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ScienceDirect

Procedia Computer Science 253 (2025) 612–625

Procedia Computer Science

www.elsevier.com/locate/procedia

6th International Conference on Industry 4.0 and Smart Manufacturing

Towards Efficient and Fine-Grained Traceability for a Live Lobster Supply Chain using Blockchain Technology

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Abstract

Product traceability has become essential in modern supply chain management, ensuring product safety, quality, and transparency. However, implementing traceability, especially for live biological products managed by Small and Medium Enterprises (SMEs) with limited resources, presents challenges. The balance between traceability performance and costs is critical for adoption. Recently, the integration of Internet of Things (IoT) and Blockchain technology has shown promise in revolutionizing traceability systems, offering unprecedented data granularity and integrity. Yet, few studies explore these technologies' design within SME-dominated, live product supply chains. Addressing this gap, our study introduces a novel technological architecture and three data validation models: lightweight, detailed, and intermediate. We evaluated these models in a Canadian seafood supply chain, focusing on live lobster products, using simulation platforms. Our findings highlight a trade-off between traceability and operational costs, with the intermediate solution offering promising benefits without compromising cost-effectiveness.

Keywords: Blockchain; Supply Chain; Traceability; Seafood

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1. Introduction

In today's interconnected world, the demand for robust supply chain traceability has soared to new heights. Companies face increasing challenges in ensuring the quality, safety, and sustainability of their products from source to customer, especially in the food industry [1]. In response, various technologies and solutions have become key in gathering and tracking product-related data, underscoring the importance of traceability solutions that offer comprehensive tracking and environmental condition monitoring capabilities. These seemingly straightforward tasks, however, be-

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10.1016/j.procs.2025.01.123

come formidable in the complexity of today's supply chains, especially those that are multi-echelon and comprise numerous dispersed Small and Medium Enterprises (SMEs) without a central governing entity. A prime example of such complexity can be observed in the Canadian lobster industry, a sector characterized by its sprawling geographical distribution of SMEs and the absence of a dominant central authority to oversee governance, customer interaction, or product design. This supply chain is tasked with the capture, transformation, and distribution of a sensitive biological product—live or processed lobster—which necessitates stringent management of environmental conditions in compliance with various norms and environmental laws. Challenges abound, including issues with information accuracy, data consistency, reliance on manual traceability systems, and vulnerabilities to product fraud and mislabeling.

In response to these challenges, innovative technologies and approaches are being developed. Particularly, in the era of the 4th Industrial Revolution (Industry 4.0), there is a growing consensus among scholars and practitioners alike regarding the potential of Blockchain-based Distributed Ledger Technology (DLT) integrated with the Internet of Things (IoT) [2]. This integration is believed to foster more traceable, transparent, adaptable, secure, and responsive supply networks. Beyond traceability, Blockchain technology holds the promise of automating numerous transactions across the supply chain via smart contracts, enabling the automatic verification and execution of transactions upon meeting predefined conditions [3].

Despite the burgeoning research at the intersection of blockchain technology and supply chain management, a notable gap persists, especially concerning the business context imposed by the live lobster supply chain, and on an industrial scale. Recent meta-reviews and literature surveys [4] reveal an absence of research efforts addressing the unique challenges of the live lobster supply chain from a blockchain perspective. Specifically, there is a dearth of studies on solution architectures or detailed investigations into the trade-offs between tracking performance and cost—factors critical for the adoption of such technologies by SMEs.

Aiming to bridge this gap, our study aims to navigate the intricate design space by conceiving and assessing different approaches for balancing supply chain traceability performance and costs, in a context where SMEs deal with live products. Our contribution unfolds in four distinct but connected parts:

- Initially, we delve into the complexities of the lobster supply chain (a cold chain) by developing a hybrid discrete-event and agent-based simulation, leveraging real-scale industrial data from a Québec-based lobster supply chain. This Simulation Platform generates data for evaluating a novel blockchain-based traceability architecture tailored for efficiency and cost-effectiveness for live lobster SMEs.
- Introduction of a novel Traceability Architecture designed to enhance the monitoring and tracking of live lobsters throughout the supply chain. By extracting and utilizing IoT data through this architecture and employing smart contracts on the blockchain, we facilitate the verification of product origin and quality, enhancing trust and transparency.
- A specific part of this architecture involves the design of three distinct Blockchain-based Traceability Validation Methods tailored to address the extremes of the traceability design space. The spectrum ranges from a 'minimum' method, focusing on low granularity tracking, to a 'maximum' method that aims to capture every possible data point on the blockchain. Additionally, we introduce a balanced approach that optimizes both traceability performance and operational costs by leveraging Bloom Filters for efficient product tracking and Stream processing middleware for effective IoT sensor data management.
- A comprehensive evaluation of these methods through a Proof-of-Concept in a simulation environment, embedding our Supply Chain Platform in the Traceability Architecture, integrated into a real-world blockchain technology, specifically the EOSIO platform, along with a commercial IoT middleware solution, the Pareto Anywhere. This approach simulates a highly realistic operational environment, allowing us to explore and demonstrate the intricate balance between traceability performance and associated costs.

The paper continues with Section 2, which explores related works in the field. Following this, Section 3 provides foundational background information, introducing fundamental concepts used in our study. Next, Section 4 presents the research design, Section 5 introduces the proposed architecture and the three blockchain methods. The simulation results are presented and discussed in Section 6, and, finally, the conclusions are outlined in Section 7.

