Blockchain-based Digital Product Passports and their Feasibility in Steelmaking

Sadeer Beden[0009−0009−7564−7726], Connor Blake Hurley, Cinzia Giannetti[0000−0003−0339−5872], and Arnold Beckmann[0000−0001−7958−5790]

Swansea University, SA1 8EN, United Kingdom
sadeer.beden@swansea.ac.uk

Abstract. The transition toward a circular economy requires continuous tracking of material lifecycles through Digital Product Passports (DPP). Blockchain has been proposed for DPP implementations due to their immutable nature, but its application within the steelmaking sector remains largely unexplored. This paper investigates the technical feasibility of a permissioned blockchain framework to serve as a foundational infrastructure for steel DPPs. The proposed framework utilises Hyperledger Fabric with a hybrid storage strategy and cryptographic hash pointers to ensure data integrity and scalability. To validate the framework, we conducted a performance assessment simulating approximately 11.5 years of industrial activity across a 12-node distributed network. The simulation processed over 48 million transactions, displaying ledger stability and storage scalability under operational pressure. Our results display a consistent mean throughput of approx. 210 TPS and stable transaction latency even as the ledger grew linearly. The hybrid data strategy provided pruning that effectively managed storage overhead. These findings suggest that permissioned blockchains are technically feasible to serve as the foundational framework covering the requirements of DPP implementations within the steel supply chain.

Keywords: Blockchain · Digital Product Passport (DPP) · Steelmaking · Hyperledger Fabric.

1 Introduction

As part of the circular economy movement, there is a regulatory push to record the full lifecycle of a product [5], leading to the introduction of Digital Product Passports (DPP) [8]. These passports serve as the digital backbone for this transition and are becoming a mandatory requirement to produce and sell products in the European market under the Ecodesign for Sustainable Products Regulation (ESPR). Under this framework, DPPs are designed to function as digital identity cards throughout a product's lifecycle, storing a variety of data such as material origins, environmental footprints, and recyclability [4].

However, current DPP implementations remain fragmented, often facing limitations with data integration, storage scalability, as well as privacy, transparency, and security [13]. Traditional centralised databases require stakeholders to trust a single managing entity, creating potential conflicts of interest.

Blockchain technology has emerged as a potential solution to address these challenges [3]. Blockchain is a distributed ledger technology that records information across multiple nodes, ensuring that no one single party can alter on-chain information without leaving evidence. This approach provides the transparency, security, and integrity required for multi-stakeholder supply chains. Blockchain also provides smart contracts to enable automation of tasks such as updating, collating and verifying information [10]. The use of cryptographic hashes and links to existing databases provides flexibility, allowing companies to integrate the framework with their established data infrastructures. These core characteristics justify the adoption of blockchain, making it suitable for supporting DPP implementations.

The steel industry is one domain that is transitioning towards the adoption of DPP. Steelmaking encompasses many complex processes, from raw material extraction to finishing processes, all of which generate disparate data points that must make their way into the DPP. Sharing this data across stakeholders without exposing proprietary information requires a decentralised approach. Despite the potential, there is limited literature investigating the adoption of blockchain-driven DPPs for the steelmaking industry.

This paper addresses this gap by evaluating the performance of a blockchain-based framework tailored for steel manufacturing. The scope is not to propose a comprehensive DPP with complex application-layer interactions e.g., audits or economic cost analyses. Instead, the focus is on the performance evaluation of this framework using a simulated system, specifically to establish a baseline for throughput, latency, and storage scalability in this domain.

To achieve this aim, our objectives are to identify a suitable architecture, design a scalable framework, and validate its performance under realistic industrial stress. Consequently, we investigate the following research questions:

- What are the available and most suitable blockchain technologies for this task?
- How can we assess and evaluate the impact and technical feasibility of using blockchain technologies for a steelmaking DPP?
- How can we validate this assessment with an experiment modelling a realistic segment of the UK's steel supply chain?

