Optimizing warehouse management system with blockchain and machine learning predictive data analytics

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ABSTRACT

Blockchain technology is proving to be a disruptive technology in many areas of supply chain, manufacturing, medical, agriculture, and so on. Warehouses are an inevitable part of the supply chain. Issues like space optimization, route optimization, quick item pick-up, demand forecasting, and transaction management are of importance to address in warehouse management systems (WMS). Traditional database systems have limitations of interoperability among different entities involved in warehouses. This paper presents an innovative application of blockchain technology and machine learning (ML) to build a smart warehouse management system in Web3 (SWMW3). We developed a decentralized application (DApp) using Web3.0 principles, integrating ReactJS for the frontend, express for the backend, and blockchain through smart contracts. This integration enhances security and transparency by storing WMS operational data in the blockchain and automating payments and verifications through smart contracts. Additionally, we implemented a ML model for predicting the total time from order receipt to delivery, leveraging historical data to optimize workflow, reduce delays, and improve overall efficiency. This combination of blockchain for secure transactions and ML for predictive analytics generates a robust, efficient, and optimized management system for the warehouse.

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1. INTRODUCTION

Supply chain management (SCM) is crucial for the global delivery of products, goods, and services from manufacturers to retailers and consumers. SCM involves a network of organizations ensuring smooth product delivery. Warehouses are key components of SCM, handling the physical storage and movement of products. As warehouse operations grow in size and complexity, managing them becomes increasingly challenging. Warehouse management systems (WMS) are software solutions designed to automate warehouse operations. Traditional WMS rely on databases for record-keeping, inventory management, item tracking, and order fulfillment. However, these systems have limitations, such as vulnerability to data tampering and interoperability issues across different inventory software [1], [2].

Blockchain technology, initially developed for cryptocurrency, has found applications in various industries, including SCM [3]. In WMS, blockchain can enhance security and transparency by providing an immutable, decentralized ledger for warehouse operations. Each item in the warehouse is tagged with a barcode, serving as a digital twin in the blockchain. This system ensures end-to-end product tracking and reduces data validation time, thereby increasing delivery efficiency [4]. The decentralized nature of blockchain guarantees data originality, as every block holds unique data and every system maintains an updated, immutable copy. However, adopting a blockchain-based WMS requires significant changes to existing systems or complete replacements.

Recent trends in WMS focus on using machine learning (ML) to improve efficiency. ML algorithms can analyze large datasets to predict patterns and optimize warehouse operations. In WMS, data is collected through barcodes and stored in the blockchain as transactions or events. ML can address issues like unpredictable customer ordering patterns, product demand, inventory forecasting, and delivery schedules [4], [5]. Blockchain supports inventory record-keeping by eliminating paperwork and ensuring transparency between entities [6], [7]. It allows end-to-end tracking of items and events in the supply chain, with distributed, immutable records stored in blocks [8].

Blockchain technology's decentralized, distributed ledger is updated and maintained at each node in the network, ensuring trust among entities [9], [10]. Existing peer-to-peer networks can support this structure, along with IoT or sensor-based hardware. Each block in the blockchain contains information about previous and next blocks, secured cryptographically through hash functions. The size of the block varies by application, storing data about events, transactions, or records. Once added, a block becomes a permanent part of the chain. Hash functions validate block transactions, with miners solving cryptographic puzzles to add new blocks using a nonce. The first block is the genesis block, and a consensus protocol like proof-of-work (PoW) is used for validation [11]. Performance measurement of warehouse operations relies on collecting information about items, customers, retailers, manufacturers, and transactions. This data is transferred to the blockchain for further processing. ML algorithms can optimize various aspects of warehouse operations, such as inventory management, physical space utilization, item pickup time, and route optimization. Integrating blockchain with ML provides a robust solution for predictive data analytics, enhancing the overall efficiency of WMS.

Traditional database management system used in WMS is different than the blockchain based approach. Specifically, the structure of blockchain and its data arrangement in the blocks as well as historical approach of storing data, makes it more suitable for predictive data analytics. Table 1 justifies the use of Blockchain technology for implementation of WMS by comparing it with traditional database.

