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Cross-chains and BIM for Dynamic Material Passports Circularity in Construction Supply Chains

Yasin Celik^{1,2,*}, Ioan Petri¹, Yacine Rezgui¹

¹ School of Engineering, Cardiff University, Cardiff, UK

² Department of Architecture, Artvin Coruh University, Artvin, Türkiye

*Presenting author: celiky@cardiff.ac.uk

ABSTRACT: *Achieving circularity in construction supply chains necessitates sophisticated digital solutions that enable comprehensive asset tracking, traceability, and interoperability. Blockchain technology offers a foundation for enhancing transparency, optimizing resource utilization, and facilitating the circular use of construction materials. This paper presents a technical framework for integrating Blockchain technology with Building Information Modeling (BIM) to develop dynamic material passports that enable lifecycle tracking of construction assets. A novel cross-chain material circularity system is introduced to address interoperability challenges across heterogeneous blockchain networks. This system aims to improve the coordination and traceability of construction materials across distributed project environments. The proposed approach is evaluated through a proof-of-concept implementation using BIM models representing two project scenarios: (i) a bridge construction project and (ii) a building construction project. These case studies illustrate the system capabilities in material traceability, ownership verification, and resource circularity. The framework leverages Ethereum and Polkadot blockchain platforms, augmented by LayerZero interoperability protocols to ensure secure, transparent, and better cross-chain transactions. Real time material status is monitored using IoT enabled solutions, including QR based identification, to support on-site validation and logistics tracking. Performance evaluation of the system focuses on key metrics such as cost efficiency, transaction speed, scalability, security, and implementation challenges. Results demonstrate that the cross-chain framework significantly enhances material provenance, facilitates reuse, and improves supply chain efficiency, thereby contributing to the broader goal of sustainable construction practices.*

Keyword: *Blockchain, Cross-Chain, Construction, Supply Chains, Circularity, Sustainability, Material, Interoperability*

1. Introduction

The construction industry is a major source of emissions, material consumption, and waste generation (Layke et al., 2016). These impacts have increased interest in circular economy (CE) practices that reduce resource use and support reuse and recycling (Kazancoglu et al., 2021). In construction, circularity supports preserve material value while reducing resource demand (Lei et al., 2021).

Construction supply chains involve multiple actors coordinating procurement, transportation, use, disposal, and reuse (Caldas et al., 2015). However, these processes often experience challenges related to traceability, quality verification, inventory management, and compliance (Li et al., 2020). Effective lifecycle supervision is therefore required (Li et al., 2022).

Sustainable construction depends on reliable material tracking (Almusaed et al., 2024). Lifecycle traceability supports waste reduction, reuse, and recycling while improving transparency across project phases (Gherman et al., 2023). Conventional systems lack transparency, security, and real-time visibility, increas-

ing risks of delays, errors, and fraud (Boppana, 2024).

To address these limitations, this study integrates blockchain with BIM for material lifecycle management. BIM supports lifecycle data sharing and material passports (Munaro et al., 2019), while blockchain provides decentralised and tamper-resistant records. NFTs support authenticity, ownership, and secure transfer of material information (Trivedi, 2024). These technologies enable persistent digital material identities containing provenance, quality, sustainability, and certification data (Atta et al., 2021).

This paper presents a BIM-integrated cross-chain material passport framework supporting material provenance and interoperability between blockchain networks such as Ethereum and Polkadot. The main contributions of this paper are as follows:

- Explores the integration of cross-chain blockchain systems with BIM to support asset tracking and circularity across construction ecosystems.
- Demonstrates the potential of blockchain to enhance material circularity, transparency, traceability, and sustainability in procurement and utilisation.

- Practical insights for blockchain-enabled circularity adoption in construction, derived from a proof-of-concept implementation using representative BIM models.

The remainder of the paper is structured as follows: Section 2 reviews the relevant literature on cross-chains and construction circularity, Section 3 outlines the methodology, Section 4 presents the system architecture and implementation, Section 5 evaluates cross-chain performance, Section 6 discusses the results, and Section 7 concludes the paper.

