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RESEARCH ARTICLE

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Toward resilient cloud warehousing via a blockchain-enabled auction approach

Abstract Cloud warehousing service (CWS) has emerged as a promising third-party logistics service paradigm driven by the widespread use of e-commerce. The current CWS billing method is typically based on a fixed rate in a coarse-grained manner. This method cannot reflect the true service value under the fluctuating e-commerce logistics demand and is not conducive to CWS resilience management. Accordingly, a floating mechanism can be considered to introduce more flexible billing. A CWS provider lacks sufficient credibility to implement floating mechanisms because it has vested interests in terms of fictitious demand. To address this concern, this report proposes a blockchain-enabled floating billing management system as an overall solution for CWS providers to enhance the security, credibility, and transparency of CWS. A one-sided Vickrey–Clarke–Groves (O-VCG) auction mechanism model is designed as the underlying floating billing mechanism to reflect the real-time market value of fine-grained CWS resources. A blockchain-based floating billing prototype system is built as an experimental environment. Our results show that the O-VCG mechanism can effectively reflect the real-time market value of CWSs and increase the revenue of CWS providers. When the supply of CWS providers remains unchanged, allocation efficiency increases when demand increases. By analyzing the performance of the O-VCG auction and comparing it with that of the fixed-rate billing model, the proposed mechanism has more advantages. Moreover, our work provides novel managerial insights for CWS market stakeholders in terms of practical applications.

Keywords resilient cloud warehousing, blockchain technology, floating billing management system, auction mechanism, third-party logistics

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1 Introduction

Since the outbreak of coronavirus disease 2019 (COVID-19), all countries have made efforts to control the pandemic. The impact of COVID-19 on the global supply chain has been far-reaching (Ivanov and Dolgui, 2020; Choi, 2021; Choi and Shi, 2022). COVID-19 killed a large number of people worldwide, destroyed the global economy, and slowed the development of some industries. Previous supply chain research involves many aspects, such as preventing supply chain risk disruption (Li et al., 2020a), supply chain contract strategies (Li et al., 2021), supply chain network design (Rezapour et al., 2017; Nili et al., 2021), supply chain coordination (Xie et al., 2021), and pricing decisions (Wu et al., 2012). In addition, some research, such as the studies by El Baz and Ruel (2021), Dolgui and Ivanov (2021), Singh et al. (2021), and Queiroz et al. (2022), has focused on the impact of COVID-19 on the resilience of supply chains. When the COVID-19 outbreak continues to intensify, and government controls tighten, consumers are increasingly turning to e-commerce platforms to buy various groceries, household items, and medical supplies. For example, Amazon's profits increased by 70% in the first nine months of 2020, and the proportion of sales carried out through e-commerce in China in 2021 reached 52%. These rapidly growing e-commerce order demands introduce challenges to logistics warehousing and delivery. Addressing these challenges to enhance the resilience of the logistics supply chain in the post-COVID-19 period is the top priority of the current supply chain. Cloud warehousing service (CWS) provides a possible solution for this problem.

CWS is an emerging third-party logistics (3PL) service paradigm that relies on warehouse facilities and utilizes cloud computing techniques to virtualize and encapsulate physical storage and distribution resources as diversified cloud services to satisfy the socialized demand for goods circulation (Ma et al., 2011). The CWS market has rapidly expanded in China in recent years, particularly since the outbreak of COVID-19, which has been promoted by cloud manufacturing and e-commerce, attracting a number of logistics and real estate giants, such as SF Express, JD Logistics, and Prologis, to enter this field. The general operation scheme is that merchants sign warehousing agreements with CWS providers and distribute inventory on cloud warehouses. When customer orders are placed, CWS providers are responsible for fulfilling them in the warehouse and performing the final deliveries to customers. In addition, CWS providers can reasonably allocate inventory to the warehouse nearest to the consumers in advance by predicting sales to shorten the delivery and lead times of order completion. As a result of this approach, more types of CWS products have been launched (e.g., "same day delivery" by SF Express and "211 limited delivery" by JD logistics) to ultimately optimize the order completion time.

Efficiency and accuracy are two important indicators to measure the quality of warehousing services in practice (Staudt et al., 2015; Yang et al., 2021a). To improve both indicators, information technology is widely adopted in CWSs to gather operational big data to improve the demand forecast and provide timely information to stakeholders (Baruffaldi et al., 2019). Moreover, intelligent warehousing facilitates the perfecting of warehousing infrastructure by collecting real-time operational data and performing intelligent automation (Zhang et al., 2021). CWS can respond to orders more quickly by integrating warehousing facilities with other related operational resources. Although the sound infrastructure and simple service pattern appear to make cloud warehousing operations not that difficult, the actual business itself has encountered several specific issues with the expanding service scope of CWSs.

The most troublesome issue is billing management for multiple types of merchants because the detailed warehousing requirements for order fulfillment may exhibit differences. These problems hinder the development of CWSs and affect the flexible management of CWS providers to merchants. According to our investigations of several CWS providers in the Pearl River Delta in China, the billing methods of the same provider significantly differ depending on its served merchants in terms of billing and content at the granular level. For example, Diethelm Keller Siber Hegner (DKSH), as a CWS provider, offers various billing options. One of the simplest methods only calculates a fixed rate of warehousing fees, order picking fees, and delivery fees inside Guangdong Province. Meanwhile, complex methods have been used in a fine-grained manner, billed by the number of actual warehousing activities carried out with a predetermined price for each type of task within a certain period, which is typically one month. This work observed a trend toward more fine-grained billing based on warehousing resource occupation per unit of time, similar to that in cloud computing. However, deficiencies have been gradually exposed with the rapid development of CWS.

The most serious deficiency is the widespread application of a fixed rate to charge warehousing activities. Although a fixed rate is easier to implement and simple for settlement, it neglects the actual market value of warehousing resources given the frequent fluctuation in CWS demand, particularly due to e-commerce promotions in China, such as Double-11 and Women's Day. Moreover, the use of a fixed rate has created greater barriers to the implementation of different CWSs. When the market is a seller's market, CWS providers prefer to perform warehousing activities that have larger profit margins to the detriment of fairness with respect to merchants. Although some merchants are willing to pay more money to obtain warehousing priority, an effective adjustment mechanism for the pricing of fragmented CWSs is lacking. In the post-COVID-19 era, the fixed-rate billing model cannot reflect the real-time value of the CWS market with the increase in the number of e-commerce orders and is not conducive to its long-term development. Hence, an efficient adjustment mechanism must be developed to obtain resilience in terms of price.

Floating billing methods have been explored by academia and industry to address this issue. Specific pricing strategies and mechanisms have been widely investigated for 3PL firms, which is highly relevant to us from the logistics resource perspective (Lukassen and Wallenburg, 2010; Ülkü and Bookbinder, 2012). The rapid development of the logistics industry means that logistics resources are no longer a bottleneck, but the logistics services for delivery tend to be mature with a standardized pricing system (Borgström et al., 2021). By contrast, CWS still exhibits a capacity constraint (Shaw et al., 2016). First, the storage space is difficult to extend because a warehouse is a type of fixed infrastructure. Second, operational resources, including humans and machines, are at the upper limit in terms of expansion. Accordingly, in the case of limited warehousing resources, the floating billing method can be conducive to a more reasonable allocation of resources. The CWS industry has tried some experimental practices to improve the efficiency of logistics and warehousing. For example, DKSH will charge merchants a fee higher than the fixed rate during peak hours but offers preferential discounts to attract other merchants for off-season periods. In addition, DKSH will attempt to separately bill the promotional period. Although these attempts have helped improve CWS resilience in terms of price, these floating mechanisms cannot reflect the true value of warehousing resources in a timely manner under the dynamic market demand for CWSs. Given that CWS providers are the beneficiaries, providing data on order-processing capabilities is impractical for them. Moreover, demand information is typically strictly protected and not allowed to be released as evidence to support such decisions. In light of these issues, the research objectives of this work are summarized as follows:

• How can a floating billing mechanism be reasonably designed to achieve resilience in CWS pricing considering the real-time market value of CWSs?

