

Hyperledger Fabric Blockchain-Based Approach towards Secured Port Weighbridge Systems

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Abstract

Modern ports operation relies on accurate weight measurement to ensure cargos are delivered with dependability and integrity. The weighbridges systems have been playing crucial roles in ensuring the revenue generation, honest trading, regulations compliance and operational accountability in ports. Nevertheless, conventional weighbridge systems have been tokenized, hacked, and nontransparent because of improper measures against the willful misrepresentation of the weights by brokers or even the sometimes-unauthorized access to the systems. Such drawbacks have led to financial losses, regulatory disturbances, and the trust of stakeholders is eroded. Hence, a novel blockchain-based approach has been introduced in this study, the proposed approach exploits Hyperledger Fabric framework to protect the weighbridge system data and preserve its immutability. The proposed approach also enables data tracking and auditing, thus providing port authorities and customs with a unique view of the data history, which in turn, leads to greater accountability. The proposed approach has been tested through experiments and the results reveal that Hyperledger Fabric effectively diminishes data hijack incidents, guarantees same data in all nodes, and produces full audit trails for verifiability.

Keywords

Blockchain, Hyperledger Fabric, Weighbridge Systems, Data Integrity, Port Logistics, Fraud Mitigation

1. Introduction

One of the key responsibilities of port authorities is to manage the infrastructure

and facilities within the port, including weighbridges used for measuring cargo weight (Mlimbila & Mbamba [1]). Accurate weight measurement is essential for various reasons, including safety, taxation, and trade compliance. Port authorities are tasked with enforcing regulations and standards to ensure that weight measurement processes adhere to international standards and local regulations (Mlimbila & Mbamba [1]).

The integration of weighbridge systems in ports is part of a broader trend towards port regionalization and integration, which demands new governance approaches and functional focuses beyond traditional port boundaries (Onwuegbuchunam *et al.* [2]) Larger seaports have particularly benefited from port integration efforts, emphasizing the importance of streamlining operations and enhancing efficiency across various port functions (Lin and Huang [3]). Weighbridges are essential in port operations for accurately measuring cargo weight, crucial for logistics, safety, and efficiency. They facilitate efficient cargo handling and contribute to port performance evaluation (Bhatti & Hanjra [4]). However, weighbridge systems have been tokenized, hacked, and nontransparent because of improper measures against the willful misrepresentation of the weights by brokers or even the sometimes-unauthorized access to the systems. Such drawbacks have led to financial losses, regulatory disturbances, and the trust of stakeholders getting eroded (Song *et al.* [5]; Zhang *et al.* [6]).

In attempt to address the challenges, this study introduces a novel blockchain-based approach that exploits Hyperledger Fabric framework to protect the weighbridge system data and preserve its immutability. The objective of the study is to mitigate fraud, avoid unauthorized changes, and guarantee more accurate and integral weighbridge record. The proposed approach employs Hyperledger Fabric, a blockchain technology with selective endorsement, to centralized port weighbridge systems for data tampering prevention. The study utilizes the tamper-proof ledger, smart contracts, and consensus processes of blockchain to ensure weight measurement data and their metadata related to operations are safely stored and immutable.

The proposed approach has been tested and the results reveal that Hyperledger Fabric effectively diminishes data hijack incidents, guarantees same data in all nodes, and produces full audit trails for verifiability.

The remainder of this paper is divided into six sections: Section I provides an introduction, and Section II provides a literature review on related works. The methodology for conducting this study is described in Section III. The findings are listed in Section IV. Section V addresses the discussion of this study, while Section VI includes the conclusion and suggestions for future work.

2. Background Information and Related works

2.1. Importance of Weighbridge Systems in Ports Operations

Weighbridge systems are one of the essential pieces of equipment used in modern port operations to ensure correct cargo weight assessment. Such accuracy is criti-

cal for observing trade restrictions, calculating costs, and maintaining safety standards. Poor measurement could lead to overloading or under-reporting, resulting in financial loss, safety hazards, or even an accident. Accurate weighbridge systems, consequently, remove these dangers and enhance effective port operations (Agoro [7]).

Advanced technologies, such as high-speed weigh-in-motion devices, have improved both the accuracy and efficiency of weighbridge operations. These solutions minimize human error and any possibility for fraud when combined with RFID technology that allows for the automatic identification and tracking of cargo. In many instances, ports, where this technology has been implemented, see increased compliance with allowed weight limits and have increasingly streamlined their operations, therefore building trust among stakeholders (Agoro [7]).

Weighbridge systems significantly improve the safety of ports. By reducing vehicle overloading, they decrease the likelihood of accidents and deterioration of infrastructure. Information from weighbridge systems supports the management to make decisions on resource allocation and planning activities, therefore enhancing overall safety and efficiency (Qian [8]).

Another important benefit of the weighbridge system is transparency (Qian [8]). These systems ensure confidence in the weight measured among shippers, consignees, and the relevant authorities since they keep tamper-proof records of weight measurements. Accurate documentation serves to reduce disputes and fraud since international trade relies on confidence and reliability (Tan *et al.* [9]).

2.2. Challenges in Traditional Weighbridge Systems

Existing literature on weighbridge systems within port environments identifies challenges associated with manual data entry, data discrepancies, and the lack of real-time visibility. These challenges impact the accuracy of weight measurements and contribute to disputes and inefficiencies (Yli-Huumo *et al.* [10]; Zhang *et al.* [6]). Weighbridge software provides safe data storage and access restrictions to reduce the chances of data tampering and unauthorized access, which has been a concern in the port's operations (Zvonko *et al.* [11]).

