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Article

Stackelberg Game-Based Resource Allocation with Blockchain for Cold-Chain Logistics System

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Abstract: Cold-chain logistics system (CCLS) plays the role of collecting and managing the logistics data of frozen food. However, there always exist problems of information loss, data tampering, and privacy leakage in traditional centralized systems, which influence frozen food security and people's health. The centralized management form impedes the development of the cold-chain logistics industry and weakens logistics data availability. This paper first introduces a distributed CCLS based on blockchain technology to solve the centralized management problem. This system aggregates the production base, storage, transport, detection, processing, and consumer to form a cold-chain logistics union. The blockchain ledger guarantees that the logistics data cannot be tampered with and establishes a traceability mechanism for food safety incidents. Meanwhile, to improve the value of logistics data, a Stackelberg game-based resource allocation model has been proposed between the logistics data resource provider and the consumer. The competition between resource price and volume balances the resource supplement and consumption. This model can help to achieve an optimal resource price when the Stackelberg game obtains Nash equilibrium. The two participants also can maximize their revenues with the optimal resource price and volume by utilizing the backward induction method. Then, the performance evaluations of transaction throughput and latency show that the proposed distributed CCLS is more secure and stable. The simulations about the variation trend of data price and amount, optimal benefits, and total benefits comparison of different forms show that the resource allocation model is more efficient and practical. Moreover, the blockchain-based CCLS and Stackelberg game-based resource allocation model also can promote the value of logistic data and improve social benefits.

Keywords: Cold-chain logistics; resource allocation; Stackelberg game; blockchain

1 Introduction

Cold-chain logistics system (CCLS) is an essential part of the modern logistics industry, which takes responsibility for the logistics data management of frozen food delivery [1]. However, the food security problem is increasingly prominent with centralized management, which usually causes data tampering and information leakage [2,3]. Meanwhile, the mutually independent systems for different kinds of frozen food go against the resource allocation related to the integrated requirements [4,5].

Blockchain technology has gradually penetrated people's production and life, such as education [6], employment [7], old-age care [8], commodity anti-counterfeiting [9], medical and health care [10,11], which guarantees the security of the system data that cannot be tampered. This technology has also been applied to the modern logistics industry to improve data security and transparency [12–14]. It helps establish an integrated platform that contains the entities that contain the production and circulation of goods and record the logistics data and processing records into the public blockchain ledger. In addition, some cryptographic algorithms are inserted into the blockchain to protect distributed systems [15–17]. These schemes focus on transaction verification and identity authentication in the data processing procedure in blockchain-based systems. Although the blockchain-based CCLS establishes a distributed logistics data management and sharing platform, the optimal resource allocation and shared incentive mechanism are new issues that should be considered more.

Resource allocation is essential for frozen food, and the cold-chain logistics data can support frozen food allocation [18,19]. With the continuous expansion of the frozen food market, managing vast amounts of cold-chain logistics data becomes a big challenge, and allocating frozen food resources becomes more complex. The blockchain-based CCLS aggregates the related entities from the generation to consumption of frozen food [20,21]. Meanwhile, the logistics data are recorded in the public blockchain ledger. These data also show the resource supplement and demand in the frozen market [22,23]. Therefore, it can improve the resource value by giving full play to the value of logistics data. Then, to promote allocation efficiency, some methods based on reinforcement learning, smart contract, and could computing are proposed [24–26]. However, security and efficiency are two main parts of logistics data management, and a suitable algorithm that can consider these two requirements has been the goal of pursuit.

This paper mainly focuses on logistics data security management and resource allocation in CCLS. A distributed CCLS model based on blockchain technology has been proposed to achieve secure logistics data management. A Stackelberg game-based resource allocation model has been introduced to balance the data resource supplement and consumption in blockchain-based CCLS. The main contributions are summarized as follows:

- A distributed CCLS based on blockchain technology has been established, aggregating the production base, storage, transport, detection, processing, and consumer together to form a cold-chain logistics union. The blockchain ledger can guarantee that the logistics data cannot be tampered with and establish a traceability mechanism for food safety incidents.
- A Stackelberg game-based resource allocation model has been proposed between the logistics data resource provider and the consumer. This model establishes a competition mechanism between resource price and volume, which helps to balance the resource supplement and consumption. The two participants can maximize revenue with the optimal resource price and volume when the Stackelberg game obtains Nash equilibrium.
- The performance of the variation trend of data price and amount, optimal benefits, and the transaction throughput and latency in CCLS are presented. The evaluation results show that

the proposed distributed CCLS is more secure and stable, and the resource allocation model is more efficient and practical.

