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Blockchain-Enabled Life Cycle Assessment Data Governance: A Framework for Audit and Incentive Mechanism Design

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Abstract. Life Cycle Assessment (LCA) is a crucial method for evaluating the environmental impact of products throughout their entire lifecycle. However, its practice still faces challenges, including insufficient data credibility, rigid auditing methods, and low motivation for enterprise participation. Research has found that introducing blockchain technology can improve the credibility and auditability of LCA data and incentivize enterprises to participate in LCA calculations. Therefore, this paper proposes a multi-level LCA data governance framework based on blockchain technology. It constructs a corresponding auditing system and a token incentive mechanism that combines cost compensation and quality incentives. This paper provides a generalizable theoretical framework for the design of LCA data supervision and incentive mechanisms.

Keywords: Life Cycle Assessment, Blockchain, Data Governance, Audit Mechanism, Data Analysis

1. Introduction

Life Cycle Assessment (LCA) has played an irreplaceable role across a range of sustainable development areas, including calculating the carbon neutrality of products and materials. However, LCA has limitations in terms of verification, auditing, and incentive mechanisms. As an emerging data storage architecture based on distributed ledgers and hash-chain encryption, blockchain technology offers unique advantages such as immutability, traceability, and decentralization, making it highly valuable in economics, management, and information storage. Existing research mainly focuses on single-point technological adaptation of blockchain and LCA, lacking a comprehensive and in-depth analysis and systematic solutions of the entire process.

This paper systematically analyzes the main problems of LCA data and the potential of integrating blockchain technology. Furthermore, it proposes a five-layer architecture to explore the potential of blockchain technology to address LCA's limitations and to assess the feasibility of computational auditing and token incentive mechanisms. This paper aims to provide theoretical guidance for enterprises to ensure the trustworthiness of LCA data. It offers a feasible framework for future regulatory needs and incentive mechanisms in the field of LCA data and blockchain.

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2. Literature review

2.1. Related research

Jaiman et al. have explored the integration of blockchain with LCA, primarily focusing on using encryption to enhance data credibility or to record lifecycle information [1, 2]. Mostly, research remains confined to a general framework of information security and lacks a systematic design for incentive mechanisms and regulatory needs [3]. In addition, there is a lack of targeted research on personalized functions (audit, incentives, and not limited to credibility issues). Therefore, this paper conducts a comprehensive, five-layer framework from a data governance perspective to address these gaps.

2.2. Life Cycle Assessment

LCA is a systematic method for compiling and evaluating the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle (International Organization for Standardization, ISO). It is generally used to calculate the carbon emissions from a product's raw materials, manufacturing processes, and transportation, providing a preliminary estimate of total carbon emissions before product production and allowing integration into a larger LCA network. However, because LCA results depend heavily on input data and computational assumptions, their credibility and verifiability are often challenged in practical applications.

2.3. Blockchain technology

Blockchain, as an emerging decentralized data recording technology based on a distributed ledger, enables data to be written into blocks in timestamp order, possessing characteristics such as immutability and traceability in data storage [1]. Once recorded, the data is replicated across multiple parties through a consensus network, thereby reducing reliance on centralized third-party trust institutions [2].

Structurally, blocks are linked in a chain, each containing a timestamp and a cryptographic hash of the previous block. This design ensures that any modification to a block would be detectable, guaranteeing tamper-proof continuity between blocks. These features provide a technological foundation for building a traceable and auditable data governance system, making blockchain potentially valuable in scenarios requiring continuous monitoring of the data generation process.

3. Analysis of the pain points of traditional LCA

3.1. Lack of credibility of enterprise LCA data

The authenticity and reliability of LCA data have always been the core challenge in LCA research. On the one hand, LCA has variability in models, process parameters and the data itself. Core LCA inventory data is highly dependent on industry averages, which are subjected to temporal and spatial limitations and inherent variability, rather than precise field measurement data. Inconsistent collection and calculation methods can lead to divergent results even when different studies follow the same standard for the same products, due to structural selection and data deficiencies [4].

On the other hand, corporate data fraud and selective disclosure are important reasons. Under the current LCA Framework, product-level results are typically based on data provided either by enterprises themselves or by third-party environmental auditors. However, whether submitted

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directly by the enterprise or aggregated by a third-party institution, the original data on which LCA depends is still mainly controlled by the enterprise during the generation stage. This concentration of data control enables enterprises to selectively disclose or manipulate data to meet policy requirements or reduce compliance costs. At the same time, third-party audits are mostly focused on verifying input data and its calculation process. Without continuous verification of the data source, it is difficult to identify deviations between input data and actual production activities, thereby weakening the overall credibility of the LCA results [5].