The contributions of this paper are twofold: (1) A comparative evaluation of blockchain technologies for industrial DPP feasibility, and (2) The deployment of a realistic demonstrator based on steel supply chain parameters to evaluate the performance of the proposed framework. The full results are available in the open-source repository.[1]

[1] https://github.com/bedening/steel-dpp-feasibility-experiment

2 Literature Review

This section reviews blockchain-based DPP implementations with similar methodologies and application domains to provide a basis for our first research question.

Hulea et al. [6] implemented a DPP using Hyperledger Fabric for product lifecycle management. Particularly, their data model captured *Product, Manufacturer, Supplier* and *Material* information, using *cheqd.io* to create unique product identification for each category. The chaincodes were created using *Node.js* and executed CRUD operations. The authors stated that their evaluation focused on response time of CRUD operations, omitting other impacts such as high-volume throughput and storage bloat. Our methodology challenges this by stress-testing these parameters under steelmaking conditions.

Kim et al. [11] focused on solving supply chain privacy using a multi-channel Hyperledger Fabric architecture. The authors set up multiple channels to manage different product stages (material supply chain, product manufacturing, recycling) within the supply chain. The data was segmented into its corresponding channel based on the lifecycle stage of each product, and assigned decentralised identifiers for improved security. The authors stated that although this overall approach enhanced system security and privacy, challenges relating to data integration across various channels remained. In contrast, our focus is less on specific system architecture, and instead aims to understand the feasibility of DPP for steelmaking. We argue that a single-channel hybrid approach with off-chain storage provides a scalable solution as a baseline for the steel industry.

Paolucci et al. [15] investigated the use of the DPP for electronics manufacturing. The authors developed a DPP prototype using eXtended Markup Language (XML) for data digitalisation and blockchain technology for data communication and storage. They validated their model using Ganache, a local Ethereum testing environment, which demonstrated the advantages of adopting Ethereum to track ownership of a washing machine product over its lifecycle. However, the paper also highlighted the limitations in data privacy inherent in Ethereum. This presents a challenge for our use case, which requires the protection of proprietary manufacturing data. The authors further abstracted from details relating to network latency and consensus overhead of a distributed production system. We address these gaps by deploying a distributed permissioned network.

Kannappan et al. [9] proposed a system that combined blockchain and digital twin technologies to enable the creation and sharing of product lifecycle data for DPP. The authors utilised a multi-layer architecture where Ethereum was employed for automation, security, and improved traceability using smart contracts. The authors deployed their network in a development mode that forced instant transactions. This assumption masked the throughput bottlenecks inherent to permissionless networks. Our research addresses this gap by configuring consensus protocols to reflect representative industrial latency.

Xia et al. [18] focused on integrating blockchain technology with DPP in the Reverse Supply Chain (RSC). The authors presented a novel conceptual framework comprising four layers: user interface, application service, blockchain, and data. This structure managed user access, data standardisation, and the distributed ledger of the RSC. The authors stated that RSC often faces issues with uncertainty and low trust, which blockchain generally overcomes. Similarly, Stodt et al. [17] designed a blockchain-enabled DPP framework for healthcare devices such as pacemakers and surgical instruments. This approach established a primary security layer to defend against cyberattacks. They formulated a multi-stage framework covering the full lifecycle of devices, from manufacturing to recycling. Both studies rely on theoretical designs but leave implementation as future work. This highlights a recurring limitation in current literature where theoretical blockchain architectures are rarely validated against realistic industrial constraints. In contrast, this paper evaluates the feasibility of a blockchain-driven DPP for steelmaking based on a realistic use-case.

Furthermore, Canciani et al. [2] proposed a hybrid blockchain to address existing challenges of implementing blockchain-based DPP. Their design used a public blockchain to mirror the state of private data for end-user access. However, this hybrid approach introduced additional layers of complexity that might not be suitable for all industrial contexts. In contrast, our approach explores a different blockchain model tailored to the specific operational demands of the steel industry, prioritising feasibility over architectural complexity.