Next, Section 2 presents the related work, Section 3 introduces the distributed CCLS with blockchain, Section 4 describes the proposed Stackelberg game-based resource allocation model and its solution, Section 5 gives the performance evaluations, and Section 6 shows the conclusion.

2 Related Work

This section presents detailed reviews of the distributed CCLS with blockchain and the resource allocation mechanism for CCLS.

2.1 Distributed CCLS with Blockchain

The deepening application of blockchain in IoT shows a very promising application in CCLS. The distributed CCLS based on blockchain has been proposed to change the centralized management form in traditional systems. Kim et al. applied the Hyperledger fabric to establish a Blockchain-based CCLS for blood transactions among medical institutions [27]. Bamakan et al. reviewed the applications, challenges, and future trends of pharmaceutical logistics with blockchain technology [12]. Mendonça et al. designed a Blockcoldchain platform for a vaccine cooling track facing the COVID-19 pandemic, which could provide public and verifiable logistics records [28]. Menon et al. proposed an IoT blockchain for quality assurance in CCLS, and it established an immutable and decentralized database to store the logs transactions [29]. Bamakan et al. reviewed the applications, challenges, and future blockchain technology trends for drug delivery in CCLS [30]. Si presented a blockchain-enabled multi-mode data model for agriculture and adopted a native storage model to lighten the redundancy of an online ledger [31]. Hu developed a monitoring system for CCLS based on IoT, blockchain, and computer technologies, which could collect real-time dynamics data to adjust logistics conditions [32]. Wisessing et al. utilized IoT and blockchain technologies to establish a distributed cold-chain platform for food monitoring applications [20]. Zhang et al. proposed a data traceability system based on blockchain technology, which could grasp fresh agricultural products' dynamic real-time logistics data [21]. These work design various Blockchain-based CCLSs for cold-chain logistics data management and usually focus on data collection and storage. However, the overall data management and sharing process is rarely considered in this literature. Therefore, this paper plans to establish a distributed Blockchain-based CCLS for frozen food delivery, which can achieve logistics data supervision from generation to consumption.

2.2 Resource Allocation Mechanism for CCLS

A resource allocation mechanism is a powerful tool for playing the value of resources in IoT systems, especially for the frozen food allocation in CCLS. A variety of these mechanisms have been proposed to take full use of the cold-chain logistics data resource in CCLS. Bashir et al. applied the logistic regression and multicriteria decision-making method to allocate resources with IoT fog computing [22]. Kang et al. utilized the auction approach to realize cloud service allocation and sharing, which could improve the resource utilization efficiency in the logistics product service system [23]. Yu et al. introduced a reinforcement learning method for resource allocation for humanitarian logistics [24]. Cheng et al. proposed a trusted resource allocation model with blockchain and smart contracts to optimize the allocation of resources in IoT [25]. Wei et al. utilized multi-objective optimization and cloud computing to allocate resources in vehicular networks [26]. Then, the Stackelberg game was used to establish a competition mechanism between two parties and achieve resource allocation. Shi et al. utilized the Stackelberg game to guide a deep reinforcement learning approach that could allow multi-agent device-to-device resource allocation [33]. Li et al. proposed a vehicular paradigm based on fog-edge computing and formulated a multistage Stackelberg game for offloading computing tasks [34]. Liu et al. presented a Stackelberg game method that depends on the price-penalty mechanism to allocate device-to-device resources in a vehicular communication system [35]. As resource price and trading volume are two conditioned upon each other factors, balancing the resource supplement and consumption to obtain optimal price and volume is the way to maximize the use of resources. Therefore, this paper proposes a Stackelberg game-based resource allocation model to cover this demand in CCLS.

3 Distributed Cold-Chain Logistics with Blockchain

To improve logistics data security, a distributed CCLS based on blockchain technology. This CCLS contains six parts: production base, storage entity, transport entity, detection entity, processing entity, and consumer entity. Blockchain technology can aggregate these entities and establish a distributed cold-chain logistics data management system shown in Fig. 1. This distributed system can collect multi-source data and form an untampered public ledger.

