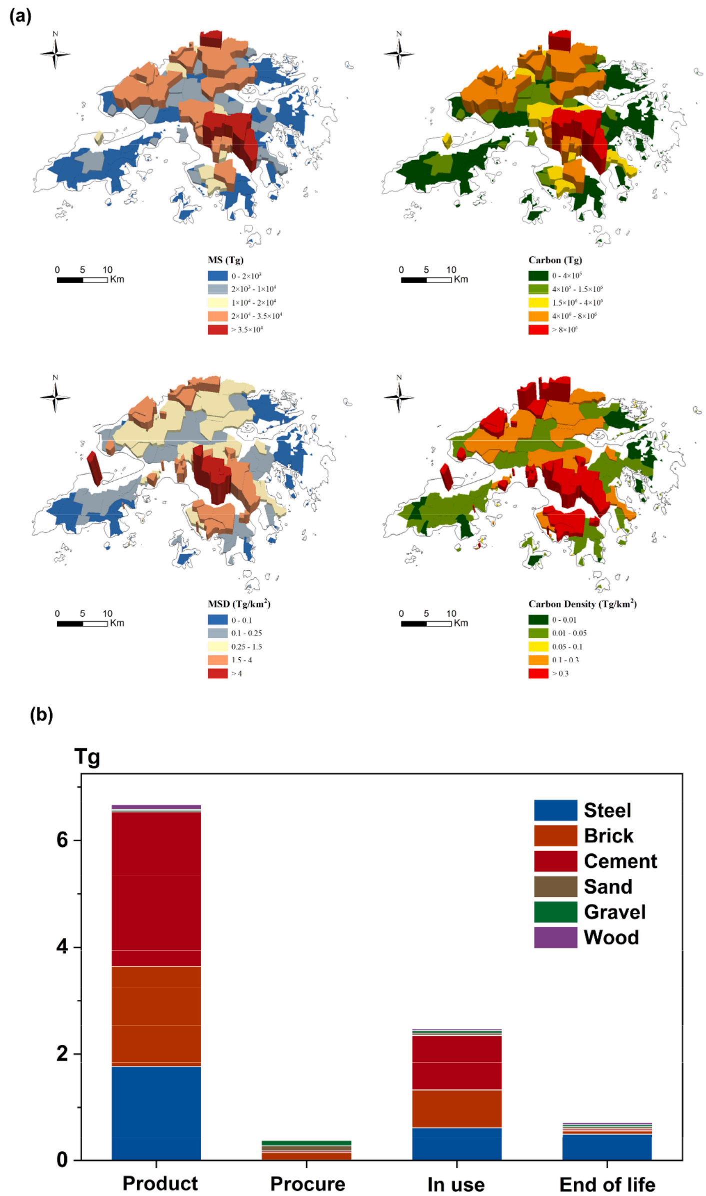

Fig. 5. (a) The spatial distribution of building MS and embodied carbon emission in Hong Kong, and (b) the life cycle perspective.

reveals a concentration of these MSs primarily in Hong Kong Island and the northern half of the New Territories.

4.3. System demonstration

The blockchain-implemented information management system proposed in this work records detailed, tamper-proof and traceable building life cycle carbon emissions data, which makes it possible to account for the contribution of different categories of building materials to the embodied carbon throughout the “Cradle to Grave” process in a time series (Fig. 6). In this section, for the purpose of feasibility testing and validation, this blockchain tool is attempted to manage and audit the embodied carbon of the construction sector in Hong Kong in 2020. For presentation purposes, Hong Kong’s 2020 MS as a whole is deposited into the system and embodied carbon is accounted for by the built-in calculator, which is finally presented in the front-end interface of the system.

As presented in Fig. 6, the developed system enables to monitor and report the carbon emissions data related to different life cycle stages in the building sector. Lifecycle emissions are relevant to different stakeholders with varying data needs. For example, in the product stage, material suppliers and manufacturers need data from the MRV system on the embodied carbon emissions of each building material consumed during production, processing, and transportation, as well as the sources of these materials and the manufacturing processes involved. Besides, data on the potential recyclability of the materials at the end of the building’s life, waste management measures, etc. are also needed to help demonstrate the sustainability efforts of suppliers and manufacturers that are unintended during the product stage. Such data as above will help identify potential hotspots for abatement efforts and help them in ESG reporting. During the procure stage, contractors, who are the main actors in construction activities, usually need data on energy consumption during this stage, carbon emissions from construction activities (excavation, concrete pouring, etc.), embodied carbon emissions from the use of construction materials, as well as data on the waste generated (including recycling rates, hazardous materials disposal, etc.). All these data are useful for companies to produce sustainable ESG reports and thus build a good brand reputation. During the in use stage, building managers and owners are the main construction actors. They usually need information on the carbon emissions generated during the

