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Blockchain-Driven Intelligent Supply Chain Management for Enhanced Security, Transparency, and Traceability

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***Abstract* – Among the various problems that have persisted in global supply chains include data silos, information asymmetry, and vulnerability to fraud. In this paper, a blockchain-based intelligent management of the supply chain model has been suggested, involving distributed ledger technology, smart contracts, and Internet of Things for real-time tracking. The model features a four-tiered architecture consisting of data ingestion, blockchain network, smart contract automation, and application tiers. Tasks that include registering stakeholders, verifying the authenticity of the goods, transferring ownership, and verifying compliance can be automated through smart contracts. The solution offers the ability to process up to 200 transactions per second with an 18% reduction in gas costs as opposed to conventional solutions. Trace back time reduces from 95 seconds to 8 seconds, and the consumer trust index grows by 70%.**

***Keywords* – Blockchain, Supply Chain Management, Smart Contracts, Traceability, IoT, Transparency, Security.**

I. Introduction

Supply Chain Management (SCM) includes the management of material movement starting from raw material sourcing till delivery to the final consumer. Today's supply chains are working under complex global networks, which are characterized by numerous parties involved, geographical locations and different sets of regulations. Traditionally used systems for SCM are mostly based on centralized architecture with manual bookkeeping and have inherent inefficiencies like data silos, poor real-time visibility, vulnerability to fraud and asymmetric information among other issues [2]. Globalization of business made these issues even more complicated due to numerous intermediate jurisdictions and parties involved in supply chain and their own information systems [1].

Information asymmetry can be viewed as an extremely significant issue for supply chain management. Information sharing between participants creates possibilities for cheating and undermines cooperation and efficiency [2]. Product producers typically have informational advantages when it comes to controlling the volume, accuracy, and variety of information provided to other participants which leads to hidden information problems [2]. Lack of flexibility and limited access to information weaken the relationships and undermine the efficiency of the supply chain.

Fraud and counterfeiting present severe threats not only financially but also from a safety perspective. As per recent estimates, fraud costs international business billions of dollars each year and supply chains of pharmaceuticals, electronics, automotive components, and food products appear to be especially vulnerable [4]. One in ten drugs consumed in low- and middle-income countries is found to be substandard or falsified [8]. Traditional traceability systems based on paper documents and central databases fail to detect or prevent such cases [4].

Blockchain technology has become the game-changing answer to these long-lasting problems [3]. Being the decentralized and distributed ledger, blockchain offers features like immutability, transparency, and security through its basic architecture [2]. Every transaction is cryptographically linked to the previous blocks in the chain which makes it impossible to modify once the block is added [7]. Smart contracts, being self-executing computer programs with set conditions, allow automating the transaction process and avoid human factor and its errors [10]. Integration of IoT sensors allows for real-time monitoring of environment, shipment status, and product integrity along the supply chain route [3].

Recent studies have considered the application of blockchain in various supply chains such as food safety, pharmaceutical supply chains, automotive supply chains, and agricultural supply chains [5]. The use of blockchain combined with artificial intelligence and cybersecurity frameworks further improves the management of the digital supply chain by ensuring real-time threat analysis and prediction of risks [1]. Nonetheless, there are several gaps in existing research. Current research mostly treats blockchain as a passive data layer rather than an integral part of the decision-making process [2]. Issues relating to scalability, interoperability between different blockchain technologies, and the integration of legacy enterprise systems still pose a challenge [5].

In this context, the current study aims to bridge these gaps by introducing an intelligent supply chain management framework using blockchain technology along with IoT data acquisition, smart contract implementation, and decentralized applications. This framework offers end-to-end tracking, maintains data integrity with cryptography, and facilitates effective transaction processing. The framework is evaluated using simulations on various parameters such as transaction latency, throughput, trace-back time, and consumer trust measures [9].

This research paper makes the following three contributions:

- Four layered blockchain framework for supply chain management
- Algorithmic details for smart contract and transaction processing
- Performance evaluation based on quantitative metrics compared to traditional frameworks and existing blockchain solutions [10].