2. Related Work

Material passports are becoming recognised as a sustainability tool within CE practices (Hernandez, 2024). They provide digital records of material provenance, use, processing, and end-of-life status, supporting reuse and recycling (Gómez-Gil et al., 2024). Material passports depend on lifecycle data collection from design to demolition (Leising et al., 2018). However, lifecycle management across multiple projects remains difficult because of limited standardisation and weak interoperability between tracking systems (Chen et al., 2022).

Blockchain strengthens material passport systems through decentralised and tamper-resistant records. Integrated blockchain systems support secure tracking from procurement to reuse or recycling. Reported benefits include improved transparency, real-time traceability, and automation through smart contracts (Junussova et al., 2023). When integrated with BIM, blockchain can improve model reliability and trust in supply-chain data exchange (Hijazi et al., 2022). Cross-chain interoperability is important for projects operating on different blockchain ecosystems. Platforms such as LayerZero, Cosmos, and Polkadot enable communication between blockchains and improve material tracking across sites (von Eitzen et al., 2024). This reduces fragmentation and improves the exchange of ownership and status information (Tezel et al., 2020).

NFTs support material tracking by assigning unique digital identities to materials. NFT-based systems enable ownership transfer, provenance verification, and sustainability compliance while maintaining traceability across reuse cycles (Chiacchio et al., 2022). Smart contracts integrated with NFTs and BIM can also automate procurement, payment, and compliance verification (Jaskula, 2024). Despite these advantages, blockchain adoption in construction remains limited because of industry fragmentation, skills shortages, and collaboration challenges (Tezel et al., 2020). Broader adoption still requires further experimentation

and implementation frameworks (Dounas et al., 2020).

Integrating blockchain with GIS, IoT, and smart contracts can further improve material passport systems by incorporating location and operational data (Götz et al., 2020). BIM complements these technologies through structured digital building representations and lifecycle data management (Hijazi et al., 2022). BIM and blockchain can support a Single Source of Truth (SSoT), improving transparency, compliance, and auditability (Hijazi et al., 2023).

The integration of blockchain, material passports, BIM, and cross-chain interoperability presents a promising approach to addressing material management challenges in construction. This combination supports material reuse and recycling, improves track-ing efficiency, and facilitates the transition toward a more sustainable and circular construction industry.

3. Methodology

This study follows a two-stage methodology: (i) BIM-blockchain based asset tracking and circularity, and (ii) cross-chain interoperability for secure material transactions across blockchain networks. These stages support automated tracking, transparent asset management, and end-to-end material traceability throughout the construction lifecycle.

The framework is evaluated through a controlled proof-of-concept implementation using representative BIM models of a building construction project and a bridge construction project. Material attributes, identifiers, and transaction sequences were generated to represent realistic steel-beam and structural-material lifecycles. The blockchain-enabled material transfers were executed within a testnet environment using real data from two construction case studies. The Building Project operates on a private blockchain, such as Hyperledger or VeChain, for inventory management, ownership verification, and supply-chain tracking, whereas the Bridge Project uses a public blockchain, such as Polkadot or Tezos, to support procurement, sustainability monitoring, and asset management. Since both projects are based on different blockchain infrastructures, cross-chain interoperability is necessary to ensure secure material transfers while maintaining ownership records, origin information, and lifecycle traceability.

To implement this workflow, Ethereum and Polkadot are used as the main blockchain networks, while LayerZero provides a compatibility layer for cross-chain communication. Additionally, QR codes, RFID tags, and IoT technologies have been integrated to support real-time tracking and synchronization between physical assets and their blockchain-based digital rep-

representations. All blockchain transactions included in this study were performed on the public Ethereum and Polkadot test networks, using LayerZero’s testnet interoperability services.

