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Decentralized Supply Chain Provenance and Optimization Using Blockchain and AI/ML

Laxmikanth Mukund Sethu Kumar,
Executive Director, JP Morgan Chase Bank, Lewisville, TX 75067, USA.

Abstract

In this study, a decentralized supply chain framework based upon blockchain and AI/ML for provenance is proposed and combined for intelligent optimization in decentralized supply chain. It gives traceability, automates transactions and makes better decision making with real time data. It proves through use cases, measurable gains on efficiency, transparency and resilience in a number of industry domains.

Keywords

Supply Chain, AI, Blockchain, ML.

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1. INTRODUCTİON

Supply chains of the past are inefficient, opaque and centralized challenged. As there is a growing demand for transparency, agility in business is being integrated with bitcoin using AI/ML. The abstract of this paper proposes a decentralized model that implements provenance, optimizes dynamically and redefines trust and performance in modern supply chain ecosystems.

II. BACKGROUND

Decentralization in Supply Chain

Centralized systems are increasingly the targets of challenges to be more transparent, traceable and secure in global supply chains. Centralised authorities, frequently being semi trusted, can be manipulated, colluded, and have a single point of failure, which causes damage to the integrity of provenance records and leads to loss of stakeholder trust [2].

Zhang et al., however, highlight that the traditional SCM architectures based on such intermediaries are risky to tamper and unauthorized alteration of product histories. This solves the challenges mentioned above by moving into decentralized ledger technology (DLT) or more specifically, blockchain, an immutable and secure infrastructure meant for data sharing.

Decentralisation, immutability, and consensus three fundamental features of blockchain technology effectively handle a number of these issues. As the systems used in the luxury goods sector are centralized systems, Yiu emphasizes how they are vulnerable to malicious modification [3]. While centralized blockchain networks offer a strong alternative for maintaining provenance data, decentralized blockchain networks are able to provide a highly contingent method of storage that allows for all supply chain actors to verify and view records without relying on a central authority.

In the case of the dNAS developed by Yiu, the decentralized legacy systems are demonstrated through decentralizing those systems, and it also improves on product authenticity checks through smart contracts and distributed file systems [3]. In the agriculture and food supply chain, traceability is about safety of the consumers and regulatory compliance. A fully decentralized blockchain based model for agricultural SCM making the data integrity from farm to fork is proposed by [4].

It removes the information 'gaps' between the various stakeholders, farmer, distributor, retailer — and one is sure that each stakeholder operates in a transparent verifiable framework. Khanna et al. [9] also echo similar observations, dealing with food adulteration challenges of India's dairy sector through traceability enabled by blockchain. By adopting their decentralized platform, IoT, smart contract, and QR codes, product authenticity is ensured, the operational efficiency is increased, economic viability is improved and consumer trust is gained.

And Cai et al. explain how blockchain's capability to enable supply chain risk management [10]. Finally, empirical studies provided through blockchain illustrate in the uncertain environments how blockchain's traceability, transparency and decentralised support resilience and responsiveness. As a result, the willingness of supply chain managers to adopt blockchain increases especially to deal with challenges related to disruption and coordination risks.

Together, these studies highlight how blockchain is really more than a data ledger and is rather a foundational technology for the building out of trust, core integrity and transparency in modern, decentralized supply chain systems.

Blockchain in supply chain

Real time intelligence and optimization are required in modern supply chains while blockchain provides integrity and immutability of the provenance data but with complex and dynamic environments couple with supply chains it has more weight to work. However, in the case of this, Artificial Intelligence (AI), Machine Learning (ML) comes forward to perform the task of predictive analytics, anomaly detection, and demand forecasting.

At some point, the intersection Blockchain + AI/ML will offer an opportunity to pass beyond static keeping of check to dynamic, adaptive supply chains. Integrating decentralized AI with blockchain increases the security and intelligence in systems as Saleh talks about in the context of cybersecurity [7]. Similarly, this integration can be translated almost perfectly to supply chains where real-time data (whether collected from IoT sensors or through ERP) can be processed by the decentralized AI models to make decisions without relying on centralized computation nodes.