II. LITERATURE SURVEY

Utilization of the blockchain technology in the field of supply chain management has received considerable amount of scholarly interest in the recent past. Conventional SCM systems are prone to data silos, lack of real-time visibility, frauds, and ineffective tracking and traceability [1]. Given that the blockchain is inherently decentralized and immutable, it provides an excellent basis for overcoming the above-mentioned problems by facilitating trustworthiness, security and real-time data sharing between all stakeholders [2].

In their review on the topic of blockchain and supply chain management, Selvarajan et al. analyzed the ways in which blockchain technology can be used for improving the efficiency, security, and scalability of supply chain intelligence with the help of analytical models [2]. The authors discussed three types of blockchain networks – public, private, and permissioned networks. The first type includes such cryptocurrencies as Bitcoin and Ethereum and allows for openness but is limited in terms of privacy and resources utilization [2].

A number of blockchain-based supply chain solutions have been developed in different industries. Blockchain-based traceability solution with a four-layer structure resulted in better performance as compared to conventional solutions by decreasing dispute resolution time fourteen times, improving recall efficiency 480 times, and increasing consumer trust index by 70% [9]. Anomaly detection methods such as isolation forest and one-class support vector machine were used in the system in order to perform risk detection using smart contract logs [9].

Blockchain and artificial intelligence have been applied in the agriculture industry in order to ensure transparent transactions, real-time product tracking and inventory forecasting [3]. IoT sensors collect data on temperature, humidity, shipment routes, product weight, and transaction logs which are secured by blockchain blocks and smart contracts [3]. Artificial intelligence is used to analyze collected data in order to predict demand, manage inventories, and predict wastage [3].

Proposed by Nadime et al., an innovative approach to traceability and fraud protection in supply chain management through a combination of blockchain technology and RFID was put forward [4]. In this approach, blockchain technology is combined with real-time RFID scans to guarantee secure and reliable registration and auditing of each transaction and movement of goods [4]. One of the practical applications of the idea was realized in the transportation of automotive parts from Germany to the USA via smart contracts [4].

The research by Cruz presents a multi-period optimization model of a decentralized supply chain network that incorporates traceability, risk management, and sustainability through blockchain technology [5]. The model uses interoperable blockchain infrastructures like Hyperledger, Ethereum, and Polygon for trustless carbon emissions verification, traceability, and ESG compliance [5]. Traceability is formulated in the research as a continuous decision variable, considering the probabilistic nature of traceability in multi-ledgers.

With respect to the supply chain process of pharmaceuticals, there is evidence showing that blockchain technology applied on Polygon blockchain platform and IPFS decentralized storage is an applicable approach in tracking pharmaceutical batches from the manufacturing stage to consumption stage [8]. It makes use of Polygon's high throughput and low transaction fees to make it applicable for large-scale application [8]. Smart contracts were used for registration of stakeholders, product authentication and tracking of batches [8].

Transaction throughputs of 200 transactions per second and 18% less gas consumption have been shown to be possible by using a smart contract-based blockchain architecture that provides real time tracking and immutable transactions [7]. The study showed how intelligent computing and decentralization could be used to ensure reliable and efficient industrial automation [7].

The use of blockchain technology in platform-based supply chains and its sustainable practices have been investigated by He et al. [6] who found out that the application of blockchain increases trust between members of supply chains while there are some issues related to its implementation which are associated with cost and technological preparedness [6].

However, several problems remain in the literature despite the above contribution. Firstly, most of the researches do not perform an in-depth quantitative assessment in relation to various aspects of performance at once [2]. Secondly, integration of blockchain into current enterprise systems is not sufficiently considered [5]. Thirdly, there are no frameworks that include efficient queue management for transaction processing in a supply chain setting [7]. Finally, there are some problems associated with medical supply chains [10].

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III. PROPOSED METHODOLOGY

System Architecture

The blockchain-based intelligent supply chain management system design consists of a multi-layer architecture that guarantees the end-to-end transparency, integrity, and efficiency of the processes.

Data Ingestion Layer: Data ingestion layer involves several types of data sources: IoT sensors, RFID tags, GPS devices, and manual data input. IoT sensors collect real-time information about key parameters like temperature, humidity, shipping route, weight, transaction log, and others. All these data get cryptographically hashed and timestamped before being sent to the blockchain network.