2. Related Works

The literature in the field of traceability using blockchain is fruitful. Remarkable examples of recent developments can be found in Badreddine et al. [5], which proposes a real-time Internet of Things data sharing and monetization framework, emphasizing the integration of the MQTT protocol with Ethereum smart contracts to achieve a robust traceability mechanism. They present three solutions with varying costs and levels of effectiveness. Maximum Traceability solution involves rigorous data logging in the blockchain, offering robust fraud detection but at higher operational costs. Minimal Traceability solution opts for frugality, registering only data size in the blockchain, sacrificing some fraud detection reliability for reduced costs. Bloom Filter-Based Traceability solution strikes a balance by introducing representative logging, storing data hash positions in a Bloom filter on the blockchain with a moderate cost, ensuring effective fraud prevention. This solution stands out for its accurate traceability performance. However, it's worth noting that it does not allow for tracking the history of data ownership, which may pose a limitation in certain contexts of use. Each of these traceability mechanisms addresses a specific trade-off between reliability and cost, providing valuable insights for the development of our own traceability system.

One of the most important applications of blockchain-based traceability discussed in the literature concerns the supply chain field. Employing a blockchain tracing system is considered very promising for enhancing transparency within the supply chain [6]. The literature in this field is gripping exponentially [4], from both of a technical or managerial perspective [7]. For example, Varriale et al. [8] concentrated on simulating order management in the cheese supply chain, comparing two scenarios. One scenario excluded new technologies, while the other integrated blockchain with IoT. Their findings demonstrated that the adoption of these technologies, not only contributes to advancements in sustainability within the cheese supply chain but also ensures the certification, authentication, and improved traceability of the final product, eliminating the need for external intermediaries.

Shahid et al [9] introduced a blockchain-based strategy to address challenges in the agri-food supply chain, specifically focusing on product traceability, trading party credibility, and delivery mechanisms. The devised system ensures comprehensive recording of all transactions on the blockchain, with subsequent data uploaded to the InterPlanetary File Storage System (IPFS).

However, these solutions have exhibited limitations in throughput and high network latency. Additionally, the second challenge lies in the associated gas fees, making Ethereum not the optimal choice for supply chain traceability applications, which are designed to trace the journey of products and therefore involve a large number of transactions to be executed. Malik et al. [10], propose an approach to ensure the authenticity of recorded data in the supply chain by assigning trust and reputation scores in real-time. This study also faced limitations in terms of throughput and latency due to the application of Hyperledger Fabric. In [11], Sharma et al. compares the efficiency of Delegated Proof-of-Stake (DPoS) as a consensus mechanism for a blockchain-based pharmaceutical supply chain with other existing consensus protocols in terms of processing time. The results show that DPoS has a significantly higher throughput compared to Proof of Work and Practical Byzantine Fault Tolerance.

Tripathi et al. [12] introduces a Blockchain-IoT model for a food traceability system, connecting each product to its source for detailed raw material information. The authors implement the system on both Ethereum and EOSIO. Analysis reveals EOSIO's suitability over Ethereum.

Within the realm of blockchain-enhanced supply chain traceability, various simulation techniques have been employed to explore the capabilities of this nascent technology in addressing intricate issues within supply chains. For example, Martinez et al. [13] delved into the process of managing customer orders, evaluating the implications of implementing blockchain over various time spans. Manupati et al. [14] leveraged blockchain technology as a means of communication to foresee and counteract disruptions through the application of smart contracts. Additionally, Ashraf and Ali [15] sought to evaluate the advantages of employing blockchain technology in a traceability system for project-oriented supply chains, utilizing smart contracts to monitor package ownership and assess project timelines under disruptive conditions. Nevertheless, it appears that the challenge of managing biologically sensitive products within decentralized supply chains, without a centralized authority, has not been adequately addressed in existing research. This underscores the importance of further investigation into this specific area to enhance understanding from the perspectives of both supply chain management and technological solutions.

3. Background

This section covers the key technologies: EOSIO blockchain, Bloom filters, Substreams, and a brief overview of the supply chain simulation approach.

3.1. Blockchain Platform: EOSIO

EOSIO is a blockchain platform designed to facilitate the development and execution of decentralized applications (DApps) by offering a robust infrastructure for smart contracts [16]. One of its notable features is the use of Delegated Proof-of-Stake consensus, providing fast transaction speeds and scalability, with a transaction rate of up to thousands of transactions per second (TPS), making it a popular choice for various decentralized applications.

When it comes to resource consumption, EOS, the native cryptocurrency of the EOSIO network, is used for resource allocation. Users on EOSIO network need to stake EOS tokens to access resources like CPU and NET. CPU, indicating processing power, is vital for executing transactions, while NET represents network bandwidth. RAM, on the other hand, is crucial for storing data on the blockchain. Users must purchase RAM using EOS tokens to allocate storage space on the network. This resource allocation system ensures that users have a direct stake in the network's operation, preventing misuse and encouraging responsible usage.

In our research, we are leveraging EOSIO to create a supply chain traceability solution that meets the specific needs of our ecosystem. For example, particularly for SMEs, EOSIO offers advantages related to cost-efficiency, scalability, flexibility and usability, secure and transparent operations, customizable permission structure, community and support. In particular, for SMEs lacking resources, EOSIO is designed to reduce transaction fees, which can be a significant advantage for SMEs looking to leverage blockchain technology without the high costs associated with some other platforms [17].

