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How Blockchain Is Improving Trust and Transparency in Global Supply Chains

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ABSTRACT

The dynamics of supply chains are growing to be multi-geographical and multi-stakeholder, and that further increases the burden of trust, transparency, and traceability (Saberi et al., 2019). Data silo and fraud are common issues that cannot be addressed using existing centralized systems, as it creates inefficiencies and becomes devoid of accountability (Kouhizadeh et al., 2021). This paper explores the way the blockchain technology may reshape global supply chains providing the users with decentralized and unchangeable ledgers and, thereby, increasing trust among the actors (Casino et al., 2019). In this study, the researcher combines the existing records and completes a prototype based on Hyperledger Fabric in combination with smart contracts to gauge the enhancement of the traceability and verification mechanisms (Dolgui et al., 2020). We used a model of machine learning to assess the transaction pattern and identify anomalies and took instructions on the models that were already exemplified in supply chain fraud detection (Jin et al., 2020). According to results, the level of traceability metrics has also increased significantly and by 35% less data inconsistent is generated compared to the traditional ERP systems (Queiroz & Wamba, 2019). The study joins the list of works promoting the idea of the prospective blockchain-based supply chain and indicates realistic consequences regarding scalability and interoperability (Francisco & Swanson, 2018). Future solutions should try to add cross-chain communications and AI-based optimization to improve the transparency and efficiency of operations further (Zhang et al., 2021).

Important keywords: Block chain, Supply chain, Transparency, Trust, Smart contract, Traceability, Hyperledger Fabric

Introduction

Globalization of all forms of supply chain has posed serious issues to organizations trying to uphold transparency, genuineness and trust in supply chain networks that have become very lengthy and complicated (Saberi et al., 2019). When goods and resources cross geopolitical borderlines with numerous intermediaries in the process, the chances of frauds, counterfeitting practices, and the manipulation of data increase, and this results in inefficiencies in operations and major risks of reputation compromise on the side of companies (Kouhizadeh et al., 2021). To illustrate, the pharmaceutical sector alone continues to lose billions of dollars a year because fake drugs enter existing legitimate supply chains necessitating risks of harm to patients and loss of faith by the general population (Mackey & Nayyar, 2017). Likewise, the provenance of the ingredients is often the problem of food industry, and a series of fraudulent cases of mislabeling proves the inefficiency of historical supply chain tracking (Galvez et al., 2018). Such instances demonstrate a more general industry-level requirement involving an effective traceability system in terms of which data integrity and product authenticity between source and shelf can be ensured.

The classic supply chain management systems, which are often constructed over centralized enterprise resource planning (ERP) systems, have been able to achieve better visibility but usually fail to attain real-time verification, tamper-resistance, and multi-party trust (Treiblmaier, 2019). The concerned centralized systems are dependent on intermediaries and trust-based relationships and thus subject to data silos, lack of consistency in records and fraud. The latest series of high-profile well-publicized supply chain failures, to such a degree as counterfeit products and recall of products to COVID-19 relationships manufacturing bottlenecks, has revealed the vulnerability of supply chains and highlighted the need to innovate the validity and sharing of data across the environment (Ivanov & Dolgui, 2020).

Blockchain technology in this sense has turned out to be a potential instrument to resolve long-established problems of trust and transparency issues. As a source of a decentralized and immutable ledger, blockchain provides a secure means of exchanging information in real-time between stakeholders that may not trust one another or perform within a single regulatory regime (Casino et al., 2019). Such a fundamental move aggravates centralized to decentralized records promises to reduce intermediaries as well as the hazard of fraud. Blockchain-based solutions to trace provenance, automate, and create compliance processes and sustainable reporting have started to be explored in sectors as diverse as agriculture and mining through to luxury goods and pharmaceuticals (Francisco & Swanson, 2018; Saberi et al., 2019).

Smart contracts, which are self-executing agreements written directly on the blockchain, include one more layer of automation combined with accountability to supply chain transactions (Kouhizadeh et al., 2021). Using the example of automatic release of a payment after the goods reaching a hardware authenticated checkpoint, this reduces the need to manually reconcile transactions and hand off opportunities to manipulate such transactions. In addition, together with the Internet of Things (IoT) appliances, blockchain can record environmental and geospatial information in real-time which means that the conditions, e.g. temperature and humidity, adhere to the contractual requirements during the transportation of goods (Lin et al., 2018). Systems that have such integration produce a solid digital copy of physical goods, injecting increased transparency and allowing situational monitoring of actions within the supply chain (Queiroz & Wamba, 2019).

The implementation of blockchain in the supply chain management is far much easier said than done. One of the most significant challenges associated with the technology is scalability that takes place when thousands or even millions of transactions should be performed in real-time and on a global network (Zhang et al., 2021). Ethereum, a public blockchain, has problems with the throughput of transactions and energy usage, whereas enterprise-level permissioned blockchains, including Hyperledger Fabric, should have better regulation and privacy but demand governance models that would grant shared incentives to diverse participants (Kumar et al., 2020). The privacy of data is also a source of a paradox in that as transparency is considered to be a major advantage of blockchain, it is impractical that all information on the supply chain should be publicly available, particularly when the information is sensitive to business or personally identifiable, to an extent to which it is not or should not be public (Casino et al., 2019). To counter this, studies have resorted to hybrid blockchain architecture, zero-knowledge proofs, and other privacy-preservation-based methods that enable the information to be shared selectively (Zhang et al., 2021).

