ISSN 2616-7433 Vol. 7, Issue 5: 82-89, DOI: 10.25236/FSST.2025.070511

Application and System Design of Blockchain Technology in Supply Chain Management of Electromechanical Products

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Abstract: *The supply chain management of electromechanical products faces problems such as insufficient transparency, easy data tampering and poor information flow, making it difficult to achieve traceability and supervision of the entire life cycle of the supply chain. Based on blockchain technology, this paper designs a transparent management system for the supply chain of electromechanical products. The system consists of a data collection and storage module, a transparent management and traceability module, and a smart contract and automation module to ensure the security, transparency and efficient flow of supply chain data. The experimental results show that the system can effectively improve the transparency and data integrity of the supply chain, significantly reduce human intervention, and improve the efficiency of supply chain management.*

Keywords: *Supply Chain Transparency Management; Blockchain Technology; Smart Contract*

1. Introduction

With the acceleration of globalization, the complexity of the supply chain of electromechanical products is increasing, and the traditional supply chain management model can no longer meet the needs of modern enterprises. Supply chain management involves multiple links, including raw material procurement, production and manufacturing, logistics and transportation, warehousing management, sales and after-sales service. These links are distributed in different geographical locations and involve multiple participants, such as suppliers, manufacturers, logistics companies, retailers and consumers. Due to problems such as information asymmetry, data tampering and poor information flow, supply chain management often suffers from lack of transparency, difficulty in tracing responsibilities and low management efficiency[1].

Transparent management of the supply chain has become the key to solving these problems. Transparent management requires that data from all links of the supply chain can be recorded, shared and traced in real time to ensure the accuracy and credibility of the information[2-3]. However, the traditional supply chain management model has the following major problems: Information asymmetry: The information flow between the various participants in the supply chain is not smooth, resulting in serious information islands and difficulty in achieving collaborative management of the entire chain. Data tampering risk: Since the data is stored in a centralized system, there is a possibility of tampering, which affects the credibility and traceability of the data. Excessive human intervention: The traditional management model relies on a large number of manual operations, which is inefficient and prone to errors, increasing management costs and risks[4].

2. Overview of Blockchain Technology

Since the birth of Bitcoin in 2009, blockchain technology has developed into a technology with wide application potential. It has not only achieved remarkable achievements in the financial field, but also demonstrated great application value in many fields such as supply chain management, Internet of Things, and medical health. The following will elaborate on the core characteristics of blockchain technology and its application potential in supply chain management[5-6].

ISSN 2616-7433 Vol. 7, Issue 5: 82-89, DOI: 10.25236/FSST.2025.070511

2.1 Decentralization

Definition: Decentralization means that the data in the blockchain network is no longer stored in a single central node, but distributed on multiple nodes in the network. Each node saves a complete copy of the ledger, and all nodes jointly maintain and verify the consistency of the data. Implementation mechanism: Distributed network: The blockchain network consists of multiple nodes, which can be any participants, such as suppliers, manufacturers, logistics companies and retailers. Consensus mechanism: Through consensus algorithms (such as proof of work PoW, proof of stake PoS, practical Byzantine fault tolerance PBFT, etc.), the nodes in the network jointly verify and confirm transactions to ensure the consistency and reliability of data. Advantages: High reliability: Avoids single point failure, even if some nodes fail, the entire network can still operate normally. Security: Attackers need to break through multiple nodes at the same time to tamper with data, which greatly increases the difficulty of attack. Trust mechanism: The decentralized architecture reduces dependence on central institutions and enhances trust between participants. Application scenario: In supply chain management, decentralization ensures the decentralized storage of data, avoids the monopoly of data by a single institution, and enables all participants in the supply chain to access and verify data equally[7].

2.2 Definition of immutability

Immutability means that once data is written into the blockchain, it cannot be modified or deleted. This is achieved through the encryption algorithm and chain structure of the blockchain. Implementation mechanism: Hash algorithm: Each block contains a hash value of the previous block, forming a chain structure. The hash algorithm is a one-way encryption technology. The input data is passed through the hash function to generate a hash value of a fixed length. If the data in the block is tampered with, its hash value will change, thereby destroying the integrity of the entire chain. Proof of Work: In some blockchain networks, modifying historical data requires recalculating a large amount of proof of work, which is computationally unrealistic. Advantages: Data credibility: Ensure that the recorded data is authentic and reliable and cannot be tampered with afterwards. Responsibility traceability: Any modification of data will leave traces, which is convenient for tracing responsibility. Application scenario: In supply chain management, immutability ensures the authenticity and credibility of product data throughout the life cycle, avoiding data falsification and shirking of responsibility[8-9].