3.2. Rigid audit model

In the traditional audit process, audit units generally review reports submitted by the enterprises, but lack a basis for verifying the authenticity of data generated by LCA. Due to tight audit timelines and limited resources, the relevant institutions have difficulty matching sufficient resources and capabilities to verify the accuracy of the final Environmental Product Declaration (EPD) results. Because EPD reviews and judgments rely on the manual evaluation report, it is difficult to establish unified objective standards for enterprise assessment. Therefore, in actual operation, there is a large degree of subjective arbitrariness. This audit model, which is mainly based on post-event document review, objectively limits the ability to verify the authenticity and integrity of the data generation process in practice, keeping the audit at the level of "result verification" rather than "process auditing" [6].

3.3. High costs and imbalanced incentives

The high cost of LCA practice and the lack of effective incentive mechanisms are the main reasons for enterprises' low willingness to participate in LCA, which restricts the expansion and improvement of the LCA industry network. For instance, the LCA process includes multi-stage data collection, human accounting, modeling and analysis, and third-party verification. Each step requires labor, financial, and material resources, which have become significant obstacles to LCA development [7].

Furthermore, the main reasons for enterprises to conduct LCA data computation are currently policy or regulatory requirements. Therefore, in the absence of incentive mechanisms, enterprises lack the motivation to maintain high-quality data while investing in costs to meet formal disclosure requirements. Therefore, currently, simply requiring the development of the LCA industry from a legal perspective is insufficient to support the long-term advancement of LCA networks [8].

In summary, the three core pain points of traditional LCA stem from data governance failures, lagging regulatory measures, and insufficient motivation to participate. The distributed ledger, traceability, and smart contract features of blockchain technology can precisely address these problems, and their application in the LCA field is highly feasible.

4. Possibility of blockchain adapting to LCA

The distributed ledger, immutability, traceability, and smart contract features of blockchain can enhance the feasibility of blockchain applications in LCA from three aspects: improving data credibility, enabling automated auditing, and constructing incentive compensation mechanisms.

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4.1. Distributed ledger solves data credibility

Blockchain technology, as a multi-party verification mechanism that allows records to be replicated and validated across the network, can be set to participate synchronously when the enterprise calculates LCA data, thereby achieving real-time monitoring. Lin et al. propose that enterprises can upload raw data to the blockchain throughout the life cycle of raw material procurement, energy consumption during production, and waste discharge, helping ensure end-to-end traceability [2].

Man et al. explore a verifiable model based on zero-knowledge proofs (zk-SNARK) at the cryptographic level [9]. For enterprises unwilling to disclose commercially sensitive information, preventing regulators from obtaining real data, the correctness of reported data or calculations can be verified without disclosing specific sensitive content. This technical solution fundamentally addresses the problem of data trust asymmetry between enterprises and regulators [9].

4.2. Automated auditing

The immutability and real-time updating of blockchain can not only be used for secure data recording, but also for rule-based data auditing. Therefore, based on the review report, it is possible to access the relevant data and verify it directly. The Hong Kong Green Building Council (HKGBC) has already introduced a blockchain framework to enable real-time review of intermediate data by synchronously recording data generated at each stage of building construction, without relying on manual report submission by enterprises [10]. This practice verifies the feasibility of blockchain technology in LCA automated auditing by process traceability replacing result verification [10]. In addition, for agricultural, Lei et al. propose a prototype of a Trusted Auditing Chain that combines the one-way immutability of blockchain with automated auditing procedures for encrypted verification, making the auditing process a real-time, dynamic, and periodic mechanism [11]. These cross-industry cases demonstrate that blockchain technology is feasible for integrated and manual verification in real regulatory scenarios, providing an institutional and technical foundation for alleviating the rigidity of traditional auditing models [10].

4.3. Incentive compensation mechanism

Existing research has provided cases for the construction of an LCA incentive compensation mechanism. Jaiman et al. have proposed a cost compensation model that sets the compensation ratio based on enterprises' actual expenditures, which to a certain extent promotes the increase of enterprises' willingness to participate [12].