The current trend is also the combination of the blockchain with artificial intelligence (AI) and machine learning (ML) to improve issues of anomaly detection and fraud prevention in supply chains. Through the analysis of high amounts of transaction and sensor data, the AI models extract suspicious traces or abnormal behavior deviation patterns, providing a predictive ingredient to the naturally reactive nature of blockchain verification (Jin et al., 2020). ML algorithms are also able, for example, to identify duplicates of a certain entry or even identify supply chain bottlenecks so that they do not become key disruptions that cost a fortune (Patel et al., 2019). Such an integration has the potential of building more robust and flexible supply chain ecosystems that bring together the best of both worlds by using immutable data with smart information.

The importance of supply chains trusts and transparency is also accentuated by regulatory requirements and voluntary demands to sustainability and ethical sourcing by customers. Regulations like the General Data Protection Regulation (GDPR) of the European Union and the future Digital Product Passport program will mandate the organizations to have verifiable, auditable product origin, product materials and product lifecycle impact records (Saberi et al., 2019). Brands which do not show responsible conduct face a risk of reputation and earning shaming, fines, and market loss. The capabilities of blockchain to deliver an immutable audit trail are in line with these needs, though only in case its use is technically competent and cost-effective (Francisco & Swanson, 2018).

With this background, the following research question is addressed in this paper: How may blockchain technology enhance trust and transparency in the international supply chains? Whereas it has also been shown that blockchain theoretically has its benefits, and that the technology has witnessed proof-of-concept pilots, there is still a gap in undertaking rigorous and reproducible research, which integrate blockchain with other technologies, such as artificial intelligence in fraud detection and internet of things in real-time data collection (Kouhizadeh et al., 2021; Jin et al., 2020). In this research we attempt to fill this gap by (i) conducting a synthesis of the existing literature on blockchain-enabled supply chains, (ii) implementing and testing a prototype supply chain network with the Hyperledger Fabric portal, a permissioned blockchain framework that shows great promise in enterprise use case lockbuilttresseatersiminformationfx Bert (cacorsz dig astronomic rather tensile (Bert, 2018), and (iii) Benchmarking traceability and fraud detection in light of an anomaly detection model based on machine learning methods.

The remaining part of this paper is organized in the following way. In section 2, the review of the existing literature on blockchain applications in the sphere of supply chain management will be done, showing the main frameworks, models, and empirical data. In section 3, we clearly state the problem that this study is trying to answer and point out the motivation of our approach. In section 4, there are details of the methodology, such as the design of the research, data sources, tools, and measures of evaluation. In section five, we provide our experiment results and assess the performance of our prototype to the conventional systems. Section 6 explains why our findings are important and answers to the intended research questions and sections 7 answer limitations and offer recommendations about a future research that can help build resilient, transparent, and trusted global supply chain with the integration of blockchain and AI.

Literature Review

In recent years, the largely untapped potential of blockchain to manage the supply chain has become a subject to numerous studies due to the increasing interest of people around the globe in transparency, data integrity, and trust between the diversely affiliated stakeholders (Saberi et al., 2019). Initial research identified blockchain as a technological solution to an existing problem of traceability, particularly in such sectors in which provenance and authenticity are primary concerns. Indicatively, one can mention the article by Saberi et al. (2019) wherein the researchers emphasize the potential of blockchain in modernizing the traditional chain of supply by supporting a single source of truth that can be shared by all involved actors and hence cause a reduction of the risks of tampering with the data and data fraud.

One of the most detailed systematic literature reviews involving blockchain applications was implemented by Casino, Dasaklis, and Patsakis (2019) who classified the existing studies and identified the main technological, managerial, and organizational parameters that hold influence in this sphere of adoption. They underlined that the potential of blockchain is not debatable, though real-world applications with a high integration level with other technologies, e.g., the Internet of Things (IoT) and artificial intelligence (AI), is essential to provide real-time data and smart insights. Such a requirement of interoperability has become the major focus area in new studies (Kouhizadeh et al., 2021).

Hyperledger fabric, which is one of the most widely known blockchain frameworks used in supply chain applications, is a permissioned blockchain that supports modularity, scalability, and privacy protection; these factors are highly desirable in supply chain applications (Androulaki et al., 2018). Time-saving smart contracts In Hyperledger Fabric, Francisco and Swanson (2018) examined the potential of transaction verification and enforcement automation as well as the provision of transparent audit trails in logistics systems. Reduced manual action, mistakes, and conflicts have been demonstrated by smart contracts, which automatically apply the pre-determined rules once preconditions are fulfilled (Kshetri, 2018). There is also documented evidence of real-world pilots that include IBM food trust network and Maersk TradeLens platform, which indicate that blockchain has the potential to increase data integrity and chain efficiency (Mohan, 2021).

Though this is a promising development, implementation is not balanced. As it was observed by Kouhizadeh et al. (2021), privacy mechanisms remain unready particularly in cases where sensitive business information has to be selectively disclosed with specific stakeholders without having to be revealed to any other party. It is very important in the competitive industries that the supply chain partners can conflict in their interests. This issue was repeated by Zhang, Xue, and Lai (2021), who noted that although the levels of access can be provided by permissioned blockchains, such as Hyperledger Fabric, they will still necessitate strong governance structures to make sure that players can follow the agreed-upon procedures.

Scalability is another of the significant obstacles found in the literature. Ethereum and other public blockchains have a potential throughput, latency and energy requirements that make the use of these platforms to enable large-scale and real-time supply chains rather challenging (Casino et al., 2019). In response to this, scientists have tried out the idea of bridging both permissioned and public blockchain using hybrid and layered architectures (Li et al., 2021). According to Kumar, Vealey, and Srivastava (2020), some recently emerging research on consensus algorithms, like Proof-of-Stake (PoS) and Byzantine Fault Tolerance (BFT) mechanisms, are potentially more efficient and some might be scalable systems.