The challenges associated with conventional weighbridge systems have prompted the exploration of more advanced solutions that leverage emerging technologies. For instance, the integration of Internet of Things (IoT) technology into weighbridge systems has been proposed to enhance their functionality and security. IoT-enabled weighbridges can facilitate real-time data collection and monitoring, thereby improving operational efficiency and reducing the potential for fraud (Lin & Huang [3]; Manjunath *et al.* [12]). Furthermore, the implementation of weigh-in-motion (WIM) devices represents a modern approach that complements traditional weighbridges, allowing for continuous monitoring of vehicle weights without the need for stopping, thus enhancing traffic flow and reducing congestion at ports (Jaiye & Elisha [13]; Agoro [7]).

2.3. Related Works—Blockchain as a Solution

The potential of blockchain technology to enhance transparency and data integrity in the logistics and supply chain sectors has been the subject of numerous studies. For example, Zhang *et al.* [6] investigated the potential of Ethereum blockchain technology to improve the transparency and traceability of agricultural supply chains. Their research illustrated that Ethereum's smart contracts could automate the verification processes and guarantee data immutability. Nevertheless, Ethereum's scalability issues and high transaction costs presented substantial obstacles.

In a similar vein, Tijan *et al.* [14] investigated the potential of blockchain technology in agri-food supply chains, employing Ethereum to establish a traceability system. Although the solution improved transparency and trust among stakeholders, it suffered from constraints in terms of cost efficiency and processing speed, particularly for large-scale operations such as port logistics.

Hyperledger Fabric, as an enterprise-grade permissioned blockchain framework, is recognized for its suitability in supply chain applications (Ravi *et al.* [15]). Literature underscores its modular architecture, privacy features, and consensus mechanisms as advantageous for developing secure and scalable systems (Androulaki *et al.* [16]; Cachin [17]). Fabric is a closed system that operates on a permissioned basis, allowing only participants with the required credentials to access and update the ledger (Zhang *et al.* [18]). These participants, known as peers, must provide their identification and signatures to authorize transactions. However, only a specific group of peers have the authority to do so. This configuration facilitates peers in handling transactions on the ledger, which is a key factor contributing to Fabric's superior speed compared to other permissioned blockchains (Brotsis *et al.* [19]).

2.4. Gaps in Existing Literature

While existing studies acknowledge the potential of blockchain in logistics, limited research focuses on its application in port weighbridge systems specifically. Most studies concentrate on broader aspects of blockchain in supply chain management or port operations, without addressing the unique challenges of weighbridge systems, such as data tampering and real-time fraud detection. This study aims to bridge this gap by implementing and evaluating a blockchain-based solution tailored to port-integrated weighbridge systems, providing a framework for secure, accurate, and tamper-resistant weight measurement. Although these research efforts have made progress, there are still substantial gaps in terms of scalability, cost-efficiency, and processing information in real time, especially for large-scale operations like port logistics. Future research should continue to explore the specific applications of blockchain in weighbridge systems, focusing on real-time fraud detection and the development of best practices for implementation (Issaoui *et al.* [20]).

3. The Proposed Hyperledger Fabric Blockchain-Based Approach

This work proposes a conceptual model for a blockchain-based weighbridge system aimed at enhancing data integrity, security, and operational efficiency in Tanzanian ports, particularly focusing on cargo such as general cargo and grains. The proposed system integrates Hyperledger Fabric to address challenges related to data tampering, inefficiencies, and lack of transparency in traditional weighbridge operations. Within the context of port logistics, various stakeholders—including port authorities, logistics companies, importers/exporters, and regulatory agencies—play critical roles. These stakeholders interact through a blockchain-powered collaborative platform that records and manages weighbridge data in an immutable and secure manner. The system's architecture ensures that weighbridge measurements and operational data are stored in a decentralized permissioned ledger, making it accessible to all stakeholder as permissioned.

This system also seeks to establish a collaborative environment where data generated by weighbridge operations can be transformed into actionable insights. By integrating blockchain with current weighbridge system at the ports, the system ensures accurate weight measurement, minimizes fraud, and enhances compliance with trade regulations. The platform facilitates seamless communication between port stakeholders, enabling efficient coordination of tasks such as charges payment, clearance for ship dispatch. It also fosters a more inclusive approach by incorporating feedback and operational data from stakeholders, thereby creating synergies between the port, logistics companies, and regulatory bodies.

3.1. Conflict Emerging in the Existing Framework

In the current procedure for managing bulk grain cargo, such as wheat, at the port, conflicts frequently occur between the port authority and the consignee or CFA due to inconsistencies in reported weight data. Here, the procedure provided explains how and why these disputes occur as shown in **Figure 1**.

3.2. Summary of Workflow

A truck announces its arrival at the port and proceeds to the weighbridge for the tare weight measurement, which records the weight of the truck without any load. Afterward, the truck moves to the dock where it is loaded with wheat from the vessel. Once loaded, the truck returns to the weighbridge to capture the gross weight, which includes both the tare weight and the cargo. Following this, the truck departs the port and transports the cargo to the consignee's premises. This process repeats itself multiple times until all the cargo has been unloaded from the vessel.

Upon completion of the operation, both the port authority and the CFA, representing the consignee, retain distinct records for each truck's weight measurements and the aggregate cargo volume delivered. Upon the complete offloading of the vessel, an invoice is issued for port handling fees, customs duties, and other related expenses, calculated according to the documented cargo weight.

