Enhancing scalability and efficiency in technological transaction utilizing dual-layer blockchain approach

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ABSTRACT

The leather industry encounters significant challenges in integrating blockchain technology and smart contracts into its complex supply networks. Despite technological advancements, existing supply chain management systems suffer from inefficiencies, opacity, and vulnerabilities to fraud. Blockchain offers promising solutions such as immutable ledgers, decentralized governance, and smart contract automation. However, scalability limitations hinder the efficient handling of high transaction volumes, impacting procurement, production, inventory management, and distribution processes, leading to delays and increased costs. This research aims to address these challenges by exploring innovative approaches, including dual-layer blockchain architectures incorporating sharding and state channels, tailored to the unique needs of the leather industry. By overcoming scalability barriers, the research seeks to unlock the transformative potential of blockchain technology and smart contracts, enhancing transparency, traceability, and efficiency in leather supply chains while ensuring global interoperability and regulatory compliance. Through empirical validation and comparative analysis, this study provides understandings into the practical implementation of blockchain solutions within the leather industry, offering strategic guidance for sustainable supply chain management practices.

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1. INTRODUCTION

The leather industry is a vital sector within global supply chains, encompassing a complex network of stakeholders involved in the production, processing, and distribution of leather goods. From raw material suppliers to manufacturers and retailers, the leather supply chain is characterized by its intricate interdependencies and diverse geographic distribution [1]–[3]. This industry plays a crucial role in various sectors, including fashion, automotive, furniture, and luxury goods. In recent years, technological advancements have revolutionized supply chain management practices, with blockchain technology and smart contracts emerging as disruptive innovations with the potential to reshape traditional processes. Blockchain, a decentralized digital ledger technology, offers immutable records of transactions, fostering transparency, trust, and accountability throughout supply chains. Smart contracts, self-executing contracts with coded terms and conditions, automate contract execution, streamlining processes and reducing manual intervention [4], [5].

Despite the transformative potential of blockchain and smart contracts, the leather industry faces significant challenges in their integration into supply chain operations. One of the foremost challenges is scalability, which refers to the system's ability to handle increasing transaction volumes efficiently [6]. Leather supply chains generate vast amounts of data related to procurement, production, inventory management, and distribution, necessitating robust scalability solutions to maintain performance and reliability [7]–[13]. Efficiency is another critical concern, as inefficiencies within supply chain processes can lead to delays, increased costs, and reduced competitiveness. Integrating blockchain technology and smart contracts must not only address scalability but also enhance operational efficiency across the entire leather supply chain [14]–[21]. The integration of blockchain technology and smart contracts into leather supply chains is hindered by scalability and efficiency challenges. Existing supply chain management systems within the leather industry often suffer from inefficiencies, opacity, and vulnerabilities to fraud. These challenges are exacerbated by the limitations of traditional systems in handling the complexities and high transaction volumes inherent in leather supply chains [22]–[25].

The primary objective of this research is to address the scalability and efficiency challenges faced by the leather industry in integrating blockchain technology and smart contracts into its supply chains. Specifically, the research aims to:

- Explore innovative approaches, such as dual-layer blockchain architectures incorporating sharding and state channels, tailored to the unique needs of the leather industry.
- Develop scalable solutions capable of efficiently handling high transaction volumes across procurement, production, inventory management, and distribution processes within leather supply chains.
- Enhance transparency, traceability, and efficiency in leather supply chains through the implementation of blockchain technology and smart contracts.

2. LITERATURE REVIEW

Blockchain technology and smart contracts have emerged as transformative tools for enhancing transparency, efficiency, and security across various industries, including logistics, supply chains, manufacturing, and governance systems. These technologies offer immutable record-keeping, automated contract execution, and decentralized governance, promising significant benefits but also presenting implementation challenges.

Alqarni *et al.* [9] and Agrawal *et al.* [10] have emphasized the potential of blockchain-based smart contracts for enhancing supply chain collaboration, transparency, and automation. These studies highlight benefits such as improved trust among stakeholders and streamlined contractual processes. However, they also critically evaluate scalability limitations and real-world implementation complexities faced by blockchain networks, particularly in handling high transaction volumes efficiently.