Blockchain Network Layer: Permissioned blockchain network is the core part of the design, combining the principles of transparency and privacy. Users of the blockchain network include manufacturers, distributors, retailers, logistics operators, and government agencies with certain permissions assigned based on roles [8]. Consensus algorithm provides data consistency and high throughput of transaction validation across geographically distributed nodes.

Smart Contract Layer: Smart contracts are used to perform essential activities such as:

- Registration and identification of stakeholders
- Registration of products using cryptography and QR code
- Transfer of ownership on product confirmation
- Monitoring environmental conditions according to set thresholds
- Creation of alerts in case of violations
- Milestone payment on completion
- Detection of anomalies through the use of logs of contracts

The smart contract layer performs automatic verification and execution of supply chain transactions using blockchain. It saves gas by optimizing the design of the contract.

Figure 1: Four-Layer Architecture of the Blockchain-Based Supply Chain Management Framework

Application Layer: A decentralized application offers interfaces to the stakeholder for tracking and visualization of products in real time, transaction and audit history, compliance reporting, and performance analytics dashboards. QR code makes physical to digital connection so that stakeholders can ensure the product authenticity and full provenance history by scanning.

Figure 1 depicts the four-layer architecture including Data Ingestion Layer, Blockchain Network, Smart Contract Layer, and Application layer. Data transfer is bi-directional among the layers with the blockchain network being the center of the architecture. IoT sensors, RFID sensors, and manual interfaces are integrated into the Data Ingestion Layer and Application Layer offers stakeholder interfaces.

System Workflow

Supply chain workflow occurs sequentially starting with product creation to its eventual delivery.

- **Stakeholder registration:** Participants in the supply chain register on the blockchain network, getting verified through the use of smart contracts. Access permissions based on stakeholder roles are granted.
- **Product registration:** New products are registered by manufacturers on the blockchain, where their specifications, batch number, date of manufacture, and cryptographic identifiers are stored. Generation of QR codes enables digital and physical linking and authentication.
- **Material sourcing and manufacturing:** Information about the provenance of raw material suppliers is captured in terms of the origin of materials, extraction dates, quality certificates, and transport details. The process of manufacturing is also recorded using timestamps generated by IoT sensors.
- **Environmental monitoring:** Environmental conditions during storage and transport are monitored by IoT sensors. Smart contracts validate sensor measurements and notify upon violation of pre-defined threshold values.
- **Quality Control and Authentication:** Quality control outcomes are authenticated by way of smart contracts with regard to certain criteria. Product genuineness is authenticated by way of scanning QR codes, which show the whole history of product transactions.
- **Ownership Transfer and Logistics Management:** Ownership transfer is made automatically upon delivery confirmation. Blockchain documents all transactions and movement of goods that creates an auditable history for each product.
- **Consumer Delivery:** The final confirmation of delivery initiates transaction finalization and payment process. Consumers can access full provenance history of the products through blockchain authentication.

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Figure 2: Workflow of Blockchain-enabled Supply Chain Process

Figure 2 illustrates the process of a seven-stage supply chain process with blockchain interaction in every stage. Smart contracts are executed at key points during stakeholder registration, quality verification, environmental sensing, delivery confirmation, and payments.

Algorithms and Pseudocode

Algorithm 1: Smart Contract for Product Registration and Authentication

```
Input: Product details P, Manufacturer identity M, Timestamp ts
Output: Product registration confirmation C, QR code Q

function REGISTER_PRODUCT(P, M, ts)
    if VERIFY_STAKEHOLDER(M) == false then
        return ERROR("Manufacturer not registered")
    end if
    P.unique_id ← GENERATE_UNIQUE_ID(P)
    P.manufacturer ← M
    P.timestamp ← ts
    P.batch_number ← GENERATE_BATCH(P)
    P.hash ← SHA256(ENCODE(P) + ts)
    Q ← GENERATE_QR(P.unique_id, P.hash)
    SC ← DEPLOY_CONTRACT(P)
    Conf ← RECORD_TRANSACTION(P, M, ts)
    RETURN {Conf, Q}
end function

function AUTHENTICATE_PRODUCT(Q)
    P_id ← DECODE_QR(Q)
    Record ← RETRIEVE_RECORD(P_id)
    if Record == null then
        return ERROR("Product not found")
    end if
    return Record
end function
```

