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INVENTORY PLEDGE FINANCING DECISIONS BASED ON A PERMISSIONED BLOCKCHAIN BY CONTROLLING FRAUDULENT RISK

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Abstract. Inventory pledge financing (IPF) is a crucial financing way for small and medium-sized enterprise (SMEs). But banks are reluctant to finance SMEs due to fraudulent risk in practice. This paper discusses the application of blockchain in IPF, particularly its impact on mitigating fraud risks. Utilizing game theory models, we illustrate how the finance and operation decisions of participants, along with supply chain efficiency, are influenced by the introduction of blockchain. Meanwhile, equilibrium outcomes are analysed and numerical study is given. Our analysis reveals that under certain conditions, blockchain integration can lead to reduced loan interest rates, lower wholesale prices, increased order quantities by buyers, and enhanced supply chain efficiency. Lastly, we develop a protocol to demonstrate the transfer of digital warehouse receipt on a permissioned blockchain to avoid fraudulent risk. This study provides a theoretical foundation, and a guidance for decisions-making in blockchain-enabled IPF schme.

Mathematics Subject Classification. 90B06, 91A04.

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1. Introduction

Due to the absence of credit and transaction history, small and medium-sized enterprises (SMEs) encounter challenges in securing bank credit financing. Additionally, their limited bargaining power hinders them from obtaining trade credit from upstream suppliers. Despite maintaining viable operations and exhibiting strong customer demand, these enterprises often face liquidity constraints, particularly for procurement activities. Consequently, inventory pledge financing (IPF) becomes an important financing option for SMEs. IPF involves a borrower applying for financing based on goods stored in warehouses. Specifically, the borrower deposits and pledges inventory to a warehouse approved by a bank. Subsequently, the warehouse issues a warehouse receipt to the bank in favor of the borrower. This receipt serves as collateral, enabling the borrower to secure a loan from the bank against the pledged inventory.

Banks face significant challenges in successfully implementing traditional IPF [1]. For instance, the lack of monitoring the status of pledged assets has led to various issues frequently occurring in developing countries. These issues include duplicate pledges and fraudulent warehouse receipts. A prime case is the warehouse contract dispute involving Foshan Zhongjin Shengyuan Storage Management Co., LTD, which sent shockwaves through

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Keywords. IPF, warehouse receipt, fraudulent risk, finance and operation decisions, blockchain.

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China's banking sector. It was disclosed in 2022 that a substantial quantity of 4125.13 tons of aluminum ingots had been fraudulently pledged across multiple warehouses[1]. The existing risk mitigation strategies within the supply chain finance (SCF) ecosystem are susceptible to shortcomings, largely due to the complex interplay of numerous participants spanning various operational stages. This complexity poses challenges for creditors seeking to effectively manage the pledged assets within the SCF framework.

Frontier technologies like the internet of things (IoT) and blockchain are expected to help traditional banks to control the loan risks in SCF by streamlining the information flow among supply chain members [2,3]. For example, combining IoT technology and inventory transactions can significantly improve the transparency of the pledged digital warehouse receipt and reduce operational risk [4]. Companies in China, like Huawei Technologies Co., Ltd[2] and 66 Yuanlian LogisTech[3], are also using blockchain in digital warehouse receipt financing with commodities. A company called YJ uses the integrative system formed by blockchain and the IoT to manage the status of warehousing activities and assets in real-time [5]. With the help of IoT devices, items in the warehouse is mapped into digital asset on a blockchain. The digital receipts are allowed to be issued, transferred on blockchain by pre-programmed smart contract and participants' verification. These digital receipts can't be duplicated [6] since they can't be spent more than once when there is a consensus of transaction records. By facilitating trustless technologies such as smart contract, the interaction of human relations has been changed by blockchain [7,8]. In brief, blockchain technology has the potential to mitigate the shortcomings in IPF, and both enterprises and the bank are eager to practice in it. As a possible future business form, it is necessary to theoretically explore its inherent decision-making mechanisms.