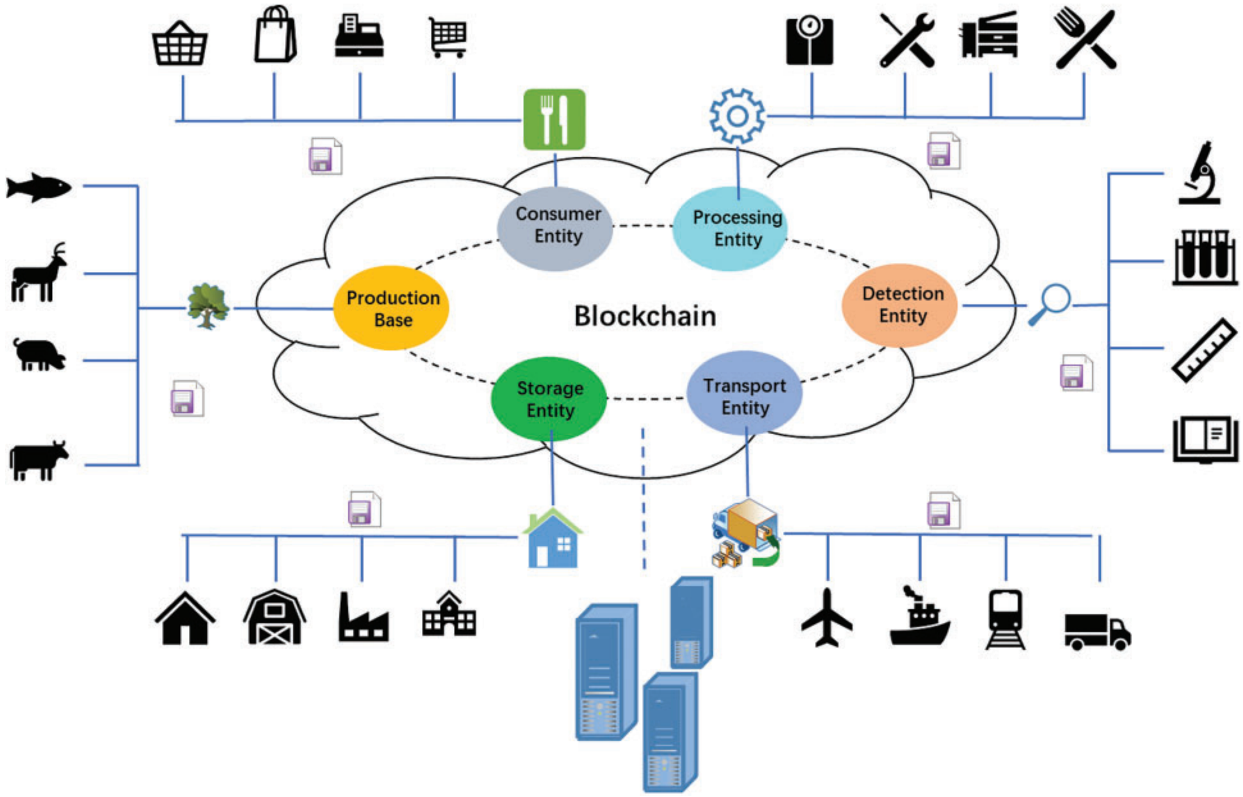

Figure 1: Distributed cold-chain logistics system

- Data collection. From the production to consumption of frozen food, the life cycle data of cold-chain logistics are collected, which guarantees food safety. Many temperatures, humidity, and location sensors collect real-time monitoring data. These data will be uploaded on the distributed CCLS with wireless transmission modes such as Bluetooth, WIFI, and Zigbee.

Meanwhile, information on the operator, car, factory, and store is also packaged into the corresponding data bag in every phase. These data provide evidence for process tracing. Then this distributed system also plays a resource allocation role in providing the production trading of frozen food. It can help the resource provider and consumer find more suitable clients and resources, respectively. These data are also recorded on the public ledger.