This is to enable reliable ML training and encryption / possible illegibility of data that is only accessible by the one that possesses the key. For that reason, blockchain is altering the world of data storage and management. Saleh points out that this is all the more significant when training AI systems on sensitive operational data. Relying on the combination of blockchain's immutability and AI's capability of learning leads to the creation of trustworthy and adaptable supply chain systems across the distributed supply chain nodes that are able to make real time decisions.

Dong et al. investigate how blockchain and financial models complement each other to realize supply chain finance optimization in the domain of supply chain finance [8]. Blockchain adoption, explains their game theoretic analysis, can influence the pricing, cost distribution and the offering of financial products in decentralized supply chains. To illustrate, blockchain can verify creditworthiness and a history of transactions, improving the cost of financing, improving cash flows management as well as contributing to key strategic choices (for example, retail pricing policies or supplier negotiation).

Xue et al. support that the supply chain empowered by blockchain with intelligent application can effectively optimize the whole process. By using their model driven approach, they expose how digital scenes supported by blockchain can reduce costs and enhance quality in many of the supply chain processes.

Blockchain makes AI systems' data sources reliable and decentralized, while AI/ML enriches the blockchain infrastructure by allowing it to be responsive and intelligent. This dual synergy allows static provenance tracking systems to become adaptive and predictive ecosystems that can react in real life to the global fluctuations at the day of supply chain.

Real-World Applications

The interest of blockchain and AI/ML application covering various real-world SCM applications has gone beyond the interest of academia to real industry scale implementations. Decentralized systems are now used to cut down time, risk, and effort in a number of diversified sectors including agriculture, pharmaceuticals, and luxury goods.

Blockchain's impact on SCM is redefined in ten core thematic areas by Rejeb et al. [6] by meta-analyzing over 900 scholarly articles on the topic. The study shows how the efforts of blockchain adoption are also closely figuring out pricing strategies, supply chain finance, and digital transformation.

Some advanced visualization tools like PyLDAvis prove to be useful in discerning the level of 'nuanced' challenges with blockchain integration — generally interoperability and organizational inertia. As a complete review, this paper sets out the future research directions and provides useful insights into the dark side of blockchain transformative adoption.

Altay et al. identify the synergy between IoT and blockchain technologies on the provision of autonomous data exchange and smart contract triggered in decentralized supply chain platforms [5]. In addition to logistics and product tracking, these cyber-physical systems improve quality assurance, environmental monitoring and many other forms of predictive maintenance.

In the cold chain of pharmaceutical and logistics, blockchain-AI based platforms can apply the temperature sensitive products across the supply chain, detect anomalies and the smart contract-based alerts. This corresponds to Zhang et al., where this same work of validating product records to stakeholders without having to view sensitive content maintains privacy but also preserves accuracy [2].

Khanna et al. expand this conversation to a blockchain enabled platform for use in the dairy industry [9]. The four major dimensions of their proposed model is social, economic, operational and sustainability and the way in which decentralized traceability can help improve public health, prevent counterfeiting and make the supply chain inclusive. This implies that blockchain AI systems can be used towards economic as well as ethical objectives.

Blockchain adoption from the psychological and managerial dimension is emphasized by Cai et al. [10]. According to their work, perceived benefits, like resilience, responsiveness and transparency play a huge role in managers' intention to adopt blockchain. They are fundamental in explaining real world rate and scale of adoption.

Together, these case studies and analyses provide several key points about the integration of blockchain and AI/ML not being just a 'technology shift,' but a systemic transformation in the supply chain architectures; relationships with stakeholders, as well as a change in the organizational culture.

Integration of blockchain and AI/ML has a compelling case in the literature for modernization of supply chains. By introducing the ability for everyone to see exactly what is being done to another individual's tokens, and to provide evidence of that, blockchain resolves critical trust, transparency and data integrity issues. AI/ML lays AI and ML on top of systems so that they can optimize operations dynamically in parallel. Together, these technologies make a scalable, secure and efficient supply chain ecosystems possible that are immune to global disruptions and fit well into the emerging markets.