3.2. Validation Method: Bloom Filter and Substreams

Bloom Filters are commonly employed in applications prioritizing search speed and minimizing memory usage [18]. They perform by using a series of hash functions to represent a set of elements. They are designed to provide a probabilistic answer regarding the presence of an element in a dataset, indicating whether an element is 'probably in the dataset' or 'certainly not in the dataset'. Unlike many other data structures, Bloom Filter uses only a small number of bits to represent a large set of elements. Elements are added over time by applying several independent hash functions to each element and setting the corresponding bits in the array. The size of a Bloom Filter is determined by the number of elements to be stored and the acceptable probability of false positive responses.

The main idea behind Bloom filters is to minimize the number of false positive responses, while enabling rapid response to queries. This property makes them ideal for our supply chain traceability use case, as they reduce the time needed to search for specific information while maintaining an acceptable level of accuracy.

Substreams [19] is a powerful platform for the parallel transformation of streaming data. It enables developers to write modules in Rust, leverage community modules, and offer extremely high-performance indexing, while allowing data to be routed to multiple destinations. Substreams offer an optimal and revolutionary experience in managing the flow of blockchain data based on gRPC, protobuf, and the Firehose [20].

Firehose is responsible for extracting data from blockchain nodes. Substreams collaborate seamlessly with it to execute massive operations on historical blockchain data in an extremely parallelized manner. This combination offers a powerful blockchain indexing technology, with a particular focus on low latency extraction, modularity and ease of use.

3.3. Supply Chain Simulation: A Hybrid Approach

In the realm of Supply Chain Management, the literature is predominantly governed by three main simulation approaches: System Dynamics (SD), Discrete-Event Simulation (DES), and Agent-Based Modeling and Simulation (ABMS). Initially, SD focuses on continuous simulation through the use of differential equations to model relationships. It relies on constructing models with stocks, flows, and feedback loops as its core elements, grounded in System Theory. Conversely, DES employs a process-oriented methodology, centering around entities that instigate events which, in turn, define system states at precise, discrete points in time through a stochastic method. ABMS, on the other hand, is characterized by autonomous, interacting entities that adhere to predefined protocols and rules while responding to their environment, leading to a form of simulation that is significantly abstract and powerful, capturing a high level of social behavior, as Ferreira et al. [21] have pointed out. These authors [21] also defines the concept of Hybrid Simulation (HS), which involves combining two or more approaches. HS fuses these methodologies to refine the model's logic, thereby paving the way for new possibilities in blending physical and informational flows, as demonstrated by the synergy between blockchain technology and supply chain management.

For the purposes of this research, we integrated DES and ABMS to forge a HS-based simulation platform. This integration aims to accurately represent the complexity inherent in the targeted supply chain, details of which are elaborated in the following section.

4. Research Design

This research employs the Design Science Research (DSR) approach [22], which is commonly employed in the fields of engineering, information systems and operations management, among others, for its practical relevance and scientific rigor. The DSR methodology has garnered extensive citation across various scientific databases. It supports the creation of new artifacts, ranging from systems and applications to algorithms, models, and frameworks. These artifacts are aimed at addressing real-world issues or boosting organizational efficiency [21].

The DSR methodology involves a design cycle that begins with recognizing a business need or problem identified by the researcher. The next step involves generating potential solutions based on an existing knowledge base, which includes theoretical foundations and methodologies. This is followed by evaluation and refinement stages, such as simulations, proof-of-concept, or empirical studies, which may inform future research directions [21].

Our study begins with a comprehensive literature review to outline the research problem and potential solution approaches. Following this, we proposed first a Supply Chain Simulation platform combining DES and ABMS to capture the complexity of a lobster-based supply chain in Québec, Canada. Next, we proposed a novel Traceability Architecture, designed to enhance the monitoring and tracking of live lobsters throughout the supply chain. By extracting and utilizing IoT data through this architecture and employing smart contracts on the blockchain, we facilitate the verification of product origin and quality, enhancing trust and transparency. We employed EOSIO and some IoT technology for this architecture, as explained in the next section. Next, inside the proposed architecture, we designed three distinct Blockchain-based Traceability Validation Methods tailored to address extremes of the traceability design space, using different approaches, notably Bloom Filters and Substreams.

Finally, we performed a comprehensive evaluation of these methods through a Proof-of-Concept in a simulation environment, embedding our Supply Chain Platform in the Traceability Architecture, emulating a highly realistic operational environment of a live lobster supply chain, allowing us to explore and demonstrate the intricate balance between traceability performance and associated costs.

For capturing the complexity of the live lobster supply chain, we have conducted a field study in Gaspesie (Quebec, Canada), allowing us to better understand the characteristics of this supply chain. To do so, we interviewed different members of the supply chain (fishermen, associations, processing units, transporters and retailers) using a qualitative semi-structured interview protocol, supported by an ethics certificate. In addition, we collected quantitative data from some supply chain information systems, providing detailed data about the behaviour of its supply chain operations.

5. Contributions

In this section, we first introduce our Supply Chain Simulation Platform. Next, we present our Traceability Architecture and finally the proposed Validation Methods.