- Data verification. For the logistics data, the system management nodes verify the authenticity of the collected data. They check the timeline of the logistics process to judge whether there exists data falsification or not. For the transaction data, management nodes verify the legality and validity of the transaction process. Meanwhile, it also needs to verify the distributed system and achieve the consensus of the whole network when these data are packaged into the temporary block. The data transaction consistency processes are shown in Fig. 2, and they contain five steps: broadcast, verify, feedback, confirm, and public. In this network-wide verification process, the leader node broadcasts the transactions to other general nodes; General nodes verify the received transactions, sign with their signature, and send them to other nodes; Other nodes also verify, sign, and return them; General nodes confirm the verification results and return them to leader node; The leader checks the verification results and public them to the whole network.
- Data recordation. When the logistics data and transaction data are all passed the verification process, they will be packaged into the block and recorded on the public ledger. Once these data are recorded in the blockchain ledger, they become records that can never be tampered with. Here, this ledger generally records the light-weight information about logistics information, transaction data, storage addresses, and operating record to decrease ledger redundancy. Then, the actual data are stored in the native server. The system derives an index that contains the storage address and keywords about the actual data and uploads the index to the public ledger.

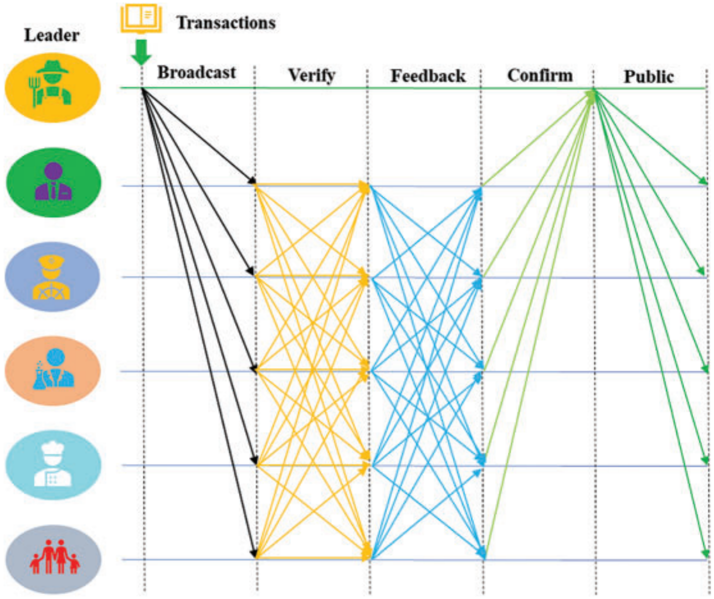

Figure 2: Data transaction consistency process

This distributed system provides security assurance for a frozen food resource's logistics data and trading platform. Through this system, people can check historic logistics information about frozen food to find more relieved goods, the related logistics parties can grasp the real-time logistics data to guarantee the transportation safety of frozen food, and the researcher can optimize the logistics scheme to improve transportation efficiency. Meanwhile, this system can strengthen the food safety oversight capability as the logistics data are transparent and open in the distributed blockchain ledger. However, balancing the frozen food resource supplement and consumption, and achieving benefit maximization are the main concerns which need a more efficient algorithm.

4 Stackelberg Game-Based Resource Allocation Model for CCLS

A Stackelberg game-based resource allocation model is proposed to balance resource supplements and consumptions in CCLS.

4.1 Stackelberg Game-Based Resource Allocation Model

This distributed CCLS serves as the resource allocation platform and establishes a connection between the frozen food resource provider and consumer. To achieve resource optimal allocation, a Stackelberg game-based resource allocation model has been designed [36]. This model selects one resource provider and N resource consumers to compete in price. Assume that the resource provider attempts to set higher resource price and obtain more benefits. The resource consumers attempt to accomplish the expected amount with a more suitable resource price. Therefore, it becomes the resource optimal price competition game between the resource provider and consumers.

Firstly, the resource provider serves as the game "leader" and sets a price range $\left\{p = [p_i]_{i \in N} : p_{\min} \leq p_i \leq p_{\max}\right\}$ for one piece of resource data, where $p_i\ (i = 1, 2, \ldots, N)$ is a price for the i-th resource consumer, $p_{\max}$ and $p_{\min}$ are the maximum and minimum resource price respectively. Here, the resource price cannot be inferior to the lowest cost value $p_{\min}$ and exceeded the maximum resource price $p_{\max}$. Therefore, when the resource consumer's input amount is d_i, the expected reward by removing the extra system service fee γ can be described as:

$$R_L = \sum_{i \in N} (p_i d_i - \gamma d_i) \tag{1}$$

Secondly, the resource consumers serve as the "follower" and decide their resource demand amounts d_i according the bidding strategy set by resource provider. Here, d_i is the amount of i-th resource consumer, which has a lowest need $d_{\min}$. Then, the satisfaction function of i-th resource consumer by removing the extra system service fee e_i can be expressed as:

$$S_{sat} = \alpha_i ln\,(d_i - d_{\min} + e_i) \tag{2}$$

Note that α_i is a predefined nonzero positive factor.