In summary, current literature lacks rigorous performance evaluations of blockchain-based DPPs within high-volume industrial settings. While conceptual frameworks have been proposed for other sectors, empirical data regarding throughput and storage scalability remain scarce, particularly for the unique demands of steel manufacturing. This paper addresses this research gap by characterising the technical resilience of a permissioned blockchain infrastructure under realistic industrial stress levels.

3 Research Methodology

This research follows a structured methodology to evaluate the technical viability of blockchain as a framework for DPPs in the steel supply chain. The process consists of three distinct phases. First, we evaluate the infrastructure of blockchains suitable for industrial data. Second, we design a hybrid on-chain and off-chain architecture tailored to manufacturing privacy and scalability requirements. Third, we simulate and stress-test the framework using real-world production parameters to establish a performance baseline for throughput and latency. Our use case focuses on system capabilities under intensive conditions rather than specific end-user features of DPP.

3.1 Assessing Blockchain Infrastructures

The steel industry presents unique challenges, recording high transaction volumes, sensitive propriety data, and the need for low-latency verification. As established in the literature, we evaluate three architectural types to address these needs:

- Permissioned Blockchains (e.g., Hyperledger Fabric): These are privatised frameworks that provide a controlled environment where participants on the blockchain are pre-authorised. Additionally, they offer modular consensus mechanisms and fine-grained access control, which are essential when handling sensitive data. Existing studies show private blockchains provide higher transaction *Throughput Per Second* (TPS) with lower latency compared to public blockchains [12].
- Permissionless Blockchains (e.g., Ethereum): These are public frameworks offering decentralisation and high transparency but often at the cost of a transaction fee [14]. They can handle multiple transactions but output a lower TPS and higher latency compared to permissioned blockchains. Additionally, all metadata is publicly visible, which conflicts with privacy requirements in steel manufacturing.
- Decentralised Off-chain Storage (e.g., IPFS, Arweave): These frameworks are effective for storing large documents and certificates [7]. They often focus on one-off payments but lack computational logic and real-time management.

Table 1 summarises the trade-offs between these architectures, demonstrating that permissioned models are best suited for industrial supply chains. We select Hyperledger Fabric for our framework for many reasons, including its channel-based architecture that ensures data privacy between specific consortium members, required for proprietary steel data. Furthermore, its modular consensus and lack of cryptocurrency satisfy the throughput demands of the steel sector more effectively compared to other permissioned blockchains.

Table 1. High level summary of blockchain architectures

	Permissioned	**Permissionless**	**Off-chain**
Throughput	Higher ($> 2,000$ TPS)	Lower ($\approx 15 - 30$ TPS)	N/A (Storage only)
Latency	Milliseconds to seconds	Seconds to minutes	Variable
Data Privacy	Higher (Channels)	Lower (Public Ledger)	Variable (Encrypted)
Costs	Internal costs	Per transaction	Storage-based fees
Governance	Centralised consensus	Decentralised	Decentralised

Beyond infrastructure, storing DPP data directly on the blockchain will eventually lead to ledger bloating and scalability issues [1]. To mitigate this, our study implements a hybrid data strategy that utilises hash pointers [16]. Hyperledger Fabric serves as the on-chain infrastructure to store unique product IDs and cryptographic hashes. Additionally, we use CouchDB as the world state database over alternatives like LevelDB, as CouchDB supports rich JSON querying needed for complex DPP metadata. The primary data payload remains in secure off-chain databases. This approach ensures data integrity, as any off-chain modifications will result in a hash mismatch. In the event of a mismatch, the smart contract flags the DPP as invalid and halts further state transitions until the authentic payload is restored from backups.