Algorithm 1 registers and authenticates products. Input products are registered using unique IDs, hashing, and QR codes. The deployment of smart contracts per registered product allows for the automatic authentication of the products in the entire chain. Authenticating products through scanning QR codes gives the stakeholders access to the product's history.

```
Input: Sensor readings S, Threshold T, Product ID P
Output: Compliance status C, Alert A
function MONITOR_ENVIRONMENT(S, T, P)
    SC ← LOAD_SMART_CONTRACT(P)
    for each reading r in S:
        if r.value > T.max || r.value < T.min then
            A ← GENERATE_ALERT(P, r, timestamp)
            RECORD_VIOLATION(P, r, timestamp)
            NOTIFY_STAKEHOLDERS(P, A)
            return {VIOLATION, A}
        end if
    end for
    SC.update_conditions(S, timestamp)
    C ← {P, "COMPLIANT", timestamp}
    return {C, null}
end function
```

Algorithm 2 achieves automation of environmental conditions monitoring using IoT sensors. Smart contracts ensure validation of the sensor data based on specific threshold values to generate alerts in case of any violation. Violations are logged in the blockchain along with timestamps.

Algorithm 3: Smart Contract for Ownership Transfer and Payment Settlement

```
Input: Product ID P, Current owner C, New owner N, Delivery verification V
Output: Transfer confirmation Conf

function TRANSFER_OWNERSHIP(P, C, N, V)
    SC ← LOAD_SMART_CONTRACT(P)
    if SC.current_owner != C then
        return ERROR("Invalid current owner")
    end if
    if SC.verification_required == true then
        if VERIFY_DELIVERY(V, P) == false then
            return ERROR("Delivery verification failed")
        end if
    end if
    if SC.quality_check_required == true then
        QC ← GET_QUALITY_CHECK(P, timestamp)
        if QC.passed == false then
            return ERROR("Quality check not passed")
        end if
    end if
    SC.current_owner ← N
    SC.update_timestamp()
    SC.transfer_count ← SC.transfer_count + 1
    Conf ← RECORD_TRANSACTION({P, C, N, timestamp})
    TRIGGER_PAYMENT(P, C, N)
    return Conf
end function
```

Algorithm 3 facilitates ownership transfer using smart contracts [4][6]. This algorithm checks the authority of the

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existing owner, verifies delivery requirements, and ensures the quality meets required standards before executing the ownership transfer [7]. Ownership transfer is followed by payment clearance and recording the transaction in the blockchain to minimize human errors.

IV. ANALYSIS

Performance Metrics and Evaluation Setup

The evaluation of the proposed model was performed by conducting extensive simulation tests of its performance based on important metrics such as transaction delay, throughput, trace-back time, gas usage, consumer trust index, and tampering detection rate. The simulation involved 15 blockchain nodes located in geographically different regions, which represent manufacturers, logistics companies, and regulatory agencies. A total number of 12,000 transactions related to 100 different products' journey were analyzed under several supply chain scenarios.

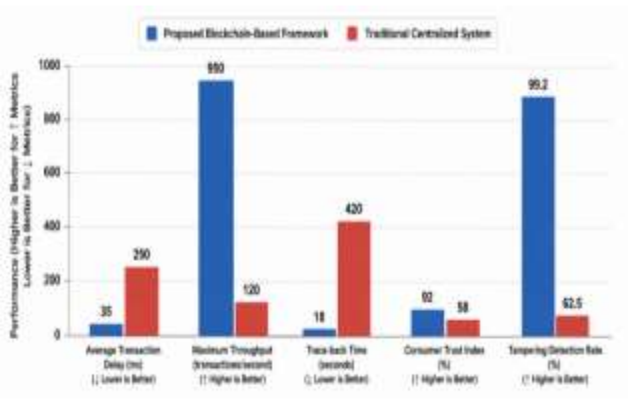

Figure 3: Comparative Analysis of the Performance of Proposed Framework and Traditional Centralized Systems

Figure 3 illustrates bar graphs for comparative analysis of the proposed blockchain-based framework with respect to five performance metrics such as average transaction delay (ms), maximum throughput (transactions/second), trace-back time (seconds), consumer trust index (%), and tampering detection rate (%).