5.1. Supply Chain Simulation Platform

The development of our Supply Chain Simulation Platform to capture the complexities of blockchain-based traceability systems entailed several challenges. First of all, a supply chain is a complex system itself [23]. To deal with this complexity, we modelled the supply chain using the SCOR (Supply Chain Operations Reference) framework, which

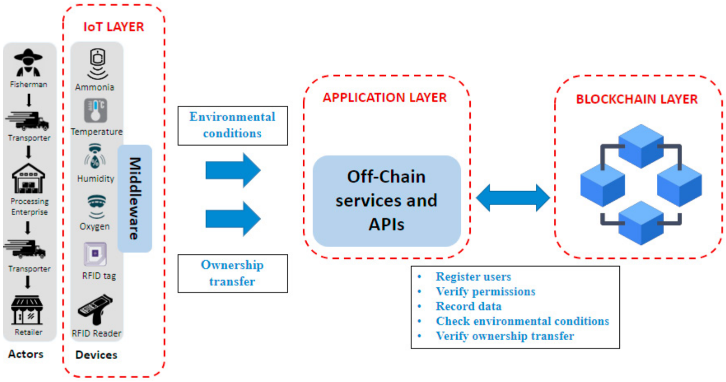

Fig. 1. Proposed System Architecture

is widely employed by scholars and practitioners [24]. Adopting a process perspective, SCOR encompasses all supply chain activities from suppliers to customers, providing standardized process definitions, metrics, best practices, and activities.

Second, the traceability aspects add another layer of complexity to our model, thus we were inspired by GTS from GS1 [25]. GST stands for Global Traceability Standard and it is a framework that designs and manages a system of global standards for the identification and communication of product information across supply chains. The GTS aims to provide a consistent method for tracking products and information flow from the point of origin to the final consumer, enhancing transparency, safety, efficiency, and collaboration across supply chains.

Third, to model the complexities of interacting entities of our Hybrid Simulation platform, a discrete-event-oriented approach allows us to create stochastic events across the supply chain; for example, lobster shipping, contamination, transformation and transportation events, according to some distributed functions modelled from the practice. These events are managed by an agent-based logic that captures the social behaviors of a supply chain. To do so, our agents were inspired by the ADAptive holonic COntrol aRchitecture (ADACOR), which is originally related to distributed manufacturing systems [26], and has recently been used in the literature for the agentification process to assist the development of modelling frameworks in the context of Industry 4.0 [21]. The Platform was developed using FlexSim® and Java, providing us with an environment for modelling, analyzing, visualizing, and sharing simulation data.

In summary, our Supply Chain Simulation Platform replicates supply chain operations (in line with SCOR principles), incorporates traceability mechanisms (based on GTS standards), and simulates operational events using the ADACOR framework. This combination results in a realistic simulation environment for supply chain operations, which serves as the foundation for a Blockchain-based Traceability Architecture discussed in the subsequent subsection.

5.2. Blockchain-based Traceability Architecture

In our supply chain, comprising fishermen, transporters, processing enterprises, and retailers, the focus is put on maintaining the freshness and quality of lobsters. Our system architecture, depicted in Figure 1, seamlessly integrates stakeholders and cutting-edge technologies to achieve precise traceability and maintain superior lobster quality. The stakeholders in our supply chain include fishermen responsible for lobster harvesting, transporters managing logistics, processing enterprises handling tasks like disgorging and sorting, and retailers.

To enhance traceability, we employ Radio-Frequency Identification (RFID) as a tracking technology. Fishermen affix RFID tags to each lobster and corresponding containers, referred to as Logteks, facilitating product grouping into lots. Figure 2, captured in Gaspesie by our team, illustrates a Logtek holding a set of lobsters. Each lobster will be individually identified through an RFID tag attached to its claw, acting as a digital fingerprint and recording ownership transitions across the supply chain. This meticulous tracking not only simplifies traceability but also ensures transparency and accountability.

Our system incorporates sensor technology in each Logtek, measuring vital factors for lobster well-being, such as temperature, humidity, dissolved oxygen, and ammonia concentration. Specific value ranges are set for each pa-

Fig. 2. Lobsters packed in a Logtek

rameter, ensuring quality. If values fall outside the designated range, indicating a violation of environmental required conditions, our system detects and identifies the responsible party.

Figure 1 illustrates the architecture, showcasing stakeholders, devices, and an IoT middleware. The IoT middleware standardizes data before transmission to our decentralized application (DApp). This middleware processes and transmits IoT devices data, providing ownership transfer information and environmental conditions details to our decentralized application.

In our traceability DApp, users can register, permissions are verified, data is stored, and conditions and ownership transfers are verified. This comprehensive integration of technologies ensures a robust and transparent lobster supply chain.

Dual-Check Method for the Transfer of Ownership: In order to enhance traceability, we have devised a dual-check method for the transfer of ownership. This method ensures a robust tracking mechanism when products transition from one owner to the next, involving the execution of two crucial actions, as illustrated in Figure 3.

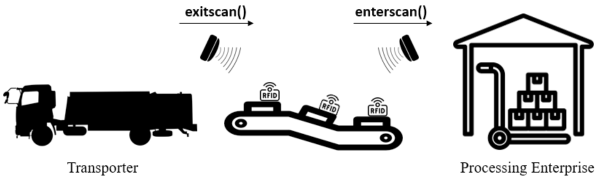

Fig. 3. Dual-Check Method for Ownership Transfer

The first action, denoted as *exitscan()*, signifies that the transporter, acting as the initial owner, has successfully delivered the products. The second action, *enterscan()*, is executed by the subsequent owner (e.g., a processing enterprise in Figure 3) to confirm the receipt of the products.

Both *enterscan()* and *exitscan()* are triggered when the RFID reader of the respective actor detects the RFIDs associated with the products. This method enables the detection of potential violations, losses, or any malicious intent where an actor falsely claims to have dispatched products that have not been received by the next entity. Furthermore, the implemented mechanism serves as a formidable deterrent against counterfeit products. Any actor attempting to introduce counterfeit items would be unable to produce the authentic ownership history, providing an additional layer of security. In instances where the receiving actor suspects foul play, the option to reject products is facilitated by a *rejectscan()* function.