IoT-enabled QR/Rfid tracking and passport data: A QR/Rfid tracking system is implemented to verify physical movement and circularity events. Each material is assigned a QR or Rfid tag linked to its MaterialNFT. The encoded data include material type, token ID, provenance, ownership, production details, certifications, and logistics information to support lifecycle visibility. As shown in Figure 1, a steel beam in the Building Project is tokenised as an ERC-721 asset and linked to a QR/Rfid tag. During cross-chain transfer, LayerZero verifies the asset and enables conversion into a wrapped NFT on Polkadot. IoT sensors and GPS tracking continuously update logistics and status data, while QR scans record departure and delivery events on-chain.

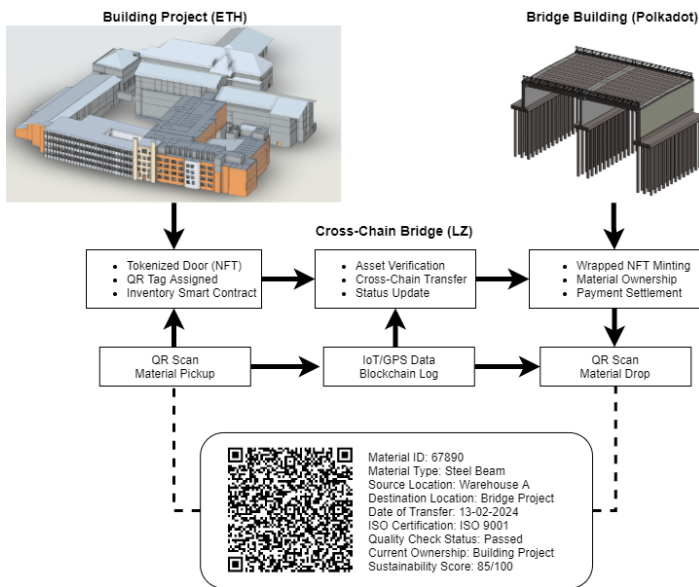


Fig. 1. Asset circularity framework using QR-based verification system for materials involving (i) Building Project and (ii) Bridge Project

Traceability and sustainability verification: The QR/Rfid system enables stakeholders to access real-time material information through scanning. This supports verification of material identity, ownership, certification, transfer history, and sustainability indicators while reducing manual documentation errors. Blockchain metadata stored within the QR include the target blockchain, smart contract address, and transaction history. Sustainability indicators such as carbon footprint, reuse potential, and disposal recommendations are also recorded to support lifecycle management aligned with circular economy objectives.

Smart contract integration and verification workflow: The methodology combines cross-chain smart contracts, IoT tracking, and decentralised verification to support efficient material reuse. Rfid

tags automate verification at key checkpoints, while a Python-based QR generator encodes material information into QR images attached to physical assets. Each QR tag is linked to a MaterialNFT and stores material details, provenance, ownership, logistics, blockchain references, and sustainability indicators such as carbon footprint and reuse potential.

4. System Implementation

Ethereum is used in the Building Project to tokenise construction materials as ERC-721 NFTs. Each NFT stores attributes such as type, origin, supplier, ownership, and status. The *MaterialNFT.sol* smart contract governs minting and lifecycle updates, enabling secure and transparent tracking. Polkadot is adopted in the Bridge Project because of its interoperability capabilities. Materials transferred from Ethereum are represented as wrapped NFTs, enabling management and reuse within the Bridge Project ecosystem. Cross-chain communication between Ethereum and Polkadot is implemented using LayerZero. During transfer, the Ethereum NFT is locked and replaced by a wrapped NFT on Polkadot, preserving ownership and provenance consistency across networks. QR codes and Rfid-based IoT tracking synchronise digital records with physical movement. Each material is linked to its blockchain token, while IoT devices provide real-time updates regarding location and condition.