The substantial labor and financial resources are invested in collecting and accounting for energy consumption, material use, and environmental data related to the construction process, and these investments are difficult to convert directly into short-term economic benefits, which weakens enterprises' enthusiasm. Scholars have proposed an Environmental Sustainable Contribution (ESC) token incentive model to verify the possibility of market momentum. By transforming LCA from an obligatory cost into a behavior that can obtain tokenized returns, it increases enterprises' willingness to participate and promotes development [13].

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5. Conceptual system architecture

5.1. Five-layer system design

Based on the existing token incentive model, this paper further optimizes the incentive structure, and divides the entire life cycle of LCA into multiple stages to calculate incentives separately. The model adds a dual-dimensional design of cost compensation and quality incentives. At the same time, it sets an upper limit for the incentives throughout the entire cycle, which solves the problem that the existing model is prone to causing excessive enterprise costs and insufficient quality incentives. Logically, the framework is divided into five levels:

Layer 1: Product System/Life Cycle Layer: Defines system boundaries as Cradle-to-Gate and divides the product lifecycle into various stages. A rough assessment of real-world workflows is made in advance, and approximate LCA (Limited Time Acquisition) data for the product is estimated based on known operational processes.

Layer 2: Data Collection & Preprocessing: Physical sensors to detect data in real time, package and classify the generated data, and perform simple preprocessing operations on the data.

Layer 3: Distributed Ledger Layer: Data is standardized and stored on different types of blocks according to different data types: Process Blocks (energy consumption, machine hours), Supplier Blocks (material origins, transport distances, sales, EoL), and Transaction Blocks (inter-facility transfers) [3]. Through timestamps and chain structure, it provides immutable existence and time-series proof for all inputs.

Layer 4: Blockchain-based LCA Calculation Layer: After obtaining and confirming the specific raw LCA data on the chain, this data will be input into the pre-set LCA calculation logic and algorithm module to complete the quantitative calculation of the life cycle environmental impact and output the corresponding LCA results.

Layer 5: Application/Service Layer: This layer interfaces with external stakeholders: enterprises access dashboards for LCA monitoring, auditors retrieve verification reports, and regulators query aggregated environmental performance.

5.2. Audit framework logic

In the specific audit process, the audit framework employs parallel verification logic: Enterprises calculate LCA results using their chosen models and submit the results. Simultaneously, the audit system independently calculates carbon emissions for each stage based on the raw sensor data recorded on-chain and the existing LCA data for each process flow and raw material. Discrepancy analysis occurs at each stage:

Stage 1: Project Initialization (Goal & Scope): Enterprises declare functional units, system boundaries, and allocation methods. The blockchain records these parameters in an immutable configuration block, preventing retroactive modifications that could skew results.

Stage 2: Upstream/Sourcing: Material inventories are cross-referenced with supplier blockchain records. Data archiving helps verify whether there are discrepancies between the theoretical carbon emissions of the product and the simulation results based on historical LCA data. It also verifies whether the material quality is balanced between the product's raw materials and the final product.

Stage 3: Manufacturing/Processing: Although the process steps differ, the carbon and emission data generated are relatively consistent. Therefore, this stage mainly checks whether there is a discrepancy between the equivalent carbon emission data generated by the enterprise's process and the simulation results from previous LCA data.

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Stage 4: Packaging & Distribution: Set up a special audit of the enterprise's transportation and packaging system. Confirm whether there is a discrepancy between the transportation carbon emission data provided by the enterprise and the simulation results based on previous LCA data.

Summary Calculation and Disclosure: Based on the overall simulation results and enterprise-provided LCA data for each stage, determine whether the LCA data passes the audit. Although the proposed audit framework may introduce additional technical complexity in the initial stage, the automation of data verification and the availability of interim results are expected to reduce the marginal audit cost in repeated assessments [14].

5.3. Token incentives

The ESC token incentive model transforms the mandatory costs of LCA into tokenized revenues. Unlike the direct economic returns in the ESG (Environmental, Social and Governance) field, this type of token has both cost compensation and reputational symbol attributes [15]. While policy requirements or specific disclosure needs often drive current LCA calculations, this paper proposes a general token-issuance model to shift companies' motivations in calculating LCA [14].