As the development of blockchain continues, conducted in parallel, the literature is also growing with the implication that blockchain will be more effective in supply chains by integrating with other emerging technologies. The first area in which the IoT devices can be integrated is often regarded as the key aspect of solving the gap between actual objects and their digital counterparts in the blockchain (Lin et al., 2018). IoT sensors can supply pixellevel task sensing paradigm data regarding an environmental condition, a location and have a handling of goods, conform more dependable provenance tracing and compliance surveillance (Queiroz & Wamba, 2019). Nevertheless, Lin et al. (2018) warn that the integrity of IoT data should be guaranteed because incorrect or malicious sensor data might interfere with the integrity of the whole solution even when blockchain would be immutable.

A second layer is artificial intelligence (AI) and machine learning (ML) models as an alternative essential layer used especially in detecting frauds and detecting anomalies in supply chains (Jin et al., 2020). Patel, Singh and Shah (2019) showed that deep learning models had the potential of providing better results than traditional statistical models when it comes to detecting unusual transaction patterns that can be used to point out fraudulent practices. This is similar to the analysis provided by Saberi et al. (2019), who stated that blockchain as a separate tool cannot identify any type of fraud due to its inability to predict and diagnose without the functionality provided by AI.

Some recent research has started building the foundations of both linking the immutable ledger of blockchain with analytics-driven by AI to develop extremely resilient and self-healing supply chains (Jin et al., 2020; Queiroz & Wamba, 2019). As an example, Galvez et al. (2018) have suggested a traceability scheme of the food supply chain based on blockchain with a built-in AI model that evaluates inconsistencies in the records and possible fraud in real-time. This hybrid model presents potential in overcoming shortcomings in manual monitoring procedures which are usually time-consuming and inaccurate due to human failure.

Besides technological frameworks, the social and organizational implications of using blockchain were reviewed by researchers. Treiblmaier (2019) noted that the success of blockchain also requires the involvement of the stakeholder to place its bets on trust, certain clarity of regulations or governance clarity in the process. As Mohan (2021) claimed, industry consortia, standardization, and regulatory sandbox may become the key to escaping obstacles to cooperation and data sharing. According to Francisco and Swanson (2018), successful pilots could be observed in cases of highly regulated industries (such as pharmaceuticals and food), where the traceability and compliance incentives are high.

The use of proof-of-concept pilots and case studies is discussed in the literature extensively, whereas large-scale empirical evidence is rather uncommon. Most are early, or restricted to in-situ test areas (Saberi et al., 2019). Such a lack of large-scale experiments in the real world reinforces the need of reproducibility and transparent reporting of blockchain research. Zhang et al. (2021) encourage the idea of open-source framing and standard intervention pathway because such a possibility will guarantee the reproducibility and comparability of the findings.

On top of that, the new research areas are being developed to address the cross-chain interoperability problem which is fundamental to the process of linking the disparate supply chain networks which can be based on various blockchain platforms (Zhang et al., 2021). Sidechains, cross-chain bridges, and decentralized identifiers (DIDs) are some of the technologies that are being investigated to support an efficient data exchange process with its security and privacy guarantees (Li et al., 2021). Patel at al. (2019) recommend that future research ought to also take into account the ethical considerations using the example of the algorithms fairness and the possibility of biasness in the AI models applied in combination with blockchain.

Overall, the current body of literature has created a pas de deux and apparent yet promising scenario regarding the role of blockchain in enhancing the supply chain trust and transparency. The conceptual value of implementing E-IT in the education sector has been confirmed in foundational researches (Saberi et al., 2019; Casino et al., 2019), whereas case studies and pilot implementation (Francisco & Swanson, 2018; Mohan, 2021) have already demonstrated their practical value within a particular context. However, there remain great holes regarding the issue of scalability, privacy-preserving layers, cross-chain interoperability, and empirical testing on a large scale. Current developments of combining AI and IoT are promising to a solution to these problems (Jin et al., 2020; Lin et al., 2018). Our study follows this increasing body of research and develops a prototype based on the blockchain and machine learning-driven anomaly detection with Hyperledger Fabric that provides reproducibility and practical applicability in the global supply chains.

Problem Statement and its Motivation

In the contemporary international economy, supply chains are defined as large, complex structures of suppliers, manufacturers, logistics firms, and shops positioned in several jurisdictions and regulatory systems (Ivanov & Dolgui, 2020). Although this globalization has brought organizations to new levels of efficiency and expansive market penetration, there have been greater risks associated to frauds and counterfeiting; and absence of transparency on product origins. Centralized supply chain management (SCM) and conventional enterprise resource planning (ERP) systems have had an extended history serving as a backbone in management of such intricate activities. Nevertheless, even after decades of development of new technologies, such systems are still not capable of ensuring real-time verification of transactions and product history with a high degree of trust (Kouhizadeh et al., 2021).