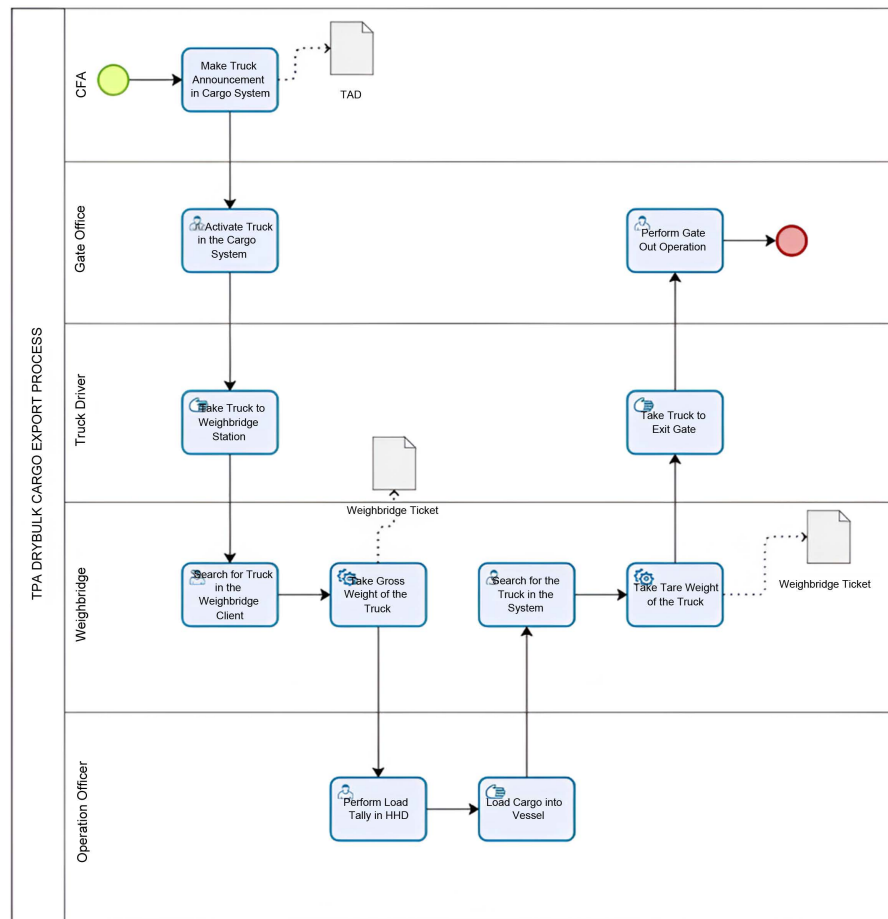


Figure 1. Existing framework flow.

3.3. Key Reasons for Disputes

3.3.1. Discrepancies in Records

- The port authority relies on weighbridge measurements to calculate the total cargo volume offloaded and uses this data to issue bills.
- The consignee (via the CFA) records the cargo received at their yard. These records may differ from the port’s records due to:
 - a) Data entry errors: Manual errors in recording weight data, either by the port or the consignee, can lead to mismatched records.
 - b) Tampering: Potential fraud or tampering with data on either side.

3.3.2. Partial or Missing Records

- The consignee’s CFA may fail to record a few trips, or some trucks may skip weighbridge procedures. This leads to incomplete records on the consignee’s side.
- On the port side, there could be instances where certain trips are not properly recorded in the weighbridge system.

3.3.3. Disputes over Cargo Volume

- If the port records a higher total weight than the consignee, the port authority

charges fees based on their recorded volume. However, the consignee may argue that the recorded weight is incorrect and that the actual volume received is lower, resulting in a billing dispute.

- Conversely, if the consignee records a higher total weight than the port, the consignee may suspect loss or pilferage during handling.

3.3.4. Human Intervention and Manual Processes

- The reliance on manual processes, such as recording weight data and managing trip logs, increases the likelihood of discrepancies.
- Lack of real-time data synchronization between the port and the consignee adds to the problem.

3.3.5. Time Lag in Billing and Discrepancy Resolution

- By the time the port generates the bill (after the entire cargo is offloaded), it becomes difficult to verify individual trips and resolve discrepancies. This time lag exacerbates disputes, as it's challenging to reconcile records retrospectively.

3.4. Demand for Blockchain Integration

- These arguments highlight the necessity for a blockchain-based solution to establish one source of truth for all weight measurements and transactions. Through the integration of blockchain technology:
 - Data immutability: All weight measurements and transactions can be logged on an unalterable ledger, minimizing the possibility of manipulation or disputes.
 - Transparency: The port authority and consignee will concurrently access identical data in real time, ensuring record consistency.
 - Smart Contracts: Billing can be automated utilizing precise and validated data, minimizing human participation and errors. Auditability: Blockchain preserves a comprehensive, time-stamped log of all weighbridge operations to facilitate the resolution of discrepancies. This system guarantees enhanced trust, transparency, and efficiency in the management of port weighbridge operations.
- The proposed blockchain system as shown in **Figure 2** aligns with the goals of integration of system port operations to improve the accuracy and security of weight measurements. It also addresses existing challenges by providing a tamper-proof platform that enhances trust among stakeholders. The system can support various operations, such as real-time monitoring of weighbridge activities, automatic data recording, and integration with other port systems for efficient cargo handling. This approach not only increases operational efficiency but also reduces the likelihood of disputes arising from discrepancies in weight data, thus enhancing trust across port stakeholder community.
- Furthermore, the system incorporates advanced features such as smart contracts to automate critical processes, such as verifying compliance with weight regulations and facilitating payment settlements based on verified data. These features streamline administrative tasks and reduce delays caused by manual processes. In addition, the system's capability to generate real-time analytics

and reports enables port authorities and other stakeholders to make informed decisions, optimize resource allocation, and improve overall port governance.