• How can a billing system be implemented to provide a creditable, transparent, and intelligent settlement infrastructure to apply the abovementioned mechanism for multiple stakeholders in CWS?

To achieve these objectives, this work proposes a blockchain-enabled floating billing management system (BCFBMS) that incorporates a one-sided Vickrey–Clarke–Groves (O-VCG) auction mechanism to facilitate the settlement of CWSs with multiple stakeholders. Driven by real-time service demand, a floating billing mechanism is designed to align the trading of CWSs with the market. To guarantee the truth of service demand, blockchain technology (BCT) is introduced to realize the full lifecycle supervision of the service trading process.

In this study, we focus on the resource allocation of CWS providers for warehousing order processing, which is important to realize the market value of CWSs and for the logistics industry. Despite the existence of the impossibility theorem (Myerson and Satterthwaite, 1983), four important properties can be realized in a one-sided auction (Kong et al., 2018; Chu et al., 2019): 1) allocation efficiency (AE), where social welfare can be maximized through design of the auction mechanism; 2) individual rationality (IR), where all agents who participate in the auction have nonnegative utility; 3) incentive compatibility (IC), where the bidder who participates in the auction must make a real bid to achieve the Bayesian–Nash equilibrium; and 4) budget balance (BB), where the auction has no deficit. We introduce the O-VCG auction mechanism for resource allocation with multiple types of storage orders to achieve these four important properties. Many studies (Xu and Huang, 2014; 2017; Xu et al., 2018; Zhang et al., 2019; Shao et al., 2020; Ning et al., 2021) have shown that the auction mechanism is more likely to provide higher benefits to third parties in the long run if the market efficiency is higher. Thus, this work develops a warehousing order resource allocation based on the O-VCG auction mechanism, which is of great significance to the logistics industry. The proposed O-VCG auction mechanism can effectively solve this problem because no mechanism can truly reflect the real-time value of the CWS market, which is extremely unfavorable to the long-term development of this market. Moreover, we introduce BCT and integrate the O-VCG auction mechanism and blockchain into the system to ensure the authenticity and tradability of the auction.

The main research contributions of this work are threefold. First, to the best of our knowledge, this research is the first to propose the O-VCG auction mechanism to realize the real-time market value of CWSs. This mechanism can effectively increase the income of CWS providers and the utility of merchants. Second, although the proposed O-VCG auction mechanism is useful for the CWS market, literature on the integration of this mechanism into the system to achieve credibility, transparency, and intelligence in transactions is yet to be published. Accordingly, we develop a BCFBMS framework for the CWS market for the first time. This framework integrates BCT and can ensure the authenticity and security of transactions. Third, we obtain key findings by analyzing the performance of the O-VCG auction mechanism and comparing it with that of the fixed-rate billing model. These findings provide rich insights for CWS providers and merchants and confirm the effectiveness and applicability of the proposed method.

The remainder of this paper is organized as follows. Section 2 reviews the relevant research on the dynamic pricing of 3PL, BCT, and auction mechanisms. Section 3 illustrates the conceptual framework of the BCFBMS. Section 4 specifies the auction mechanism for CWSs. Section 5 uses a case study to verify the rationality and effectiveness of the transaction mechanism proposed herein. Finally, Section 6 discusses the conclusions, research limitations, and directions for future work.

2 Literature review

This work investigates a BCFBMS for CWS. Hence, studies on (1) 3PL pricing, (2) BCT, and (3) auction mechanisms are closely related.

2.1 3PL pricing

Pricing is one of the key factors for 3PL success. Accordingly, determination of 3PL pricing has become the primary problem to be solved by 3PL providers. Selviaridis and Spring (2007) reviewed the literature related to 3PL and provided scholars and practitioners with a conceptual diagram of the existing 3PL research but did not provide in-depth insights into the operational practices of 3PL pricing. Lukassen and Wallenburg (2010) used the group relationship management framework to conduct a comprehensive review of the literature on logistics and industrial services pricing. They also reviewed the studies related to 3PL pricing, limited only to the pricing of long-term contracts between 3PL and customers. Ülkü and Bookbinder (2012) studied the influence of four different pricing schemes on 3PL providers. The results showed that charging based on the arrival time of the order may not be the optimal pricing scheme. The authors also performed a sensitivity analysis for the various parameter changes to demonstrate the effectiveness of the model. Given that 3PL pricing is an extremely difficult problem, Dimitris (2013) developed a comprehensive record system to identify and classify the key criteria of 3PL pricing methods to help 3PL service providers in determining pricing. Zhang et al. (2015) proposed a stochastic nonlinear dynamic pricing model to study the pricing problem of 3PL providers. The model considered the cost and transportation capacity of 3PL providers, the customer's delivery date, and other factors. A comparative analysis with static pricing showed that the proposed model was beneficial for 3PL providers and customers. The review articles by Barker et al. (2021), Hua et al. (2021), and Mahmoudi et al. (2021) did not involve 3PL pricing at all.

The core content of 3PL pricing is a resource allocation problem under capacity constraints and dynamic demand. Ren et al. (2020) applied the Seq2Seq (sequence to sequence architecture)-based CNN-LSTM (Convolutional Neural Networks - Long Short-Term Memory) method to model the system dynamics and dependencies among different demands of third-party freight forwarding logistics services to optimize logistics resource allocation but did not consider service pricing. Liu et al. (2014) studied the transportation tasks and resource scheduling problems of fourth-party logistics and constructed a multi-objective scheduling model to maximize the cost and time without considering the pricing problem of order processing. Rajesh et al. (2013) built models and algorithms to balance the distribution problem (i.e., distribute customers' products to different warehouses to improve storage and transportation efficiency). Chen et al. (2022) studied the joint inventory and online resource allocation, the core of which is the warehousing and transportation of logistics, without considering the pricing of logistics services. Unnu and Pazour (2022) constructed a multiphase mixed integer linear programming location model to quantitatively study distribution strategies in supply chain networks. Although our work and the abovementioned literature study the problem of resource allocation, our work also considers the price of resource allocation.

After reviewing the abovementioned literature, we find that many studies focus on cooperative operations with 3PL logistics providers even though 3PL pricing is important to its logistics providers, and only few studies investigate 3PL pricing issues. Accordingly, this work studies the pricing of CWS providers to fill this gap in the existing research. In addition, majority of the existing studies related to 3PL pricing consider only the factors related to logistics services (such as logistics costs, storage costs, and delivery dates), but few studies have examined market factors (such as off-season and peak season). Specifically, the existing research does not consider the real value of storage resources under the dynamic market demand for CWSs. Hence, an effective market pricing mechanism must be considered to obtain realistic results.

2.2 BCT

Since blockchain has the characteristics of being unforgeable, traceable throughout, open and transparent, and collectively maintained, it has been widely used in many fields, such as energy trading systems (Wang et al., 2019; Yang and Wang, 2021; Yang et al., 2021b), supply chain (Shemov et al., 2020), smart mobility data-markets (López and Farooq, 2020), port logistics capability (Wang et al., 2021), supply chain finance solution (Li et al., 2020b), intelligent manufacturing (Zhen et al., 2020), and medical systems (Gong and Zhao, 2020; Du et al., 2021; Połap et al., 2021). Considering the potential impact of BCT on the logistics and supply chain industries, Tönnissen and Teuteberg (2020) applied case analysis to develop a model for the relevant stakeholders in blockchain design to illustrate the potential disruptions that blockchain may bring to the industry. Dutta et al. (2020) formulated a possible future research agenda based on current development trends and challenges by reviewing 178 documents related to blockchain and the supply chain. Li et al. (2020c) proposed a blockchain-based logistics financial execution system to solve financial problems in the supply chain and provide a credible operating environment for 3PL firms and retailers. Wu et al. (2021) analyzed the optimal operational strategies of the blockchain traceability system led by the three different entities in a fresh supply chain composed of 3PL, suppliers, and retailers. The above research showed that the use of BCT was beneficial to the stakeholders in the supply chain. Liu et al. (2021) applied blockchain to the maritime supply chain, proposing a blockchain-based maritime supply chain system that contributed to the future maritime supply chain, because it has several characteristics, such as decentralization, nontamperability, and traceability. BCT can ensure the security, transparency, and visibility of the system. Hakak et al. (2020) applied this technology to smart cities and identified the characteristics of BCT.