Such an approach is one of the inherent disadvantages of centralized systems of SCM, because to make data verification they rely on siloed databases and trusted intermediary to validate data (Treiblmaier, 2019). Different participants usually have their own copies of a transactional records, which gives way to inconsistencies in data and possible threats of malicious parties exploiting information voids. As an illustration, fake goods with a supposed market value of $461 billion a year pass through the legal international chain of supplies, including pharmaceuticals, electronics, luxury products, and car parts (Organisation for Economic Co-operation and Development [OECD], 2019). The pharmaceutical sector itself, especially, shows what dangerous effects poor traceability can have on life. The investigation by Mackey and Nayyar (2017) revealed that facilitated by the shadowy supply chain and the inefficiency of the system of verifications, counterfeit drugs remain one of the most threatening problems in terms of their impact on the health of the population all over the world costing millions of lives.

Moreover, existing SCM systems do not usually support delivering transaction records that cannot be altered or tampered with and that are available to all interested parties in possibly real time (Saberi et al., 2019). The importance of this lack is further elaborated by the ever-larger number of regulators, investors, and consumers, who require evidence of this product having been sustainably sourced, ethically produced and ethically consumed, and with a sustainable carbon footprint (Queiroz & Wamba, 2019). The conventional forms of using paper-based certificates or isolated digitized files are susceptible to falsification and therefore destroying the sustainability efforts as well as putting organizations at risks of both reputational and financial losses.

As a solution to these persistent challenges, blockchain technology has been proposed as a solution because it offers decency, transparency, and security of data exchange across the supply chain (Casino et al., 2019). Blockchain also helps various parties to connect to one shared version of truth through the use of distributed ledger technology (DLT), which minimizes the possibility of fourth-party manipulation of the data, and increases certainty among stakeholders that might be deemed competitors (Francisco & Swanson, 2018). Additionally, verification and compliance can be programmed in smart contracts - self-executing programs that operate on a blockchain, which requires fewer manual verifications and intermediaries (Kouhizadeh et al., 2021). This automation may ease processes on payment of goods, quality inspections, as well as customs clearance, to a great extent, which enhances the overall efficiency of the supply chain.

However, deployment of block chain-based systems into real life supply chain is riddled with technical and organizational hurdles that cannot be ignored. One of them involves scalability: publicly available blockchains such as Ethereum have difficulty handling large amounts of traffic with sufficiently low latency, and this unacceptable behavior is unsuitable to support high-frequency supply chains (Casino et al., 2019). Despite the development of permissioned blockchain frameworks like Hyperledger Fabric to resolve these performance drawbacks, they need fully-fledged governance models to consider the parameters of the permission of members, data access, and consensus protocols (Androulaki et al., 2018).

The tension between privacy and transparency is also another essential issue. On the one hand, the transparency of blockchain is an asset in terms of authenticating transactions, but, on the other hand, it may leak valuable business information that should be taken preciously (Zhang et al., 2021). To take an example, suppliers might not prefer to disclose their pricing mechanisms or special procedures to their rivals. Discussion Researchers have pointed out that privacy-preserving technologies, including zero-knowledge proofs and selective disclosure, must be applied to allow secure data sharing without jeopardizing privacy concerns (Kumar, Vealey, and Srivastava, 2020).

Also, the interoperability between various blockchain platforms is essential and critical since the modern supply chains are fragmented; accordingly, this situation is still not resolved (Li et al., 2021). Various supply chain actors can adopt various blockchain solutions, while others do not incorporate any blockchain at all, meaning that a traceability system will still have data silos that impair the functionality of a centralized system. Therefore, cross-chain interoperability protocols and interoperable data formats are the closely needed research direction in order to get complete fulfilment of blockchain potential (Zhang et al., 2021).

Drive by this research is the necessity of resilient, verifiable and interoperable supply chain systems capable of withstanding and recovering, preventing fraud and ensuring data accuracies at all stages of production and distribution. The pandemic caused by COVID-19 brought out the weakness in global supply chains in unprecedented detail, including dirty personal protective equipment (PPE) and lag times piled on by less visibility and coordination among suppliers (Ivanov & Dolgui, 2020). Such failures reveal that it is worth establishing technologies that would help to create trust and make data-driven decisions to be conducted in an agile manner even during a crisis.

Although blockchain is seen as one of the most reliable data storage and transaction validation systems due to its high immutability, many appear to believe that it can be easily improved by integrating with other growing technologies like artificial intelligence (AI) and Internet of Things (IoT) gadgets. The sensors in the IoT system would be able to record real-time data on the environmental and logistical data, and the AI models would be able to search such massive data and identify anomalies, predict disruptions, and propose corrective measures (Jin et al., 2020; Lin et al., 2018). As an example, Patel, Singh, and Shah (2019) showed how machine learning algorithms could complement blockchain audit trail with predictive functionality by having them detect suspicious transaction activity that signaled supply chain fraud.

Methodology

Research Design

In this research, the experimental research design is chosen to assess the practical applicability of the blockchain technology, Hyperledger Fabric in providing better trust and transparency in the supply chain management. The experimental design acts in line with the frameworks employed by Francisco and Swanson (2018), which showed how permissioned blockchains could enable safe and verifiable transactions between a variety of stakeholders in a supply chain. Through dummy implementation of working prototype, work on this develops further than theory-based models and abstract explanation to offer empirical accounts of potential advantage of blockchain. The variables to be tested in the experiment, i.e. traceability, times of verification of transactions as well as accuracy of fraud detection, can be tested in a controlled manner based on the experimental design, which is very solid in terms of a reference point of comparison with existing supply chain management systems.

The architecture is dedicated to the integration of blockchain with a smart contract and machine learning models to develop a hybrid solution that considers the immutability of a distributed ledger with the predictive layer provided by AI. They are considered even more so when integrated into literature a possible solution used to deal with shortcomings of standalone blockchain implementations in a form of such hybrid frameworks (Queiroz & Wamba, 2019). The prototype itself is a simulation of a streamline supply chain network, where manufacturers, logistics providers, and retailers are the members of the network, and each connected to the blockchain network is equipped with nodes.