Then, the utility of i-th resource consumer by removing the resource costs $p_i d_i$ can be calculated as:

$$R_F = S_{sat} - p_i d_i \tag{3}$$

Therefore, the resource provider and consumers all attempt to obtain maximized benefits, and the following two optimization problems A and B are the objectives for these two kinds of parties, respectively. The resource price p_i and amount d_i are two main factors which can influence the two kinds of parties' benefits. As problem A is mainly related to the resource price p_i, the higher price is with more less resource output amounts, and then the expected reward of resource provider is more less. While problem B is mainly related to the resource amounts d_i, and the less amounts lead to less utility for resource consumer.

$$A: \max_{\lambda_i} R_L\left(p_i, d_i\right), \quad s.t.\, p_{\min} \leq p_i \leq p_{\max}, p_{\min} \geq \gamma, \forall i \in N \tag{4}$$

$$B: \max_{d_i} R_F\left(d_i, p_i\right), \quad s.t.\, d_i \geq d_{\min}, \alpha_i \geq 0, \forall i \in N \tag{5}$$

Moreover, the following problem C represents the system maximized benefits which contain the expected reward of resource provider and the utility of resource consumers.

$$C: \max \left\{R_L + \sum_{i \in N} R_F\right\}$$

$$s.t. \begin{cases} p_{\min} \leq p_i \leq p_{\max}, \forall i \in N \\ d_i \geq d_{\min}, \forall i \in N \\ \alpha_i \geq 0, \forall i \in N \\ e_i > 0 \end{cases} \tag{6}$$

4.2 Optimal Resource Prices Solving

To solve the optimal resource price and transaction amounts, it needs to find the Nash equilibrium point for Stackelberg pricing game [37]. Therefore, the problems A and B can be maximized simultaneously by achieving this point which is described by the following *Definition 1*.

Definition 1: Assume the resource demand d_i of N resource consumers are same, the Stackelberg pricing game can achieve the Nash equilibrium point (p^*, d^*) when Eq. (7) holds, where p^* is the resource optimal price, d^* $\left(d^* = \sum_{i \in N} d_i^*\right)$ is the resource optimal output amounts and d_i^* is the resource optimal demand for i-th resource consumer.

$$\begin{cases} \partial R_L\left(p^*, d^*\right) = \partial R_L\left(p_i, d^*\right) \\ \partial R_F\left(p^*, d^*\right) = \partial R_F\left(p^*, d_i\right) \end{cases} \tag{7}$$

Firstly, it utilizes the backward induction method to compute Eq. (7), and calculates the optimal resource demands d_i^* [38]. The one and two-order derivatives of R_F are computed in Eqs. (8) and (9) respectively.

$$\frac{\partial R_F}{\partial d_i} = \frac{\alpha_i}{d_i - d_{\min} + e_i} - p_i \tag{8}$$

$$\frac{\partial^2 R_F}{\partial d_i^2} = -\frac{\alpha_i}{\left(d_i - d_{\min} + e_i\right)^2} < 0 \tag{9}$$

Here, the Eq. (9) shows that the utility function R_F is strictly concave. Therefore, the optimal resource demands d_i^* can be derived by solving $\frac{\partial R_F}{\partial d_i} = 0$.

$$d_i^* = \frac{\alpha_i}{p_i} + d_{\min} - e_i \tag{10}$$

Secondly, it calculates the optimal resource price p^*. By substituting d_i^* into Eq. (1), the expected reward R_L is transformed into Eq. (11).

$$R_L = \left(d_{\min} - e_i\right) p_i - \frac{\gamma \alpha_i}{p_i} - \gamma\left(d_{\min} - e_i\right) + \alpha_i \tag{11}$$

By utilizing the same solving method for utility function R_F, the one and two-order derivatives of R_L are computed in Eqs. (12) and (13) respectively.