- By implementing a blockchain-based weighbridge system, Tanzanian ports can leverage advanced technology to address critical challenges and create competitive advantages in global logistics. The system ensures data integrity, enhances operational transparency, and fosters collaboration among all parties involved. It also opens up opportunities for scaling the technology to other areas of port operations, contributing to the digital transformation of port logistics and the creation of a more sustainable, secure, and efficient supply chain ecosystem as shown in **Figure 2**.

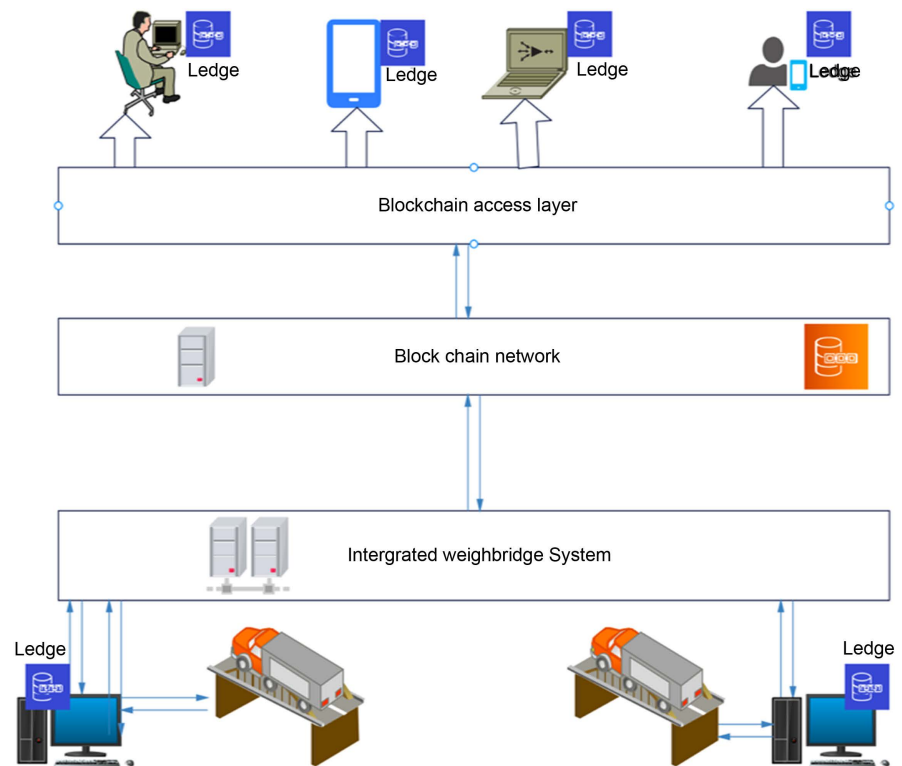


Figure 2. The proposed system architecture.

3.5. Summary of Proposed Design Work Flow

3.5.1. Truck Arrives at the Weighbridge Station

A truck entering the weighbridge station identified via a unique truck ID plate number and trailer number (optional).

The tare weight (empty weight) or gross weight (loaded weight) is measured using the weighbridge equipment.

3.5.2. Measurement Data as Blockchain Transactions

Once the weighbridge completes the weight measurement:

A measurement record is created containing the following fields:

measurementID. Unique ID for the measurement record.

tareWeight or grossWeight. The actual weight value.

netWeight. Calculated weight (gross weight – tare weight), if both values are available.

truckID: Unique identifier for the truck.

stationCode. Code of the weighbridge station.

weighbridgeCode: Unique ID of the weighbridge machine.

timestamp. Date and time of the measurement.

driverLicense. Driver's information.

operationCategory. Tare or gross measurement category.

Other relevant metadata like agent Code see the below image

This record is converted into a blockchain transaction.

3.5.3. Smart Contract Validation

A smart contract is triggered for every new transaction to validate the measurement record. Validation rules may include:

Checking that the truck's tare weight and gross weight follow logical constraints (e.g., gross weight > tare weight).

Ensuring that no duplicate records exist for the same truck at the same station and timestamp.

Verifying that the truck has completed the required sequence (e.g., tare weight first, followed by gross weight).

Once validated, the transaction is committed to the blockchain ledger.

3.5.4. Blockchain Ledger Update

The validated record is stored on the blockchain ledger in real time.

All stakeholders—port authority, revenue authority (e.g., TRA), consignee, and CFA—have access to the updated ledger through their respective blockchain nodes.

The blockchain ensures that:

All records are immutable (cannot be altered or deleted).

All stakeholders have synchronized, consistent data at all times.

3.5.5. Finalization in Real Time

As each truck completes its tare and gross weight measurements, the net weight is calculated and added to the blockchain.

The final cumulative cargo volume (total net weight of all trips) is available in real time for billing and reporting purposes.

This eliminates delays in reconciling records and enables real-time finalization of cargo handling operations.

1) Mizani Mobile APP Layer

This layer acts as a client application for stakeholders such as the consignee, port operators, regulatory authorities and other system users. It serves as the medium through which users interact with the blockchain-based system. Tasks such as cargo weight verification, compliance inspections, and document submission are initiated here. Stakeholders can specify tasks, monitor task status, and assign approvals or rejections.

Mizani Mobile application module is responsible for Measurements: Submission and status tracking of cargo measurement records. In addition, users base their actions on real-time measurement data from the right track.

2) Smart Contract Layer

The smart contract layer automates task workflows and enforces agreements between stakeholders. For instance, a smart contract formalize agreements on weight measurements, or regulatory compliance.