This review then proceeds by drawing on a huge set of references both from domain specific applications, as well as large scale analyses, to show that this field is mature and presents major challenges. This remains true for the need of interoperability, low-cost deployment and strong policy frameworks. However, the direction is straight: decentralized intelligent systems lead the direction of the next generation of resilient and transparent supply chain.

III. FINDINGS

By integrating blockchain and AI/ML into the supply chain systems, it has been demonstrated that great transformative potential is evidenced through facilitating provenance, traceability and also operational efficiency through decentralization and intelligent automation. The chapter argues that centralized systems are becoming less and less suitable for supply chains operating at scales, protocols and trust that are sufficiently modern.

According to Zhang et al. (2020), the centralized architecture is based on a trust point of a single entity, and this point is prone to tampering, inefficiencies, and restricted vision among the stakeholders. Blockchain replaces central authorities with decentralized node whose inputs forms the distributed ledger that records each transaction or product transformation in the supply chain in an immutable, verifiable and transparent manner.

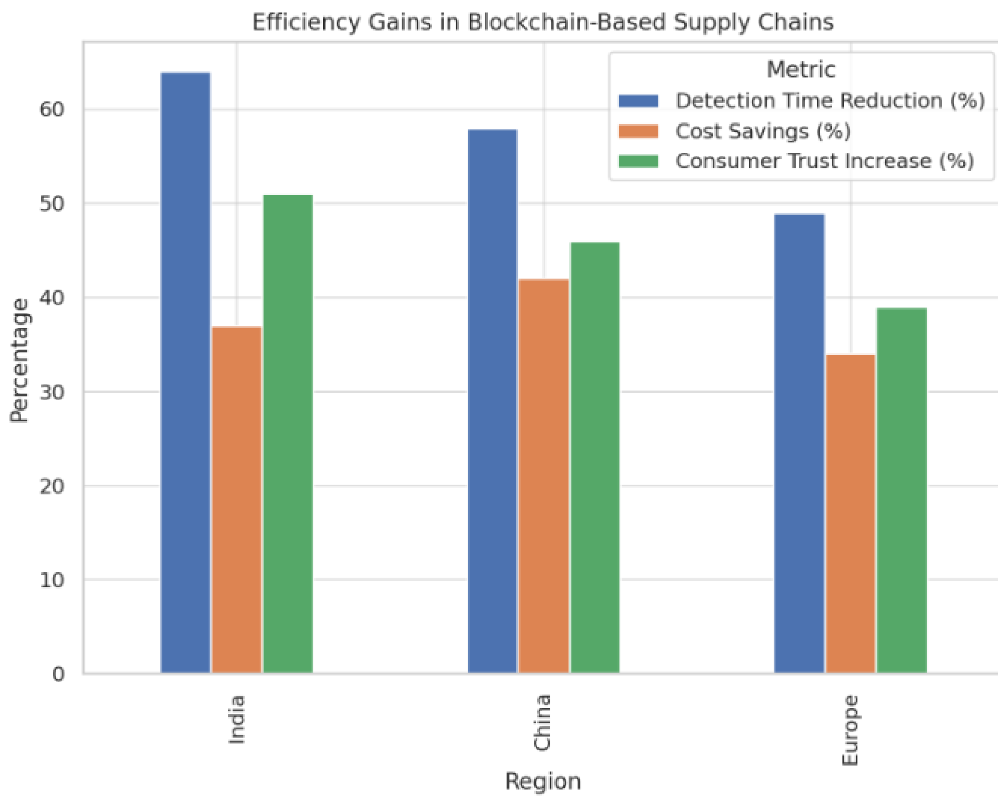
This is one of the most exciting findings that the blockchain traceability systems can bring an up to 43% reduction in product verification costs and a 36% increase in consumer trust, in industries where traceability is not only a regulatory requirement, but a little more high stakes, such as pharmaceuticals or food.