3.2 Framework Architecture and Lifecycle

Figure 1 represents the application of our proposed framework to a physical steel product. The product transforms with different properties and ownership throughout its lifecycle, which is recorded and tracked through a DPP.

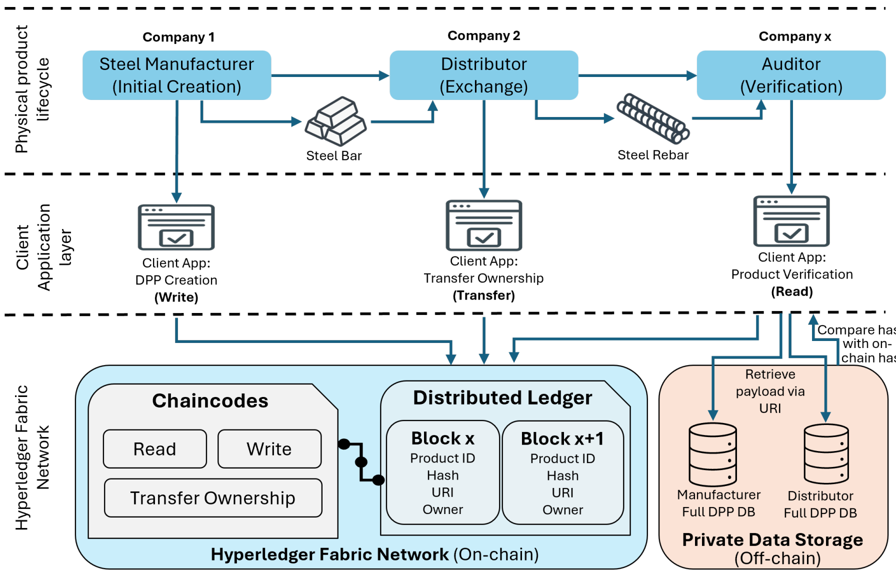

Fig. 1. Proposed Blockchain-based Digital Product Passport for Steelmaking.

The proposed framework reflects the multi-stage lifecycle of steel, tracking a product from its initial creation through various transformations. Typically, this lifecycle is dynamic and decentralised, involving multiple stakeholders, manufacturers, and distributors. We model these interactions as a series of digital state transitions within the blockchain environment. We create smart contracts (chaincodes) implemented via Hyperledger Fabric that execute the following fundamental operations:

- **Write**: Simulating the creation of a new DPP with batch-specific data (e.g., chemical composition and initial carbon footprint). This operation generates a unique product ID and a cryptographic hash of the initial production data.
- **Read**: Enable stakeholders to retrieve the current *State of Truth* for a specific product. This operation returns the on-chain hash, a pointer to the off-chain data, and a validation status, serving as a mechanism to verify the product's documentation matches the record on the ledger.
- **Transfer Ownership**: Simulating the exchange of the product (e.g., from steel bar to rebar). This process updates the *owner* attribute on-chain while maintaining a linked history of previous owners, ensuring transparency.

4 DPP Use Case and Implementation

The objective of this experiment is to evaluate the technical feasibility of a blockchain-driven DPP for the UK steel sector. We simulate the creation and management of DPPs for rebar and tin can production over an extended duration. In this scenario, all products originate as raw steel batches that undergo transformation into specific materials by downstream manufacturers.

To determine the suitability of the framework for this industrial context, we establish three evaluation criteria based on the primary barriers to high-volume blockchain deployment: *(1) Transaction throughput*: the capacity to process concurrent transactions per second, *(2) Latency*: the duration required for a transaction to be committed to the ledger, and *(3) Storage scalability*: the ledger's capacity to manage data growth over a simulated decade of production. We focus exclusively on these metrics because they represent the operational bottlenecks for enterprise ledgers in steel manufacturing.