This paper divides the LCA process into several typical stages, including project initialization and boundary definition, raw materials and upstream supply, manufacturing and processing, packaging, distribution, and transportation (identical to the stage divisions in auditing). Token incentives are calculated and distributed separately for each stage.

$$T_i = \underbrace{\alpha \cdot \lambda \widehat{C}_i}_{\text{cost-compensation}(\alpha \le 0.7)} + \left| \frac{\beta \cdot f(Q_i)}{\text{quality-basedincentive}} \right| \tag{1}$$

Where Ci verifies actual monetary cost of stage. λ represents the conversion rate of verified monetary costs (real costs) to token units, as its value must be linked to real economic variables (costs, energy prices, revenues) [16].

T_i represents the equivalent amount of token rewards received by the enterprise after data verification in the i-th LCA stage. $f(Q_i)$represents the quality reduction function that ensures reasonable marginal returns on quality improvement. β is the quality incentive coefficient, adjusting the weight of data quality in token rewards.

The quality Q_i score is derived from blockchain-ensured attributes, including the traceability, verifiability, and consistency of data sources, thereby minimizing the potential for manipulation [17].

Since the determination of quality stems from a comprehensive analysis of data source and evidence integrity, traceability and immutability, third-party verification and consistency checks, and data reproducibility and reusability, the use of pre-set standards and blockchain characteristics greatly reduces the space for human manipulation.

$$T_{total} = \min\left(\sum_i T_i, \gamma \cdot \lambda \sum_i C_i\right) \tag{2}$$

Where $0 < \gamma \le 0.7$

$\sum_i T_i$ represents the total token reward accumulated across all stages.

$\gamma \cdot \lambda \sum_i C_i$ represents the capped upper limit of token incentive, which is determined based on the verified total LCA cost. λ is the cost-to-token conversion rate that maps verified LCA costs to token units. $\sum_i C_i$ is the sum of verified LCA costs across all stages.

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T_{total} represents the total token incentive obtained by the enterprise for a specific product's complete lifecycle evaluation process. This total equivalent incentive amount cannot exceed the cap determined by multiplying the verified total actual cost of the LCA by the token conversion rate and then by a fixed percentage γ.

γ is the total incentive cap coefficient, which constrains the total token incentive for the enterprise's entire lifecycle LCA and prevents strategic cost inflation to maximize rewards. The total token incentive amount is set to a fixed percentage γ of the verified total cost of the LCA.

The upper bound of $0 < \gamma \leq 0.7$ is derived from empirical analysis of LCA cost structure across typical industries such as manufacturing, construction and agriculture, ensuring the incentive covers cost while deterring cost overstatement.

The coefficient α and γ form a dual constraint mechanism. α controls the cost compensation ratio for a single stage, while γ controls the total incentive across the full cycle, forming a dual constraint. Note that this ratio can be appropriately adjusted through voting to suit different mechanisms for different industries. The values of α and γ can be dynamically adjusted by the industry association through node voting to adapt to the changing characteristics of LCA costs in the industry.

6. Discussion

The conceptual framework offers a new approach to empowering LCA data governance through blockchain technology, but it still faces inherent technical limitations and practical application constraints.

First, due to the characteristics of full-node storage and immutability of blockchain technology, LCA data are typically high in volume and granularity. However, this creates tension with scenarios involving high-frequency data recording and long life-cycle coverage. If all the original data is placed on the chain and stored by all nodes, it will lead to rapid chain growth, reduce synchronization and query efficiency, and endanger the network's long-term scalability. Therefore, massive amounts of data would need to be replicated across nodes and can only be appended without modification, placing extremely high demands on the storage speed and capacity of blockchain storage technology [1].

In addition, this framework applies mainly to product systems with stable production processes and clear data collection points. For these products, life-cycle stages are well-defined, and environmental data can be automatically captured. They are more easily integrated into the automated audit and incentive process described in this paper. However, for highly customized or personalized products, it is difficult to predefine LCA data collection points, so further adjustment is needed.

7. Conclusion

This paper systematically analyzes the limitations of traditional LCA practice in terms of data governance, audit mechanisms and incentive systems, focusing on the three main issues of Life Cycle Assessment (LCA). To address these issues, this paper proposes blockchain technology and demonstrates its theoretical feasibility in the LCA field. It goes beyond simple information security guarantees to further strengthen process auditing and the design of incentive mechanisms. Furthermore, the study proposes a multi-level blockchain integration architecture for LCA data governance, along with its corresponding data-auditing and incentive mechanisms.

However, the theoretical framework and corresponding auditing and token incentive logic proposed in this paper have not been fully tested with specific enterprise data and lack practical

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support. Therefore, the universality and effectiveness of this framework still need to be verified and supported through further theoretical development and subsequent practical exploration.

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