Between the *enterscan()* and *exitscan()* actions, the receiving actor has the opportunity to conduct verifications on the state of the received products. This includes examining the ownership history of the products to validate their origins and assessing environmental conditions throughout the entire supply chain.

The implemented dual-check mechanism not only enhances traceability but also empowers entities within the supply chain to ensure the integrity of product transfers and proactively address any discrepancies or concerns that may arise. In the next section, we will explore how these functions are uniquely implemented to establish three distinct traceability validation models. Following that, we will compare their effectiveness and costs.

5.3. Validation Methods

Our supply chain traceability project is built upon an innovative approach, which involves the development of three distinct validation methods that are embedded in the Traceability Architecture: MAX-MAX-Trace, MIN-MIN-Trace, and BF-Substreams-Trace. In this section, we provide detailed descriptions of each of these solutions, outlining the property transfer tracing method and the environmental conditions tracing method for each. We specify the data recorded on-chain and off-chain, along with the associated verification process for each solution.

5.3.1. MAX-MAX-Trace method

This method aims to achieve the highest level of traceability for both products and environmental information throughout the supply chain. It emphasizes the comprehensive retention of data within the blockchain.

Ownership transfer traceability. For each product recorded in the blockchain, a detailed ownership history is maintained. This history includes essential elements such as owner, state (delivered, accepted, or rejected), and timestamp. An entry is appended to this historical record every time *exitscan()*, *enterscan()*, or *rejectscan()* action is executed. Given the secure and immutable nature of these records in the blockchain, they serve as trustworthy and unalterable evidence of the product's journey. The complete history recorded for each lobster in the blockchain ensures the assurance of its origin, providing a transparent account of its journey from capture to its current point in the supply chain.

Environmental data traceability. Sensor data is logged in *Entries* table of the smart contract. Every entry undergoes a meticulous verification of environmental conditions. If an entry fails to comply with the required conditions, the condition status for concerned products is set to false. Simultaneously, for each product, a list of non-conforming entries' IDs is documented, providing swift access for subsequent verification. The integrity of this information is bolstered by its secure and unchangeable status within the blockchain.

5.3.2. MIN-MIN-Trace method

This method is designed for achieving a minimum level of traceability at a lower cost. The approach involves two key aspects:

Ownership transfer traceability. All product details are recorded in a centralized database, and to maintain traceability, the *exitscan()* function registers the quantity of products delivered, while the *enterscan()* function logs the received quantity in the blockchain.

The validation process consists of carefully examining the records on the blockchain, to ensure that the quantity of products delivered corresponds to the quantity received. Verifying the coherence of these blockchain records allows the system to detect inconsistencies, offering insights into potential losses, violations, and responsible entities. It's crucial to note that in the MIN-MIN-Trace method, blockchain does not play an active role in ensuring product provenance; rather, product provenance relies on off-chain data.

Environmental data traceability. All sensor data is recorded in the centralized database. However, the blockchain specifically tracks and counts non-conforming entries—those not adhering to the environmental required conditions. This approach aims to fortify the system against potential falsification, alteration, or deletion of the most sensitive sensor data. Validation involves comparing the count of non-conforming entries in the centralized database with the count stored in the blockchain. While effective in preventing the removal or modification of non-conforming entries, this method doesn't ensure the accuracy of the values within these entries. Therefore, there is no guarantee that these values haven't been adjusted to approximate conforming values while still remaining non-conforming, and such adjustments may go undetected.

5.3.3. BF-Substreams-Trace method

To address the limitations of the other two proposed models and ensure dependable traceability with lower resource consumption compared to MAX-MAX-Trace, this method leverages Bloom filters for product ownership traceability with Substreams technology for environmental information traceability, offering a balanced approach.

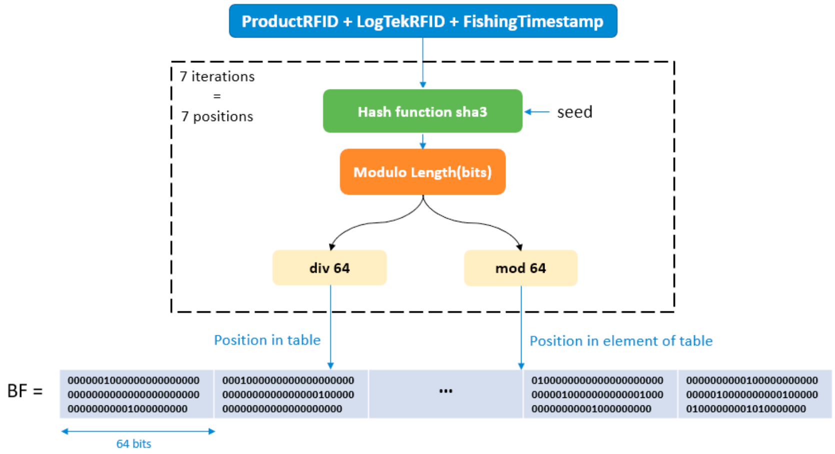

Fig. 4. Bloom Filter Data Insertion

Ownership transfer traceability. In this approach, individual product details are stored in a centralized database. Simultaneously, Bloom filters are utilized and implemented in the smart contract to facilitate ownership transfer traceability. For each transfer, two Bloom filters are generated. The first filter denotes that the original owner has transferred these products to the new owner, while the second filter indicates that the new owner has received these products from the original owner. To facilitate up to 5,000 product ownership transfers between two parties, we designed a Bloom filter with a size of 47,965 bits and a hash rate of 7 [27], aiming for a false positive probability of 10^{-2}.