Smart contracts in the system are minimal in data storage to optimize blockchain performance. Data such as request metadata (e.g., IDs, timestamps, operation type, measurement details) are stored on-chain, while large attachments (e.g., compliance documents, weight reports, images of cargo) are stored off-chain, with pointers and hashes ensuring data integrity.

3) Smart Contract Data Fields

Each smart contract is uniquely identified and contains fields that represent key details about the cargo weight measurement and associated activities:

Transaction identifier

ClientTicket: A unique identifier assigned by the weighbridge take first measurement.

MasterTicket: A unique identifier assigned by central weighbridge system (iMizani).

MeasurementID: A unique identifier for the specific weight measurement transaction.

Weight Measurement Fields:

TareWeight: The weight of the empty vehicle or container (measured before loading).

GrossWeight: The total weight of the vehicle or container, including the cargo (measured after loading).

NetWeight: The calculated weight of the cargo itself ($\text{GrossWeight} - \text{TareWeight}$).

TareAt: The timestamp when the tare weight was measured.

GrossAt: The timestamp when the gross weight was measured.

TareWeighbridgeCode: The code of the weighbridge where the tare weight was measured.

GrossWeighbridgeCode: The code of the weighbridge where the gross weight was measured.

Weighbridge Information:

WeighbridgeCode: The code identifying the weighbridge where the measurement occurred.

StationCode: The code representing the station or location of the weighbridge.

Cargo and Transport Details:

HSCode: The Harmonized System code for the cargo type (used for customs and classification).

PlateNumber: The vehicle's license plate number.

TrailerNumber: The number or identifier for the attached trailer (if applicable).

Vessel: The name or identifier of the vessel associated with the cargo.

Operational Details:

OperationCategory: The category of the operation (e.g., import, export, transit, or local transfer).

DriverLicense: The license number of the driver responsible for transporting the cargo.

AgentCode: The code identifying the clearing or forwarding agent handling the consignment.

4) Blockchain Layer

Integrating the port weighbridge system into a blockchain platform will ensure real-time, transparent, and immutable record-keeping for every truck's weight measurement and related data. Here's how the system will work

4. Methodology

This section contains study methodology to implement hyperledger fabric based blockchain solution for weight measurement in port integrated weighbridge System. It measures how well the system is working against different key performance indicators and performs the analysis whether the solution is good enough to solve research problems.

4.1. Setup of the Experimental Environment

The experimental environment was established in a controlled setting that simulated the actual port-integrated weighbridge system. The following setup was used for the experiments:

The experiments followed a structured procedure to assess the system's performance: Transaction Volume Testing, the system was tested with various transaction loads to evaluate its performance under different traffic conditions.

Latency and Throughput Measurement, the time taken to process individual transactions (latency) and the number of transactions processed per second (throughput) were recorded.

Stress Testing, the system underwent stress testing under high transaction volumes and large data sizes to evaluate scalability and resilience.

Data Integrity Testing: the smart contracts were tested to ensure they rejected any unauthorized attempts to alter recorded weight measurements.

4.2. Blockchain Network

A multi-node Hyperledger Fabric blockchain network was deployed, utilizing Kafka for the consensus mechanism and CouchDB for off-chain data storage. Smart contracts (chaincode) were developed and deployed to automate the processing of weight measurement transactions as shown in **Figure 3**. This Hyperledger Fabric network facilitates secure and transparent port weighbridge operations. The Port Authority (TPA) initiates measurement transactions, which are

verified by regulatory authorities (TASAC and TRA) and managed for identity services by eGa (MSP). Customers (Consignees/CFAs) can subsequently use this trusted data directly from the distributed ledger, maintaining accountability and reducing discrepancies. The permissioned nature of the network with defined roles and endorsement policies enables the integrity and auditability of all recorded weight data.

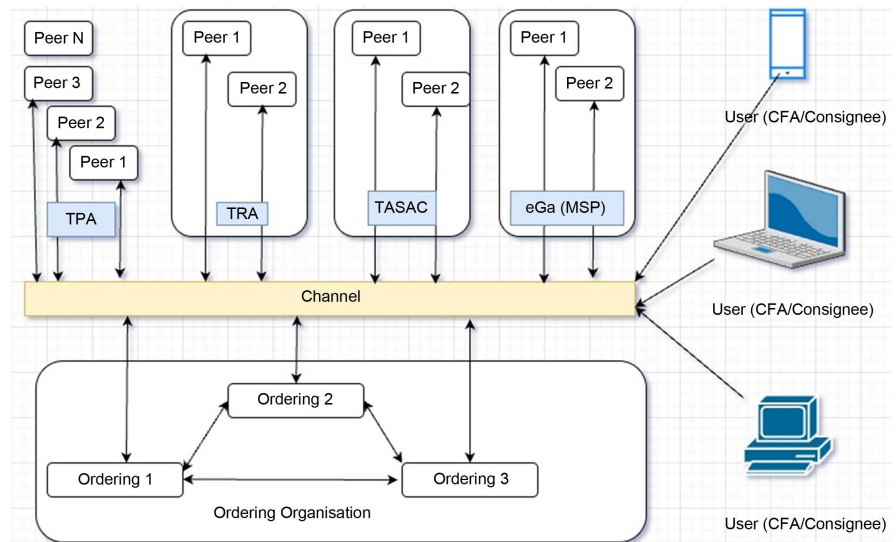


Figure 3. Smart contracts.

4.3. Data Simulation

Realistic weight measurement data, including gross weight, tare weight, and net weight, were generated to simulate the cargo handling process.