Table 1. Comparison of traditional database with Blockchain

Parameters	Traditional database	Blockchain technology
Data storage	Good at accessibility, performance and speed	Good at transparency, trust, security, and traceability
Data permanency	Data may be tampered or modified	Data is immutable
Transparency	Not supported	Supported
Data structure	Tables	Blocks
Data accessibility	Centralized	Decentralized
Approach towards data	Record keeping	Digital ledger

ML algorithms are categorized into supervised learning and unsupervised learning [12]. Supervised learning uses labeled data whereas unsupervised learning uses unlabeled data. ML algorithms are still new for warehouse process analysis and implementation [13]. The ML model needs the data of the warehouse processes and information flow from inbound to outbound items including route management and space management. All the processes of the warehouse cannot be incorporated in one ML model so we need to build multiple sub-models and later integrate them based on requirements of data analysis [14], [15]. The remaining paper is organized as follows. In section 2 discusses the method of Blockchain as a technology and the use of ML in WMS along with the data collection approach in WMS and the use of the bar-coding system and smart contract as integration elements. In section 3 discusses results and section 4 concludes the paper.

2. METHOD

Our proposed smart warehouse management in Web3 (SWMW3) framework uses the MERN stack, Ganache, Truffle, Web3, and ML for WMS using blockchain with ML integration. The following subsections will discuss each component in detail.

2.1. Data collection for ML and sample data

Data originates from various sources within the warehouse, primarily through product handling. Stock keeping units (SKUs) or universal product codes (UPCs) are used to uniquely identify products, facilitating stock management [16], [17]. As shown in Figure 1, WMS collects and maintains product data through stages like receiving, put away, storage, order picking, checking, and packing. These stages follow an extract, transform, and load (ETL) framework, linking the collected data with ML models for analytics. At each stage, data entries are updated in the system: receiving notes for entry, stock updates during put away, space optimization in storage, billing transactions during order picking, final order verification in checking, and preparation for outbound delivery during packing.

To support real-time data capture, technologies such as RFID, barcodes, IoT sensors, and NFC tags are employed [18], [19]. This data is centralized for further processing. Barcode-based data tagging is essential for connecting the physical and digital spaces, facilitating the creation of digital twins and supporting blockchain-based records. The GenData file is crucial for generating key features of this data to train the ML model and simulate blockchain transactions. Data from Kaggle is used as a foundational dataset. The GenData file generates important features such as item type, quantity, and timestamps, creating a realistic sample for blockchain, and ML model training (Algorithm 1).

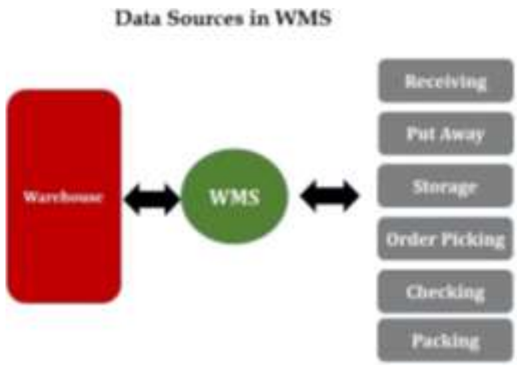

Figure 1. Data sources in WMS

Algorithm 1. Pseudocode for Data Generation Algorithm

```
FUNCTION GenerateData():
data = LOAD KaggleDataset()
    FOR each item IN data:
item_id = GENERATE_UNIQUE_ID()
item_type = item['type']
quantity = item['quantity']
arrival_time = GENERATE_TIMESTAMP()
departure_time = arrival_time + RANDOM_DELAY()
barcode = GENERATE_BARCODE(item_id)
        ADD_TO_BLOCKCHAIN(item_id, item_type, quantity, arrival_time, departure_time,
barcode)
    RETURN data

FUNCTION GenerateBarcode(item_id):
barcode = CREATE_BARCODE_FROM_ID(item_id)
    RETURN barcode
```

This approach ensures efficient data collection, essential for linking physical warehouse activities with digital records, thereby supporting both blockchain transactions and ML predictive analytics. As shown in Table 2, the item information is being managed and handled through the bar-coding process.