Motivated by the above, we research on questions as follows. (1) What is the optimal decision in SCF when considering interaction operations with finance? (2) How interest rate, wholesale price and order quantity change in blockchain-enabled IPF when comparing with traditional IPF? (3) What is the influence of blockchain-enabled IPF on supply chain efficiency? Focusing on the questions mentioned above, we model theoretical models to evaluate how decisions shift under various conditions in traditional IPF and blockchain-enabled IPF. We also analyse the effectiveness of implementing blockchain technology within SCF.

This paper discusses the rationality of blockchain applied in IPF by addressing the risks associated with fraud. It combines theoretical analysis with practical demonstrations to illustrate the benefits. The main contribution of this paper are in three ways.

(1) This paper advances the theoretical understanding of IPF by highlighting a significant factor yet underexplored area: the impact of fraudulent risk. While the majority of existing literature on supply chain financing concentrates on contract terms, demand uncertainty, and the consequences of bankruptcy. Less attention has been given to fraud risk, especially regarding the repeated pledging of warehouse receipts. This study takes a step to bridge this gap by examining how the presence of fraud risk can influence both the repayment amounts and the financing costs for borrowers within the IPF scheme.

(2) This paper contributes to the theory of decisions on blockchain-enabled IPF. It investigates the interaction of supply chain financing and operation decisions by focusing on how blockchain-enabled IPF influences decisions of various participants, including the bank, the buyer and the supplier. Furthermore, the theoretical conditions for the application of blockchain in supply chain finance are discussed.

(3) This paper verifies feasibility of IPF on blockchain platform by experiments. While current research on blockchain technology are mainly focusing on performance optimization of components of various blockchain frameworks. There is a relative scarcity of studies on the practical application of blockchain within the supply chain finance sector. It is the potential benefits for the financial industry that could be more significantly realized. To address this, We develop a financial system utilizing the permissioned blockchain framework, Hyperledger Fabric. This system serves as a demonstration on how the technology can effectively facilitate and enable financing processes associated with digital warehouse receipts.

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[1] `https://news.sina.cn/2023-01-19/detail-imyatrfe5507062.d.html`.

[2] `https://www.huaweicloud.com/solution/blockchain/bulk-warehouse-receipt.html`.

[3] `https://baijiahao.baidu.com/s?id=1732973711995346865`.

The rest of our paper is structured as follows. Section two is the summary of literature review. Section three is notations and sequence of events. Section four are decision models of traditional IPF, blockchain-enabled IPF schemes and the first-best solution. Section five are analysis of the equilibrium in two financing schemes to find the equilibrium results and supply chain efficiency. Section six is the numerical study. Section seven are experiments, including deployment procedure and performance test result of the system. Section eight is conclusion and management insights. All proofs of propositions are in appendix.

2. Literature review

In this study, we model a theoretical model to examine the effects of fraudulent risk on the financial and operational decisions of participants involved in IPF. We propose that banks could leverage blockchain technology as a means to mitigate the risks associated with fraudulent warehouse receipts. Furthermore, through experimental validation, we illustrate the potential of blockchain application in industries.

Accordingly, our literature review is structured around three themes related to this paper: interaction of finance and operation, supplier financing and blockchain application in finance. This comprehensive review provides a solid foundation for understanding the broader context and implications of our research.

2.1. Interaction of finance and operation decisions

Inventory management has been researched on green supply chain [9–11], resilient supply chain [12,13], and perishable products supply chain [14,15]. These works have proposed solutions to inventory optimization and decision-making problems without considering capital constraints in supply chain. However, the decisions made in supply chains are is usually related to capital. Therefore, the study of interaction of finance and operation decisions in supply chain can provide a better reference for enterprises.

The interaction of finance and operations becomes active in recent research area. A firm's short-term finance and operation decisions are determined by trade credit [16–18], bank credit [19–21] and asset-based financing (a financing secured by inventory or trade accounts receivable) [22]. Our work is close to inventory-based financing scheme. Authors have researched on inventory-based financing scheme from different aspects. For example, from contract terms [23,24], and risks [25,26].