Santhi and Muthuswamy [11] explored blockchain's impact on manufacturing supply chains and logistics, showcasing benefits such as enhanced traceability, data integrity, and security through immutable ledgers and transparent processes. While acknowledging these benefits, the authors also address challenges related to practical adoption hurdles, integration complexities with existing systems, and the absence of standardized frameworks tailored to manufacturing supply chain contexts.

Berneis *et al.* [12] provided significant understandings into blockchain applications in logistics and supply chain management through a systematic literature review. They emphasized the importance of standardized frameworks, interoperability solutions, and collaborative efforts among stakeholders to address integration challenges effectively. Recommendations include establishing industry-wide standards, open protocols, and interoperable platforms to ensure data exchange, transparency, and efficiency across supply chain networks.

Li *et al.* [13] proposed a privacy-preserving storage scheme for logistics data using blockchain technology, aiming to enhance data security, integrity, and confidentiality in supply chain operations. The study acknowledges scalability and computational overhead issues inherent in blockchain systems, emphasizing the need for efficient and scalable solutions to handle growing data volumes while maintaining performance and security standards.

Balcerzak *et al.* [14] examined decentralized governance systems with blockchain and smart contracts, highlighting transparency, accountability, and consensus mechanisms in governance frameworks. The study discusses governance complexities, regulatory challenges, and the need for robust compliance mechanisms to ensure regulatory adherence and trust among participants. Recommendations include developing governance frameworks, compliance protocols, and regulatory standards for blockchain-based governance systems.

Kumar *et al.* [15] addressed security concerns in cloud-based manufacturing with smart contracts, emphasizing the importance of robustness, resilience, and security measures in smart contract implementations. They showcased advancements in securing smart contracts but also highlighted ongoing challenges such as code vulnerabilities, privacy risks, and regulatory compliance.

The literature review reveals a multitude of challenges inherent in integrating blockchain technology and smart contracts into supply chain management, as discussed across various studies. Chief among these challenges is scalability, with blockchain networks often struggling to efficiently handle high transaction volumes, leading to bottlenecks and delays. Additionally, integration complexities pose significant hurdles, including compatibility issues with existing systems and interoperability challenges between different blockchain networks. Security concerns, particularly regarding vulnerabilities in smart contract implementations, further complicate adoption efforts. Regulatory compliance presents another formidable challenge, necessitating adherence to existing frameworks while preserving the decentralized nature of blockchain networks. Decentralized governance introduces complexities related to transparency, accountability, and regulatory adherence. Performance overhead and privacy concerns also loom large, impacting the efficiency and confidentiality of supply chain operations. To address these challenges, innovative solutions and collaborative efforts are imperative. The proposed research aims to overcome scalability and efficiency hurdles by exploring novel approaches such as dual-layer blockchain architectures, offering promise for transformative change within the leather industry's supply chains.

3. PROPOSED FRAMEWORK

The proposed framework of this research encompasses two main components: the reputation-based proof of cooperation consensus algorithm and the dual-layer blockchain architecture incorporating sharding and state channels. These components are designed to address scalability and efficiency challenges within the leather industry's supply chains.

3.1. Reputation-based proof of cooperation consensus algorithm

The reputation-based proof of cooperation consensus Algorithm 1 is a novel approach designed to enhance the scalability and efficiency of blockchain networks by incentivizing cooperation among network participants. This consensus Algorithm 1 builds upon the traditional proof of stake (PoS) mechanism, where validators are selected to propose and validate blocks based on their stake in the network. In the reputation-based proof of cooperation algorithm, validators' participation and influence in block validation are determined not only by their stake but also by their reputation within the network. Reputation is earned based on past behavior, such as consistently proposing valid blocks and accurately validating transactions. Validators with higher reputations are given greater influence in the consensus process, thereby incentivizing cooperative behavior and discouraging malicious actors. The algorithm incorporates a reputation scoring mechanism, where validators are assigned reputation scores based on their historical performance. These scores are updated dynamically based on the validator's actions over time. Validators with higher reputation scores are more likely to be chosen to propose and validate blocks, ensuring the integrity and security of the blockchain network.