4.1. Material Circularity Workflow

The workflow consists of four phases: (i) material identification and tokenisation, (ii) transfer request and verification, (iii) cross-chain transfer and logistics tracking, and (iv) delivery confirmation and settlement. Excess materials are first registered on the Building Project blockchain and tokenised as NFTs containing dimensions, condition, ownership history, and sustainability indicators. When the Bridge Project requests the material, the bridge verifies authenticity and availability before locking the Ethereum NFT and minting a wrapped NFT on Polkadot. Before dispatch, QR or Rfid verification is performed. During transportation, GPS and IoT devices continuously update logistics and condition data on-chain. Upon arrival, a final scan confirms delivery and updates ownership on Polkadot through a proof-of-delivery mechanism. Where required, payment settlement can be automated through stablecoins or CBDCs. Sustainability monitoring records the reuse transaction to support circular economy objectives.

The cross-chain material circularity workflow begins when the Building Project initiates a material

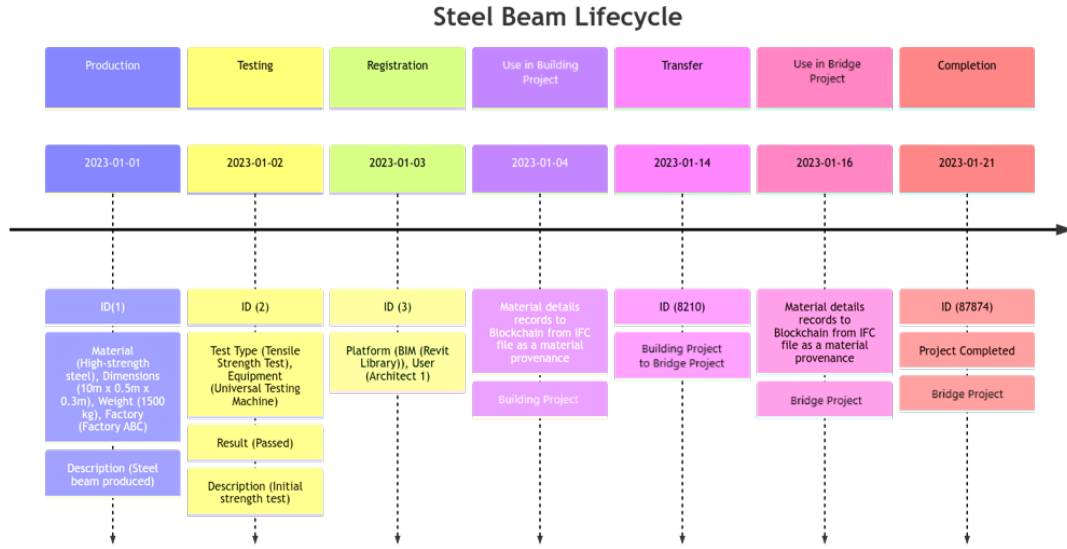


Fig. 2. Steel beam lifecycle process

transfer request to the Bridge Project. The Cross-Chain Smart Contract then verifies material availability and initiates the transfer on the blockchain. During the transaction, quality validation and ISO compliance checks are performed to ensure that the material satisfies required standards. Following verification, the blockchain updates the ledger with the material information and confirms successful transfer completion. Finally, the Bridge Project receives the transfer details, and the Building Project is notified that the transaction has been completed successfully.

4.2. Implementation

The system is implemented using smart contracts and material tracking components to support reuse between projects.

4.2.1. Smart Contracts for Asset Transfer Between Projects

The smart-contract framework supports BIM-blockchain integration requirements. The contracts define rules for circularity functions including transfer management, quality testing, material utilisation, supply-chain verification, and BIM document management. *Material Circularity Contract* manages quantity, schedules, quality requirements, and costs. *Quality Testing Contract* records testing procedures and authorised results on-chain. *Material Utilisation Contract* tracks lifecycle status and usage across project phases. *Supply Chain Contract* records provenance, logistics, certifications, and payment conditions. *Document Management Contract* manages BIM-related documents, permissions, and version control. Smart contracts support asset exchange by recording material details, verifying transactions,

and maintaining auditable records for compliance and monitoring. Figure 2 illustrates the lifecycle of a steel beam from manufacturing and testing to BIM/blockchain registration, reuse, and lifecycle completion.