Table 2. Information to be maintained for the items

Sr No	Data element of the item/product
1	Item number
2	Item type/category
3	Item name
4	Manufacturer details
5	Shipping address
6	Item cost
7	GST number
8	Date and time of order
9	Date and time of shipping
10	Time of arrival at the warehouse
11	Time of departure from the warehouse

2.2. Integration of blockchain and ML

2.2.1. Barcoding system in WMS

Blockchain technology and ML significantly enhance WMS efficiency by providing transparency and managing transactions through smart contracts, addressing global interoperability issues in inventory management [20]. Barcodes, created using react-barcode, encode data into graphical forms, and facilitate digital twin creation for data recording and storage. Predominantly, 1D barcodes are used to improve location accuracy and visibility in warehouses. Collected barcode data integrates with the blockchain layer of the WMS, creating decentralized, immutable records of all processes and transactions [21]. Blockchain ensures process transparency, as data can be verified and validated but not modified by third parties [22]. Implementing blockchain-based solutions often requires modifying or replacing existing data collection systems.

2.2.2. Smart contracts

Smart contracts, a key blockchain feature, are self-executable codes triggered by predefined conditions for automation and verification of payments [23], [24]. These contracts, stored on the blockchain server, are immutable and can only be verified by system agents, ensuring secure transactions [25], [26]. In warehouses, smart contracts handle item tracking, movement, and transactions via IoT sensors, RFID, or barcodes, converted into on-chain data [27], [28].

The proposed system as shown in Figure 2 digitizes item data using barcodes, converting it to on-chain data in the blockchain. This is implemented using an integrated decentralized computing platform like ganache for private blockchain, with truffle for development, solidity for writing smart contracts, solc for compilation, and Web3js for blockchain interaction. This innovative approach ensures transparency, security, and efficiency in warehouse operations.

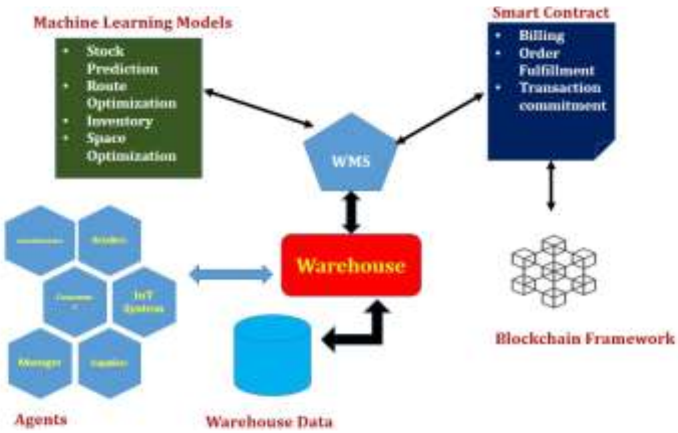

Figure 2. System architecture

2.2.3. Frontend, Backend, ML, and Web3 integration

Inventory management smart contracts in a WMS automate tracking, updating, and reordering inventory. Activated when items are scanned, these contracts update inventory levels on the blockchain for real-time tracking and accuracy. They monitor inventory levels, initiating reorder processes when quantities fall below a threshold [29]. Payment and invoicing smart contracts streamline financial operations by generating invoices upon delivery confirmation and overseeing payment processes. These contracts can integrate with external payment gateways or cryptocurrency wallets for flexible transaction processing [30].

The frontend of the system is built using ReactJS, with react router DOM for seamless navigation and cookies for authentication management. The backend is developed using ExpressJS, where JWT is utilized for secure authentication. Web3js is used for communication with the blockchain, ensuring decentralized and secure transactions. All user operations and ETL processes are managed via smart contracts stored on the blockchain, thus eliminating the need for traditional databases. This approach enhances security, transparency, and efficiency in warehouse operations.

A ML model using long short-term memory (LSTM) networks is developed to predict the total time from order receipt to shipping. This model was created in Python using TensorFlow, trained on historical data to provide accurate predictions. The model was saved in HDF5 format and is loaded into the backend using TensorFlow.js (TFJS) for real-time predictions. These predictions are displayed on the frontend dashboard, with data communicated through REST APIs in JSON format. This integration of ML with blockchain and decentralized applications (DApp) showcases a novel approach to optimizing warehouse management, improving both predictive accuracy and operational efficiency.