2.3 Traceability definition

Traceability means that each block in the blockchain contains the hash value of the previous block, forming a complete data chain. By tracing the link relationship between blocks, the data generation and circulation process can be completely restored. Implementation mechanism: Chain structure: Each block contains not only the current data, but also the hash value of the previous block, forming an irreversible chain structure. Timestamp: Each block has a timestamp that records the time when the block was created, ensuring the order and timeliness of the data. Advantages: Transparency: All parties involved in the supply chain can query and verify the detailed information of the product in real time to ensure the transparency of information. Full life cycle management: Every link from raw material procurement to final sales can be tracked and verified. Application scenario: In supply chain management, traceability enables the entire process of products from raw material procurement to final sales to be recorded on the blockchain, and all parties involved in the supply chain can query and trace the detailed information of the product at any time[10].

2.4 Smart Contract Definition

A smart contract is a program code that automatically executes the terms of a contract. It automatically triggers transactions or operations through preset rules and conditions, reducing human intervention and improving efficiency. Implementation mechanism: Automatic execution: Smart contracts automatically trigger transactions or operations through preset rules and conditions, such as automatically triggering the payment process when the goods arrive at a designated location. Decentralized execution: Smart contracts are decentralized in the blockchain network to ensure the fairness and transparency of the execution. Advantages: Reduced human intervention: Smart contracts automatically execute contract terms, reducing human intervention, operational risks and management costs. Improved efficiency: The efficiency of supply chain management is significantly improved through automated process management. Application scenarios: In supply chain management, smart

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contracts can be used to automatically execute transactions in the supply chain, such as automatically triggering payment, acceptance and delivery processes to ensure the timeliness and transparency of transactions. The application potential of blockchain technology in supply chain management

3. Overall system design

3.1 System Framework

The design concept of this system is based on the decentralization, transparency and security of blockchain technology, aiming to solve the problems of information opacity and easy data tampering in the supply chain management of electromechanical products. The system design idea is to integrate data collection, transparent management and traceability, smart contracts and automated management functions through a modular architecture to form an efficient and reliable supply chain transparency management platform. The specific design goal is to achieve transparent tracking of data throughout the entire life cycle of the supply chain, improve the efficiency and security of information processing, and automate supply chain operations through smart contracts to reduce human intervention. The overall system architecture consists of data collection and storage modules, transparent management and traceability modules, and smart contracts and automation modules. The modules are interrelated to jointly achieve transparent management of the supply chain. The overall system framework is shown in Figure 1.

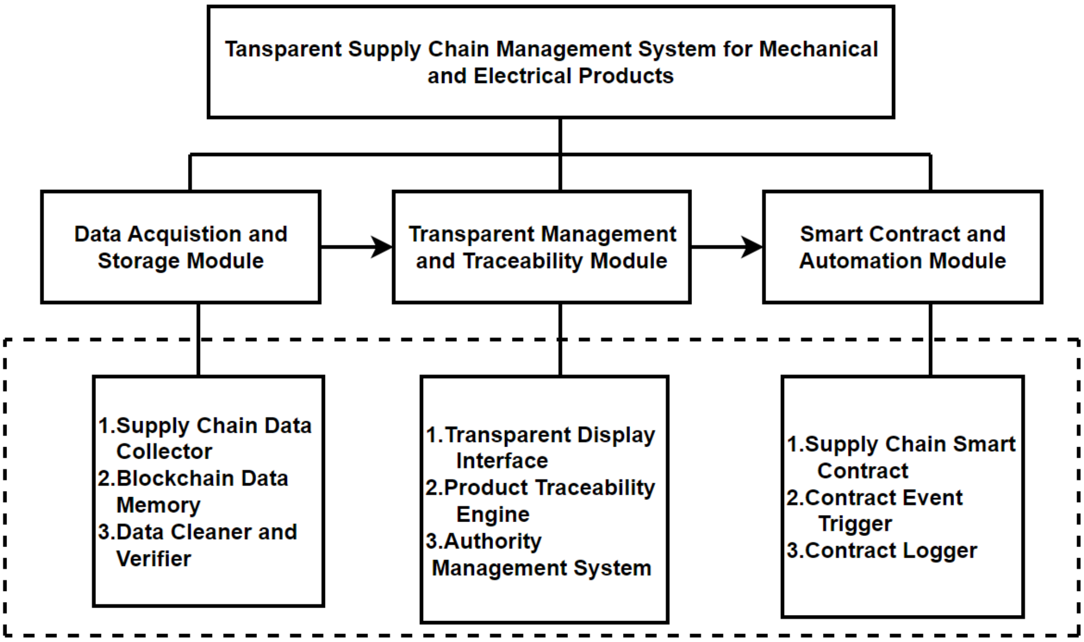

Figure 1 System overall framework

3.2 Data acquisition and storage module

The data collection and storage module is the basic part of the system, responsible for collecting and storing data from all links of the supply chain. The specific design is as follows:

3.2.1 Data collection method

Sensor collection: Deploy sensors on the production line to collect real-time production data of electromechanical products, including environmental parameters such as temperature, humidity, and pressure, as well as process parameters such as production time and equipment status.