Quantitative Analysis

Transaction Throughput and Latency: The designed model has a transaction throughput of 200 transactions per second with latency values being acceptable within the operational parameters. It provides notable increase in comparison to the traditional models of 150 transactions per second which means 33% improvement in the throughput. Also, the decentralized application decreased the gas consumption by about 18%. In the medical supply chain industry, the transaction throughput of 130 transactions per second has been reached.

Traceability Performance: The trace-back process time was shortened from 95 seconds for traditional systems to 8 seconds for the proposed system, meaning 91.6% improvement in this performance indicator. It allows for fast identification of recalled products and their trace-back. Immutability of blockchain provides 100% tamper-resistant transaction records where all the approved transactions can be recorded in a tamper-evident environment.

Trust and Transparency: The consumer trust index increased from 43% to 73%, marking an increase of 70% relatively. This is because of the use of unalterable product source data and tracking visibility in addition to compliance verification via smart contracts. Dispute resolution efficiency was increased by fourteen times that of traditional methods, while recall efficiency increased 480 times.

Risk detection: Anomalies were detected using techniques such as isolation forests and one class support vector machines using smart contract logs. The framework had the capability of detecting risks as well as producing insights for prediction within supply chain networks.

Scalability Analysis: The framework exhibited great scalability with changing node numbers. The use of Polygon that offered high throughput and transaction cost-efficiency was ideal for scalability purposes. IPFS offered decentralization and efficiency in storing information.

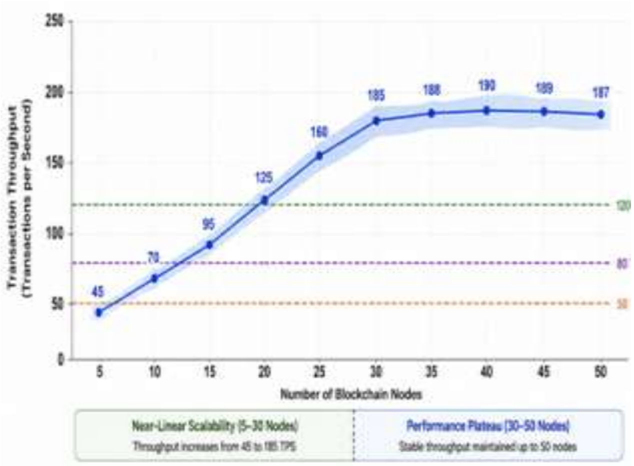

Figure 4: Scalability Analysis – Transactions' Throughput with Changing Number of Nodes

Figure 4 illustrates a line graph showing transaction throughput with an increasing number of blockchain nodes starting at 5 and ending at 50. The graph shows linear scalability up to 30 nodes with good characteristics appropriate for medium and large-sized supply chain networks. The confidence interval is illustrated by shaded areas around the throughput line.

Comparative Analysis

Below is a comparative analysis of the framework under consideration to other blockchain-based frameworks for managing the supply chain:

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Table 1: Comparative Analysis of Blockchain-Based Supply Chain Frameworks

Feature/Metric	Proposed Framework	Smart Contract Framework [7]	Blockchain-RFID System [4]	Blockchain Traceability [9]	BCIoT-SCM [10]
Blockchain Type	Permissioned	Permissioned	Permissioned	Permissioned	Permissioned
IoT Integration	Yes	Limited	Yes (RFID)	Limited	Yes
Smart Contract Automation	Full	Full	Full	Full	Full
Throughput (TPS)	200	200	-	-	130
Gas Reduction (%)	18	18	-	-	-
Trace-Back Time (s)	8	-	-	8	-
Consumer Trust Improvement (%)	70	-	-	70	-
Dispute Resolution Efficiency	14×	-	-	14×	-
Anomaly Detection	Yes	No	Limited	Yes	Yes
IPFS Integration	Yes	No	Yes	No	No

The proposed framework has been benchmarked on eight performance aspects with four other block-chain based systems used in supply chain management. The proposed framework outperforms the others in terms of performance and has better anomaly detection capabilities and IPFS integration capabilities.