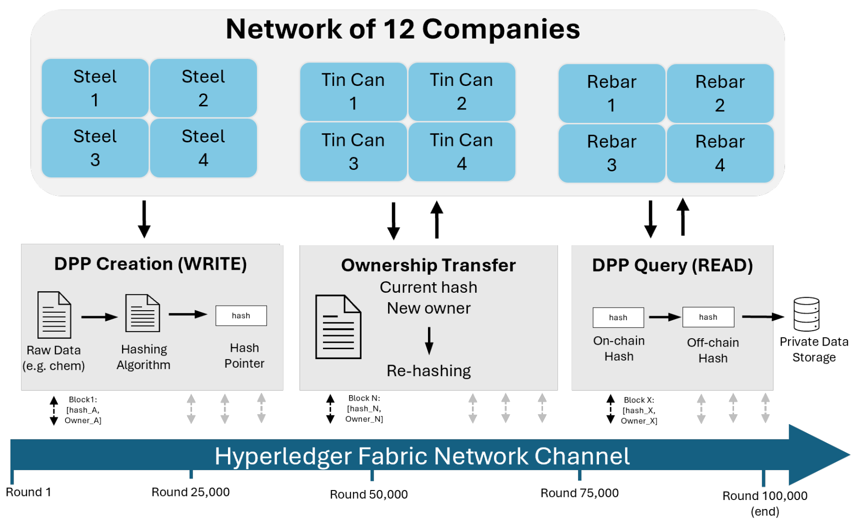

Fig. 2. Proposed Implementation use case network and channel.

The implemented system comprises 12 organisations, as illustrated in Figure 2. Each organisation operates a dedicated Linux server running Ubuntu 24.04.2 LTS, equipped with 4 vCPUs and 8GB of RAM. To evaluate storage performance across varying capacities, nodes were configured with either 250GB or 500GB of SSD storage.

Each organisation maintains a peer node to host the ledger and execute smart contracts (chaincodes). Additionally, three companies also host an orderer, a specialised node responsible for gathering endorsed transactions, sequencing them into batches, and distributing blocks to the peers. These orderers utilise

Raft consensus protocol to ensure a decentralised and synchronised transaction order across the network.

These peers and orderers join one common channel that forms the private communication backbone of the network. Although Hyperledger Fabric allows for partitioning, we utilise a single channel architecture to establish a baseline for simplicity. This environment hosts the chaincode, which implements the smart contracts and logic required for our steelmaking use case. The ledger executes three primary operations: write, read, and change ownership. These functions simulate product creation, data retrieval, and material movement. This experiment focuses on the two fundamental operations: production creation *(Write)* and changing product ownership *(Transfer)*.

To simulate an industrial environment, the experiment is structured into hourly rounds using batched transactions. We define a transaction as a direct interaction between a company server and the blockchain network. We utilise batching instead of individual operations to align with standard industrial production cycles. This approach also enhances storage efficiency, as each transaction in the 12-company network requires 12 cryptographic signatures. Batching mitigates the metadata overhead and space inefficiency associated with individual submissions.

The simulation parameters are grounded in actual industrial volumes, assuming an annual UK production of 1.5 million tonnes of steel for rebar and tin cans. This volume is modelled as 1.2 million tonnes for rebar and 0.3 million tonnes for tin cans, distributed across twelve companies. Each steel company generate 25 billet batches per hour. Downstream, each rebar company consumes 20 billet batches to produce 1–5 rebar batches, while each tin company consumes 5 billet batches to produce 1–3 batches per hour.

Algorithm 1 details the execution logic for a single simulated hour within the environment. The process is executed in parallel across the 12 nodes to ensure the network handles concurrent demands effectively. This operational logic was executed for a total of 100,000 rounds, representing approximately 11.42 years of continuous operation. This resulted in a total of 10,000,000 *Write* operations from steel producers, 10,000,000 *Transfer* operations, and up to 46,000,000 further *Write* operations from downstream manufacturers. This high-volume simulation allows for a comprehensive assessment of the ledger's stability and storage requirements over an extended industrial lifecycle.