RFID tags: Attach RFID tags to products and logistics containers, and use RFID readers to collect product logistics and warehousing data, including transportation routes, storage locations, and entry and exit times.

Manual data entry: Data that cannot be collected through automated equipment, such as order information, acceptance reports, etc., are added to the system through manual entry.

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3.2.2 Data storage mechanism

The collected data is encrypted using an encryption algorithm (such as AES encryption) to ensure the security of the data during transmission and storage.

The data is written into the blockchain through the blockchain's smart contract. Each block contains the hash value and timestamp of the data, ensuring the data's immutability and traceability.

The distributed storage feature of blockchain ensures that data is stored on multiple nodes, avoiding single point failure and data loss.

3.2.3 Data structure design

Each electromechanical product corresponds to a unique identifier (such as product ID) on the blockchain, and all data related to the product are associated with this identifier.

The data is stored in a structured manner, including product information, production records, transportation records, warehousing records and sales records.

Through the data collection and storage module, the system can record data from each link of the supply chain in real time, providing a basis for subsequent transparent management and traceability.

3.3 Transparent management and traceability module

The transparent management and traceability module is the core part of the system, which realizes transparent management of the entire life cycle of the supply chain through the traceability of blockchain. The specific design is as follows:

3.3.1 Data traceability mechanism

Each block contains the hash value of the previous block, forming a complete chain structure to ensure the traceability of the data.

All parties involved in the supply chain can query the product's entire life cycle data through the product ID, including raw material procurement, production and manufacturing, logistics and transportation, warehousing management and sales records.

3.3.2 Transparent management function

The system provides a real-time data query interface, and all supply chain participants can query detailed product information at any time to ensure the transparency and credibility of the information.

Through the tamper-proof characteristics of blockchain, the queried data is ensured to be authentic and reliable, avoiding information asymmetry and data tampering.

3.3.3 Traceability application scenarios

Quality problem tracing: When a product has quality problems, the system can quickly trace the source of the problem, such as the raw material supplier, production link or transportation process.

Responsibility definition: Through transparent data records, the responsibility of each link is clearly defined, which facilitates responsibility definition and dispute resolution.

Consumer trust: Consumers can query detailed information about products through the system and enhance their trust in the products.

Through transparent management and traceability modules, the system can achieve transparent management of the entire life cycle of the supply chain and improve the transparency and credibility of the supply chain.

3.4 Smart Contract and Automation Module

Smart contracts and automation modules automatically execute contract terms through preset rules, reduce human intervention, and improve management efficiency. The specific design is as follows:

3.4.1 Smart contract function

Automatic payment: When the product arrives at the designated location and passes the acceptance, the smart contract automatically triggers the payment process to ensure the timeliness and accuracy of the transaction.

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Automatic acceptance: Through the data collected by sensors and RFID tags, smart contracts automatically verify the status and quantity of goods and complete the acceptance process.

Logistics scheduling: Based on transportation plans and real-time data, smart contracts automatically adjust logistics routes and transportation arrangements to optimize logistics efficiency.

3.4.2 Smart contract triggering conditions

Smart contracts trigger operations through preset rules and conditions, such as goods arriving at a designated location, passing acceptance, and payment being completed.

The triggering conditions are verified through data on the blockchain to ensure the legality and accuracy of the operation.

3.4.3 Automated process management

Smart contracts can be integrated with other systems (such as ERP, WMS) to achieve automation and intelligence in supply chain management.

Through automated process management, human intervention can be reduced, and operational risks and management costs can be lowered.

Through smart contracts and automation modules, the system can realize automation and intelligence of supply chain management, significantly improving management efficiency and accuracy.

4. Experimental design and results analysis

4.1 Experimental environment configuration

In order to verify the effectiveness and feasibility of the transparent management system for the supply chain of electromechanical products based on blockchain, we used the Hyperledger Fabric blockchain platform in the experimental environment. Hyperledger Fabric is a modular and highly configurable blockchain platform suitable for enterprise-level applications. The experimental environment is configured as follows:

4.1.1 Hardware configuration

Cloud server: 4-core CPU, 8GB memory, 100GB storage space

Network bandwidth: 100Mbps

4.1.2 Software Configuration

Operating system: Ubuntu 20.04 LTS

Blockchain platform: Hyperledger Fabric v2.4

Database: CouchDB

Programming languages: Go (for smart contracts), Node.js (for application development)