Unlike the previous literature, we first study the application of blockchain in CWS and develop the BCFBMS, which uses a layered architecture based on the conceptual framework of cyberphysical systems. The integration of blockchain technology into the proposed O-VCG mechanism will realize the whole process management of CWS providers and merchants. First, this system ensures that the data of merchants and CWS providers are traceable, not easily tampered with, and clearly recorded. Second, the system automatically records winning merchants and bills to facilitate implementation. Failure to incorporate the blockchain technology into the proposed O-VCG mechanism can potentially affect merchants because CWS providers can tamper or misreport the available order-processing capability data. Meanwhile, the data information of CWS providers and merchants must be kept confidential, and the blockchain technology is advantageous for encryption privacy. Accordingly, the blockchain technology must be added to the proposed O-VCG mechanism. Similar to Li et al. (2020c), we study CWS providers, 3PL firms, and merchants. The difference is that our BCFBMS has more diversified functions and can achieve more refined management than those in previous works. In addition, our BCFBMS has a five-layer structure instead of four main layers.

2.3 Auction mechanism

The auction mechanism, as an effective pricing method, has been widely used in many fields (Huang and Xu, 2013; Basar and Cetin, 2017; Xiao and Xu, 2018; Shao et al., 2020; Liu et al., 2022; Cheng et al., 2023). An auction relies on the bids of participants to determine reasonable pricing to achieve effective resource allocation (McAfee and McMillan, 1987). In auction theory, auctions can be divided into one-sided and double auctions according to the number of participating parties (Dibaj et al., 2020). Xu and Huang (2014) developed an O-VCG combined auction mechanism for the distributed transportation procurement problem to minimize the total transportation cost and induce participants to bid to achieve IC. Tanaka and Murakami (2016) proposed a dynamic programming algorithm to be applied to cloud service selection and VCG payment calculation and then extended it. The results showed that the proposed method can effectively solve practical problems. Xu et al. (2018) proposed the O-VCG auction for the synchronization problem of urban logistics and realized the four above-mentioned properties. Kong et al. (2018) developed an effective auction mechanism design for shared parking spaces and resource allocation to maximize social welfare and applied the O-VCG auction mechanism to reallocate parking space resources. Zhang et al. (2019) proposed an auction mechanism with supply and demand as a new factor to maximize the social welfare of channel resource allocation and proved that real bidding was also the best strategy for secondary users. Liang et al. (2020) designed VCG and bilateral auctions to solve the problem of quantity discounts that have rarely been considered in purchase auctions, both of which can achieve IR, IC, BB, and asymptotical efficiency. Liu et al. (2022) applied the traditional VCG auction mechanism and combined it with baseline price control to promote passenger participation in carpooling, which can achieve IR, IC, price controllability, and reasonable detour discounts.

An examination of the literature shows that, to the best of our knowledge, no reports on the application of the O-VCG mechanism and blockchain in the CWS market have been published even though this auction mechanism has been widely used in many fields. Thus, this work attempts to couple the O-VCG mechanism with blockchain for the first time to effectively allocate logistics and warehousing resources. Moreover, previous CWS pricing focused on fixed rates, which may not effectively reflect the real-time value of the CWS market. Hence, we develop a CWS resource allocation method based on the coupling of blockchain and auction mechanisms to fill this gap in the existing research.

3 BCFBMS framework

The BCFBMS framework is designed (Fig. 1) to realize the full lifecycle management of billing in cloud warehousing, adopting a layered architecture based on the conceptual framework of a cyberphysical system. We illustrate the coupling level of the O-VCG auction mechanism and BCT in Fig. 1. The pre-auction, mid-auction, and late-auction of the O-VCG mechanism are supervised by BCT, which realizes the authenticity and traceability of the entire process and ensures transaction security. The responsibility of each layer is described below.

3.1 Physical layer

The physical layer works in the physical space to generalize all warehousing facilities that physically exist and are logically associated with final billing decision-making and supervision. This layer undertakes warehousing activities to fulfill CWS demands and generates real-time data through these activities. The infrastructure is integrated in an indirect manner through its dedicated control or management system because the focus of the BCFBMS is more to supervise the physical layer than to control and manage it.

3.2 Transfer layer

The transfer layer is responsible for promoting the establishment of the connection between the physical and the network layers, integrating three middleware systems and realizing a three-level conversion. The data interoperability middleware focuses on the data-level transformation in terms of data type, structure, format, and protocol to shield the data heterogeneity from multiple sources in physical layers. The object gateway middleware is responsible for establishing a uniform communication channel to address the object-level heterogeneities from

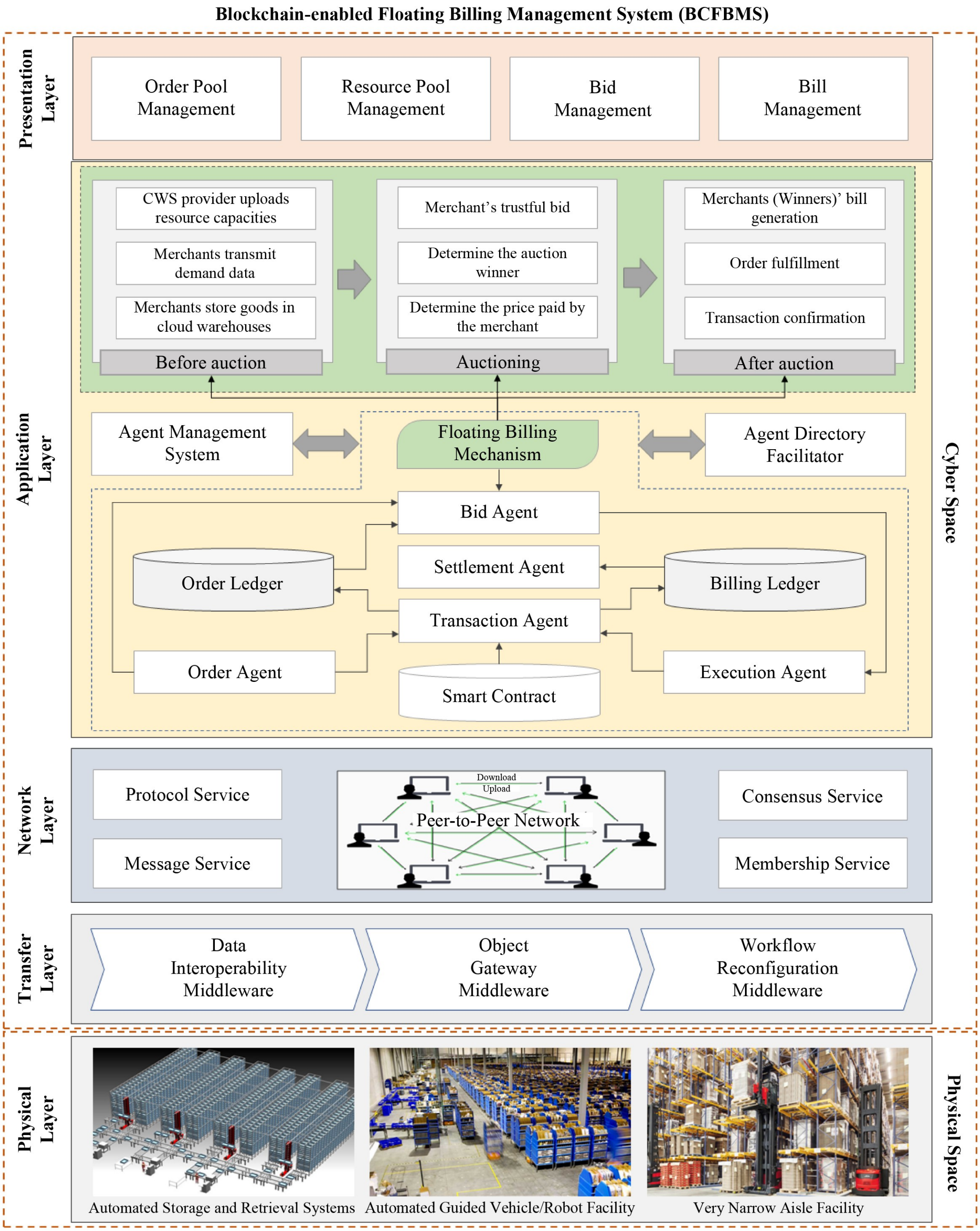

Fig. 1 BCFBMS framework.

the runtimes, dependencies, frameworks, and hardware architecture to ensure that the software entities, such as agents, digital twins, and smart objects from different systems, can seamlessly exchange information. The workflow reconfiguration middleware takes effect at the execution level to interpret, configure, and convert the working logic of objects to ensure that they can be ubiquitously organized and effectively collaborate to satisfy the diverse demand for CWSs.