To implement this solution, we create an array consisting of 750 elements of 64 bits each. For each product ownership transfer, we combine its RFID with that of the corresponding LogTek and its fishing date. This concatenation is performed to keep a record in the blockchain of the lobster's freshness based on its fishing date and to maintain a link with the associated LogTek. The SHA3 function is then applied to hash the output of the concatenation. To determine its position within the Bloom filter, the resulting hash is divided by the filter size. It's crucial to note that this sequence iterates seven times for each product, ensuring the acquisition of seven distinct positions within the Bloom filter.

After identifying the position by dividing the hash by the filter size, we then derive the positions in our array. We do this by dividing the position by 64 to locate the element needing modification in the array. Following that, we take the remainder after dividing the position by 64 to pinpoint the exact bit within that element that requires alteration. Figure 4 visually represents these steps for a clearer understanding.

To verify the consistency of ownership transfer, the Dice coefficient is employed [28]. Calculated as:

$$DiceCoefficient = \frac{2 \times h}{(a+b)} \tag{1}$$

This formula assesses the similarity between two Bloom filters. Here, h represents positions set to 1 in both filters, and a and b represent positions set to 1 in each individual Bloom filter. A higher Dice coefficient indicates increased similarity.

The ownership transfer's coherence is determined by evaluating the Dice coefficient, serving as a similarity metric between the two Bloom Filters. A Dice coefficient of 1 signifies a perfect match, ensuring a seamless transfer with no loss, no anomalies, or risk of counterfeiting. This rigorous approach guarantees the legitimacy of products and verifies the absence of unauthorized transfers. It's noteworthy that the provenance in this method can be verified by the blockchain. This is achieved by checking if the product exists in the Bloom filter of the fisherman who caught the lobster. Therefore, a function *exists()* is created to search for an element in a Bloom filter.

Environmental data traceability. Figure 5 illustrates data storing and verification steps. First, the *setentry()* function records sensor data in a centralized database. It then sends this data to the blockchain. The smart contract increments the entry counter for the corresponding actor involved in the process.

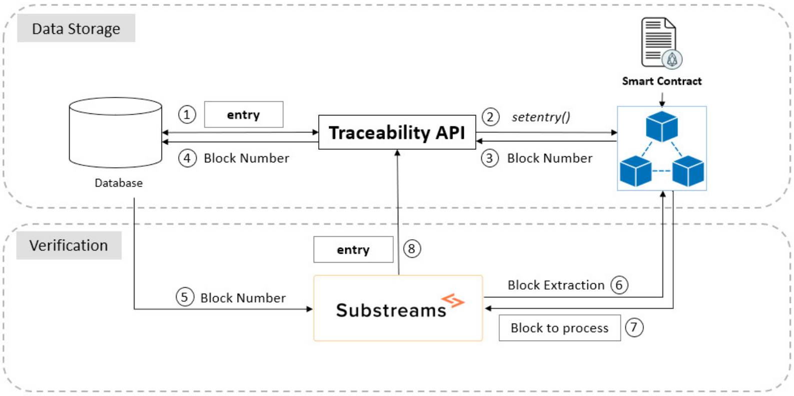

Fig. 5. Verification Process with Substreams

From the output of the transaction, the block number is extracted and stored in the entry's record in the centralized database. This creates a trace for future verification. Substreams is employed for verification. Using the recorded block number, Substreams accesses the corresponding block on the blockchain, filters, and extracts parameters specific to that transaction.

The extracted values are compared with the corresponding entries stored in the centralized database. If the values match, it indicates no tampering or falsification of data. Finally, to ensure that no entries have been deleted, the blockchain counter value for each actor is compared with the total entries in the centralized database for that specific actor.

6. Proof-of-Concept Case: Live Lobsters Traceability

Each fishing season, the permitted period for lobster harvesting, spans ten weeks within a year. During this time frame, approximately 15,000 lobsters are in circulation, being both caught and transferred. Managing this process is critical, considering the elevated risk of lobster mortality if required environmental conditions are not adhered to.

In this context, our supply chain has two important characteristics: (1) each lobster must be tracked during the entirety of the supply chain, from when it is caught all the way to its delivery at the retail, grouped in LogTeks, (2) proper environmental conditions must be respected at all times for temperature, oxygen, humidity and ammonia.

6.1. Simulation Results

In this section, we detail our experimental set-up and present performance results concerning the traceability performance and costs and, finally we engage in a concise discussion.