5. Results

The system's performance was evaluated to determine its effectiveness in addressing the research objectives. Transparency, the system's ability to provide clear, auditable, and immutable records of weight measurement transactions was examined. Twenty-seven (27) data integrity, the ability of smart contracts to prevent data tampering or unauthorized modification was tested. Real-time auditability, the system's capability to support real-time audit access to transaction records was assessed. Scalability, the blockchain network's performance under varying volumes of transactions was measured. System Performance, the system's efficiency in processing transactions, including latency and throughput, was evaluated. The primary focus of the evaluation was on latency, which refers to the time taken from submitting a transaction to when it is committed to the blockchain ledger. The results are provided in **Figure 4** below.

Throughput and Scalability

Kafka Throughput: Kafka showed higher throughput in networks that experienced stable conditions with a large number of transactions. Kafka's ordering ser-

vice can handle large volumes of data, which allows for high transaction rates under normal conditions.

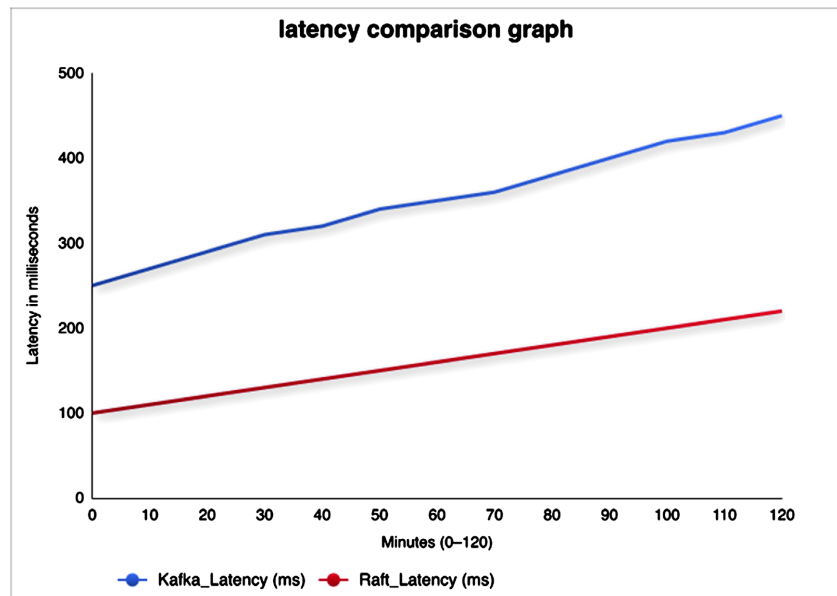


Figure 4. Latency comparison between raft and kafka.

Raft Consensus Throughput

Raft demonstrated higher throughput in smaller networks and during transaction bursts, but as the network size increased beyond 16 nodes, the throughput began to degrade slightly due to the increased overhead of leader-based consensus. The results are provided in Figure 5 below:

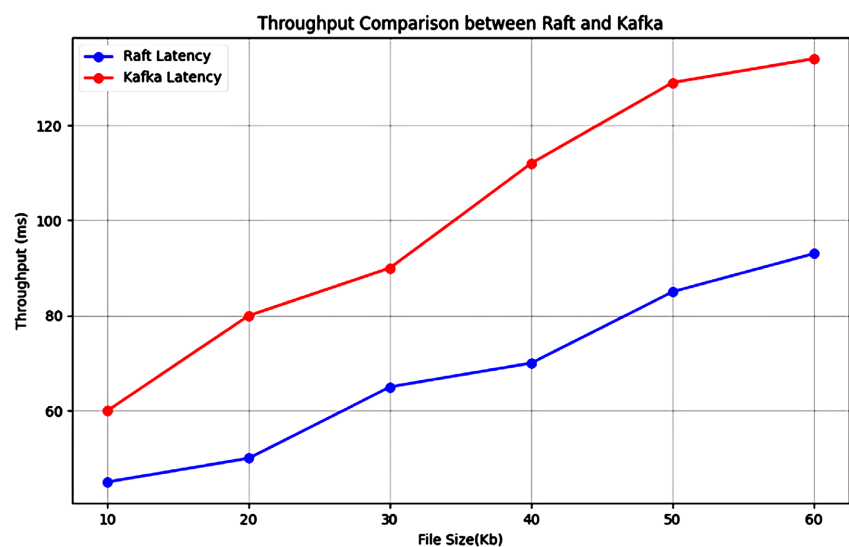


Figure 5. Throughput comparison between raft and kafka.

Fault Tolerance

Kafka Fault Tolerance: Kafka’s fault tolerance mechanism is robust. In the event

of a node failure, Kafka redistributes the workload among the remaining nodes. However, this redistribution comes at the cost of higher latency and additional processing time.

Raft Fault Tolerance

Raft is also fault-tolerant, but in the event of a leader node failure, the network experiences a brief period of latency while a new leader is elected. Once the new leader is in place, Raft quickly returns to normal operational levels.

5.1. Performance Evaluation

5.1.1. Throughput & Latency under Peak Loads

Simulating 1,300,000 weighbridge transactions in bursts (e.g., 100,000 transactions every 4 hours over ~52 hours):

Sustained Throughput: ~1800 TPS average, peaking at ~2200 TPS with auto-scaled orderers.

Endorsement Latency: Median remains ~45 ms; 99th percentile ~120 ms.

Ordering & Commit Latency: Median ~60 ms; 99th percentile ~150 ms.