4.2.2. Smart Contracts for Cross-Chain Material Circularity

In the Building Project, *MaterialNFT.sol* implements the ERC-721 standard to tokenise materials such as steel beams and doors. Each NFT stores metadata including origin, ownership history, sustainability rating, and project information. On the Bridge Project blockchain, *WrappedMaterialNFT.sol* represents materials transferred from Ethereum by minting wrapped NFTs on Polkadot. This preserves ownership integrity and prevents double spending. Cross-chain communication is managed through *LayerZero* using the *CrossChainTransfer.sol* contract, which verifies ownership and stakeholder approval before transfers are executed. The contracts support NFT creation, transfer, and interoperability. *MaterialNFT* handles minting and ownership transfer, while *CrossChainTransfer* locks NFTs on the source chain during transfer. *WrappedMaterialNFT* then generates a wrapped NFT on the destination network.

Cross-Chain Communication Using LayerZero

Because Ethereum and Polkadot use different blockchain architectures, interoperability is achieved through *LayerZero*. Transfer requests are submitted through *CrossChainTransfer.sol* on Ethereum and verified through *LayerZero's* Oracle and Relayer network before asset metadata and ownership information are transmitted to Polkadot. Once verified, a wrapped NFT is minted and registered within the Bridge Project inventory system. The original NFT remains locked

on Ethereum to prevent duplication and maintain consistency. This process provides end-to-end verification of material transfers while maintaining alignment between physical movement and digital records. The LayerZero-based framework improves security, scalability, and interoperability while supporting material traceability and circularity across blockchain ecosystems.

5. Evaluation

The proposed framework was evaluated through a proof-of-concept application carried out using BIM models representing a building construction project and a bridge construction project. The system was implemented in a controlled test network with the aim of evaluating blockchain-supported material transfers, interoperability, material traceability, ownership verification and lifecycle management. The evaluation focused on transaction success rates, confirmation times, gas consumption, execution reliability and cross-chain interoperability between Ethereum and Polkadot.

5.1. Material Circularity from Building Project to Bridge Project

In this scenario, steel beams from the Building Project are reused in the Bridge Project through a blockchain-based process ensuring quality, sustainability, and traceability. The workflow begins with a reuse assessment within the Building Project model. If the materials satisfy reuse criteria, their status is updated on the blockchain and the circularity process begins. Otherwise, they undergo quality testing. Quality test results are recorded in BIM and verified on-chain, ensuring that only compliant materials are approved. A sustainability assessment is then performed before transfer to the Bridge Project is initiated and recorded on the blockchain, creating a tamper-proof history of material reuse. Materials failing assessment are recorded for recycling or disposal. As shown in Figure 3, the process begins with a Material Reuse Assessment evaluating whether steel beams can be reused in the Bridge Project. Reusable materials proceed through blockchain registration and transfer, while non-compliant materials undergo additional quality testing. The case study demonstrates that blockchain-BIM integration supports transparent and efficient material reuse across projects.