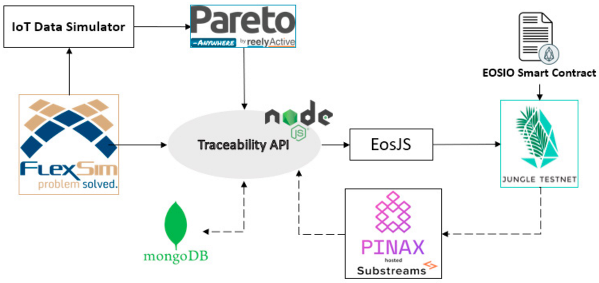

Fig. 6. Experimental Setup

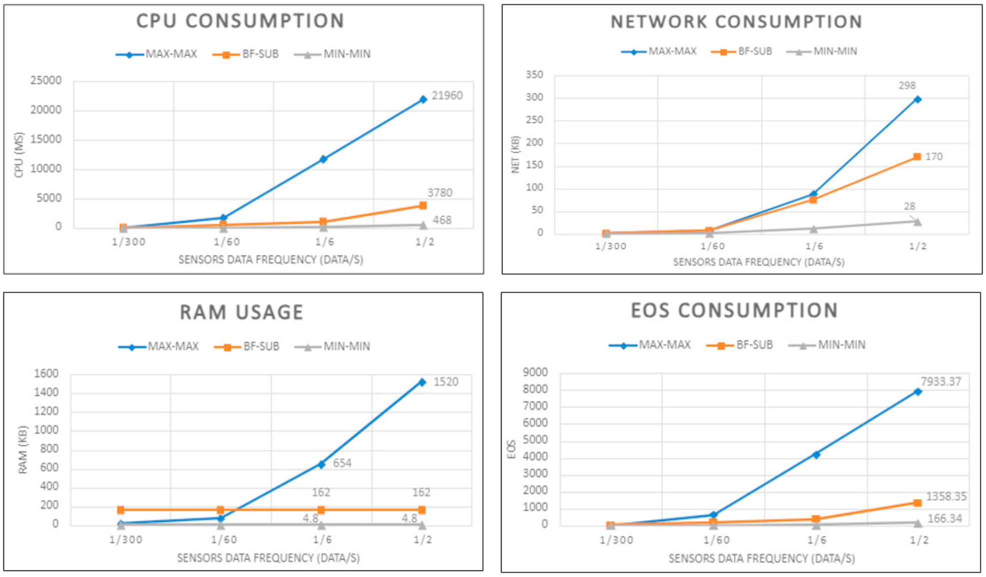

Fig. 7. Sensor data frequency effect on resource consumption

6.1.1. Setup

Our test environment consists of a hardware setup featuring a PC with an Intel(R) Core(TM) i7 CPU 2.00 GHz and 8GB of installed RAM. The software environment is illustrated in Figure 6 and includes:

- FlexSim: A simulation platform designed for modeling and analyzing complex processes that we used to simulate our supply chain.
- Pareto Anywhere [29]: Developed by reelyActive, is a middleware solution designed to integrate and manage data from various IoT devices, including RFID tags. In our implementation, lacking access to IoT devices, we simulated IoT data and forwarded it to Pareto Anywhere for processing before transmitting it to our DApp.
- Jungle Testnet: A test environment we use to evaluate our approach under conditions similar to those on the main network. We have deployed our contracts, written in C++, on this network.
- EosJS: A Javascript library for interacting with the EOSIO blockchain enabling communication with smart contracts.
- MongoDB: Used for the storage and management of off-chain data, MongoDB excels in high-speed writing and flexible query capabilities.
- Substreams: Hosted by Pinax [30], this indexing service extracts, filters, and delivers blockchain data.

6.1.2. Performance evaluation

To evaluate the performance and compare the operating costs of the proposed models, we have developed test scenarios for the supply chain using our simulation. These scenarios are developed by manipulating two key parameters: the number of products in transit and the frequency of sensor data.

In order to accurately measure resource consumption, we have integrated a specific function into our implementations. This function analyzes the results of each transaction, extracts CPU and network bandwidth (NET) consumption, and accumulates these values throughout the scenario. In addition, to evaluate RAM consumption, we compare the amount of RAM used before and after execution, thus isolating the RAM consumption related to the scenario data. Subsequently, we can determine the corresponding EOS consumption, which represents the equivalent value of these resources.

In the first experiment, we manipulated the sensor data frequency parameter, testing four scenarios in which data was sent at intervals ranging from 2 seconds to 300 seconds. Figure 7 illustrates the results.

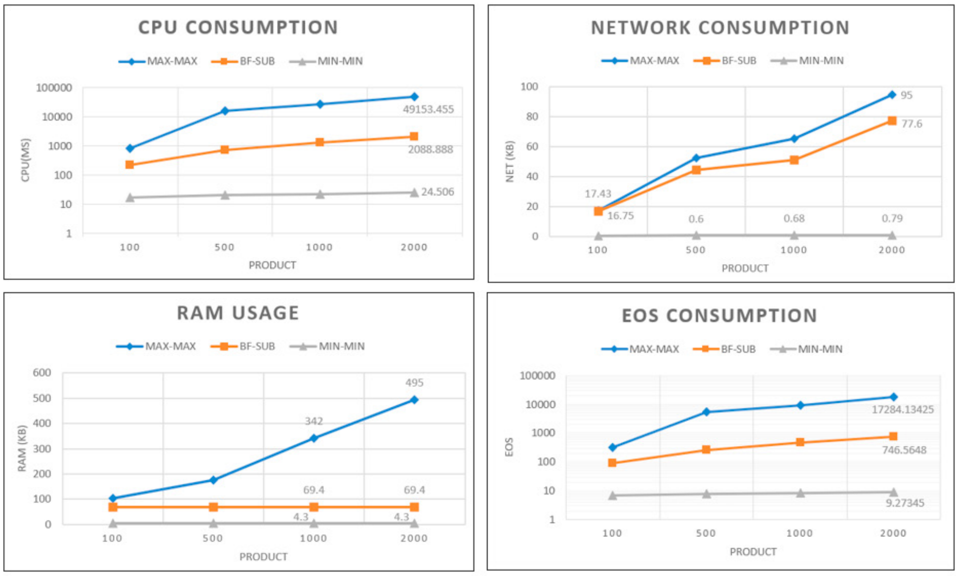

Fig. 8. Number of products effect on resource consumption

MAX-MAX-Trace proves to be the most resource-intensive in terms of CPU and NET consumption. This is attributed to its requirement to record all information, including sensor data, in the blockchain. The consumption escalates significantly with an increase in sensor data frequency, reaching up to 22s of CPU time and 298KB of NET for the most exhaustive iteration in our case. In terms of RAM, MAX-MAX-Trace exhibits poor scalability, peaking at nearly 10 times more than the BF-SUB-Trace solution. Consequently, MAX-MAX-Trace emerges as the most EOS-consuming solution.