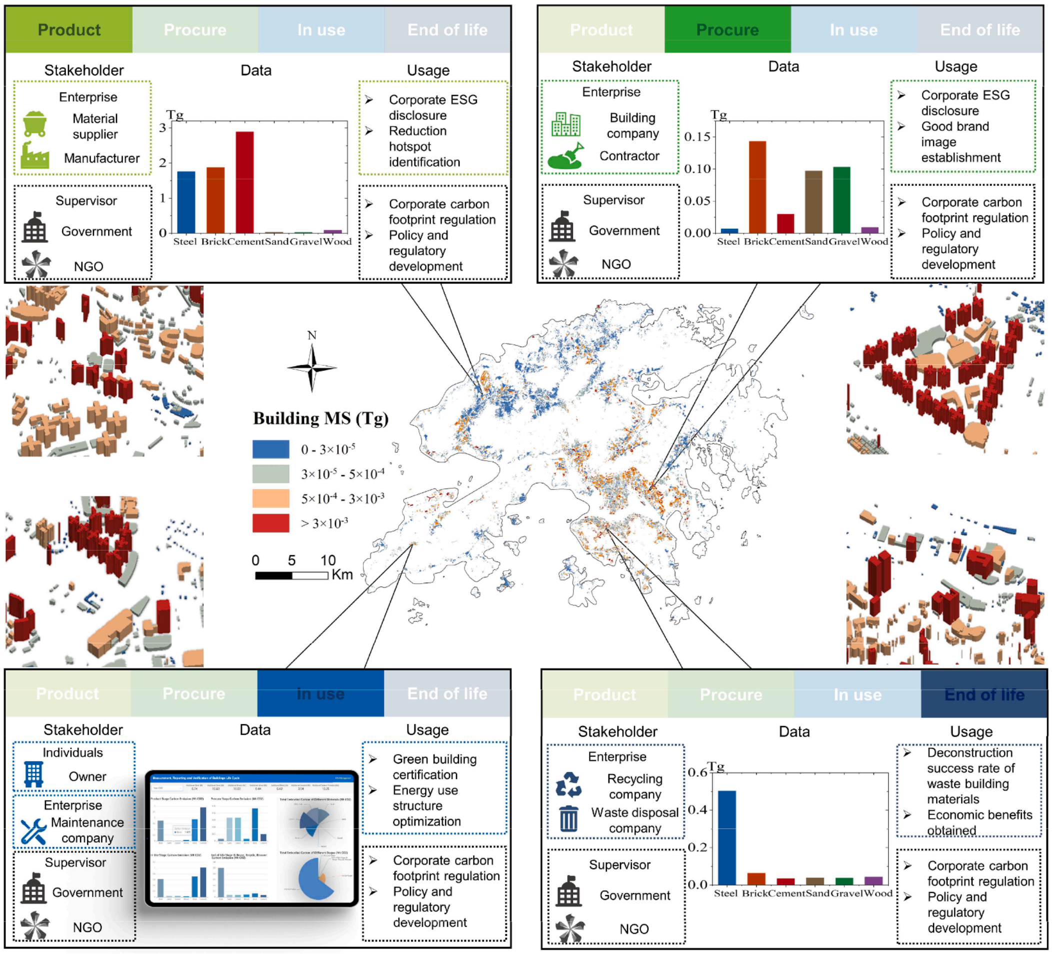

Fig. 6. Carbon audit interface for the embodied carbon emission of different building materials and different stages in the building life cycle.

production and construction of the building, the energy consumption during the operation phase (including electricity consumption, water consumption, etc.), as well as the embodied carbon emissions generated during the renovation and maintenance process. These data can help them understand the energy performance of the building and identify opportunities for energy savings or efficiency improvements. In addition, having this data can help demonstrate that a building meets sustainability standards and contribute to goals such as green building certification. At end of life, waste disposal and recycling companies need building materials usage data related to the manufacturing and construction phases of a building to improve the success of deconstructing waste building materials. As government and non-government regulators with viewing and regulatory rights in the system, they can access carbon footprint data generated by different stakeholders at different stages of a building's life cycle from the MRV system. This helps in formulating effective policies and regulations to mitigate the environmental impact of the construction industry. Therefore, the system is further expected to provide a platform for the better management on the climate related data regarding to different agents in the building supply chain.