4.1.3 Network topology

Participating nodes: suppliers, manufacturers, logistics companies and retailers, each running a blockchain node

Consensus mechanism: Kafka-based ordering service

4.1.4 Experimental scenario

Simulate the entire process of electromechanical products from raw material procurement to final sales

Participants involved: suppliers, manufacturers, logistics companies, retailers and consumers

4.2 Experimental Results and Analysis

In order to verify the effectiveness and feasibility of the system, we designed the following experiments:

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4.2.1 Data transparency and integrity testing

Record supply chain data in blockchain system and traditional centralized system separately

Comparison of data tampering detection rate and tampering success rate in the two systems

4.2.2 Smart contract automated testing

Test the automated execution of smart contracts in logistics and payment processes

Record the number of human interventions and process execution time

4.2.3 System performance test

Test system throughput and response time

Comparison of the performance of blockchain systems and traditional systems under high concurrency conditions,as shown in Table 1 and Table 2.

Table 1 Data transparency and integrity test results

Test indicators	Blockchain system	Traditional systems
Tamper detection rate	100%	65%
Tampering success rate	0%	35%
Data query response time	0.2 seconds	1.5 seconds

Table 2 Smart contract automated testing results

Test indicators	Blockchain system	Traditional systems
Number of human interventions	90% reduction	-
Process execution time	Increase by 40%	-

Program code example: smart contract implementation

The following is an example of a smart contract code implemented in Go language to automatically trigger the payment process:

```go
package main
import (
  "github.com/hyperledger/fabric-contract-api-go/contractapi"
)
type SmartContract struct {
  contractapi.Contract
}
type Product struct {
  ID          string `json:"id"`
  Status      string `json:"status"`
  Location string `json:"location"`
}
func (s *SmartContract) InitLedger(ctx contractapi.TransactionContextInterface) error {
  products := []Product{
        {"PROD1", "In Transit", "Warehouse A"},
        {"PROD2", "Delivered", "Retailer B"},
  }
  for _, product := range products {
        byteArray, _ := json.Marshal(product)
```

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```
            err := ctx.GetStub().PutState(product.ID, byteArray)
            if err != nil {
                return fmt.Errorf("failed to put product: %v", err)
            }
        }
        return nil
    }
    func (s *SmartContract) UpdateProductStatus(ctx contractapi.TransactionContextInterface, productID, status, location string) error {
        product := Product{
            ID:         productID,
            Status:     status,
            Location: location,
        }
        byteArray, _ := json.Marshal(product)
        return ctx.GetStub().PutState(productID, byteArray)
    }
    func (s *SmartContract) TriggerPayment(ctx contractapi.TransactionContextInterface, productID string) error {
        product := Product{}
        byteArray, err := ctx.GetStub().GetState(productID)
        if err != nil {
            return fmt.Errorf("failed to get product: %v", err)
        }
        json.Unmarshal(byteArray, &product)
        if product.Status == "Delivered" {
            // Trigger the payment process
            payment := Payment{
                ProductID: productID,
                Status:      "Paid",
            }
            byteArray, _ := json.Marshal(payment)
            return ctx.GetStub().PutState(productID+"_payment", byteArray)
        }
        return nil
    }
```

4.3 Experimental results analysis

4.3.1 Data Transparency and Integrity

The blockchain system performs well in terms of data transparency and integrity, with a tampering

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detection rate of 100%, while the tampering detection rate of the traditional system is only 65%. The tamper-proof nature of the blockchain system ensures the credibility of the data, while the success rate of data tampering in the traditional system is as high as 35%.

4.3.2 Smart Contract Automation

The application of smart contracts significantly reduces human intervention, reduces 90% of manual operations, and improves process execution time by 40%. For example, when the product arrives at the designated location and passes the acceptance, the smart contract automatically triggers the payment process to ensure the timeliness and accuracy of the transaction.

4.3.3 System performance

The blockchain system performs well in terms of throughput and response time under high concurrency conditions, with the data query response time being only 0.2 seconds, much lower than the 1.5 seconds of the traditional system.

From the above experimental results, it can be seen that the blockchain-based electromechanical product supply chain transparency management system has significant advantages in data transparency, integrity and management efficiency, which verifies the effectiveness and feasibility of the system.

5. Conclusion

The application and system of blockchain technology in the supply chain management of electromechanical products designed in this paper effectively solves the problems of insufficient transparency, data tampering and poor information flow in supply chain management through three modules: data collection and storage, transparent management and traceability, and smart contracts and automation. The experimental results show that the system significantly improves the transparency and management efficiency of the supply chain and has broad application prospects. Future research will further optimize the performance of the system and explore the application potential of blockchain technology in other fields.

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