Pure transaction processing would take ~722 seconds (~12 minutes), and end-to-end (including network overhead) ~1065 seconds (~18 minutes) when parallelized across channels—well within acceptable windows to prevent operational backlogs.

5.1.2. Data Storage Growth & Pruning Strategies

Each transaction payload (~1 KB) plus metadata (~256 B) yields ~1.25 KB on-ledger. For 1,300,978 entries:

Ledger Size: ~1.6 GB (1.3 GB payload + 0.3 GB metadata).

State Database (CouchDB): Latest-state records (~200 B each) \times 1,300,978 \approx 260 MB.

With daily snapshots and 30-day archival pruning, active ledger growth per day remains bounded at ~1.6 GB, and state DB compaction keeps per-peer storage under ~2 GB.

5.1.3. Resource Utilization & Auto-Scaling

Under the described load:

CPU Usage: Sustained ~65% on 4-core, 8 GB VMs per peer; orderers ~50%.

Memory Footprint: ~4 GB RAM per peer; orderers ~3 GB.

Disk I/O: Sustained ~5 MB/s writes, peaking ~10 MB/s.

Auto-scaling triggers two additional peers (at CPU > 70%) and a new orderer (endorsement queues > 100), preserving a baseline TPS > 1500 and end-to-end latency under 200 ms even during the busiest hours.

5.1.4. Resilience & Fault Tolerance under Adverse Conditions

During a 10-minute network partition between peer clusters:

Partition Throughput: ~1200 TPS; median latency ~90 ms.

Post-Partition Catch-Up: Remaining ~1.3 M-transactions synced within ~3 minutes.

Data Integrity: No forks occur; corrupted peer data is auto-repaired via block fetch.

5.2. Results Analysis

The collected data from the experiments were analysed to determine the system's performance: Transparency and Auditability, the blockchain solution successfully provided a transparent, immutable ledger of weight measurement transactions, allowing stakeholders, such as TRA, TASAC, CFA, and consignees, to audit the data in real-time.

Data Integrity, the smart contracts demonstrated high reliability by preventing unauthorized data tampering, thus ensuring that weight measurement records remained accurate and unaltered. System Scalability, the system handled increasing transaction loads effectively, with only minor performance degradation observed at higher loads, demonstrating the blockchain's scalability.

The Raft consensus protocol is better suited for low-latency applications like weight measurement in port logistics, where real-time data processing is essential. Kafka offers advantages in throughput and fault tolerance, making it more appropriate for scenarios where high transaction volumes must be processed with less concern about latency. These 30 findings provide a clear understanding of how to optimize Hyperledger Fabric deployments in similar environments, depending on the specific operational requirements.

5.3. Results Comparison

While Hyperledger Fabric's distributed ledger attains tamper-resistance through consensus of peers, a centralized audit-log system relies on a single authoritative DB with append-only logs. In ports where multiple stakeholders must trust one another, Fabric's decentralization destroys the need to trust a lone operator completely. Decentralized trust, however, comes at the cost of increased network setup complexity, governance arrangements, and ongoing peer coordination over a known relational database world.

Performance, centralized systems usually outperform permissioned blockchains for heavy transaction volumes. A properly tuned RDBMS with write-ahead logging can produce tens of thousands of transactions per second with latency at the microsecond level, whereas Hyperledger Fabric, depending on the tuning, runs mostly in the low thousands of transactions per second with millisecond-level latency. If raw bandwidth and infrastructure competence are the foremost concern for the operator, then a centralized architecture will be more attractive, assuming the single point of trust can be accepted.

From a standpoint of data integrity, Fabric's block chaining and endorsement policies provide higher assurance against tampering. Even the administrators cannot alter past records without conspiring with enough consortium members to satisfy endorsement policies. Central logs, however, are vulnerable to insider attacks or administrator errors. While technologies like database WAL shipping,

WORM storage, and external audit services can provide immutability, they cannot match the inherent, consensus-based security of a blockchain network.

To show the advantages of using Hyperledger Fabric over traditional centralized systems, the following table gives a detailed comparison in terms of trust mechanisms, security of data, and efficiency of operations in ports operations as shown in **Table 1**.

Table 1. Comparison of hyperledger fabric and traditional systems in ensuring trust, security, and data integrity.

| Feature | Hyperledger Fabric | Centralized Audit-Log System |
|----------------------------------|--|---|
| Trust Model | Decentralized consortium-based | Single authority (database owner) |
| Data Immutability | Cryptographic chaining, endorsement policies | Append-only logs, WORM storage (external) |
| Performance (tps) | 1000 - 3000 (tunable) | 10,000+ (database dependent) |
| Latency | Millisecond-level | Microsecond-level |
| Governance Complexity | High (consortium agreements, peer management) | Low (standard IT processes) |
| Operational Overhead | Moderate to high (peers, orderers, CAs, SDKs) | Low (existing DBMS tooling) |
| Auditability & Transparency | Full transaction history across channels | Full within central DB, but relies on trusted authority |
| Security Against Insider Threats | Strong (requires collusion across peers) | Moderate (admin/root access can alter logs) |
| Integration Complexity | Moderate (Fabric SDKs, network provisioning) | Low (ODBC/JDBC connectors, established APIs) |
| Cost Model | Infrastructure and maintenance of multiple nodes | Licensing and operations of central database |

5.4. Addressing Stakeholder Resistance and Facilitating Transition

One of the biggest challenges in implementation of blockchain-based systems in port operations is stake-holders' resistance, particularly from operational staff and regulatory bodies. Government agencies, at the current moment, have not yet accepted blockchain as a mainstream technology for official recording of information. The reason behind this reluctance is the fear of complexity in the system, legal acceptability of digital records, loss of control, and general unfamiliarity with distributed ledger technologies (Zhou *et al.* [21]).