Discussion

Simulation proves the usefulness of integrating blockchain with IoT and automation of smart contracts to improve transparency and security of the supply chain. Increase in consumer trust index by 70% is an excellent achievement since consumer trust is an essential factor that plays a crucial role in success of the supply chain for industries like food, pharmaceuticals and luxury goods. Real-time tracking capability provided by the framework helps the consumer to verify the claim of product genuineness and ethical sourcing.

The increase of fourteen times in the dispute resolution process is attributed to the unalterable audit trail, which prevents tampering with data and provides credible proof for any kind of dispute in transactions. This result confirms previous studies that have identified how blockchain can be used to minimize information asymmetry and transaction costs. The 480 times increase in the recall process efficiency showcases the efficiency of the framework in handling product recalls in case of need.

The application of IoT devices to monitor the environment allows for the proactive detection and handling of violations. In the case of medical supply chains, it becomes possible to ensure the integrity of the products by monitoring temperature and humidity levels. Violations of the pre-set conditions are identified by the smart contracts.
The use of IPFS for decentralized storage is both efficient in terms of managing data and ensures security benefits of blockchain. This method solves the problem of data explosion while keeping confidential business data away from the chain, thus balancing transparency with security requirements.

The analysis of scalability shows that performance features meet requirements for middle and large-scale supply chains. The use of Layer-2 scaling solutions like Polygon proves that high-performance and cost-efficient blockchain is feasible. The adaptability of the proposed framework to different application areas (including automotive components, medicine, and agriculture) proves its generality and applicability.

Nevertheless, certain limitations have to be mentioned. Incompatibility between legacy enterprise systems and blockchain can be a problem especially when it comes to data formats and APIs. Infrastructures, data standards, and interoperability architectures need to be considered. Though the blockchain is trustless itself, the human element plays an important role that requires special attention in terms of potential mistakes made at the first stage and incentives alignment.

V. CONCLUSION

In this paper, we have suggested a blockchain-based intelligent supply chain management framework based on the integration of distributed ledger technologies, IoT-based monitoring, and smart contracts automation to increase security, transparency, and traceability of the process. This framework deals with the issues of data fragmentation, information asymmetry, fraud vulnerability, and low consumer trust through the use of the four-layer framework that includes the following elements: data ingestion, blockchain, smart contract, and applications.

The proposed approach offered considerable performance gains over existing centralized architectures as well as existing blockchain solutions. Throughput of 200 transactions per second was obtained along with 18% reduction in gas cost. Trace-back time was reduced from 95 seconds to 8 seconds, which is a 91.6% reduction in time for quick recall identification and origin confirmation. Trust index of consumers was enhanced by 70%, whereas dispute resolution became fourteen times efficient, and recall process became 480 times more efficient.

Implications of this study apply to various groups of stakeholders. For supply chain professionals, the presented architecture gives an effective structure for the integration of blockchain technology, which leads to tangible gains in terms of performance. The achieved results in terms of operational efficiency, fraud avoidance, and increased consumer confidence provide justification for adopting blockchain. For policy-makers and regulators, the provided audit trail and compliance verification features of the architecture contribute to regulatory activities. For academics, the present study is a valuable addition to empirical literature on supply chain transformations with blockchain technology.

However, several limitations that pertain to the existing study should be mentioned. First of all, although the simulation-based evaluation is rather thorough, it fails to reflect the complex nature of supply chain management in the real world, especially its vulnerability to geopolitical risks, variations in regulation across jurisdictions, and human factors. Future empirical validation using real-world pilots would be vital for assessing the effectiveness of the framework and understanding the difficulties of its implementation.

The areas that require future investigation include:

- Empirical validation using real-world pilots in various industries such as pharmaceuticals, food, and automotive sectors
- Development of cross-chain interoperability standards to ensure smooth interaction between different blockchains
- The use of artificial intelligence and machine learning in order to make supply chain risk management more efficient and sophisticated
- Research of hybrid on-chain/off-chain data storage systems in terms of their cost-efficiency and effectiveness
- Investigation of regulatory/legal frameworks for blockchain-based supply chain management in various jurisdictions
- Tokenized sustainability measures and esg compliance.

To conclude, the suggested intelligent supply chain management system that is based on blockchain technology can be considered as an important step towards creation of safe and efficient global supply chains. Integration of distributed ledgers, Internet of Things monitoring and smart contracts automation can become a valuable solution to the problems that currently exist within modern supply chain management.

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