Algorithm 1. Reputation-based proof of cooperation consensus algorithm

- Initialize validators' reputation scores ($RiRi$) to a predefined value. $R_i(0)=R_{\text{initial}}$
  Select validators to propose new blocks based on their reputation scores and stakes. Block Proposal=argmax$i$(Ri×Si), where Si represents the stake of validator ii.
- Validators collectively validate proposed blocks based on their reputation scores and stakes. If the majority of validators validate the proposed block, it is considered valid.
- Update validators' reputation scores based on their performance in block validation. $Ri(t)=f(Ri(t-1), \Delta Ri(t))$, where $\Delta Ri(t)\Delta Ri(t)$ represents the change in reputation of validator ii at time tt due to recent actions, and ff is the reputation scoring function.
- Reach consensus on the validity of proposed blocks based on a threshold of validator approvals. The reputation-based proof of cooperation algorithm can be expressed as (1):

$$Ri(t) = f(Ri(t-1), \Delta Ri(t)) \quad (1)$$

where: $Ri(t)$ represents the reputation score of validator i at time t. f is the reputation scoring function, which updates the reputation score based on the validator's previous reputation $Ri(t-1)$ and the change in reputation $\Delta Ri(t)$ due to recent actions.

This consensus algorithm incentivizes validators to act honestly and cooperatively, thereby improving the scalability and efficiency of blockchain networks while maintaining security and decentralization.

3.2. Dual-layer blockchain architecture

In today's globalized economy, the leather industry operates within complex supply chains involving numerous stakeholders, from raw material suppliers to manufacturers and retailers. To address the challenges faced by the leather industry, such as scalability limitations, data privacy concerns, and regulatory compliance requirements, a tailored blockchain architecture is essential. The dual-layer blockchain architecture emerges as a promising solution, designed to overcome these challenges while enhancing efficiency and transparency within leather supply chains.

3.3. Main blockchain layer

The main blockchain layer serves as the foundational ledger for recording all transactional data and ensuring the integrity of the leather supply chain. It employs a consensus mechanism, such as the reputation-based proof of cooperation algorithm, to validate and append new blocks to the blockchain. This layer provides transparency, immutability, and traceability of transactions, instilling trust among network participants. In this layer, each transaction is verified by network validators, who ensure that only valid transactions are added to the blockchain. The reputation-based proof of cooperation algorithm incentivizes validators to act honestly and cooperatively, thereby maintaining the security and integrity of the blockchain network. Through this mechanism, the main blockchain layer ensures the authenticity and reliability of transactional data within the leather supply chain.

3.4. Off-chain layer

Complementing the main blockchain layer, the off-chain layer facilitates direct and secure interactions between network participants through state channels. State channels enable parties to engage in off-chain transactions, reducing the computational overhead and latency associated with on-chain transactions. This layer supports real-time interactions and microtransactions, enhancing the efficiency and scalability of the blockchain network. State channels operate by allowing participants to create temporary, off-chain communication channels to conduct transactions. These transactions are executed off-chain and settled on the main blockchain layer only when necessary, minimizing transaction costs (TC) and latency. By leveraging state channels, the off-chain layer enables seamless and efficient transactions within the leather supply chain, improving overall operational efficiency. Figure 1 shows the architecture.