3. RESULTS AND DISCUSSION

The integration of Web3 and blockchain technologies, combined with ML, significantly enhanced our WMS. By utilizing a decentralized platform like ganache for a private blockchain, we ensured secure and transparent transaction management. The use of truffle for development, solidity for writing smart contracts, and Web3js for blockchain interaction streamlined the automation of processes such as inventory tracking, updating, and reordering. This eliminated the need for traditional databases, providing an immutable and decentralized ledger for all warehouse operations.

The frontend, built with ReactJS and react router DOM, facilitated seamless navigation and user authentication through cookies. The backend developed using ExpressJS and secured with JWT, ensured secure communication with the blockchain. Smart contracts automated financial transactions, reducing human error and improving operational efficiency. The ML model, employing LSTM networks, accurately predicted the total time from order receipt to shipping. Developed in Python with TensorFlow, the model was saved in HDF5 format and integrated into the backend using TensorFlow.js (TFJS). Real-time predictions were displayed on the frontend dashboard via REST APIs in JSON format.

The online framework, named smart warehouse management in Web3 (SWMW3), is designed to integrate blockchain and ML methods. The various user interfaces were developed for agent registration, inbound management, inventory management, labor management, and supplier registration. The following figures from Figures 3 to Figure 8 show the user interfaces of the proposed framework. Actions like agent registration, inbound management, inventory management, labor management, and supplier registration can be performed through this interface. This innovative integration of blockchain and ML, under the SWMW3 framework, resulted in enhanced predictive analytics, improved operational efficiency, and a secure, transparent WMS, showcasing a novel approach to warehouse management.

Figure 3. Home screen of framework

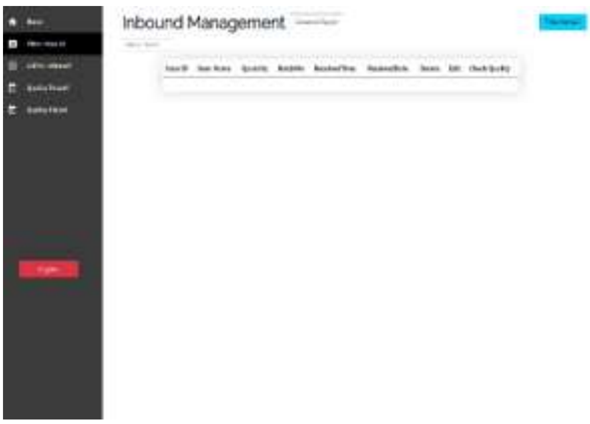

Figure 4. Inbound management

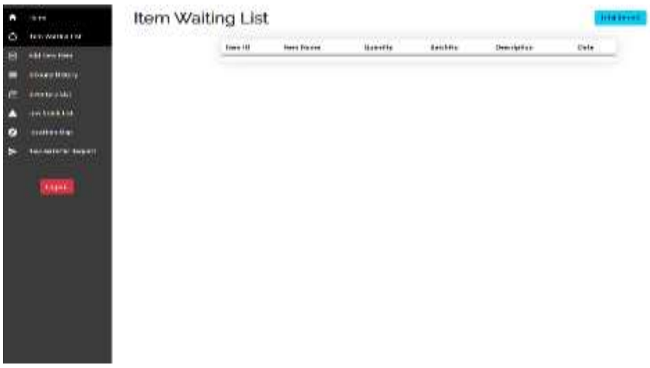

Figure 5. Item waiting list interface

Figure 6. Labor management interface

Figure 7. Pending order requests

Figure 8. Supplier registration

4. CONCLUSION

Our research developed the SWMW3 framework, integrating blockchain and ML to enhance WMS. Using barcodes, we created digital twins stored on the blockchain, ensuring secure and transparent transactions through smart contracts. The ML model, employing LSTM networks, accurately predicted total time from order receipt to shipping. This model was integrated into the backend using TensorFlow.js and displayed real-time predictions on the frontend dashboard. SWMW3 includes user interfaces for agent registration, inbound management, inventory management, labor management, and supplier registration, streamlining warehouse operations. This innovative approach improved predictive accuracy, operational efficiency, and security. Future work can focus on more integrated ML models to enhance productivity of WMS stakeholders.

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