$$\frac{\partial R_L}{\partial p_i} = \frac{\gamma \alpha_i}{p_i^2} + d_{\min} - e_i \tag{12}$$

$$\frac{\partial^2 R_L}{\partial p_i^2} = -\frac{2\gamma \alpha_i}{p_i^3} < 0 \tag{13}$$

Here, the Eq. (13) shows that the expected reward function R_L is strictly concave. Meanwhile, it discusses the size relation between $d_{\min}$ and e_i. When $d_{\min} < e_i$, it has $\lim_{p_i \to 0} R_L = -\infty$ and $\lim_{p_i \to +\infty} R_L = -\infty$. It also can derive the results as shown in following Eq. (14).

$$\begin{cases} \dfrac{\partial R_L}{\partial p_i} > 0, & \mathit{if}\ 0 < p_i < \sqrt{\dfrac{\gamma \alpha_i}{e_i - d_{\min}}} \\ \dfrac{\partial R_L}{\partial p_i} < 0, & \mathit{if}\ p_i > \sqrt{\dfrac{\gamma \alpha_i}{e_i - d_{\min}}} \end{cases} \tag{14}$$

Hence, R_L increases firstly, and then decreases. The optimal resource price p^* can be derived by solving $\frac{\partial R_L}{\partial p_i} = 0$.

$$p^* = \sqrt{\frac{\gamma \alpha_i}{e_i - d_{\min}}} \tag{15}$$

When $d_{\min} > e_i$, the resource price $p_i < 0$ which is not practical.

Then, the former theory analyses show that (p^*, d^*) is the optimal point of resource price and amount for Stackelberg pricing game. Following Algorithm 1 provides a game processes for the confirming of Nash equilibrium point. The resource provider adjusts the resource price p_i to achieve expected reward maximization, and the resource consumers adjust the resource demand amount d_i to achieve utility maximization. When the resource provider and consumers find the optimal resource price p^* and amounts d^*, they all obtain the maximized benefits R_L^* and R_F^*. Until now, the algorithm completes. In addition, CCLS achieves social welfare maximization when the two kinds of parties obtain maximized benefits R_L^* and R_F^*.

Algorithm 1: Resource pricing competition algorithm

```
Initialize: $R_L^* = 0$, $R_F^* = 0$, $p_i^* = 0$, $d_i^* = 0$
for resource consumer $i \in N$ do
    for one piece of resource price $p_i$ from $p_{\max}$ to $p_{\min}$ do
        if $d_{\min} < e_i$ then
            $p^* = 0, d^* = 0$
            Break
        end if
        Resource consumer $i$ adjusts its resource amount $d_i$ by $d_i^* = \frac{\alpha_i}{p_i} + d_{\min} - e_i$
        Resource consumer $i$ computes $R_F = \alpha_i ln\,(d_i - d_{\min} + e_i) - p_i d_i$
        Resource provider computes $R_L = p_i d_i - \gamma d_i$
        if $R_L \geq R_L^*$ then
            Resource provider records: $R_L^* = R_L$, $R_F^* = R_F$, $p_i^* = p_i$, $d_i^* = d_i$
        end if
        if $R_L < R_L^*$ then
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(Continued)

Algorithm 1: Continued

```
            Break
          end if
      end for
  end for
  $(p^*, d^*)$ is the point of resource price and amount for Stackelberg pricing game
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5 Performance Evaluation

For the former proposed Stackelberg game-based resource allocation model, the iteration is the efficiency index, and the optimal benefits represent the change in system revenue. The performance environment is a Windows 10 laptop with Intel(R) Core (TM) i7 CPU 3.0 GHz and 16 G RAM. The iterations between the resource price and amount are presented in Fig. 3. With the increase of resource price set by the Stackelberg game "leader," the resource amount approaches the minimum data resource requirements. Here, the data price will not go up forever, which generally has the maximum price limit. Fig. 4 shows the changes in optimal benefits for the resource data provider, consumer, and total system amount. According to resource price trends and amount trends, the resource provider, consumer, and CCLS achieve benefits maximization when the Stackelberg pricing game obtains the Nash equilibrium point.