4.1 Results and Discussion

We distinguish between two types of transactions in our experiment. External transactions refer to the batched requests sent by company servers to the blockchain network. Internal transactions represent the individual DPPs processed within those batches. For the purpose of evaluating industrial feasibility instead of blockchain performance, we consider internal transactions as the basis for our evaluations.

Table 2 summarises overall measures. During the simulated period, the network successfully processed a total of 48,007,083 transactions in 143.37 hours

Algorithm 1 Simulation of a single round representing 1 hour.

parallel for each Company $n \in \{1 \dots 12\}$ **do** ▷ Executed in parallel threads
  if n is Steel company i **then**
    Execute Batch_Write(25 units) ▷ Initialises 100 total DPPs
  end if
  if n is Tin company j **then**
    Execute Batch_Transfer(5 units) from Steel company
    $x \leftarrow$ random(1, 3)
    Execute Batch_Write($x \times 5$ units) ▷ Creates 20–60 Tin DPPs
  end if
  if n is Rebar company k **then**
    Execute Batch_Transfer(20 units) from Steel company
    $y \leftarrow$ random(1, 5)
    Execute Batch_Write($y \times 20$ units) ▷ Creates 80–400 Rebar DPPs
  end if
end parallel for

Table 2. Experiment total transactions and time after 100,000 rounds.

Organisation	Total Transactions	Total Time
steelCompany1	2,500,000	26,897.58s
steelCompany2	2,500,000	26,301.74s
steelCompany3	2,500,000	25,089.03s
steelCompany4	2,500,000	23,876.81s
tinCompany1	1,499,559	43,271.35s
tinCompany2	1,500,156	43,451.32s
tinCompany3	1,500,380	41,974.19s
tinCompany4	1,500,902	41,270.80s
rebarCompany1	8,002,044	61,209.73s
rebarCompany2	8,001,830	60,238.54s
rebarCompany3	8,001,892	60,880.19s
rebarCompany4	8,000,320	61,666.23s
	48,007,083	**516,127.51s**

execution effort. Specifically, the rebar companies handled the highest volume of the network load, accumulating over 32,000,000 transactions and maintaining consistent execution times. The processed volume demonstrates that the Hyperledger Fabric infrastructure can handle over a decade of simulated industrial data within a short execution window.

To analyse the performance of the simulated system, Figure 3 displays throughput as internal transactions per second (TPS). The data is grouped into intervals, where each interval represents the average of 1,000 rounds. The system shows a stable mean TPS staying in the range 200 to 220 throughout the experiment, with regular min TPS troughs related to wider system updates like pruning of CouchDB. A stable mean TPS indicates that this permissioned architecture effectively accommodates the transaction volumes for the steel domain.

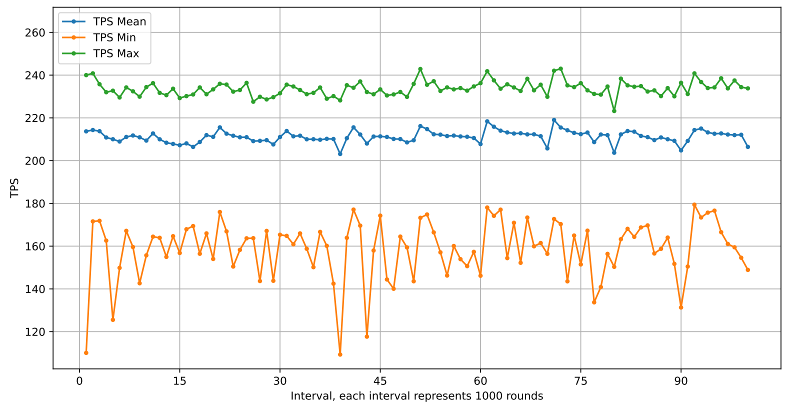

Fig. 3. Experiment results displaying internal transactions per second.