4.4. Discussions

4.4.1. Analysis with comparison to other tools

The use of blockchain technology to ensure data invariance, traceability, and transparency in the MRV process is a significant advancement over traditional MRV methods that rely on centralized data management. The unique structure and properties of the blockchain ensure data immutability. Once the carbon emission-related data recorded in this tool, only a modified version can be added after the original error message, rather than overwriting the erroneous data, which significantly reducing the risk of tampering and increasing the integrity of the data. In addition, contrast this with traditional systems, where centralized data repositories can be vulnerable to unauthorized changes and single points of failure, the inherent traceability of blockchain provides an uninterrupted audit trail, improves transparency for all stakeholders, and allows for independent verification of emissions data. Moreover, this blockchain tool also shows competitiveness in automating and intelligently assisting with cost analysis because of carbon accounting based on material and energy inventories.

4.4.2. Discussion on research limitation

On the other hand, in spite of these advantages as mentioned earlier, blockchain-based tools for MRV have the following shortcomings which can be mainly categorized into three aspects including stakeholder acceptance, integration with existing systems, and technical barrier as shown in Table 1. The first limitation faced by this tool comes from the stakeholder acceptance. Therefore, the technical performance, implementation cost, and rewards of the system should be further evaluated before actually deployed. In addition, government should also popularize carbon MRV supported by this blockchain tool through institutional measures, as well as providing financial .subsidies. Next is the integration with existing systems. Although blockchain technology can ensure the authenticity of data on the chain, it cannot guarantee the reliability of the data source. Data on energy consumption, material consumption, and so on at different stages of the building life cycle are

Table 1
Limitations and future concern of this study.

	Limitations	Future concern
Stakeholder acceptance	➢ Stakeholder concerns over cost and returnability	➢ Implementation costs, technical performance and actual benefits should be further assessed in actual projects ➢ Government requires stakeholder engagement through policy and invest in economic subsidies to ease the burden on businesses
Integration with existing systems	➢ Reliability of data source	➢ Direct uploading of data in combination with sensors and other advanced technologies instead of manual uploading
Technical barrier	➢ System scalability in real deployment	➢ Research and development of advanced algorithms

usually manually uploaded to the blockchain system when integrated with existing systems. However, this process of uploading data often involves various uncertainties that may reduce the credibility of the data source. For example, human factors and human error may lead to inaccuracies, omissions or tampering of data. In addition, reliance on manual uploading of data makes data timeliness a challenge. To address this issue, we can also utilize advanced technological tools, such as IoT and sensor technology, to automate the collection and uploading of data. By obtaining data directly from building equipment and systems, the human uploading of data can be minimized, thus increasing the reliability and accuracy of data. For the technical barrier, scalability of this blockchain-based tool can be an issue, as the distributed nature of blockchain can lead to slower transaction processing times compared to centralized databases, which can be mitigated through development of advanced algorithms. To sum up, while the methodological advances brought about by blockchain technology may have a significant impact on the future research and practice of carbon MRV, it is important to weigh these benefits against the potential drawbacks and to consider the specific requirements and readiness of the relevant stakeholders.

4.4.3. Feasibility study

Given the successful application in Hong Kong building sector, this blockchain-based tool is also expected to be applied in the MRV of carbon emissions from more diverse types of buildings over a wider area. This tool can be universally applicable by adjusting its data type, carbon accounting method, and user privileges according to the construction carbon emission regulatory system in different application areas, and it also has the potential to be used in the LCA of the construction industry chain across different regions in order to promote the decarbonization process. When extending and replicating this system, the first issue comes from differences in the boundaries, stages, and responsible entities for carbon emissions in the regulatory frameworks for the climate impacts of construction in different countries and regions, owing to the very different contexts in which the construction sector has developed. Therefore, this blockchain tool should also be adjusted accordingly to LCA requirements in terms of data types, carbon accounting methods, and users. In addition, in the context of industrial chain globalization, the building life cycle often involves cross-regional industrial cooperation. For example, in the case of Hong Kong, the acquisition of raw materials and production of building materials often come from outside the region. Therefore, this blockchain tool will face possible "carbon loopholes" in terms of consistency of assessment methods and permissions for data acquisition, transmission and access, requiring policy support and coordination. Finally, the increasing number of stakeholders joining the system on a wider scale will bring with it the burden of data collection, processing, storage and transmission, posing challenges in relation to server capacity and upfront costs, which can be solved by policy support and input from regulators.