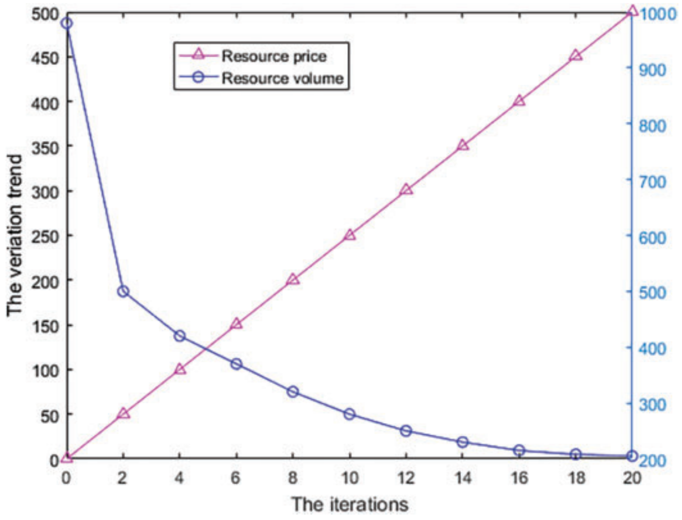


Figure 3: Variation trend of data price and amount

Fig. 5 presents the total benefits comparison of different forms. As in traditional centralized CCLSs [2–4], the manager usually sets the resource price by simple principle with high, average, and low prices. However, the total benefits do not achieve profit maximization. In practice, the resource amounts change as the price changes, and the total benefits change as the resource price and amounts change. As shown in Fig. 5, a high price leads to low benefits because resource volume is small, an average price obtains average benefits, and a low price leads to high benefits because resource volume is large. It is possible to improve the benefits of one side, but it cannot maximize revenue of both sides. Therefore, the proposed Stackelberg model can obtain profit maximization with the dynamic adjustment of resource price and amounts.