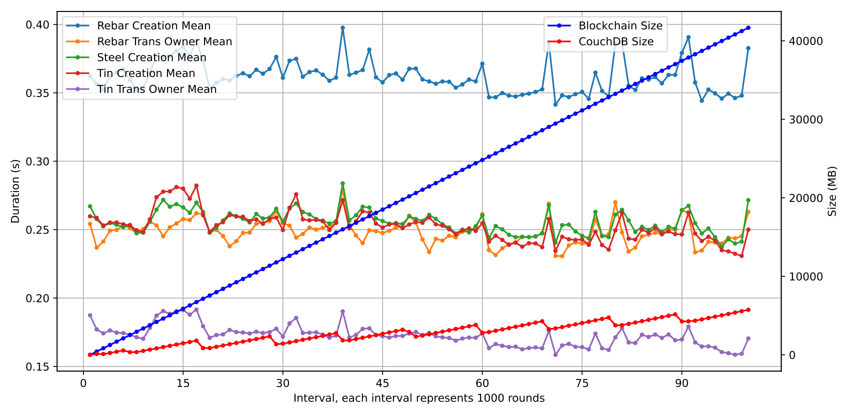

Fig. 4. Experiment results displaying throughput, latency, and size.

To further analyse the stability of the system, Figure 4 displays the performance for the different batch transactions alongside the growth of the ledger, again with a grouping of data into intervals of 1,000 rounds. The primary Y-axis represents the transaction latency/duration in seconds, while the secondary Y-axis represents the storage size values for the blockchain and CouchDB databases. The findings indicate that the performance of each transaction type remains stable over the full duration of the experiment, with latency fluctuating between 0.15s and 0.40s. Despite this stability, specific points of correlation were observed where all transaction types experienced a simultaneous increase in latency (e.g., at interval 40). This suggests that external environmental factors temporarily impacted performance, rather than an inherent bottleneck within the chaincode logic.

As expected, the blockchain grew linearly to approximately 42GB to store transaction history and cryptographic hashes. The CouchDB world state database remained significantly smaller, peaking near 5GB. Notably, the size of CouchDB exhibits "jumps" at regular intervals. This is due to the internal database pruning process that occurs periodically to optimise storage.

5 Conclusion

This paper validates the feasibility of a permissioned blockchain as the foundational infrastructure for Digital Product Passports (DPP) in the steel industry. Addressing our first research question, we establish that permissioned ledgers, specifically Hyperledger Fabric, are the most suitable blockchain technologies due to their high throughput and privacy controls. This research addresses a literature gap by providing a rigorous evaluation of blockchain performance in an industrial domain requiring both high transaction volumes and long-term data integrity.

The experimental results demonstrate the framework's feasibility for industrial applications, effectively handling the steel industry's throughput demands with low latency. During stress testing, we recorded a mean throughput of approx. 210 TPS, which far exceeded the peak demand of our realistic experiment workload of 540 transactions per hour. Additionally, off-chain storage via hash pointers effectively mitigated the risk of ledger bloat, ensuring storage scalability over a product's lifecycle. The successful pruning of the CouchDB world state database, which remained significantly smaller than the total blockchain ledger, further demonstrated this scalability.

Future work focuses on evolving our implementation into a functional DPP ecosystem. This research abstracted the data model to focus on baseline infrastructure throughput. Future iterations need to incorporate specific DPP semantics, interoperability standards, and regulatory compliance data.

Acknowledgements

For the purpose of open access, the authors have applied a CC BY licence to any Author Accepted Manuscript version arising from this submission. This project was enabled through EPSRC-funded project SUSTAIN Future Manufacturing Research Hub (EP/S018107/1).

Disclosure of Interests

The authors declare no conflict of interest.