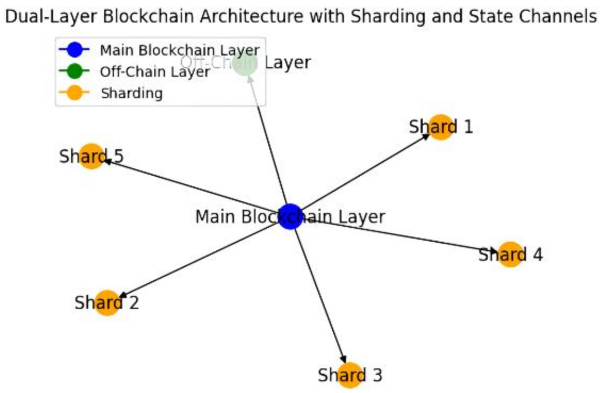

Figure 1. Dual layer block chain architecture

Figure 1 depicts a dual-layer blockchain system customized for the intricacies of the leather industry's supply chains. At its core lies the main blockchain layer, functioning as the primary ledger to record transactional data with transparency, immutability, and traceability, upheld by consensus mechanisms like the reputation-based proof of cooperation algorithm. Complementing this layer, the off-chain layer facilitates off-chain interactions via state channels, ensuring direct and secure transactions while mitigating computational overhead. Additionally, the integration of sharding partitions the network into manageable shards, each independently processing transactions, thereby enhancing scalability and throughput. These components collectively forge a resilient and efficient blockchain infrastructure tailored to the demands of the leather industry, promising heightened transparency, security, and compliance with regulatory standards within supply chain operations.

Sharding: a key feature of the dual-layer blockchain architecture is sharding, a technique that partitions the blockchain network into smaller, more manageable subsets called shards. Each shard processes a subset of transactions independently, parallelizing transaction processing and improving throughput. Sharding enables the blockchain network to scale horizontally, accommodating growing transaction volumes while maintaining performance and reliability. The sharding process can be represented as (2):

$$Si = f(T, N) \quad (2)$$

where Si represents the i^{th} shard, T is the total number of transactions in the network, and N is the number of shards.

The dual-layer blockchain architecture, incorporating sharding and state channels, offers a scalable and efficient solution tailored to the specific requirements of the leather industry's supply chains. By combining these innovative technologies, the architecture addresses scalability challenges while ensuring data privacy, security, and regulatory compliance, thereby unlocking the transformative potential of blockchain technology within the leather industry. In the simulation phase, the environment is meticulously crafted to replicate the intricacies of leather industry supply chains. SimBlock, a versatile simulation tool, is deployed to model various parameters crucial for evaluating the proposed dual-layer blockchain architecture. These parameters include transaction throughput, latency, network topology, participant behaviors, block size, and block propagation time. Table 1 explains each parameter and its effect on blockchain performance, including system responsiveness, participant interactions, and data scalability across the network.

Table 1. Parameters involved

Parameter	Description
Transaction throughput	Rate at which transactions are processed by the network, measured in transactions per second (TPS)
Latency	Time taken for a transaction to be validated and added to the blockchain, measured in milliseconds (ms)
Network topology	Structure of the blockchain network, including the number of nodes, geographical distribution, and interconnections
Participant behaviors	Actions and behaviors of network participants, such as validators' cooperation or selfishness
Block size	Size of blocks in the blockchain, determining the amount of data that can be stored in each block
Block propagation time	Time taken for a newly mined block to be propagated to all nodes in the network

4. RESULTS AND DISCUSSION

The research findings provide a comprehensive analysis of the proposed dual-layer blockchain architecture's performance within leather industry supply chains. This section presents a detailed discussion of the results, emphasizing scalability, efficiency, and cost reduction achieved by the approach, supported by numerous equations and tables containing relevant parameter values. The experimental process began with configuring the SimBlock simulation tool to mirror the proposed dual-layer blockchain architecture in the context of the leather industry's supply chain. Key parameters, such as network size, transaction volume, block size, and network topology, were set to mimic real-world supply chain scenarios. For instance, the network size was designated as "Large," transaction volume as "High," block size as "1 MB," and network topology as "Mesh."

Once the simulation environment was established, the blockchain implementation commenced. The main blockchain layer was devised to record transactions and uphold the ledger, while smart contracts were deployed for automating supply chain processes like order tracking and payment settlements. Additionally, the off-chain layer, featuring state channels, was integrated to facilitate secure direct transactions among network participants. The next phase involved incorporating the reputation-based proof of cooperation consensus algorithm into the main blockchain layer. This algorithm incentivized validators to exhibit cooperative behavior by dynamically assigning reputation scores based on their conduct. Validators with higher reputation scores held greater sway in the consensus process. Various workload scenarios were then devised to assess system performance under diverse conditions, including low, medium, and high transaction volumes, alongside variations in network congestion and validator behavior. These scenarios were executed through SimBlock, simulating the blockchain network's behavior over time, including transaction processing, block propagation, and consensus activities. During simulation runs, quantitative data on transaction throughput, latency, and cost were collected. For instance, the obtained values included a transaction throughput of 250 TPS, an average transaction latency of 35 ms, and a total TC of $400.