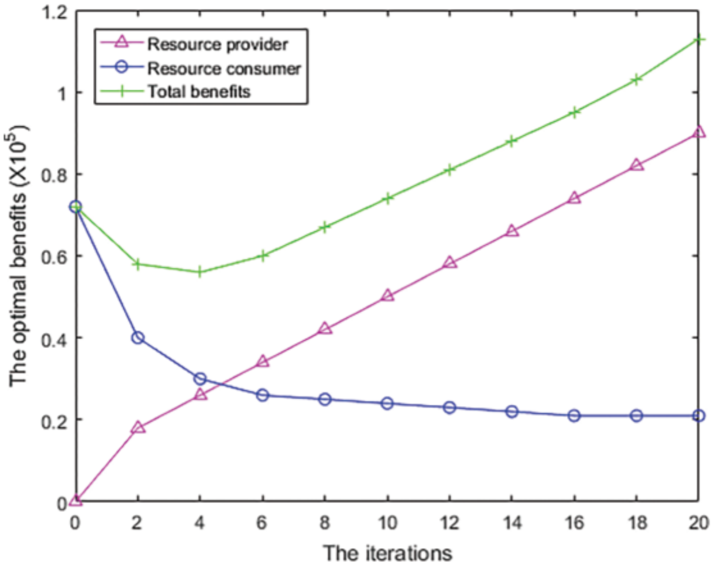


Figure 4: The optima benefits

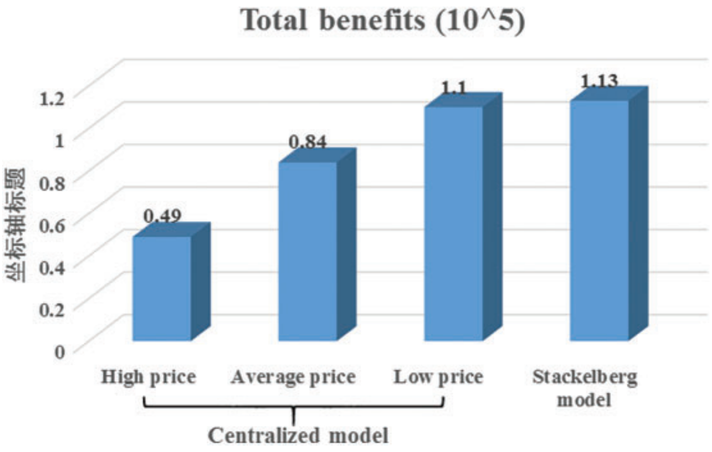
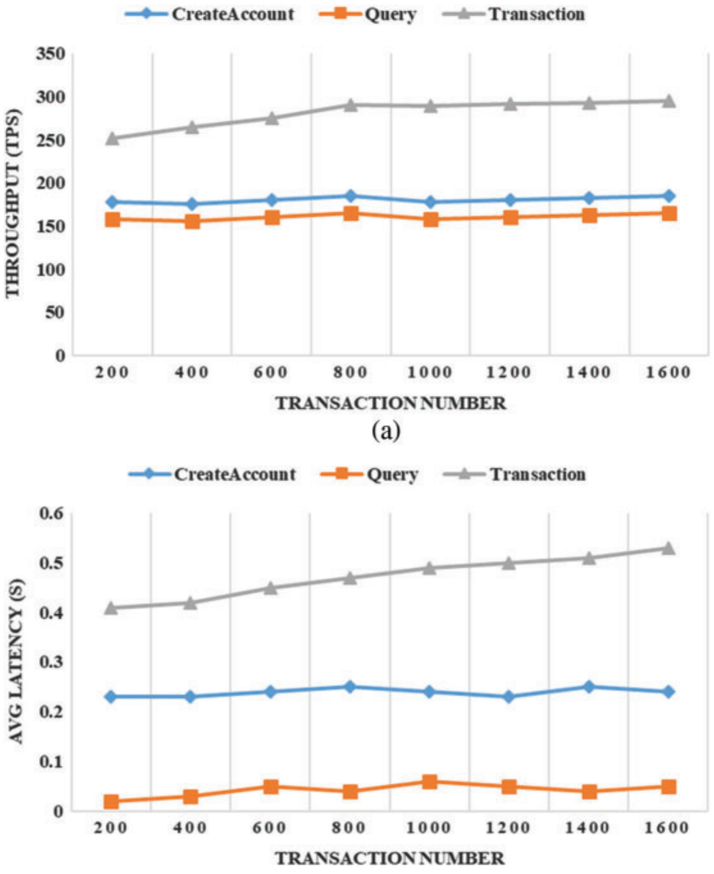


Figure 5: Total benefits comparison of different forms

Meanwhile, it performs transaction processing in distributed clod-chain logistics systems on the Hyperledger Fabric. Here, the transaction throughput (TSP) and latency (TL) have been performed, with the transaction number increasing from 200 to 1600. Three items, such as “CreateAccount,” “Query,” and “Transaction,” have been selected to describe the variation of TSP and TL with the transaction number increase. The simulation results are presented in Fig. 6, where subfigure (a) shows the trend chart of transaction throughput, and subfigure (b) shows the trend chart of average transaction latency. As the transaction throughput, the items “CreateAccount” and “Transaction” keep stable, and the “Query” increases slightly with the increase of transaction number. As the transaction latency, the items “CreateAccount” and “Query” keep stable, and the “Transaction” increases slightly with the increase of transaction number. Therefore, it can derive that the TSP and TL are less affected by the test environment, and the proposed data privacy-preserving model is practical for transaction processing in the distributed clod-chain logistics system.



(a)

(b)

Figure 6: The transaction processing in distributed clod-chain logistics system: (a) Transaction throughput; (b) Transaction latency

Former performance evaluations show that the proposed Stackelberg game-based resource allocation model can well support the resource transaction in CCLS with blockchain technology. Meanwhile, CCLS is one kind of supply chain for the transportation of frozen food. This model is also suitable for other areas of supply chain management with vast transactions among multi-parties. But it is not suitable for commodity trading as commodity prices are affected by many factors, such as supplement, demand, liquidity, policies, and so no.

6 Conclusion

This paper proposes a blockchain-based CCLS to guarantee logistics data security and establish a traceability mechanism to solve the problems of information loss, data tampering, and privacy leakage. A Stackelberg game-based resource allocation model is established to balance resource supplement and consumption. This model can help the resource provider and consumer achieve an optimal resource price and amounts, respectively. Then, the performance evaluations show that the proposed distributed CCLS is more secure and stable, and the resource allocation model is more efficient and practical. Moreover, this research can promote the transformation and upgrading of current CCLS and give full play to the value of cold chain logistics data.

In the future, some factors which affect the resource price will be added to the proposed resource allocation model to establish a more sophisticated price competition mechanism. Meanwhile, logistics data security and user privacy are significant issues that should be considered more. Moreover, it is significant to find the adaptability of this Stackelberg game-based resource allocation model in the Internet of things, Internet of medical things, and power grid.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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