3.3 Network layer

The network layer provides the necessary mechanisms to integrate the transformed items and construction of the communication links for the application layer. These mechanisms are categorized into four services. The protocol service consists of various types of established rules that dictate the basis on which to format, transmit, and receive data across the network, such as those of the

Transmission Control Protocol, User Datagram Protocol, and Hypertext Transfer Protocol. The message service realizes reliable message-based asynchronization communication in the form of queues among services, agents, and systems in the network. The consensus service adopts a specific consensus algorithm, such as proof of work, proof of stake, proof of authority, and practical Byzantine fault tolerance, to ensure that all nodes in the network are synchronized and consistent and guarantee that all transactions in each node are legitimate. The membership service is responsible for associating the intended network nodes with cryptographic identities to guarantee that they can be authorized and authenticated to enroll in a definite network. Based on these services, a peer-to-peer network is finally built and maintained in this layer to organize and associate all participants (e.g., users, facilities, and system objects), with a distributed and decentralized architecture.

3.4 Application layer

The application layer abstracts the business logic and formulates an agent-based blockchain system. This layer depends on the network layer to connect and communicate the system components, serving as the backend application for the presentation layer to actually handle the interactions. The application layer, which adheres to the Foundation for Intelligent Physical Agents framework, is composed of an agent management system, an agent directory facilitator, and a multiagent working system. The agent management system performs the lifecycle management of all types of agents in terms of agent instantiation, configuration, execution, and destruction. The agent directory facilitator maintains a directory of agents (i.e., it acts as a form of "Yellow Pages") to organize the registered services of agents and respond to service queries from agents. The multiagent working system contains five types of agents with their necessary dependencies based on the single responsibility principle. The working logic of this agent-based blockchain system is designed as follows: 1) An order agent receives demand data from external systems of merchants and converts them into a structural format. 2) After the conversion, a transaction agent is invoked by the order agent to place the received orders into an order ledger. A smart order contract is installed on this transaction agent to ensure that it can intelligently operate the order ledger. Meanwhile, a bid agent is also informed by the order agent with the need to make a bid decision based on the floating billing mechanism to obtain warehousing resources to execute orders. 3) If the bid is successfully made, then an execution agent will be assigned to supervise the order fulfillment process because it is directly associated with warehousing resources. 4) After the order is completed, this execution agent calls a transaction agent, who installs a smart billing contract to persist the order fulfillment data to the billing ledger. 5) Finally, a settlement agent is invoked through the presentation layer to perform a billing settlement for different customers based on the billing ledger.

The merchant's products need to be stored in the CWS provider's warehouse in advance regardless of the billing method. After all merchants submit their order-processing demand data, these orders are placed in the order pool. Then, the system will perform allocations according to the CWS provider's order-processing capability and the merchant's demands. When the merchant's order is traded, the price will be recorded. Finally, a unified settlement will be carried out.

3.5 Presentation layer

The presentation layer focuses on the graphical interactions that the users require for the basic management of the whole system. Four functional management modules are designed for the presentation layer. Order management is used to extract and visualize the orders from the order ledger so that users can query and revise orders on demand. Resource management maintains the information and states of all warehousing resources in the form of a resource explorer. Bid management defines and configures the bid parameters for end users and organizes the global bid executions for BCFBMS administrators. Bill management provides detailed accounts to make final settlements between CWS providers and merchants.

4 Floating billing mechanism design

The goal of this section is to design a real-time market value floating billing mechanism for CWSs to effectively allocate warehousing resources.

4.1 Problem description

In the post-COVID-19 era, an increasing number of business activities have been realized via the Internet. This work considers an agent management system platform with a CWS provider, multiple merchants, and an auctioneer. Merchants store goods in cloud warehouses and can access the platform by Internet applications or communication technologies to submit the number of orders that need to be processed. Meanwhile, the CWS provider centrally manages the goods and completes order sorting and delivery according to the merchant's order information. During peak seasons, each merchant wants its orders to be processed first to satisfy customer needs. However, the limited warehousing and sorting capacity of CWSs does not seem to support this idea. As previously mentioned, the current CWS pricing mechanism cannot truly reflect market value, particularly during peak seasons. To this end, we use the auction mechanism to reflect the real-time market value of CWSs.

To facilitate such analysis, we divide the orders that correspond to goods into different categories according to the size of the goods (i.e., goods order sets). Let H represent the goods order set of the CWS provider and I be the set of merchants. We denote the merchant as "he". The CWS providers and merchants can be called "agents". Moreover, the term "bid" is used to refer to the merchant's declaration. A set of orders and a bidding price constitute a bid.

In a logistics market with one CWS provider and n merchants, the CWS provider wants to sell a set of orders (or a single order), and each merchant i ($i \in I$) needs to purchase a set of order sets (or a single order). We assume that the demand and supply are common knowledge. Let b_i^h be the reservation value of merchant i for unit goods order set h, which is private knowledge for each merchant. The reservation value herein refers to the maximum value that may be lost by the merchant because he did not win the bid. Each merchant submits a unit sealed bid $\hat{b}_i^h$ for goods order set h. If merchant i is truthful in terms of bidding, then $b_i^h = \hat{b}_i^h$. If merchant i wins the bid, then he pays payment p_i^h. Thus, merchant i's net utility is $u_i = \sum_{h=1}^{H}(b_i^h - p_i^h)$. In addition, we assume that CWS providers and merchants are selfish; CWS providers try to maximize their revenue, and merchants expect to maximize their own utility. We also assume that all merchants have quasi-linear utility (i.e., if no trade takes place between the CWS provider and the merchant, then the merchant's utility is zero, and the CWS provider's revenue is also zero; otherwise, the merchant's utility is the difference between his reservation value and the actual amount paid).

This study aims to develop the O-VCG combinatorial auction for a logistics market with one CWS provider and n merchants to maximize revenue. Let X^h represent the quantity of goods order set h that can be processed by the CWS provider. All merchants submit atomic bids (all or nothing). Specifically, if merchant i participates in the final transaction, then he receives Y_i^h orders for goods order set h; otherwise, he does not receive any orders. In addition, we assume that the total order demand still exceeds the supply of the CWS provider if any one of the merchants is excluded. When orders are processed during peak seasons, this assumption is consistent with reality. The auctioneer (CWS provider) calculates the current optimal output by maximizing revenue. The proposed O-VCG auction can well implement IC, AE, IR, and BB.

4.2 O-VCG auction

We introduce the model, mechanism, and properties of the O-VCG auction to demonstrate that it can effectively realize IC, AE, IR, and BB.