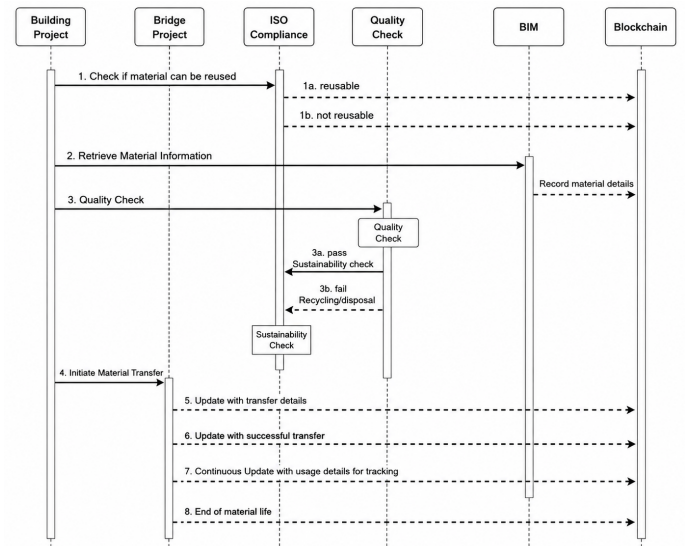


Fig. 3. BIM-Blockchain integrated material reuse across projects

5.2. Cross-Chain Material Circularity between Bridge and Building Projects

The Bridge Project faces challenges related to material tracking and ownership verification because of fragmented supply chains involving multiple contractors and suppliers. These issues often result in inventory inconsistencies and limited visibility of material provenance and condition. The proposed cross-chain framework addresses these issues through decentralised tracking and ownership verification. Materials are tokenised as NFTs and monitored using QR/RFID technologies, enabling real-time inventory visibility. Excess materials from the Building Project can be securely transferred to the Bridge Project through cross-chain interoperability, reducing waste and procurement delays. Through a cross-chain marketplace, reusable materials can be identified, verified against quality and sustainability requirements, and transferred automatically upon delivery confirmation. Proof-of-delivery smart contracts ensure that ownership updates occur only after successful verification, reducing administrative overhead and operational risk. Compared with BIM-only or single-chain blockchain systems, the proposed framework improves interoperability, traceability, and decentralised coordination across projects. This reduces data fragmentation, minimises manual processes, and supports circular economy objectives at scale.

6. Results

6.1. Results of Blockchain based Material Circularity

Blockchain technology was integrated with BIM to evaluate material circularity across construction projects.

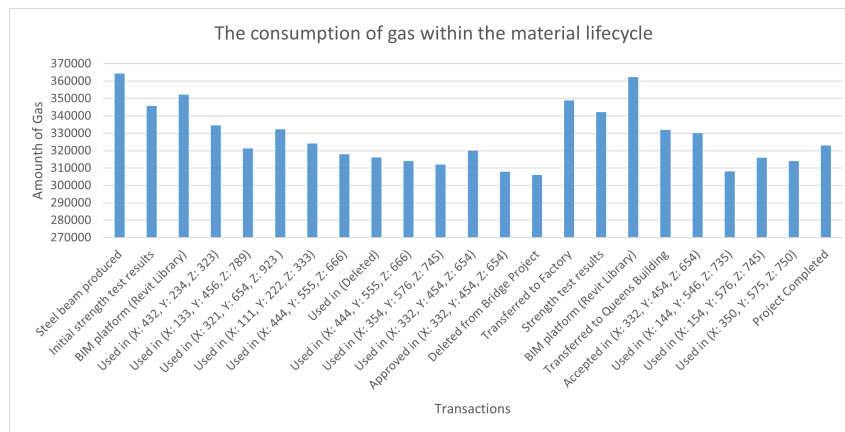


Fig. 4. Gas consumption for each transaction

Material Circularity Results: In the simulation, ten steel beams ($n = 10$ transfer trials) were transferred from the Building Project to the Bridge Project using smart contracts with automated quality checks. Nine transfers were successful, while one failed because of unmet quality requirements, resulting in a 90% success rate (9/10). Average transaction times ranged from 15–20 seconds, with total Ethereum Layer 1 gas fees of 0.00253 ETH. The failed transfer demonstrates the effectiveness of smart contracts in preventing reuse of non-compliant materials.

Blockchain Performance and Cost Analysis: The system was deployed on Ethereum Layer 1, where each transfer incurred an average gas fee of approximately 0.00032 ETH. Throughput ranged between 10 and 15 transactions per second, with confirmation times of 15–20 seconds. Although suitable for construction workflows, Layer 1 costs may limit scalability. Layer 2 solutions such as Optimism or Arbitrum could reduce gas fees by 90–95%. Smart contract execution remained stable, with an average execution time of approximately 15 seconds and no observed failures, confirming the reliability of automated material transfers and quality verification.