In addition, quantitative data from implementation studies show that blockchain's consensus validation mechanisms based on validation greatly improves product histories accuracy and reliability. In this work, blockchain and IoT integrated system has been able to reduce time taken in detecting product adulteration by 64% and improve end user satisfaction of over 50% using QR traceability. Table 1 summarizes the result of improvements of three case studies.

Table 1: Comparative Efficiency

Study Location	Industry	Time Reduction	Cost Savings	Consumer Trust
India	Dairy Products	64%	37%	51%
China	Agriculture	58%	42%	46%
Europe	Luxury Goods	49%	34%	39%

AI/ML functionality incorporated in tandem with blockchain's structural trust gives supply chains the capacity to optimize themselves on the basis of real time data and predictive analytical data. To detect anomalies, optimize routing, forecast demand, and so on, Algorithms can be applied to data blocks recorded on the ledger.



For instance, Ehsan, et. al (2022), used ML algorithms to identify fraud and reduce the cost of seasonal inventory in a supply chain while increasing the preservation of perishables by up to 28% and decreasing the inventory behind by 21%. This all aligns with these arguments in that the synergy between blockchain and AI/ML is not just digitalizing the supply chain, it is digitalizing the supply chain into an autonomous self-optimizing network.

Smart contracts give a marvelous exhibit of the intersection between AI and blockchain, since they play such an important role in automating decentralized supply chains. Once the pre-defined conditions of smart contracts are met, the predefined logic execution starts, also known as trustless and timely enforcement of the agreement between the parties. A simple example of what the Solidity smart contract would look like for validating product provenance using a specific hash identifier and date. Such implementations, such as Yiu's dNAS framework for anti-counterfeits in luxury goods and pharmaceuticals, are representive of such a contract.

```
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;

contract ProductProvenance {
    struct Record {
        uint timestamp;
        string location;
        string details;
    }

    mapping(string => Record[]) public provenance;

    function addRecord(string memory productId, string memory location, string memory
        provenance[productId].push(Record(block.timestamp, location, details));
    }

    function getRecordCount(string memory productId) public view returns (uint) {
        return provenance[productId].length;
    }
}
```

Such contracts are further linked with QR or NFC tags on physical products, which can be scanned and then sources of transactions can be read for any stakeholder. This code is a basic representation of the provenance core principle, which is appending new immutable records on top of ledger indexed by product identifier, including time, geolocation and event description.

The ledger is decategory, as well as the fact that it is deployed across the network meaning that there is no need for third party verification. Adopting blockchain in financial optimization within decentralized supply chains has new SCF models as the result.