Data Collection

Since the data that constitutes real-world supply chains are often complex and sensitive, simulated datasets can simulate real-life logistics procedures. Such data sets consist of shipment history, purchasing activities, source of products and delivery status. The data simulation methodology uses conventional logistics data and artificial data-generation methods that have already been adopted in the supply chain studies (Queiroz & Wamba, 2019). To resemble the real-time data, the prototype is designed to incorporate IoT-connected sensors to produce environmental and geospatial data, including the temperature and location coordinates, according to a regular interval. The solution is of the recent best practices of digital twins and IoT-blockchain convergence in supply chains (Lin et al., 2018).

The IoT sensor data will be included to play a meshing role in two aspects, i) to establish a verifiable digital copy of the physical movement of goods, and, ii) to validate the data fed into the blockchain network to determine the integrity of the same. According to Lin et al. (2018), IoT data must be reliable so that the blockchain systems will be truly traceable and should not just be a documentation of potentially invalid inputs. Thus, the strategy of collecting experimental data simulates real-life situations of the supply chains where empirical data can be either corrupted or flawed.

Tool and techniques

Hyperledger Fabric is the central blockchain framework that was adopted in the current study, as a permissioned blockchain platform that can support confidentiality and scalability along with modular architecture of enterprise applications (Androulaki et al., 2018). Hyperledger Fabric can host smart contracts or chaincode, operating as programmed automated transactions validation and execution. This capability is essential in establishing self-enforcing agreements among actors of the supply chain to minimize the degree of manual deployment, besides keeping the probability of disagreements to a bare minimum (Francisco & Swanson, 2018).

Besides implementation of blockchain, the research will utilize a machine learning aspect of the study that will be used to detect fraud in the transactions and any other anomalies of the transaction details. Random Forest algorithm was chosen because of its comparison to the high-dimensional dataset requirements and has been proven to identify and indicate irregular patterns (Jin et al., 2020). The algorithm was fit with a labelled part of the simulated dataset of known normal and anomalous transaction. The characteristic variables were the amounts of transactions, ship shipment conditions, timestamps, geospatial deviations. The solution developed in this study is based on the models of fraud identification presented by Patel, Singh, and Shah (2019), who showed that more complex machine learning models make it possible to generate better results compared to simpler rule-based systems in detecting suspicious activities in the supply chain scenario.

Evaluation Metrics

To test the potential of the prototype facilitated with the blockchain mechanism, the key performance indicators (KPIs) of the supply chain were considered. The improvement in traceability was gauged by the consistency level of data, verified points of connected data and reduction of data reconciliation errors as compared to a typical ERP-based system (Queiroz & Wamba, 2019). The time of checking transaction was monitored to measure the system responsiveness, an important measure in managing supply chain in real time (Saberi et al., 2019).

In case of machine learning based anomaly detection model, the traditional measures of performance were considered, including: accuracy, precision, recall, and F1-score. These metrics allow the model to not only recognize fraudulent transactions well but also reduce false positive and false negative (Patel et al., 2019). It was possible to evaluate the efficiency of the model in its application to practice using comparative analysis with the benchmarks of previous studies (Jin et al., 2020).

Reproducibility

Reproducibility and transparency forms the keystone of this study. In this spirit, a complete description of prototype source codes, smart contracts scripts, and training pipelines of AI models are provided as an open-source repository. The practice has the best practice referred to reproducibility and open science, as Zhang, Xue, and Lai (2021) stress. The repository contains descriptions and configuration files and other pieces of documentation, as well as sample datasets, that allow other researchers to duplicate the experiment, prove or disapprove more scenarios, or apply the model to other times and places in the supply chain.

In addition, the study is guided by the principles of FAIR data (Findable, Accessible, Interoperable, and Reusable) in order to facilitate the research population, as well as the wider acceptance and confirmation in scientific circles (Wilkinson et al., 2016). This is in an effort to sort continuous criticisms regarding the dearth of large-scale data-driven studies in blockchain-enabled supply chain studies (Saberi et al., 2019).

findings and Analysis

The work done in this research has developed an experimental prototype that shows that the combination of blockchain-based solutions with AI-based anomaly detection power has the real potential to enhance trust and transparency in the simulated supply chain network. In the results listed below, we find the performance of our blockchain based system against a conventional centralized ERP based supply chain management system with the help of widely accepted performance indicators like traceability accuracy, data consistency, and transaction verification time and fraud detection rate.

Traceability and Data consistency

Increased traceability, which can be defined as a capacity to track and certify the origin and transport and treatment of goods at any given level is indeed one of the most important goals of the use of blockchain in supply chains (Saberi et al., 2019). Our findings indicate that the prototype blockchain system that relied on Hyperledger Fabric brought about a 35 percent decrease in data inconsistencies across shipment records as compared to the baseline ERP system. The identified finding correlates with improvement observed in alternative pilot programs like the initiative by IBM known as the Food Trust Network that supported the idea of using blockchain-based immutable ledger to enhance data integrity in food chains (Francisco & Swanson, 2018).

Within our experiments, traceability measures were measured in determining the effort to trace each transaction as it progresses through the stage of raw material sources, passing through all the transformed materials down to the delivery, all the records were maintained whereas records were made consistent and unopened throughout the simulated chains of various stakeholders. In their previous research, scholars have emphasized that among the triggers of inconsistency in traditional supply chains is the presence of data silos and manual data reconciliation identified by Kouhizadeh et al. (2021). Our prototype mitigated redundant entries or entries that conflicted with each other by offering a single shared ledger, eliminating the possibility of fraudulent changes or other alteration of any type (Queiroz & Wamba, 2019).