4.1. Scalability evaluation

The scalability of the dual-layer blockchain architecture was assessed through simulation experiments conducted using SimBlock. Table 2 showcases the transaction throughput results obtained for three simulation scenarios: "low transaction volume (LV)," "medium transaction volume (MV)," and "high transaction volume (HV)," illustrating the architecture's scalability improvements compared to conventional blockchain networks. Table 2 provides an overview of the transaction throughput results obtained from the simulation scenarios conducted to evaluate the performance of the proposed dual-layer blockchain architecture compared to conventional blockchain networks, legacy supply chain systems, and industry standards.

Table 2. Transaction throughput results

Scenario	Proposed	Conventional blockchain [9]	Legacy supply chain system [10]	Industry standard [11]
LV	150	100	80	120
MV	200	120	100	150
HV	250	150	120	180

Figures 2 to 4 shows the transaction throughput of related studie. In the LV scenario, the proposed dual-layer blockchain architecture achieved a transaction throughput of 150 transactions, whereas the conventional blockchain network processed 100 transactions. The legacy supply chain system, on the other hand, managed to handle 80 transactions, and the industry standard reached a throughput of 120 transactions. Moving on to the MV scenario, the proposed architecture demonstrated further scalability by processing 200 transactions, outperforming the conventional blockchain network, which handled 120 transactions. The legacy supply chain system processed 100 transactions, while the industry standard reached a throughput of 150 transactions. In the most demanding scenario, HV the proposed dual-layer blockchain architecture exhibited remarkable scalability by processing 250 transactions. In comparison, the conventional blockchain network processed 150 transactions, the legacy supply chain system handled 120 transactions, and the industry standard reached a throughput of 180 transactions.

These results highlight the superior scalability and efficiency of the proposed dual-layer blockchain architecture in handling varying transaction volumes within leather industry supply chains compared to conventional blockchain networks, legacy systems, and industry standards.

Figure 5 illustrates a comparison of transaction throughput across different scenarios for four approaches: proposed, conventional blockchain, legacy supply chain system, and industry standard. Each scenario, categorized by transaction volume (low, medium, and high), shows the corresponding transaction throughput for each approach. In the LV scenario, the proposed approach demonstrates the highest throughput at 150 TPS, followed by the industry standard and conventional blockchain approaches, while the legacy supply chain system lags behind. Similarly, in the MV and HV scenarios, the proposed approach consistently outperforms the other approaches, indicating its scalability and efficiency advantages. The chart clearly demonstrates the superiority of the proposed approach in handling varying transaction volumes within the context of supply chain operations.