References

1. Alzoubi, Y.I., Mishra, A.: Techniques to alleviate blockchain bloat: Potentials, challenges, and recommendations. Computers and Electrical Engineering **116**, 109216 (2024)

2. Canciani, A., Felicioli, C., Severino, F., Tortola, D.: Enhancing supply chain transparency through blockchain product passports. In: 2024 IEEE International Conference on Pervasive Computing and Communications Workshops and other Affiliated Events (PerCom Workshops). pp. 751–756 (2024)
3. Doguchaeva, S., Zubkova, S., Katrashova, Y.: Blockchain in public supply chain management: advantages and risks. Transportation Research Procedia **63**, 2172–2178 (2022)
4. European Union: Regulation (EU) 2024/1781 (Ecodesign for sustainable products). Official Journal of the European Union (2024), https://eur-lex.europa.eu/eli/reg/2024/1781/oj
5. Geissdoerfer, M., Savaget, P., Bocken, N.M., Hultink, E.J.: The circular economy – a new sustainability paradigm? Journal of Cleaner Production **143**, 757–768 (2017)
6. Hulea, M., Miron, R., Muresan, V.: Digital product passport implementation based on multi-blockchain approach with decentralized identifier provider. Applied Sciences **14**(11) (2024)
7. Ismail, A., Toohey, M., Lee, Y.C., Dong, Z., Zomaya, A.Y.: Cost and performance analysis on decentralized file systems for blockchain-based applications: State-of-the-art report. In: 2022 IEEE International Conference on Blockchain (Blockchain). pp. 230–237 (2022)
8. Jensen, S.F., Kristensen, J.H., Adamsen, S., Christensen, A., Waehrens, B.V.: Digital product passports for a circular economy: Data needs for product life cycle decision-making. Sustainable Production and Consumption **37**, 242–255 (2023)
9. Kannappan, R., Hatin, J., Bertin, E., Crespi, N.: Enhancing digital product passport through decentralized digital twins. In: 2025 12th IFIP International Conference on New Technologies, Mobility and Security (NTMS). pp. 300–308 (2025)
10. Khan, S.N., Loukil, F., Ghedira-Guegan, C., Benkhelifa, E., Bani-Hani, A.: Blockchain smart contracts: Applications, challenges, and future trends. Peer-to-peer Networking and Applications **14**(5), 2901–2925 (2021)
11. Kim, J., Lee, S., Kim, H.: Blockchain-based digital product passport for the circular economy. In: 2024 International Conference on Platform Technology and Service (PlatCon). pp. 188–191 (2024)
12. Kwadzode, D.: Performance comparison of blockchain platforms for modeling financial transactions: A case study of ethereum and hyperledger fabric. International Journal of Finance, Economics and Business **4**, 50–58 (03 2025)
13. Lopes, C., Barata, J.: Digital product passport: A review and research agenda. Procedia Computer Science **246**, 981–990 (2024)
14. Mohammed, A.H., Abdulateef, A.A., Abdulateef, I.A.: Hyperledger, ethereum and blockchain technology: A short overview. In: 2021 3rd International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA). pp. 1–6 (2021)
15. Paolucci, A., Gianvincenzi, M., Marconi, M., Favi, C., Pennino, D.: Development of a decentralized digital product passport for enhanced lifecycle management of electrical and electronic equipment. Procedia CIRP **135**, 356–361 (2025)
16. Sheth, H., Dattani, J.: Overview of blockchain technology. Asian Journal For Convergence In Technology (AJCT) (2019)
17. Stodt, F., Ruf, P., Reich, C.: Blockchain-enabled digital product passports for enhancing security and lifecycle management in healthcare devices. In: 2024 8th Cyber Security in Networking Conference (CSNet). pp. 44–51 (2024)
18. Xia, H., Li, J., Li, Q.J., Milisavljevic-Syed, J., Salonitis, K.: Integrating blockchain with digital product passports for managing reverse supply chain. Procedia CIRP **132**, 215–220 (2025), 12th CIRP Global Web Conference (CIRPe 2024)