BF-SUB-Trace, on the other hand, experiences a more modest increase as it performs less processing on the data, reaching up to 4s of CPU time and 170KB NET. BF-SUB-Trace does not require storing sensor data in the smart contract, resulting in consistent RAM values unaffected by this parameter. Therefore, this solution consumes significantly less EOS compared to MAX-MAX-Trace. MIN-MIN-Trace demonstrates a minimal increase in CPU and NET consumption, with values consistently lower than the other solutions. Regarding RAM, this solution consumes only 4.8KB for any data frequency, as these data are not recorded in the blockchain. Thus, for these iterations, MIN-MIN-Trace incurs a maximum consumption of 166 EOS, which is negligible compared to MAX-MAX-Trace's consumption.

In the second experiment, we varied the product quantity parameter. As shown in Figure 8, the CPU consumption showed a slight increase for MIN-MIN-Trace, reaching up to 25ms, and for BF-SUB-Trace, peaking at 2s. However, for MAX-MAX-Trace, the increase was significant, reaching up to 49s. This surge is attributed to the addition of each product, along with its details, to the blockchain in the case of MAX-MAX-Trace.

Regarding NET consumption, MAX-MAX-Trace consistently emerged as the most resource-intensive. In terms of RAM, BF-SUB-Trace showcased constant consumption, indicating the fixed size of the Bloom filter regardless of the number of inserted products, a notable advantage of Bloom filters. RAM consumption remained constant for MIN-MIN-Trace as well, and it was minimal since only the number of transferred products, not the details of each product, were recorded.

Observing these results, MAX-MAX-Trace utilizes a significantly larger amount of EOS compared to BF-SUB-Trace, while MIN-MIN-Trace stands out as the most cost-effective solution.

6.2. Discussion

This evaluation allows us to compare the traceability performance and execution costs associated with each of our methods, highlighting the advantages and compromises of each one. The following table summarizes the key findings regarding the performance and cost of each method:

Table 1. Comparison of Traceability Methods

Method	**Traceability Performance**	**Security**	**Costs**
MAX-MAX-Trace	Comprehensive recording of product history, environmental conditions, and ownership changes. High traceability of origin, quality, and safety.	High security as every product detail is recorded, minimizing the risk of counterfeiting.	Most resource-intensive and costly solution, due to recording all actions, including conditions and transfers.
MIN-MIN-Trace	Fewer details are recorded. Ensures correct product count but does not guarantee the exact values for quality assurance.	Vulnerable to counterfeiting and reliability issues.	Less costly, requires fewer EOS resources but compromises reliability and security.
BF-SUB-Trace	Uses Bloom Filters to track product provenance and detect potential issues (e.g., loss or counterfeiting) when similarity is less than 1. Substreams verifies data consistency to detect alterations or missing entries.	Secure with Bloom Filters and Substreams, detects unauthorized acts and alterations with low false positives.	Moderate costs. Efficient resource use through Bloom Filters and Substreams, with good scalability.

The table compares the methods, showing trade-offs between traceability, security, and costs. MAX-MAX-Trace provides the best traceability at a high cost, while MIN-MIN-Trace is cheaper but sacrifices security and traceability. BF-SUB-Trace offers a balanced approach across all factors.

In implementing our solution, we faced several challenges that are important for future researchers to consider. The resource-intensive nature of MAX-MAX-Trace necessitated that we collect a significant amount of test tokens on Jungle Testnet to ensure we had enough resources during the execution of our scenarios, thereby preventing interruptions. Additionally, the limited availability of IoT devices led us to simulate their functionality, enabling a realistic implementation while addressing resource constraints.

7. Conclusion

This paper puts forward the critical role of blockchain technology and IoT in addressing the challenges of supply chain traceability, specifically within the context of the live lobster industry. By developing a hybrid simulation platform and proposing a novel traceability architecture with different embedded validation methods, we have not only highlighted the complexities of such supply chains but also showcased potential solutions that can enhance transparency, security, and efficiency. Our research contributes to the evolving discourse on the integration of cutting-edge technologies in supply chain management, offering valuable insights for SMEs navigating the intricate demands of product traceability and sustainability.

Despite focusing on the live lobster supply chain, we believe that our work applies to a wide variety of other supply chains with similar challenges, such as other seafood [31], food products [8], or cold chains such as pharmaceutical logistics [11].

However, in our implementation, we relied on simulations. To enhance the validity of our findings, we recommend that future research apply our approach in real-world settings. This would enable a better evaluation of the technologies and their effects on the supply chain. In addition, to further strengthen trust within the supply chain, we envision implementing a system of rewards and penalties. This system would allow stakeholders to rate the behavior of their peers, thereby establishing decision thresholds for the continuation of their participation.

Acknowledgements

We would like to express our deep gratitude to our industrial partners, reelyActive, EOS Nation, and Merinov, for their invaluable support in the success of this project. Their expertise and resources have greatly enriched our work. Special thanks to the Natural Sciences and Engineering Research Council of Canada (NSERC) for their financial support and trust.

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