Data Transparency and Security: All transfers were immutably recorded on-chain, including material identifiers, project information, timestamps, and quality assessment results. This tamper-proof logging mechanism improved transparency, accountability, and lifecycle traceability while reducing risks of disputes and fraud.

Sustainability and Cost Implications: Material reuse reduced waste generation and demand for new materials. Automated verification and documentation also reduced administrative effort and labour costs. The findings indicate that blockchain enabled circularity can improve sustainability and resource efficiency in construction projects.

Scalability and Future Considerations: Although the framework supports small-scale material circularity, large-scale deployment may require scalability im-

provements to manage higher transaction volumes and costs. Layer 2 solutions, Hyperledger, and integration with ERP and supply-chain systems could improve adoption and operational efficiency.

Smart Contract Integration and Ethereum Transaction Cost Analysis: Smart contract integration was evaluated through Ethereum gas consumption analysis. Figure 4 shows gas usage across lifecycle stages, including production, installation, and completion. Some stages required higher computational resources, indicating optimisation opportunities. Figure 5 shows that gas consumption decreased over repeated executions. Initial transactions such as *addDocument* and *addTest* consumed more gas because of setup costs, while later executions became more efficient. Other functions, including *recordTestResult*, *transferMaterials*, and *updateMaterialStatus*, showed lower and more stable gas usage. These results demonstrate that although some operations incur higher initial costs, gas consumption stabilises over time, supporting the feasibility of blockchain based BIM systems for material circularity.

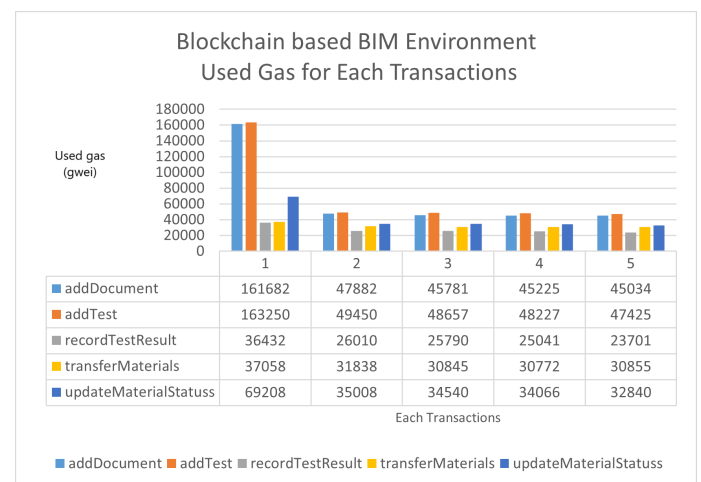


Fig. 5. Gas consumption of recording each transactions in blockchain based BIM environment

6.2. Results of OpenSea Platform for SteelNFT

OpenSea was used to evaluate the minting, trading, and visibility of SteelNFTs on Ethereum. The platform supports ERC-721 and ERC-1155 standards but lacks native cross-chain functionality. SteelNFT minting required approximately 0.00015 ETH with confirmation times of 15–25 seconds, while ownership transfers consumed around 0.00005 ETH and completed within 10–15 seconds. LayerZero token approval required 0.00008 ETH, and cross-chain transfer initiation from Ethereum to Polkadot required approximately 0.000085 ETH with execution times between 30 and 60 seconds. Each SteelNFT stored immutable metadata including token IDs, transaction hashes, and gas fees, enabling full ownership traceability. OpenSea listings also displayed minting dates, prices, and LayerZero transfer fees. Although OpenSea provides accessibility and liquidity for Ethereum NFTs, its 2.5% transaction fee and lack of native interoperability limit its suitability for multi-chain material circularity applications.