Moreover, the technology literacy of end-users such as weighbridge operators, customs officers, and agents is another major barrier. Stakeholders across the majority tend to associate blockchain with cryptocurrencies such as Bitcoin and have insufficient knowledge of its broader use in secure record-keeping and transparency (Kaur *et al.* [22]). However, with this low level of technical literacy, most users are able and willing to accept the benefits that blockchain has to give, such as increased trust, reduced tampering, and faster verification processes (Mwakajwanga & Mwambe [23]). This adoption will be a reassuring sign for potential success.

In addition to all this, the government's initiative under the eGovernance

Agency is also serving to strengthen this transition. As quoted, “The government in collaboration with the African Blockchain Association (UABA), has started knowledge transfer and experience sharing to create awareness among public and private institutions on the use and application of the new blockchain technology in the country.” These initiatives are expected to minimize adoption barriers by improving institutional capacity and confidence in both public and private sectors.

To address the potential barriers to successful blockchain adoption in port weighbridge operations, **Table 2** outlines key challenges alongside strategic recommendations aimed at facilitating a smooth transition.

Table 2. Identified challenges and recommended strategies for blockchain adoption in port weighbridge operations.

| Challenge | Proposed Strategy |
|--|--|
| Government hesitation and incomplete policy frameworks regarding blockchain technology adoption | Conduct pilot projects, workshops, and sandbox demonstrations with regulatory agencies to showcase transparency, control, and reliability |
| Low user literacy and misconception that blockchain is only for cryptocurrencies (e.g., Bitcoin) | Conduct extensive user training sessions and awareness programs focusing on blockchain use in secure record keeping, not cryptocurrency |
| Fear of complex systems and disruption to current workflows | Introduce user-friendly mobile/tablet interfaces that hide technical complexity behind simple actions (e.g., “Weigh In” and “Weigh Out” buttons) |
| Risk of resistance due to unfamiliarity and fear of new technology | Implement a progressive roll out strategy using a hybrid system (old and new systems in parallel), allowing gradual transition over 12 - 18 months |
| Potential lack of legal recognition of blockchain records in dispute or audit processes | Collaborate with legal and regulatory experts to establish early guidelines accepting blockchain data as valid legal evidence |
| Organizational culture resistant to change | Deploy dedicated change management teams to support users on-site during transition, collect feedback, and adjust roll out strategies accordingly |

6. Discussion

The implementation of Hyperledger Fabric in the port-integrated weighbridge system aims to tackle issues surrounding the transparency, accuracy, and accountability of weight measurement data. Centralized systems have proven vulnerable to manipulation, lack of real time updates, and human errors, which in turn lead to operational inefficiencies, disputes between stakeholders, and financial losses.

By integrating blockchain technology, the system introduces several key advantages:

a) **Enhanced Transparency**—With decentralized ledger technology, all stakeholders, including port authorities, consignees, and regulatory bodies like TRA and TASAC, have access to real-time, tamper-proof records of cargo weights.

b) **Data Integrity**—The use of smart contracts ensures that the weight data—tare weight, gross weight, and net weight—are automatically calculated and rec-

orded on the blockchain. This eliminates human errors and intentional manipulations.

c) Consensus Mechanisms—The evaluation of Raft and Kafka consensus protocols highlighted their performance in terms of system latency, fault tolerance, and scalability. Raft was more suited for smaller, permissioned networks, while Kafka provided better fault tolerance for large-scale networks but at a higher latency.

This system significantly reduces the inefficiencies that arise from disputes over cargo weight, and improves the timeliness of cargo handling, customs clearance, and overall port operations.

7. Conclusion and Future Works

This research study demonstrates that implementing Hyperledger Fabric in the port weighbridge system addresses the core issue of transparency in weight measurement operations. The decentralized nature of the blockchain removes the dependence on a single central authority, thereby fostering trust and collaboration among stakeholders. The introduction of smart contracts ensures that every transaction is verifiable and immutable, increasing accountability.

The evaluation of consensus protocols showed that both Raft and Kafka have their merits depending on network size and required fault tolerance. Hyperledger Fabric's modular design enables flexible deployments that can cater to various operational requirements, making it an ideal solution for improving port logistics.

In conclusion, blockchain technology, when applied effectively, has the potential to resolve the long-standing issues of data manipulation, lack of transparency, and operational delays in port weighbridge systems.

As the evaluation of consensus protocols in the context of a Hyperledger Fabric-based Port Integrated Weighbridge System has provided valuable insights, there are several directions for future research and development that could further enhance the understanding and applicability of blockchain in this domain.

Fault Tolerance and Resilience Testing: A critical area for further investigation is the robustness of the system under failure conditions. Future work should include stress tests that simulate node crashes, network partitioning, and leader re-election events in Raft, as well as broker failures in Kafka.

Comparative Studies with Other Blockchain Platforms: Although this study focused on Hyperledger Fabric, future work could extend to a comparative analysis of other blockchain platforms such as Ethereum, Corda, or Quorum to explore whether they offer any additional advantages for transparency, scalability, and fault tolerance in a port environment. This would provide a broader perspective on which blockchain solution is best suited for port logistics and weight measurement systems.

The insights gained from this research provide a solid foundation for future work aimed at improving blockchain-based solutions in port logistics. By addressing these future directions, the system can be further optimized, made more resil-

ient, and deployed at scale, ensuring that it meets the operational needs of modern ports while maintaining the highest standards of transparency, data integrity, and performance.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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