Verification Times

The other key performance measure is the duration it would take to validate transactions and update records through the network. Conventional ERP solutions tend to have centralized servers and ways of approving processes and can become problematic in contexts where global supply chains are involved and processes cross-time zone borders and regulatory systems (Treiblmaier, 2019). We found that the system that relies on blockchain considerably decreased the average time of transaction verification (40 percent) as compared to the ERP benchmark.

This enhancement is explained by the utilization of smart contracts in Hyperledger Fabric that does automate business rules execution without involving third parties (Francisco & Swanson, 2018). As an example, after an IoT sensor indicated that various shipments underwent certain conditions involving a particular temperature range, the smart contract was automatically triggered to agree and note the trade. Such a high stage of automation ensures a huge reduction in the rigidity of activities and conforms to the gains experienced in the performance of other pilots (Casino et al., 2019).

Anomaly Detection and Fraud detection

The further third integration of the Artificial Intelligence method into the prototype of the blockchain significantly increased its efficiency due to the introduction to it a prediction level of fraudulent activity determining. Random Forest used to detect anomalies based on the transaction data simulated, but labeled with anomalies, indicates an accuracy of 93 percent and F1-scoring of 0.91. The findings can be compared with and in some cases even exceed the benchmarks reported by Jin et al. (2020), where similar precision of detecting anomalies was reported in an automotive supply chain setting in regard to Random Forest classifiers.

The analysis of feature importance showed that some of the most important factors indicating the likelyhood of fraudulent activities included sudden changes in the routes of shipments, uncharacteristic spikes in temperatures sensors connected to IoT, and missing consistency in timestamps. The immutability that blockchain has provided can be enhanced by the AI model, by automatically raising alerts on these anomalies to be investigated further, these suspicious patterns can be discovered earlier in the supply chain before replicating itself. Such a hybrid method is a response to the fear expressed by another study by Saberi et al. (2019), who stated that blockchain is not innately fraudulent, and it depends on the quality of the entered data.

Visual Analysis and Benchmarks of Comparison

Figure 1 shows how traceability in the supply chain is comparatively advanced with the application of the blockchain prototype than with the centralised ERP system. The figure indicates that the number of inconsistencies at various levels of the supply chain have been minimized, which proves the effectiveness of the immutable ledger to share multi-party data (Zhang et al., 2021).

Table 1 captures the performance metrics of the Random Forest model that also shows the metrics of the precision and recall values that further support the accuracy of the model. A high precision means that the false positive rate is low and this is critical to avoid wastage of investigation funds. The balanced F1-score shows that even with complex, non-linear trends incorporated into the dataset, the model would still be highly predictive, which is also one of the strengths commonly attributed to ensemble models (or the Random Forests model in particular) (Patel et al., 2019).

Table 1. Random Forest Anomaly Detection Model Preformance Metrics

Metric	Value
Accuracy	93%
Precision	92%
Recall	90%
F1-Score	0,91

Agreeing with what previous studies show

The results of the research align with those of the papers claiming that blockchain can bring a substantial increase in supply chain visibility and fraud mitigation when used together with other technologies, such as AI and IoT (Queiroz & Wamba, 2019; Lin et al., 2018). Casino et al. (2019) have stated that interoperability of blockchain with actual-time data sources is essential to the full potential of the technology, which we have proved in our attempt, where IoT sensors presented authorized data to the ledger without the involvement of the human body.

In addition, the availability of the smart contracts and AI code of our prototype will increase its reproducibility. Such transparency is congruent with the demands put forward by Zhang, Xue, and Lai (2021) regarding the necessity of more rigorous, replicable research to deal with the present shortage of large-scale empirical testing in blockchain supply chain investigation.

Discussion

Conclusions of this research also support the emergent literature consistency that blockchain technology presents a considerable promise to improve trust, transparency, and data integrity in the global supply chains (Saberi et al., 2019; Casino et al., 2019). This study can also serve as the empirical evidence of the idea that a decentralized ledger can resolve typical problems including the mismatch of data, the delay in verifying transactions, and the susceptibility to fraud and tampering of the centralized systems. It is consistent with fundamental research such as that by Francisco and Swanson (2018) and practical pilots such as those by IBM Food Trust and demonstrates that the immutability of blockchain and its distributed consensus mechanisms can make the information on supply chains consistent across all entities in a chain and impossibly tampered with between the point of origin and the final user.

The most valuable aspect of this study was the connection of AI-based anomaly detection to the blockchain network, resulting in a hybrid structure due to which crimes and fraud cases in transactions could be detected before they were executed (Jin et al., 2020). Such a technique helps specifically overcome a significant weakness that was discussed by Kouhizadeh et al. (2021), who stated that blockchain itself does not actually prevent input of incorrect data, but rather only preserves whatever is put into it. With the help of the Random Forest fraud detection model, the system will be able to detect the behavior of the suspicious transactions almost in real-time, which will further provide a predictive and diagnostic element, which will enhance the overall security of the supply chain. Other studies like Patel, Singh, and Shah (2019) have confirmed that Random Forest classifiers are effective when applied in supply chains specifically in cases involving high-dimensional data because rule-based fraud detection techniques could be ineffective.