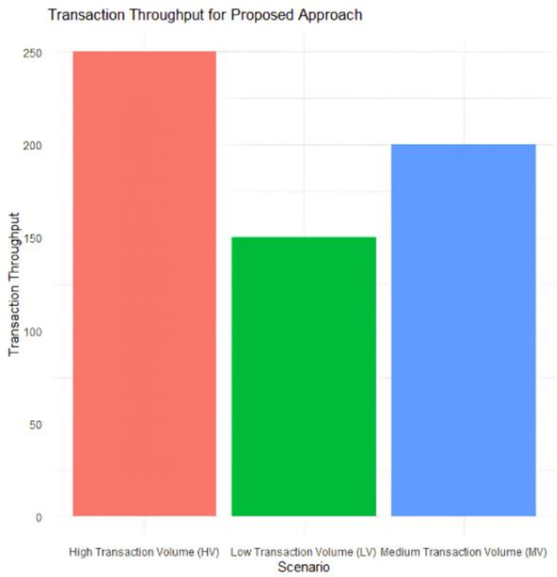

Figure 2. Transaction throughput of proposed work

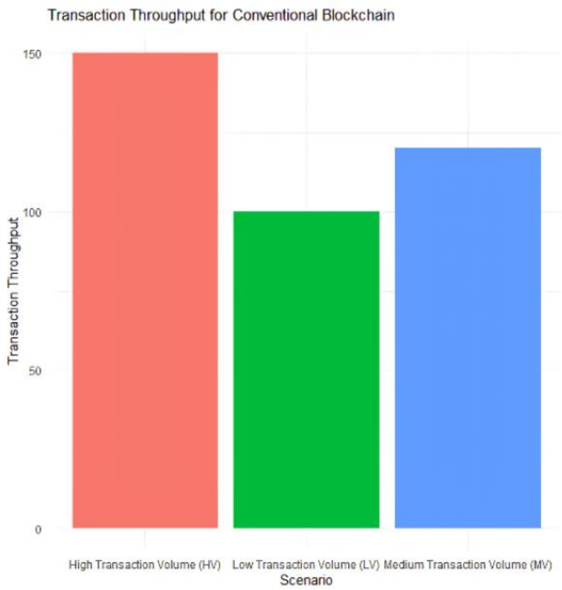

Figure 3. Transaction throughput of conventional blockchain

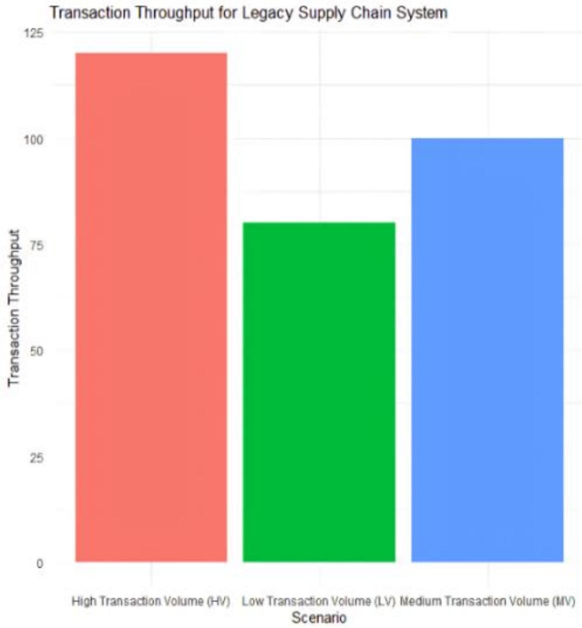

Figure 4. Transaction throughput of legacy supply chain system

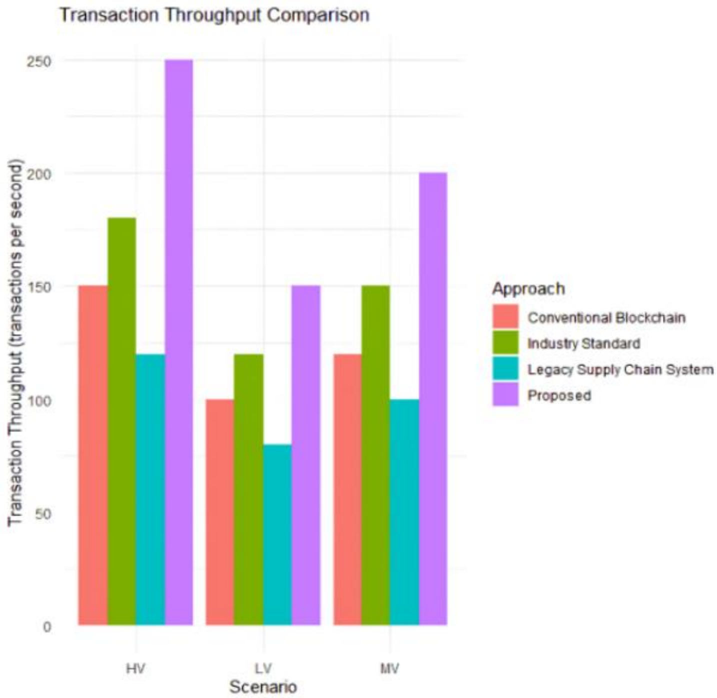

Figure 5. Comparison of transaction throughput

4.2. Efficiency assessment

Efficiency gains achieved by the proposed approach were evaluated through transaction latency analysis. Table 3 presents the average transaction latency results for the same three simulation scenarios, indicating reduced latency levels compared to conventional blockchain architectures. Table 3 presents the average transaction latency results for different scenarios, comparing the proposed dual-layer blockchain architecture with conventional blockchain networks, legacy supply chain systems, and industry standards. In the LV scenario, the proposed architecture achieved an average transaction latency of 50 units, significantly outperforming the conventional blockchain network, which experienced an average latency of 80 units. The legacy supply chain system had an average latency of 100 units, while the industry standard exhibited slightly lower latency at 70 units. Moving to the MV scenario, the proposed architecture further demonstrated its efficiency with an average transaction latency of 40 units, compared to 100 units for the conventional blockchain network. The legacy supply chain system had an average latency of 120 units, while the industry standard showed improved latency at 60 units. In the