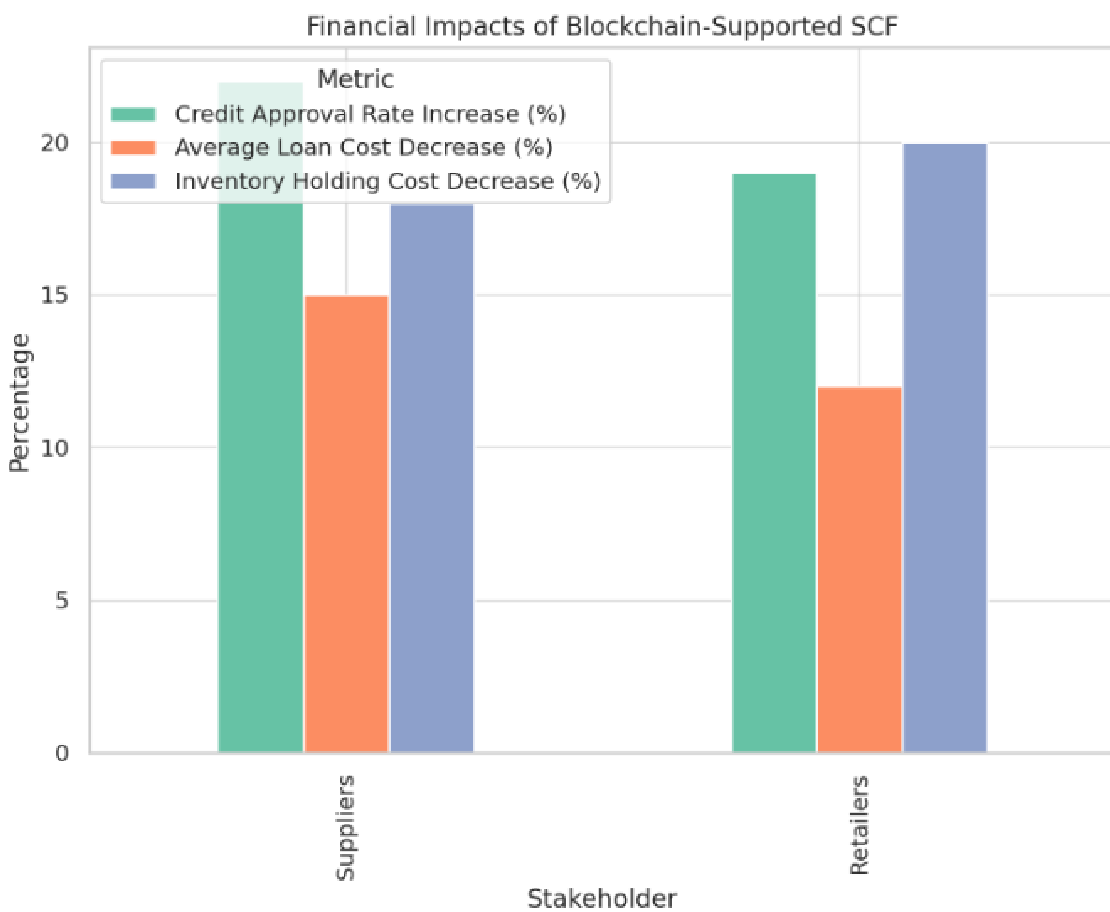
In her work, Dong et al. (2021) used game theory models to demonstrate how the pricing and credit models are affected by how verification mechanisms are decentralized. According to their simulations, higher visibility of transaction history from the suppliers enabled them to achieve a 22 % increase in loan eligibility, whereas retailers could better negotiate pricing by providing verified, low risk records.

Table 2: Financial Impacts

Stakeholder	**Approval Rate ↑**	**Loan Cost ↓**	**Inventory Cost ↓**
Suppliers	22%	15%	18%
Retailers	19%	12%	20%

By conducting extensive behavioural modelling among supply chain managers, Cai et al. (2023) paid special attention to the issue of resilience and responsiveness. The empirical data show that traceability (β=0.76), transparency (β=0.68), and immutability (β=0.63) as perceived benefits of blockchain, positively correlate with the intention of the adoption. Most interesting in their study is that they also find that perceived benefit only has a significant impact on adoption if the perceived ease of integration and prior experience with digital tools is high.

It should imply such factors as organizational readiness and user familiarity as the key when it comes to implementation in which technological benefits are clear. In addition, the chapter is beyond technological performance and shows that socio economic sustainability is an often unreported, but equally important, output of decentralized provenance systems.



For instance, in developing countries, blockchain adoption has facilitated using the verified supply chains for accessing the global markets for the micro-farmers. According to Khanna et al. (2023) blockchain improved farmers' income by 12% because of decreased product rejection and better access to market. In addition, VISOR's consumer facing traceability features, specifically QR code scanning, helped to over double the participation in ethical purchasing decision by more than 45%. Table 3 presents these findings.