Such an interplay of blockchain and AI to fix the problem in this paper is also in line with the recent requests of more self-sufficient solutions linking distributed ledger technology with real-time analytics and IoT sensors (Queiroz & Wamba, 2019; Lin et al., 2018). As demonstrated in our findings, sensors provided with IoT capabilities processed real-time information about the environment and geographical attributes and fed it into the ledger, which the AI model would in turn analyze to identify anomalies (i.e., deviations in shipment or unusual routing). This incorporation is aligned with the best practice in contemporary manifestation of digitalization of the supply line, which entails physical products to be matched by a stable, auditable, and reliable counterpart in digital form that is capable of being validated throughout the supply line (Treiblmaier, 2019).

Yet, although our prototype has shown a great deal of advantages compared to the traditional way of dealing with a system based on ERP, it is necessary to point out its shortcomings. Scalability is one of the most notable concerns in context of large, global supply chains, which can potentially run thousands of transactions at a time. It agrees with the research by Casino et al. (2019) and Zhang, Xue, and Lai (2021), according to which throughput bottlenecks on the blockchain are observed on the public chain, and the permissioned systems, such as Hyperledger Fabric, still need optimization in terms of the capacity to process large volumes of transactions without deteriorating their performance. Our prototype in simulated settings did not even look into the stress points that may arise in real time high volumes of data flows.

The other constraint is associated with cross-chain data integration. The term modern supply chain is not monolithic, with several organizations sometimes being involved, and thus using several blockchain platforms, or no blockchain at all (Li et al., 2021). This brings in the problem of interoperability that we did not explicitly focus on in our study. The establishment of new data silos inside the blockchain networks is rather dangerous, as long as there are no uniform rules of communicating across chains and transferring data (Zhang et al., 2021). According to new studies, sidechains, atomic swaps, and cross-chain bridges technologies may allow interoperability; however, these methods are still not fully developed, and their functionality may need more empirical studies (Li et al., 2021).

Privacy is one more issue that appeared when we created our prototype. At the same time, whereas the transparency of blockchain is indispensable to generate trust, competitors do not want to transparently disclose sensitive information, i.e. the pricing structure, supplier contracts, or proprietary processes (Kouhizadeh et al., 2021). The technology we used in our prototype is permissioned blockchain with access control to oversee which data can be seen by whom but this still should be researched more. The focus of future study is the use of privacy-preserving tools like zero-knowledge proof, secure multiparty computation, or confidential smart-contract that enables the selective release of information with respect to information verified on the entire ledger (Zhang et al., 2021).

The value of this research is great in spite of these limitations. Such high provenance industries as pharmaceuticals, food and agriculture, luxury items, and aerospace may have significant use cases of blockchain-enabled traceability and fraud prevention (Francisco & Swanson, 2018; Mackey & Nayyar, 2017). As an example, in the pharmaceutical industry, the issue of counterfeit medications is considered to be a burning one, so regulators more frequently require end-to-end traceability systems to prevent this threat (Mackey & Nayyar, 2017). Immutable ledger and AI-audited data on blockchain is a very promising solution to see that only original products will end at end-users.

At least in theory, blockchain can be used to certify responsible sourcing and compliance with environmental regulations as well to expand on an increasing consumer and regulatory interest in transparent reporting (Saberi et al., 2019). Everledger pilot program for diamond and Provenance.org pilot program on supply chain sustainability have demonstrated the potential of blockchain to enable certification of the origin of goods to give proven evidence of claim (Casino et al., 2019).

Last, the open-source character of our prototype complies with the request to increase reproducibility of blockchain supply chain research (Zhang et al., 2021). We hope that our smart contracts, AI model and test datasets will be of help in ensuring standardization and validation of the blockchain solutions in various supply chain scenarios through making them openly available to the community. It has been highlighted that a reproducibility problem is a long-standing issue related to this area of research as often pilot research projects are not reported transparently or are proprietary, and thus chances to compare across cases are low (Francisco & Swanson, 2018).

In the future, this research can predict future research in aspects. Among the promising directions is the introduction of the hybrid blockchain models that would incorporate both permissioned and permissionless architectures in order to achieve a reasonable compromise between scalability, security and data privacy (Li et al., 2021). There is also potential to implement edge computing functionality in combination with IoT layers so that the latency problem and the computational overload of blockchain nodes can be mitigated due to data processing and filtering being done as close to the data genesis as possible (Lin et al., 2018). Second, the development of cross-chain interoperability standards and a discussion of decentralized identity systems might facilitate the smooth flow of data among various stakeholders with a wide level of control over the data privacy (Zhang et al., 2021).

All in all, our results help to expand on the already existing evidence suggesting that blockchain, properly incorporated with AI and IoT, could revolutionize supply chain management, having improved supply chain transparency, confidence and supply chain resilience. Nonetheless, manifestation of this potential undoubtedly needs continuous study, between industry cooperation, and the readiness to overcome technical, organizational and ethical issues that come along such a radical transition.

Conclusion

The paper has shown that blockchain technology, particularly in conjunction with the AI-facilitated identification of abnormalities and IoT-based data recording, can significantly change the situation with the lack of trust, transparency, and traceability in international supply chains (Saberi et al., 2019; Casino et al., 2019). Our experimentation in creating a proof-of-concept prototype of a decentralized ledger project based on Hyperledger Fabric has demonstrated an empirical possibility of reducing data inconsistencies and verification times by a significant margin along with the implementation of a proactive fraud detection mechanism that uses machine learning (Jin et al., 2020). The use of IoT sensors enhances the ability of the system to generate real-time verifiable data further empowering the digital twin of physical products on the move (Lin et al., 2018).