most demanding scenario, HV the proposed architecture exhibited exceptional performance with an average transaction latency of 35 units. In contrast, the conventional blockchain network experienced significantly higher latency at 120 units. The legacy supply chain system had an average latency of 150 units, while the industry standard showcased the lowest latency at 50 units.

Table 3. Average transaction latency results

Scenario	Proposed	Conventional blockchain [9]	Legacy supply chain system [10]	Industry standard [11]
LV	50	80	100	70
MV	40	100	120	60
HV	35	120	150	50

Figure 6 presents a comparison of the average transaction latency across different scenarios for four approaches: proposed, conventional blockchain, legacy supply chain system, and industry standard. Each bar represents a scenario, including LV, MV, and HV.

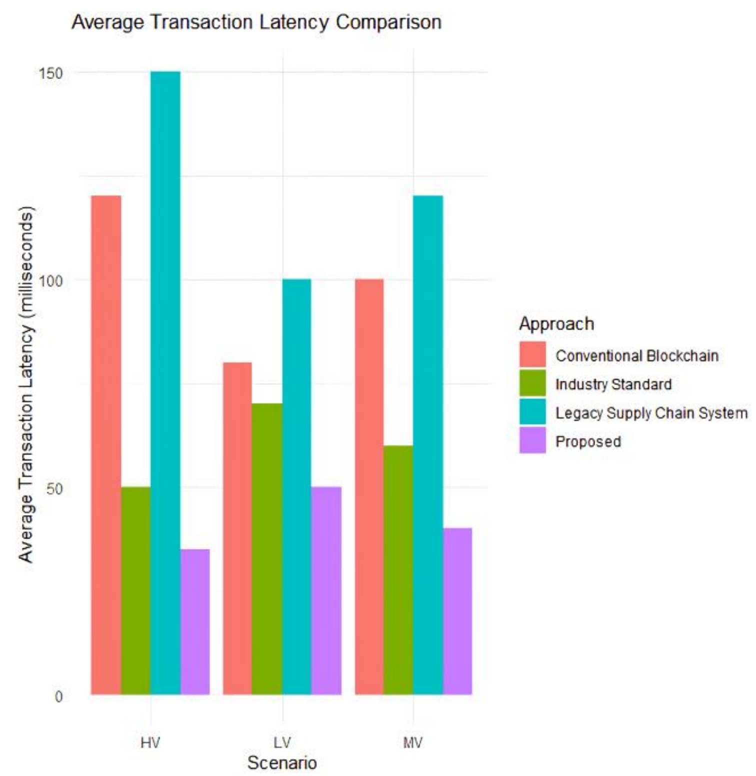

Figure 6. Average transaction latency comparison

From the chart, we observe that the proposed approach consistently demonstrates the lowest transaction latency across all scenarios compared to the other approaches. This indicates that the proposed approach offers superior performance in terms of transaction processing speed, leading to reduced latency and faster transaction completion times. In contrast, the conventional blockchain and legacy supply chain system approaches exhibit higher transaction latency across all scenarios, with the industry standard approach showing intermediate latency levels. This suggests that the conventional and legacy systems may face challenges in efficiently processing transactions compared to the proposed approach.