6.3. Results of Cross-Chain NFT Transfer

Transfers from Ethereum to Polkadot, tested across repeated trial runs, incurred an average gas cost of 0.00085 ETH and completed in approximately 45 seconds, with a success rate of 98.5%. Reverse transfers required 0.00078 ETH, completed in 42 seconds, and achieved a 97.8% success rate. By comparison, direct single-chain transfers were faster (12–15 seconds) and cheaper (0.00035–0.00042 ETH), with success rates above 99.7%. Results were consistent across all trial runs conducted for each configuration. Additional evaluations showed that transfer costs and confirmation times varied across blockchain architectures. Ethereum–Polygon transfers, evaluated across repeated trial runs, required approximately 0.0005 ETH and completed in an average of approximately 2.5 minutes (range: 2–3 minutes), while Ethereum–Klaytn transfers cost 0.0002–0.0004 ETH and confirmed in an average of approximately 6.5 minutes (range: 5–8 minutes). All figures reflect public testnet deployments. Ethereum–Polkadot transfers were the slowest and most expensive because of architectural differences between EVM and parachain systems. Across all blockchain pairs, NFT metadata remained consistent through decentralised storage solutions such as IPFS, preserving asset identity across networks. The results demonstrate that cross-chain NFT transfers introduce higher costs and latency than single-chain transactions but maintain high reliability. Despite interoperability challenges, the findings confirm the feasibility of cross-chain NFTs for material tracking and circularity

applications.

In order to situate the proposed framework within the existing research literature, Table 1 presents a qualitative comparison between traditional BIM-based materials management, BIM integrated with single-chain blockchain solutions (labelled “Single Chain” in Table 1) and the proposed cross-chain framework.

Table 1. Comparison of the proposed framework with existing approaches

Feature	BIM	BIM + Single-Chain	This paper
Material Passport	✓	✓	✓
Immutable Records	×	✓	✓
NFT Ownership	×	✓	✓
Cross-chain Transfer	×	×	✓
Multi-project Circularity	Limited	Limited	✓
Real-time IoT Tracking	Optional	Optional	✓
Material Provenance	Moderate	High	High
Interoperability	Low	Low	High

6.4. Practical Implications and Limitations

The proposed framework offers various practical benefits for stakeholders in the construction sector. Contractors can verify the origin of materials prior to their reuse, thereby reducing uncertainty in the supply chain and supporting regulatory compliance. Project owners benefit from immutable life-cycle records that support asset management and sustainability reporting. Whilst material suppliers gain access to transparent ownership histories, regulatory authorities can monitor reuse transactions via tamper-proof blockchain records. Despite these advantages, certain limitations remain. The framework has been validated through a controlled proof-of-concept implementation on a testnet infrastructure, instead of being applied to real-world construction projects. Only the Ethereum and Polkadot networks have been examined in depth, and performance has not been assessed under large-scale industrial transaction volumes. Future work will extend the framework to other blockchain ecosystems, evaluate Layer-2 applications, and validate performance under real-world construction supply chain conditions.

7. Conclusion

This study examined the integration of cross-chain blockchain and BIM to improve asset circularity in construction. The proposed material passport framework supports material tracking and management across projects while improving provenance, transparency, traceability, and security. The BIM–blockchain integration provides secure and immutable records of material circularity, quality testing, and status updates. Blockchain decentralised structure enables trusted verification of material flows and supports

more transparent supply-chain management. Overall, the proposed approach identifies several advantages:

- Automated asset tracking through smart contracts, reducing manual labour and transaction time.
- Immutable cross-chain records that improve transparency and reduce risks of fraud or data manipulation.
- Improved material reuse, waste reduction, cost savings, and sustainability performance.

The blockchain based BIM material passport functions as a digital record containing material origin, quality, sustainability, and certification information. Integrated within BIM, the framework supports provenance verification, quality assurance, and compliance with sustainability requirements. Future research will integrate Artificial Intelligence (AI) and Fast Machine Learning (FastML) to improve material tracking, predictive analytics, and decision making. Beyond construction, the framework may also support supply-chain management in manufacturing and logistics by improving material flow, inventory management, and operational coordination.

Data Availability: Implementation details and smart contract codes are available in the public GitHub repository: <https://github.com/yasincel/CrossChain-Interoperability>

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