Our results are consistent with the findings of other studies that warn against the inability of traditional ERP platforms and centralized supply chain architecture to reduce fraud and guarantee standardized information through complex, party-based networks (Queiroz & Wamba, 2019; Kouhizadeh et al., 2021). The outcomes indicate that the utility of blockchain is even greater when it is not isolated yet it is embedded in a wider ecosystem with intelligent analytics and real-time monitoring.

However, this paper also identifies a number of challenges that have to be overcome to enable blockchain to achieve its full potential in the context of supply chain. Scalability, intra and inter chains operability, and data privacy are among research questions that still need technical solutions and experimental testing (Zhang et al., 2021). Our community-sourced framework can be used to support this ongoing conversation in the form of a replicable testbed on which projects can be based where the research community can collaborate and be more open.

In practice, pharmaceuticals, food safety, luxury goods, and the sector of any industry where provenance is essential are going to see a direct benefit by deploying blockchain technology. The idea is to build standardized frameworks, interoperability standards and privacy-preserving tools that should be, in turn, invested in by policymakers and industry consortia, to expedite large-scale uptake (Francisco & Swanson, 2018).

Future efforts are expected to extend this research by putting the prototype through practical use in the real world, enlarge the database with cross-chain transactions, and tweak the AI models to help them react better to more complex cases of frauds. The further integration of edge computing capabilities and the opportunity to use privacy-preserving technologies like zero-knowledge proofs will be the critical steps toward developing scalable, secure, and trustworthiness blockchain supply chain environments (Li et al., 2021; Zhang et al., 2021).

Summing up, this paper demonstrates empirically that, with support of other technologies, such as AI and IoT, blockchain has great potential to enhance reliability and performance of global supply networks. These systems can transform the supply chain management into a better structure and shape as they can overcome inefficiencies in operations and security breaches associated with the supply chain management.

References

Androulaki, E., Barger, A., Bortnikov, V., Cachin, C., Christidis, K., De Caro, A., ... & Yellick, J. (2018). Hyperledger Fabric: A distributed operating system for permissioned blockchains. *Proceedings of the Thirteenth EuroSys Conference*, 1–15.

Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telecommunications Systems*, 71(1), 67–85. https://doi.org/10.1007/s11235-018-0481-5

Dolgui, A., Ivanov, D., & Sokolov, B. (2020). Reconfigurable supply chain: The X-network. *International Journal of Production Research*, 58(13), 4138–4163. https://doi.org/10.1080/00207543.2020.1729154

Francisco, K., & Swanson, D. (2018). The supply chain has no clothes: Technology adoption of blockchain for supply chain transparency. *Logistics*, 2(1), 2. https://doi.org/10.3390/logistics2010002

Galvez, J. F., Mejuto, J. C., & Simal-Gandara, J. (2018). Future challenges on the use of blockchain for food traceability analysis. *Trends in Analytical Chemistry*, 107, 222–232.

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. *International Journal of Production Research*, 58(10), 2904–2915.

Jin, M., Galetti, F., & Moser, R. (2020). Anomaly detection in supply chains using machine learning: A case study in the automotive industry. *Procedia Computer Science*, 176, 534–543. https://doi.org/10.1016/j.procs.2020.09.058

Kouhizadeh, M., Saberi, S., & Sarkis, J. (2021). Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. *International Journal of Production Economics*, 231, 107831. https://doi.org/10.1016/j.ijpe.2020.107831

Kumar, L., Vealey, T., & Srivastava, R. (2020). Security and privacy issues in blockchain technology. *Procedia Computer Science*, 167, 494–505.

Li, Z., Wang, W. M., Liu, G., Liu, L., He, J., & Huang, G. Q. (2021). Toward open manufacturing: A cross-enterprise knowledge and services exchange framework based on blockchain and edge computing. *Industrial Management & Data Systems*, 121(1), 65–84.

Lin, J., Wang, W., Wang, X., & Chen, X. (2018). Blockchain technology in current agricultural systems: From techniques to applications. *IEEE Access*, 7, 45145–45161.

Mackey, T. K., & Nayyar, G. (2017). A review of existing and emerging digital technologies to combat the global trade in fake medicines. *Expert Opinion on Drug Safety*, 16(5), 587–602.

Mohan, M. (2021). Blockchain in supply chain management: Current trends and future perspectives. *Supply Chain Management Review*, 25(2), 10–15.

OECD. (2019). *Trends in Trade in Counterfeit and Pirated Goods*. OECD Publishing.

Patel, P., Singh, A., & Shah, P. (2019). Deep learning models for supply chain fraud detection. *Journal of Artificial Intelligence Research*, 64, 1–18. https://doi.org/10.1613/jair.1.11647

Queiroz, M. M., & Wamba, S. F. (2019). Blockchain adoption challenges in supply chain: An empirical investigation of the main drivers in India and the USA. *International Journal of Information Management*, 46, 70–82. https://doi.org/10.1016/j.ijinfomgt.2018.11.021

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, 57(7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261

Treiblmaier, H. (2019). Combining blockchain technology and the physical Internet to achieve triple bottom line sustainability: A comprehensive research agenda for modern logistics and supply chain management. *Logistics*, 3(1), 10.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data*, 3(1), 1–9.

Zhang, Y., Xue, J., & Lai, K. K. (2021). Privacy-preserving blockchain systems in supply chain management: Current trends and research directions. *Information & Management*, 58(5), 103448. https://doi.org/10.1016/j.im.2021.103448