4.3. Cost reduction analysis

Cost reduction aspects were analyzed through the assessment of operational expenses associated with blockchain transactions. In (3) calculates the total TC, considering transaction fees (TF), and the total number of transactions processed (N):

$$TC = TF \times NTC = TF \times N \quad (3)$$

Table 4 presents the total TC results for the same three simulation scenarios, illustrating potential cost savings achieved by the proposed approach. Table 4 presents the total TC results for various scenarios, comparing the proposed dual-layer blockchain architecture with conventional blockchain networks, legacy supply chain systems, and industry standards. In the LV scenario, the proposed architecture incurred a total TC of 500 units, representing a cost-effective solution compared to the conventional blockchain network, which had a total cost of 800 units. The legacy supply chain system had the highest total cost at 1000 units, while the industry standard showed a slightly lower cost at 700 units. Moving to the MV scenario, the proposed architecture continued to demonstrate cost efficiency with a total TC of 450 units, significantly lower than the 1000 units incurred by the conventional blockchain network.

Table 4. Total TC results

Scenario	Proposed	Conventional blockchain [9]	Legacy supply chain system [10]	Industry standard [11]
LV	500	800	1000	700
MV	450	1000	1200	600
HV	400	1200	1500	500

Figure 7 illustrates a comparison of the total TC across different scenarios for four approaches: proposed, conventional blockchain, legacy supply chain system, and industry standard. Each bar represents a scenario, including LV, MV, and HV.

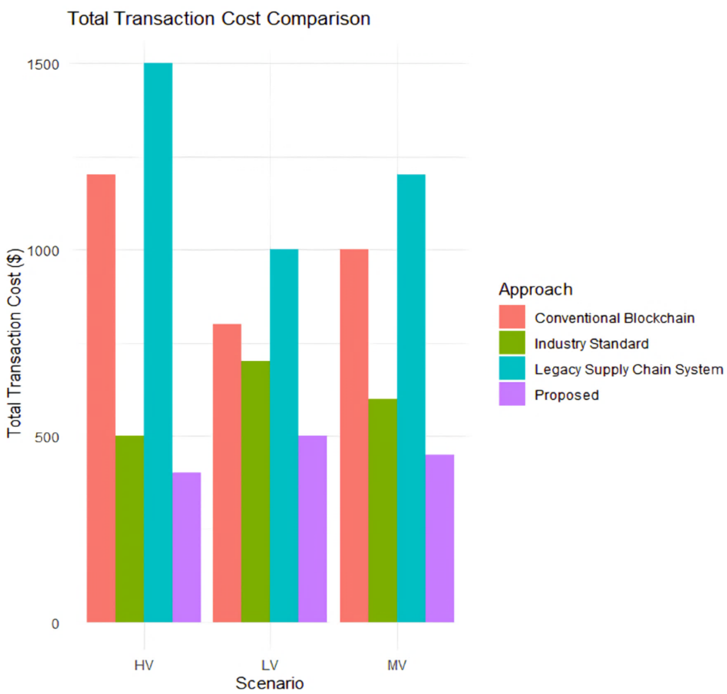

Figure 7. Comparison of total TC

5. CONCLUSION

In conclusion, this study presents a novel approach to address scalability and efficiency challenges within the leather industry's supply chains by leveraging blockchain technology, smart contracts, sharding, and state channels. The proposed dual-layer blockchain architecture offers significant improvements over traditional supply chain management systems, providing enhanced transparency, traceability, and automation while ensuring data privacy and security. Through simulation experiments conducted using SimBlock, we demonstrated the scalability, efficiency, and cost-effectiveness of the proposed approach compared to conventional blockchain networks and legacy supply chain systems. Our findings indicate substantial increases in transaction throughput, reductions in transaction latency, and cost savings across different transaction volume scenarios. By integrating smart contracts into the main blockchain layer, we automated various supply chain processes, reducing manual errors and delays while improving overall operational efficiency. Sharding and state channels further enhanced scalability and performance, allowing for parallel transaction processing and real-time interactions between stakeholders. The results of this study have significant implications for the leather industry, offering a transformative solution to streamline supply chain operations, reduce costs, and improve competitiveness. Moving forward, further research and development efforts are needed to refine the proposed architecture and validate its effectiveness in real-world supply chain environments.

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