4.2.1 Model

Recall that X^h and Y_i^h are known. The CWS provider wants to sell X^h unit orders for goods order set h, and merchant i submits bid $\hat{b}_i^h$ to buy Y_i^h unit order for goods order set h. Thus, the total bid maximization problem can be expressed as follows:

$$\mathbf{P}: \ \max \textstyle\sum_{i=1}^{n}\sum_{h=1}^{H}\hat{b}_i^h z_i^h \tag{1}$$

$$s.t. \quad \textstyle\sum_{i=1}^{n} Y_i^h z_i^h \leqslant X^h, \ \forall h \in H, \tag{2}$$

$$z_i^h \in \{0, 1\}, \ \forall i \in I, \ \forall h \in H, \tag{3}$$

$$Y_i^h \geqslant 0, \ \forall i \in I, \ \forall h \in H, \tag{4}$$

where the binary variable z_i^h indicates whether merchant i has made a transaction in the auction of goods order set h, objective function (1) represents a set of effective allocations when the total accepted bid is maximized, and constraint Eq. (2) represents that the number of orders obtained by the merchant cannot exceed the number that can be provided by the CWS provider.

4.2.2 Mechanism

To induce all merchants to truthfully submit their sealed bids, we design an efficient O-VCG auction mechanism for Model P. In the proposed O-VCG auction, we designed a second-price sealed auction to ensure that all merchants authentically bid.

Let β^h be the maximum value of function $\sum_{i=1}^{n}\hat{b}_i^h z_i^h$ and β_{-i}^h be the maximum value of function $\sum_{i=1}^{n}\hat{b}_i^h z_i^h$ if merchant i is removed from this auction. Thus, if merchant i wins the bid for goods order set h, then he pays the following to the CWS provider:

$$p_i^h = \beta_{-i}^h - \left(\beta^h - \hat{b}_i^h z_i^h\right). \tag{5}$$

Equation (5) represents the second-price sealed auction. $\beta_{-i}^h - \beta^h$ is the bonus payment made to merchant i that represents his contribution to the entire system by participating in the auction. Equation (5) also implies that merchant i who obtains order set h will pay the CWS provider the highest bid after excluding all winning merchants. We will illustrate the specific calculation of Eq. (5) with an example in Section 4.3 to further illustrate the second-price sealed auction. If merchant i does not participate in the auction for goods order set h (that is, $z_i^h = 0$), then $p_i^h = 0$. The total revenue (TR) of the CWS provider is given as follows:

$$\begin{aligned} TR &= \textstyle\sum_{i=1}^{n}\sum_{h=1}^{H} p_i^h = \sum_{i=1}^{n}\sum_{h=1}^{H}\left[\beta_{-i}^h - \left(\beta^h - \hat{b}_i^h z_i^h\right)\right] \\ &= \textstyle\sum_{i=1}^{n}\sum_{h=1}^{H}\left[\beta_{-i}^h - (n-1)\beta^h\right]. \end{aligned} \tag{6}$$

Let RV denote the reservation value of the CWS provider for all order resources. This reservation value is the maximum value obtained through the ability of the CWS provider to process orders when auctions are not used. If $RV < TR$, then the transaction is successful; otherwise, the transaction fails. No transaction cost exists between the merchant and the CWS provider. Thus, the auctioneer's revenue in this case is zero.

Considering the above analysis, our O-VCG auction mechanism procedure is given as follows:

• Collect the data of X^h and Y_i^h.

• Collect each merchant i's unit sealed bid $\hat{b}_i^h$ for goods order set h.

• Calculate price p_i^h that merchant i needs to pay for goods order set h using Eqs. (1)–(5).

• Calculate the TR of the CWS provider by using Eq. (6).

• Determine whether the transaction is successful. If $RV < TR$, then collect price p_i^h paid by the winner to the CWS provider; otherwise, the transaction fails.

4.2.3 Properties

Theorem 1. Truthful bidding is an effective method to maximize the utility/profit of each merchant i.

Xu and Huang (2014) suggested that the O-VCG auction mechanism is IC. If merchant i is truthful bidding, then $b_i^h = \hat{b}_i^h$. Meanwhile, if merchant i does not truthfully bid, then $b_i^h < \hat{b}_i^h$, and other merchants truthfully bid.

If merchant i truthfully reports the bid, then his utility is:

$$b_i^h - p_i^h = b_i^h - \left[\beta_{-i}^h - \left(\beta^h - \hat{b}_i^h z_i^h\right)\right] = \beta^h - \beta_{-i}^h. \tag{7}$$

The reservation value of merchant i is equal to the bid because he tells the truth. Thus, the result of Eq. (7) is $\beta^h - \beta_{-i}^h$.

If merchant i does not truthfully report the bid, then his utility is:

$$b_i^h - p_i^h = b_i^h - \left[\beta_{-i}^h - \left(\beta^h - \hat{b}_i^h z_i^h\right)\right] = \left(\beta^h - \beta_{-i}^h\right) + b_i^h - \hat{b}_i^h z_i^h. \tag{8}$$

The goal of merchant i is to obtain greater utility if he does not truthfully report the bid:

$$\left(\beta^h - \beta_{-i}^h\right) + b_i^h - \hat{b}_i^h z_i^h > \beta^h - \beta_{-i}^h,$$

$$b_i^h - \hat{b}_i^h z_i^h > 0,$$

$$b_i^h > \hat{b}_i^h z_i^h = \hat{b}_i^h, \tag{9}$$

which contradicts the fact that merchant i does not truthfully bid (i.e., $b_i^h < \hat{b}_i^h$). Only truthful bidding is the best strategy for merchant i regardless of the bidding strategy of the other opponents. Thus, all merchants should truthfully bid to obtain the maximum utility.

Corollary 1. The O-VCG auction mechanism herein is BB, AE, and IR.

In our proposed O-VCG auction model, only the CWS provider can receive Vickrey payments from all merchants. If $RV < TR$, then the auctioneer receives the merchant's full payment to the CWS provider, which implies that the sum of all merchants' expenses is equal to the total income of the CWS provider. If $RV \geqslant TR$, then no transaction takes place. Thus, the proposed O-VCG auction in this paper can achieve BB.

The O-VCG auction model can achieve the greatest revenue and utility for the CWS provider and merchant, respectively, based on the merchant's weak truth telling. Hence, the O-VCG auction is AE. In addition, we can easily prove that the O-VCG auction is IR. The auction is valid if and only if $RV < TR$ occurs, which ensures the IR of the CWS provider. The utility of merchant i is $u_i = \sum_{h=1}^{H}(b_i^h - p_i^h)$. Therefore, we can obtain that $u_i = \sum_{h=1}^{H}(b_i^h - p_i^h) = \sum_{h=1}^{H}(\beta^h - \beta_{-i}^h)$ by Eq. (7), and $\beta^h - \beta_{-i}^h \geqslant 0$ holds, even if merchant i is removed. Thus, the O-VCG auction is IR for all merchants.

4.3 Example

To further understand the proposed O-VCG auction mechanism, we use a simple example. We assume that the CWS provider offers warehousing services for three types of goods to five merchants, and each merchant has at least one type of goods. The order-processing capacity of CWS providers cannot satisfy the requirements of all merchants. Table 1 shows examples of the O-VCG auction mechanism in three scenarios. In Scenario 1, all merchants have one unit of order-processing requirements, while CWS providers can provide only three units of order-processing services. According to the auction mechanism procedure, merchants 1, 2, and 3 are winners, and the O-VCG price paid is six. In Scenario 2, merchant 5 has no demand for goods order set 2, so he does not bid. Merchants 3 and 4 bid a price of seven for each unit to become the winner. In Scenario 3, only merchant 1 becomes a loser, and the remaining merchants receive unit order-processing service. Here, we briefly explain the procedure to calculate p_i^h. For example, in Scenario 1, merchants 1, 2, and 3 win, so $\beta^1 = 9\times1 + 10\times1 + 8\times1 = 27$. If merchant 1 is removed, then merchants 2, 3, and 4 will win, so $\beta_{-1}^1 = 10\times1 + 8\times1 + 6\times1 = 24$. Thus, $p_1^1 = \beta_{-1}^1 - \left(\beta^1 - \hat{b}_1^1 z_1^1\right) = 24 - (27 - 9\times1) = 6$.

5 Case study

We use a practical case to illustrate the rationality and effectiveness of the proposed O-VCG auction mechanism.