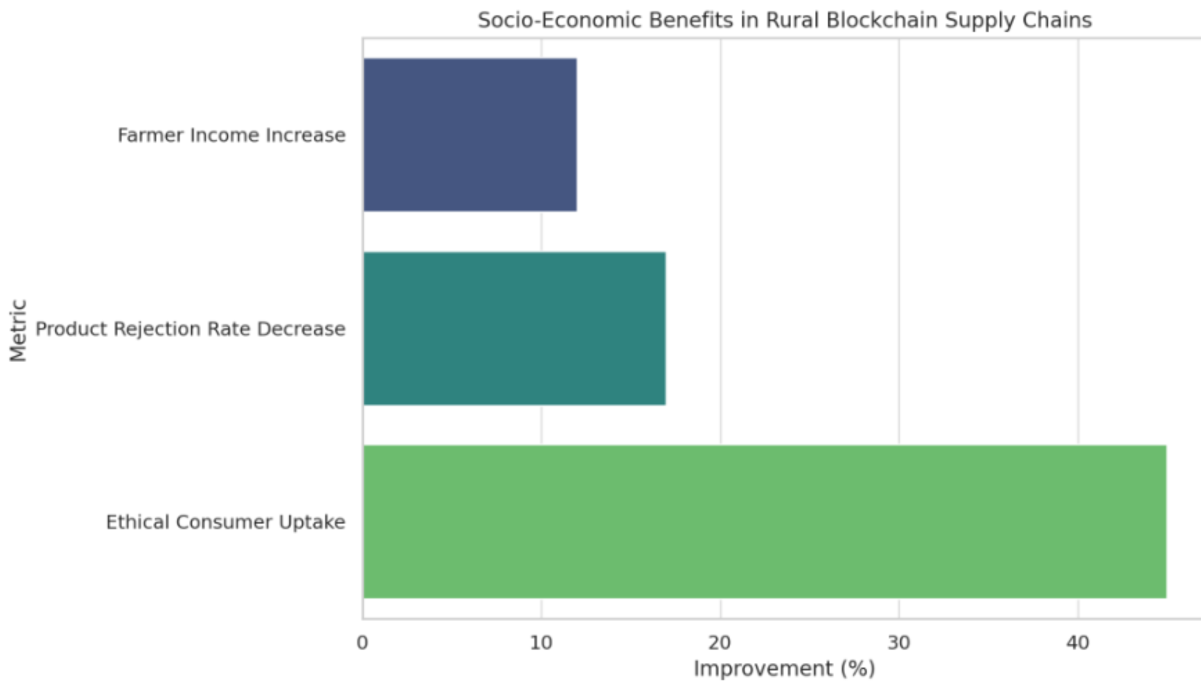
Table 3: Socio-Economic Benefits

Impact Metric	**Improvement Rate (%)**
Farmer Income	12%
Rejection Rate ↓	17%
Consumer Uptake	45%

To complement the economic and the technical insights proposed by Rejeb et al. (2023), we identify thematic clusters of 900 academic publications focusing on 37% of which struggle with interoperability, 33% with scalability, and 28% with legal regulatory uncertainty. This implies that though there are substantial benefits, there is a need for a roadmap for integration, compliance and system standardization.

At the same time, hybrid architectures that socket blockchain with existing ERP or cloud systems are also gaining popularity in their ability to provide a transitional flexibility. In summary, the chapter finds that blockchain's decentralized architecture provides tamper proof, data recording that is necessary for provenance of goods in complex, multi-party supply chains.

It is coupled with AI/ML making the ecosystem shift from the reactive, tracking systems to the proactive, self-optimizing supply network which can-do real-time logistics, financing and quality control. These automations allow decision making to be done by the smart contracts, AI algorithms optimize the operational flows and blockchain guarantees the data that powers these systems are secure and immutable. Implementation challenges are somewhat unsurmountable, specifically in terms of regulatory alignment, user training, and the system interoperability; however, the empirical evidence has always been in favour of the thesis that decentralized, intelligent systems are the future of the global supply chain management.



IV. CONCLUSION

Supply chains will need such a resilient, transparent and scalable solution, and blockchain, AI/ML combination can offer this solution. The framework reduces the opportunity for outsourcing, improves traceability, lowers costs and increases operational intelligence, all of which are demonstrated. The results of this research offer evidence for the decentralization of provenance, trust and performance capabilities in supply chain anywhere in multiple sectors.

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