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ADVANCING SUPPLY CHAIN INTEGRITY AND TRACEABILITY THROUGH BLOCKCHAIN INTEGRATION

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Summary. Blockchain technology is reshaping supply chain management (SCM) by enhancing transparency, traceability, and trust among stakeholders. This study reviews recent applications of blockchain in SCM, focusing on its integration with IoT, smart contracts, and distributed ledger technologies. Key benefits include real-time data sharing, tamper-proof records, and improved coordination across supply chain actors. The article proposes a conceptual blockchain-based model that supports secure data exchange, automated verification, and tokenized asset tracking, aimed at reducing fraud and inefficiencies. Despite its potential, blockchain implementation faces challenges such as scalability, regulatory uncertainty, and interoperability. Through analysis of recent case studies and pilot projects, the paper identifies practical limitations and future directions, including the development of lightweight consensus algorithms and ethical frameworks for decentralized systems. The findings underscore blockchain's capacity to modernize supply chains, provided that technical and institutional barriers are addressed.

Introduction. In today's globalized economy, supply chains have evolved into complex, multi-organizational networks that rely heavily on trust, transparency, and operational efficiency. These networks span across countries and industries, involving countless stakeholders such as manufacturers, distributors, retailers, and consumers. As the volume and complexity of transactions increase, the need for reliable, secure, and transparent systems has become critical. Blockchain technology, with its decentralized and tamper-evident characteristics, offers a promising solution to many of the issues that plague conventional supply chain management (SCM) systems.

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Supply chain management refers to the coordination of interconnected activities and entities involved in the production, delivery, and consumption of goods and services. While supply chains enable scale and productivity, they often suffer from lack of interoperability, transparency, traceability, and data integrity. Moreover, the rise of digital transformation, as epitomized by the Logistics 4.0 paradigm, has elevated the importance of robust information and communication technologies (ICT) within supply chain frameworks [4].

Blockchain—originally popularized by cryptocurrencies like Bitcoin—is now finding relevance across diverse domains, including logistics, healthcare, energy markets, and food supply chains. By leveraging distributed ledger technology, blockchain allows all supply chain participants to share a single version of the truth. Each transaction is immutably recorded, promoting accountability, reducing fraud, and enhancing trust.

However, the integration of blockchain into supply chain systems is not without its challenges. Existing blockchain solutions are often highly specialized, expensive to implement, or difficult to scale across industries. There is a growing need for generalized, partially distributed blockchain architectures that are adaptable, cost-effective, and interoperable. This study proposes a novel blockchain-based model tailored to these objectives, focusing on a metadata-based mediator system that enhances traceability and transparency without requiring complete decentralization or extensive customization.

Literature review. Numerous studies and pilot implementations have demonstrated the potential of blockchain in enhancing the security, efficiency, and resilience of supply chains. A widely cited implementation is IBM and Walmart's blockchain project, which tracks leafy green produce across the food supply chain, reducing traceability from days to seconds [4]. Similarly, Nestlé and Carrefour have deployed blockchain to verify food origins and improve customer trust [14].

Blockchain solutions in SCM are typically categorized into four major types based on the level of decentralization and the breadth of applicability:

- Custom Full-Blockchain Solutions: These are fully decentralized systems developed for specific supply chains. For example, Shahid et al. [7] proposed a blockchain model for agri-food supply chains that utilizes smart contracts and IPFS for decentralized data storage. While highly secure and transparent, such systems are costly and lack flexibility across different business domains.

- General Full-Blockchain Solutions: Though theoretically ideal, these systems are largely impractical due to the need to hard-code diverse business logics into smart contracts. Wu et al. [8] offered a framework that uses both private and public ledgers to enhance transparency, but scalability across sectors remains limited.



– Custom Partial-Blockchain Solutions: These integrate blockchain with traditional centralized systems to balance performance with security. Zhuang et al. [9] presented a health data exchange system that uses blockchain for permission control but relies on centralized databases for operations. These solutions offer backwards compatibility and lower costs but compromise on full decentralization.

– General Partial-Blockchain Solutions: Emerging as a practical alternative, this category includes modular and adaptable systems that can integrate with existing SCM architectures. Examples include the use of smart contract templates in energy markets [13] and visual frameworks like *-chain for low-code blockchain implementation [20].

IoT-based blockchain solutions further enrich the SCM ecosystem by enabling real-time tracking and verification of goods in transit. Rizwan et al. [10] combined blockchain and IoT sensors to enhance transparency in seafood logistics, while Bhat et al. [11] emphasized security and interoperability through the Agri-SCM-BIoT framework. However, the integration of IoT often introduces performance and scalability bottlenecks, especially when processing large data streams through blockchain nodes.

Despite the diversity of these solutions, a common challenge remains: the absence of lightweight, scalable, and easily deployable blockchain architectures suitable for small and medium enterprises (SMEs). The literature calls for models that strike a balance between decentralization and usability, with minimal disruption to existing systems [6, 17].

Proposed Model.

To address the limitations of existing approaches, this study proposes a general partial-blockchain architecture centered on a metadata mediator. The key idea is to introduce a blockchain-enabled component that logs metadata of transactions and changes in supply chain systems, without requiring full migration to a decentralized infrastructure.

The architecture builds on the assumption that most SCM systems are already centralized client-server applications. The blockchain mediator acts as a lightweight overlay that captures request metadata (e.g., timestamps, endpoints, actors, actions) and stores it immutably on a distributed ledger. This enables traceability and auditability without modifying the core application logic.

Unlike fully decentralized solutions, the mediator does not store or process actual business data on-chain. Instead, it functions as a verification layer—ensuring that all changes in the SCM system can be attributed and traced. This approach preserves system performance, reduces implementation cost, and ensures backwards compatibility.

The architecture supports flexible deployment. For SMEs, the mediator can be packaged as a Docker container with minimal setup. Larger organizations can



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integrate it as a microservice within their DevOps pipelines. This dual-mode capability makes the system adaptable to a wide range of use cases—from simple audit trails to dynamic supply chain orchestration.

Conclusion. Blockchain technology holds immense potential for transforming supply chain management by improving transparency, traceability, and data integrity. However, the current landscape of blockchain solutions reveals a dichotomy: full-blockchain models offer high security but are difficult and expensive to implement, while partial solutions often lack generalizability or require significant customization.

This study presents a general partial-blockchain solution that introduces a metadata mediator between existing SCM applications and a blockchain network. By logging transaction metadata instead of full business data, the system ensures traceability with minimal disruption. Its modular design allows for easy integration, making it particularly valuable for SMEs and organizations lacking in-house blockchain expertise.

Future work will focus on prototyping the proposed architecture, optimizing smart contract performance, and testing the system in real-world supply chains.

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