Table 1 Examples of the O-VCG auction mechanism

Scenarios	(h, X^h)	i	Y_i^h	$\hat{b}_i^h$ (unit price)	Winner	β_{-i}^h	β^h	$\hat{b}_i^h z_i^h$	p_i^h	u_i
Scenario 1	(1, 3)	1	1	9	√	24	27	9	6	3
		2	1	10	√	23	27	10	6	4
		3	1	8	√	25	27	8	6	2
		4	1	6						
		5	1	5						
Scenario 2	(2, 2)	1	1	7						
		2	1	6						
		3	1	10	√	15	18	10	7	3
		4	1	8	√	17	18	8	7	1
		5	0	0						
Scenario 3	(3, 4)	1	1	16						
		2	1	24	√	75	83	24	16	8
		3	1	19	√	80	83	19	16	3
		4	1	18	√	81	83	18	16	2
		5	1	22	√	77	83	22	16	6

5.1 Background

With the rapid development of e-commerce, companies with limited warehousing resources cannot satisfy customer needs, particularly during the peak season for order processing. The existing CWS billing method and CWS management method exhibit drawbacks during periods of high order demand. Although some CWS providers are also trying to change the current billing model (e.g., DKSH provides segmented billing and off-season discounts), they and researchers must expend more effort to find a feasible solution. In response to the urgent need for CWS providers to have a set of charging models that can reflect the current CWS market value and to ensure the execution of transactions, we investigate a number of CWS suppliers in the Pearl River Delta region of China. We attempt to develop an effective management system and apply the O-VCG auction mechanism to reflect the real-time value of CWSs during peak seasons.

In our case study, we consider a CWS provider that can provide multiple types of items and use the O-VCG mechanism to allocate this type of CWS. In the proposed BCFBMS, the CWS provider acts as an auctioneer through a blockchain-based platform system, and many merchants compete for order services of multiple types of goods provided by the CWS provider. Once the auction starts, the merchants submit bids to the platform according to the announced auction mechanism. After the auction ends, the platform empties the CWS market according to the announced O-VCG auction mechanism.

5.2 System implementation

The prototype BCFBMS is developed and implemented for verification and evaluation. The physical layer of the system is established based on our past studies (Kong et al., 2020) using a mobile picking-by-sorting system, as illustrated in Fig. 2. The key components in the transfer layer depend on the middleware of the data-source interoperability service (Pang et al., 2015), mobile gateway operation system (Li et al., 2019b), and workflow operating system (Li et al., 2019a). The network layer is implemented by using Hyperledger Fabric V2.1, which is an open-source consortium blockchain framework, due to the cooperative relationship between CWS providers and merchants. Raft is chosen for the consensus mechanism considering its high efficiency, robustness and adaptability, particularly in large-scale blockchain networks (Alexandridis et al., 2021). CouchDB is adopted because the commitment object is structured in the form of JavaScript Object Notation. The application layer is developed based on Spring Cloud, which is a mainstream technical framework to build cloud-based applications. The basic development environment is established on JDK8, Lombok, IDEA, and Gradle. Netflix-eureka is selected for service registration and discovery because of its high-availability feature. OpenFeign is enabled for interservice invocation because it can dramatically simplify system aspects, such as replaying requests, and enable easy unit testing, particularly when multiple agents are interacting. Netflix-zuul is integrated as the web gateway because it has good scalability and high availability to suit different network scales. RabbitMQ is used as the advanced message queuing protocol for message transportation because all agents follow an asynchronous communication scheme. The development of the presentation layer is based on Vue, ElementUI, and Apache Echarts, which are popular open-source development frameworks. The key user interfaces for the four components are shown in Fig. 3. Figure 3(a) shows

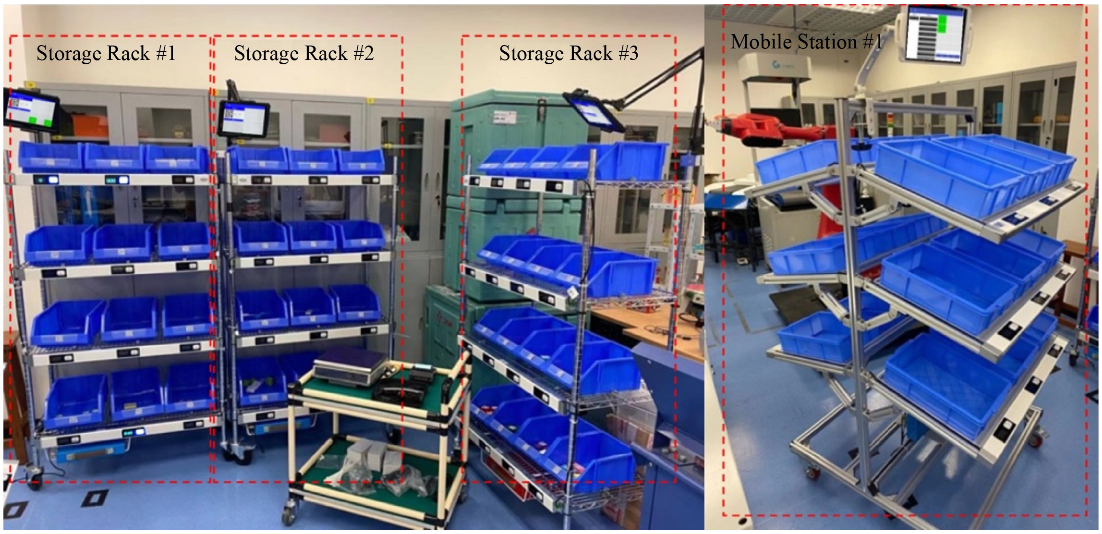

Fig. 2 Logistics infrastructure for the physical layer.

the order pool to cache all received orders with specific order attributes. Figure 3(b) presents the resource execution dashboard to provide credible visibility and traceability, as guaranteed by BCT. Figure 3(c) shows the interfaces of the auction in progress to visualize all auctions from the CWS view. Figure 3(d) presents a billing statistical summary of current CWS operations for the current day and the past 7 days.

5.3 Experimental results

Based on the data provided by the CWS provider, we categorize the order set types that can be processed into 10 types; that is, $H = 10$, as shown in Table 2. Forty merchants participate in bidding, and their demand for each goods order set is shown in Table 3. In addition, we assume that $\hat{b}_i^h$ is a random number in the interval based on the merchant's order data, as shown in Table 4.

We conduct simulations based on the data obtained from the investigation to illustrate the performance of the proposed method. The calculation experiment is performed on an ASUS VivoBook S14 (Windows 10 Enterprise) with Intel Core i5 and 4 GB of RAM. We use MATLAB 2015b to solve the proposed model. The maximum value of Model P is 2889.42, and the O-VCG payment received by the CWS provider is 2689.77. We define the ratio of O-VCG payments received by the CWS provider to the maximum value of Model P as the satisfaction degree of the CWS provider. A larger ratio corresponds to a higher degree of satisfaction of the CWS provider with the market mechanism. Thus, we obtain a satisfaction degree of the CWS provider of 93.09%.

5.4 Discussion

This section aims to analyze and discuss the performance of the O-VCG mechanism and compare the proposed auction mechanism with the original fixed-rate charging model to verify the effectiveness of the proposed method.

5.4.1 Performance of the proposed mechanism

The performance of the proposed O-VCG mechanism is examined from two perspectives: 1) Companies increase their order-processing capabilities for each type of good during peak seasons. We increase the order-processing capacity for each type of good by two, four, and six units based on the original order-processing capabilities. 2) The number of merchants varies from 40 to 100 at intervals of 20. Each goods order-processing demand of each merchant is randomly generated by the computer as 0 or 1, where 0 means that there is no demand, and 1 means that there is demand for one unit. In our experimental verification, we use the CWS provider's order-processing type, processing capacity, and merchants with order-processing requirements to measure market size. In the CWS market, the market size has grown with the number of merchants that offer order-processing services. Table 5 shows the performance of the O-VCG mechanism.