4.4.4. Policies supporting for deployment

To support the future practical deployment of the system and to enable it to play a more significant role in climate governance of construction sector, the following policies should be considered by the government as a regulator: (1) Assisting the participation of all stakeholders in building LCA to overcome the obstacles of fragmentation and complexity. (2) Promoting clear and consistent LCA standards and institutionalizing building carbon performance certification through blockchain tools. (3) Strengthening cross-regional cooperation and international action to create synergies.

4.4.5. Application in practice

In the future, it can be foreseen that this blockchain tool will play an even more crucial role in decarbonization actions in the construction sector, especially in the decision-making of all stakeholders encompassing companies, regulators, and residents, and in the collaboration between them. Companies with excellent ESG reporting can differentiate their products by establishing a green, reputable brand name. Blockchain-based traceable MRV systems can help these stakeholders directly access information that has been measured, verified, and reported throughout the building life cycle, such as carbon footprint, recycling, and resource efficiency. On the economic side, companies that excel in ESG not only ensure sustainable investments and cost reductions in the long-time dimension, but also attract environmentally conscious consumers through brand reputation, which boosts the company's economic performance. For home buyers, they will be more inclined to purchase buildings with traceable and transparent information. The disclosure of such information can assist homebuyers and the authorities that designate green public policies to reduce the environmental impact of greenhouse gas emissions by deciding in favor of more sustainable buildings and putting pressure on building contractors to make more careful and informed choices about upstream companies.

5. Conclusions and policy recommendations

5.1. Conclusions

This work presents a blockchain technology-empowered life cycle information management framework for the building carbon emission to realize the authenticity and transparency of the MRV process, which meets the need to implement the CCFBE proposed by the HKGBC. Specifically, a consortium blockchain architecture based on the Hyperledger Fabric platform for recording information in the life cycle of building is developed. Moreover, user data in Hong Kong is used as a real case to verify the feasibility of the system. The results show that the proposed framework can effectively store the information generated by various stakeholders in the building life cycle. Eventually, the developed tool is also applied in the first attempt to embody the management and auditing of carbon within the Hong Kong building industry in 2020. The results show that this blockchain tool can adequately meet the diverse needs of different users, such as businesses, residents, and regulators, for the environmental, economic, and social aspects of complex data. In conclusion, the carbon audit tool developed in this study utilizes the distributed structure, consensus mechanism and other unique components of the blockchain system to satisfy the need for information transparency and traceability, providing a feasible solution for the MRV of the building life cycle carbon emissions.

5.2. Policy recommendations

The results developed system is expected to support a number of actions and initiatives towards carbon neutrality strategy in and beyond Hong Kong:

The results will be used to evaluate the potential carbon reduction benefits of substituting building materials with biomass-based alternatives, such as bamboo, which exhibits low carbon emissions as per published literature and enjoys high popularity locally. Additionally, the MRV system can empower material suppliers and developers by facilitating carbon credit presentations and certification for green construction products, adhering to standards like the British Standards Institution.

1. The results and the MRV system are anticipated to identify the supply chain players who are accountable for carbon emissions and engaged in mitigation efforts. Consequently, this tool can function as a sophisticated carbon audit tool for supervisors, particularly the HKGBC. The results and the MRV system are anticipated to identify the supply chain players who are accountable for carbon emissions and engaged in mitigation efforts. Consequently, this tool can function as a sophisticated carbon audit tool for supervisors, particularly the HKGBC.
2. The life cycle-based material stocks and embodied carbon are expected to bolster climate-related disclosures in the building supply chain, utilizing the MRV system as an audit tool. Additionally, the reinforced ESG disclosures for building stakeholders aim to enhance climate-related disclosures and strengthen carbon auditing to mitigate carbon washing.
3. In recent years, the Hong Kong Green Finance Association has been working with the Guangdong-Hong Kong-Macao Greater Bay Area to promote green building blockchain products, while considering the building life cycle. The system developed has great potential to complement this initiative by solving issues such as cross-border building material supply, operation, and waste management. Fostering cooperation requires the engagement of cross-border stakeholders and the reduction of regulatory barriers.

CRediT authorship contribution statement

Ye Luo: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Jieling Shen:** Writing – original draft, Methodology, Formal analysis, Data curation. **Hanwei Liang:** Writing – review & editing. **Lu Sun:** Writing – review & editing. **Liang Dong:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107736.

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