Several key findings are summarized. First, when the CWS provider's order-processing capacity remains unchanged, its degree of satisfaction increases with an increasing number of merchants. The number of merchants that can win the auction is also fixed because the number of CWS provider orders processed remains unchanged. However, the total maximum social welfare increases when the number of merchants increases and social welfare loss decreases. Accordingly, the degree of satisfaction of the CWS provider increases. For example, in Scenario 1, when the number of merchants increases from 40 to 100, the degree of satisfaction of the CWS provider increases from 93.09% to 96.99%. This important

(a) Order management (b) Resource management

(c) Auction management (d) Bill management

Fig. 3 Key user interfaces for the presentation layer.

Table 2 Goods order set of the CWS provider

X^h	X^1	X^2	X^3	X^4	X^5	X^6	X^7	X^8	X^9	X^{10}
Data	8	15	12	7	13	9	6	8	11	5

finding shows that the performance of the O-VCG mechanism is improved when the number of demanders in the CWS market increases.

Second, our O-VCG auction mechanism is applicable regardless of market size. In Scenario 2, the degree of satisfaction of the CWS provider increases with the expansion of the merchant scale. Moreover, the degree of satisfaction of the CWS provider reaches 91.69% under a market size of $i = 40$, which demonstrates the effectiveness and applicability of the proposed auction mechanism.

Third, when the number of merchants remains unchanged, the degree of satisfaction decreases when the CWS provider's order-processing capacity increases. For example, the degrees of satisfaction of the CWS provider in Scenarios 1, 2, 3, and 4 are 95.31%, 94.92%, 94.15%, and 92.25%, respectively, when the number of merchants is set to 60. A possible reason is that more merchants become winners, and fewer merchants are eliminated when the CWS provider's order-processing capacity increases, which decreases the degree of satisfaction of the CWS provider. Hence, CWS providers should consider controlling their order-processing capabilities when the demand is strong to achieve higher social welfare and satisfaction. However, this mechanism may hinder the interests of merchants and even prevent more merchants from participating in the trade.

Table 3 Merchants’ demand for each goods order set

Y_i^h	$h=1$	$h=2$	$h=3$	$h=4$	$h=5$	$h=6$	$h=7$	$h=8$	$h=9$	$h=10$
$i=1$	1	0	1	1	1	1	1	1	1	0
$i=2$	0	1	0	1	1	1	1	0	0	0
$i=3$	1	1	1	0	1	1	0	0	0	1
$i=4$	0	1	1	1	0	1	0	1	1	1
$i=5$	0	1	1	0	0	0	0	1	1	0
$i=6$	1	0	0	1	1	1	0	1	1	0
$i=7$	1	1	1	1	0	1	1	0	0	0
$i=8$	0	0	1	1	1	0	1	1	0	1
$i=9$	1	1	0	1	1	1	0	0	0	1
$i=10$	0	0	1	0	1	0	1	1	0	0
$i=11$	1	1	0	0	0	1	0	0	0	0
$i=12$	1	1	1	0	1	1	1	0	1	0
$i=13$	1	1	1	0	1	0	0	1	0	0
$i=14$	1	0	0	1	0	1	1	1	1	0
$i=15$	1	1	1	0	0	0	0	0	1	1
$i=16$	0	0	1	0	1	1	1	0	0	1
$i=17$	1	1	0	0	0	0	0	0	1	0
$i=18$	0	0	1	0	1	0	1	1	1	1
$i=19$	0	1	0	1	0	1	1	0	0	0
$i=20$	0	1	0	0	0	0	1	0	1	0
$i=21$	0	0	1	0	0	1	0	0	0	0
$i=22$	1	0	1	0	0	0	0	0	1	0
$i=23$	1	0	0	0	1	0	0	1	1	0
$i=24$	0	1	0	0	1	1	0	1	1	0
$i=25$	0	0	0	0	0	1	1	0	0	1
$i=26$	1	0	0	0	1	0	0	1	1	1
$i=27$	1	1	1	0	1	0	0	1	0	0
$i=28$	0	1	0	1	0	1	0	0	1	0
$i=29$	1	0	1	0	1	1	0	1	0	1
$i=30$	1	1	1	1	1	0	1	0	0	0
$i=31$	0	1	1	1	0	1	1	1	0	1
$i=32$	1	0	1	0	0	0	1	0	0	0
$i=33$	1	1	1	0	0	0	1	1	0	0
$i=34$	1	1	1	0	1	0	0	0	0	1
$i=35$	0	1	0	1	1	1	1	1	1	0
$i=36$	1	1	1	1	1	0	1	0	1	1
$i=37$	1	1	1	1	1	0	1	1	0	0
$i=38$	1	0	1	0	0	0	0	1	1	1
$i=39$	0	1	0	0	1	1	1	1	1	1
$i=40$	0	0	1	1	1	0	0	1	1	1

5.4.2 Effect of the changes in number of goods order sets on the results

How can CWS providers adjust their strategies to improve the overall social welfare during the peak season when existing automated warehousing cannot easily increase the order-processing capacity? Here, we discussed how to achieve higher social welfare by changing

Table 4 Interval values for the merchant's goods order set bid

$\hat{b}_i^h$	$\hat{b}_i^1$	$\hat{b}_i^2$	$\hat{b}_i^3$	$\hat{b}_i^4$	$\hat{b}_i^5$	$\hat{b}_i^6$	$\hat{b}_i^7$	$\hat{b}_i^8$	$\hat{b}_i^9$	$\hat{b}_i^{10}$
Data	[40, 50]	[15, 20]	[40, 50]	[25, 35]	[10, 20]	[16, 23]	[32, 40]	[28, 35]	[20, 28]	[42, 50]

Table 5 Performance of the O-VCG mechanism

Scenarios	CWS provider order-processing capabilities	Number of merchants	Maximum value of Model P	CWS's revenue	Satisfaction degree of the CWS provider
Scenario 1	Initial order-processing capacity of each goods type (Table 2)	$i = 40$	2889.42	2689.77	93.09%
		$i = 60$	2929.08	2791.76	95.31%
		$i = 80$	3004.36	2889.01	96.16%
		$i = 100$	3004.66	2914.31	96.99%
Scenario 2	Initial order-processing capacity of each goods type increased by two	$i = 40$	3509.08	3217.47	91.69%
		$i = 60$	3574.03	3392.39	94.92%
		$i = 80$	3665.07	3508.26	95.72%
		$i = 100$	3670.04	3557.46	96.93%
Scenario 3	Initial order-processing capacity of each goods type increased by four	$i = 40$	4110.25	3730.21	90.75%
		$i = 60$	4208.97	3962.87	94.15%
		$i = 80$	4317.82	4107.47	95.13%
		$i = 100$	4330.51	4183.81	96.61%
Scenario 4	Initial order-processing capacity of each goods type increased by six	$i = 40$	4697.55	4233.59	90.12%
		$i = 60$	4832.59	4457.86	92.25%
		$i = 80$	4962.63	4704.85	94.81%
		$i = 100$	4985.52	4793.38	96.15%

the quantity allocation for different goods order sets. In Scenario A, we reduce the processing capacity of three units of the order set with the lowest value (X^5) and assign it to the order set of goods with the highest value (X^{10}). In Scenario B, we reduce the processing capacity of three units of the order set with the highest value (X^{10}) and assign it to the set of goods orders with the lowest value (X^5), as shown in Table 6. Table 7 shows the results under different scenarios.

An examination of the comparison results in Table 7 shows that more benefits can be obtained by optimizing the order quantity allocation when the order-processing capacity of the CWS provider cannot be expanded. Specifically, CWS providers allocate more resources for processing orders to higher-value order sets during peak seasons. This finding is consistent with the actual situation. In practice, companies often allocate resources to higher-value commodities to pursue greater benefits.

5.4.3 Comparative analysis

To illustrate the effectiveness of the proposed auction mechanism, we compare it with that of the fixed-rate billing model. In practice, many 3PL companies settle the merchant's order-processing services at a fixed rate. 3PL companies process orders based on the order submitted by the merchant due to limited storage order-processing capabilities. When the order-processing capacity of 3PL companies reaches the maximum, their sales during peak seasons are unchanged unless they extend their staff's working hours or improve their automated sorting capabilities. According to the 3PL historical data, we take an average fixed rate of 25.8. The comparison results of the two different charging mechanisms are shown in Table 8.

The following key findings can be obtained by comparison with the fixed-rate billing model. First, the proposed O-VCG auction mechanism can obtain greater social welfare than the fixed-rate billing model. Specifically, the proposed method can realize the real-time value of the order-processing services provided by CWS providers. Second, although the proposed auction model can achieve greater social welfare when the number of merchants increases, the social welfare obtained by the fixed-rate billing model remains unchanged, regardless of whether the number of merchants increases. Accordingly, O-VCG auctions are more advantageous than fixed-rate auctions when the number of merchants increases. Third, the gap between the O-VCG mechanism and the fixed-rate billing model gradually narrows when CWS providers improve their order-processing capabilities. For example, when $i = 40$, under total order-processing capacities of 94, 114, 134, and 154, the growth rates are 10.91%, 9.39%, 7.90%, and 6.55%, respectively, which may be because the O-VCG mechanism unit order fee decreases with increase in the order-processing capacity of the CWS provider.

Table 6 Quantity allocation for different goods order sets

X^h	X^1	X^2	X^3	X^4	X^5	X^6	X^7	X^8	X^9	X^{10}
Original	8	15	12	7	13	9	6	8	11	5
Scenario A	8	15	12	7	10	9	6	8	11	8
Scenario B	8	15	12	7	16	9	6	8	11	2

Table 7 Impact of different goods order quantity allocations on the results

Scenarios	Number of merchants	Maximum value of Model P	CWS's revenue	Degree of satisfaction of the CWS provider
Original	$i = 40$	2889.42	2689.77	93.09%
	$i = 60$	2929.08	2791.76	95.31%
	$i = 80$	3004.36	2889.01	96.16%
	$i = 100$	3004.66	2914.31	96.99%
Scenario A	$i = 40$	2985.06	2784.32	93.28%
	$i = 60$	3030.30	2899.36	95.68%
	$i = 80$	3097.89	2987.34	96.43%
	$i = 100$	3102.12	3010.96	97.06%
Scenario B	$i = 40$	2784.07	2581.69	92.73%
	$i = 60$	2823.84	2683.22	95.02%
	$i = 80$	2906.57	2787.36	95.90%
	$i = 100$	2911.59	2814.85	96.68%

Table 8 Comparison of the fixed rate and auction mechanism results

Cases	CWS provider order-processing capabilities	Number of merchants	CWS's revenue under the proposed mechanism	CWS's revenue at a fixed rate	Growth rate
Case 1	94	$i = 40$	2689.77	2425.2	10.91%
		$i = 60$	2791.76		15.11%
		$i = 80$	2889.01		19.12%
		$i = 100$	2914.31		20.17%
Case 2	114	$i = 40$	3217.47	2941.2	9.39%
		$i = 60$	3392.39		15.34%
		$i = 80$	3508.26		19.28%
		$i = 100$	3557.46		20.95%
Case 3	134	$i = 40$	3730.21	3457.2	7.90%
		$i = 60$	3962.87		14.63%
		$i = 80$	4107.47		18.81%
		$i = 100$	4183.81		21.02%
Case 4	154	$i = 40$	4233.59	3973.2	6.55%
		$i = 60$	4457.86		12.20%
		$i = 80$	4704.85		18.41%
		$i = 100$	4793.38		20.64%

5.4.4 Advantages of the developed BCFBMS

On the basis of the results of the above analysis and discussion, the proposed system based on O-VCG auction and blockchain coupling can reflect the real-time market value of CWSs. To this end, the advantages of the proposed BCFBMS are summarized as follows.

First, blockchain is a shared database, and the data or information stored in it is unforgeable, traceable throughout, open, transparent, and collectively maintained. We couple blockchain with the O-VCG auction to achieve the goals of safety, realness, and immutability. Thus, the developed BCFBMS can ensure the authenticity and security of the information on both sides of the transaction and supervise the entire transaction process.

Second, the results of the comparative study prove that our proposed O-VCG auction mechanism is more advantageous than the traditional fixed-rate billing model. Improvement of the overall efficiency of the CWS market is based on a reasonable market adjustment mechanism and resilience management of the supply chain, and the past CWS market billing model restricts its development. The O-VCG mechanism can effectively realize the resource allocation of the CWS market during peak seasons, which reflects the real-time value of the CWS market.

5.5 Managerial implications

This work provides new insights for CWS providers and merchants. Moreover, we can provide relevant stakeholders with new managerial implications based on the key findings.

First, in terms of CWS pricing in the post-COVID-19 era, the proposed BCFBMS framework can help realize the market value of CWS providers. The system supported by BCT can ensure the authenticity and security of information and supervise the transaction process. Thus, the BCFBMS based on BCT can provide better services for both transaction parties to realize CWS resilience management.

Second, the O-VCG auction mechanism can achieve more social welfare for the CWS market. The degree of satisfaction of the CWS provider can exceed 96%, indicating that this resilience mechanism between CWS providers and merchants can achieve more social net profits in the CWS market. Under the demand of the CWS real-time service market, the proposed auction mechanism can promote the development of the CWS market and motivate the CWS to integrate more resources to achieve the resilience of the supply chain.

Third, the proposed O-VCG auction mechanism is suitable for scenarios where demand exceeds supply. The revenue of CWS providers and the utility of a small number of winners significantly increase when the demand increases. The demand in the CWS unilateral auction market far exceeds supply and can effectively increase the income of the CWS provider. However, this situation may limit the number of participant transactions due to their inability to maximize their own utility. Therefore, CWS providers need to provide a reasonable supply based on the number of participants to maximize benefits.

6 Conclusions

This work discussed how to realize the value of real-time services in the CWS market for post-COVID-19 CWS management. To solve this problem, we aimed to build a BCFBMS framework and integrate the O-VCG auction mechanism into the system to maximize the benefits of CWS providers. In addition, we obtained useful key findings that confirm the validity and applicability of the proposed model and could be applied to the CWS market to provide new insights, which contribute to CWS resilience management, by analyzing the O-VCG auction mechanism and discussing the results.

The importance of our work is threefold. First, since the outbreak of COVID-19, the development of techniques for effective CWS management has become vital for achieving supply chain resilience with the surge in e-commerce orders. This work considers the real-time market value of CWSs and rationally designs a floating billing mechanism. Although the traditional fixed-rate billing model is easy to implement and simple to operate, it creates obstacles to the implementation of the differentiated CWS market and is not conducive to maximizing the benefits of CWS providers. Therefore, we introduce the O-VCG auction mechanism to solve the shortcomings of the fixed-rate billing model. This work is the first to explore the auction mechanisms proposed for the CWS market. In comparison with the traditional fixed-rate billing model, the proposed framework and method have the following advantages: 1) they can improve the revenue of CWS providers and the utility of merchants; 2) they can realize fair competition and transactions among various merchants; and 3) when the number of merchants increases, the proposed mechanism AE increases. Second, although the proposed O-VCG auction mechanism can effectively realize the real-time market value of CWSs, if an effective billing system cannot be developed to apply this mechanism, then our work becomes meaningless. In CWS transactions, merchants and CWS providers pay attention to the authenticity, transparency, and intelligence of the transaction. Accordingly, we build the BCFBMS and adopt a hierarchical architecture based on the conceptual framework of the cyber-physical system to manage the whole process CWSs. Hence, our BCFBMS framework can contribute to the CWS market. Third, BCT is integrated to guarantee the transparency and creditability of the processes before and after the auction. The combination of BCT and auction provides a new approach to address similar decision-making problems among multiple stakeholders.

In future work, we can further study O-VCG auction models with other constraints or objective functions, such as merchant satisfaction. Although CWS providers seek to maximize benefits, ensuring merchants' satisfaction is the basis for their continuous acquisition of more merchants in the long run. Investigation of this direction may be challenging, but it is also interesting. Another possible research direction for extending this research is to consider double auctions. Transactions with multiple CWS providers and multiple merchants are another interesting research topic. Merchants can distribute their goods to different CWS providers, each of which has different costs and service capabilities. The extension of our approach to this case may lead to different insights.

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