Iancu *et al.* [23] research on the efficiency of different inventory-based financing contracts of agency issues in a firm's operating flexibility under debt. It finds out inventory-heavy firms can use simple debt contracts to reap the full benefits of additional operating flexibility by inventory replenishment and partial liquidations. Alan and Gaur [24] characterize how a firm makes decisions of inventory and capital structure when getting loan by asset-based financing when considering parameters such as loan contracts, inventory investment, capital structure, and bankruptcy outcomes. Yang and Birge [25] analyse the interaction of firms' operations, capital constraints and different financing schemes to understand how demand risk sharing between the supplier and the buyer improves the supply chain efficiency. It finds out that trade credit is an essential source for inventory financing in equilibrium. Li *et al.* [26] explore optimal strategies of inventory financing in two scenarios when the risk-averse retailer facing multi risks. Only when the initial stock is relatively high, the retailer pledges part of the initial stock. Retailer's risk aversion reduces its pledged quantity and performance. When the stock is relatively high, the bank refuses to offer the loan.

The above studies have studied the inventory pledge in various conditions. They all assume there is no fraudulent risk or the risk can be controlled by contract. Moreover, they assume the warehouse does not participate in the IPF, so there is no need for them to consider fraudulent risk in their researches. However, most banks lend money to SMEs according to the warehouse receipt issued by the warehouse in IPF, where fraudulent risk of warehouse receipt pledge usually occurs in practice. The bank also price interest rate by considering the fraudulent risk of warehouse receipt on the repayment. External fraudulent risk of warehouse receipt causes the most significant losses in IPF, so that how to avoid the fraudulent risk of pledges is necessary [27]. In this paper, we model the decisions by taking fraudulent risk of warehouse receipt as an important risk control factor. And we discuss how this factor influence participants' decisions.

2.2. Supplier financing

Works illustrate financial constraints on either buyers [28] or both suppliers and buyers [29,30], or suppliers [4,31]. Our paper is closely related with papers on financial constraint of suppliers. Capital-constrained suppliers finance by various collateral cause various decisions. Suppliers finance by various assets. For example, by purchase order [32–34], accounts receivable [31,35,36], advance payment [37] and inventory [4].

Reindorp *et al.* [32] characterize supplier financing by purchasing order with buyer's commitment contract in a newsvendor model. It finds out the supplier benefits from a lower credit limit or information transparency, but buyer benefits on the contrary. Wu *et al.* [33] study that the buyer supports the capital-constrained supplier to get loan from the bank by purchase order. The buyer shares financing risk with the bank. Tang *et al.* [34] illustrate when supplier gets loan from bank with purchase order or buyer with accounts receivable, how information influences supply chain efficiency. The endogenous order fulfillment probability is the main factor influencing supply chain efficiency. Tunca and Zhu [31] study the efficiency and role of buyer intermediated financing. It can improve supply chain efficiency and benefits all participants in the supply chain. Huang *et al.* [35] empirically investigate how lead time, information sharing and the accounts receivable period affect suppliers' reverse factoring decision. It finds that lead time has positive and direct effects on suppliers' financing decisions, but has indirect effects on suppliers' financing decision through the accounts receivable period. While information sharing has negative and indirect influences on suppliers' reverse factoring decisions. Kouvelis and Xu [36] develops a supply chain theory of factoring and reverse factoring to show when these post-shipment financing schemes will be used and who will benefit from the financing. The above papers don't discuss anything related with blockchain in supply chain finance. Dong *et al.* [37] study supplier financing by advance payment in a multi-tier supply chain to mitigate the supply disruption risk in both traditional supply chain with limited visibility and blockchain-enabled supply chain with perfect visibility. Chod *et al.* [4] characterize how the supply chain efficiency is influenced by firm's operational decisions when the inventory financing is enabled in a cost-effective way. They use blockchain to reveal firm's operational capabilities. The last two works discuss the blockchain application in supply chain finance, but Dong *et al.* [37] focus on disruption risk avoidance by blockchain and Chod *et al.* [4] focus on revealing firm's operational capabilities by blockchain.

Different with most of the above works, capital-constrained supplier in our paper finance by inventory with warehouse receipt issued by the warehouse. The risk is fraudulent risk of the warehouse receipt. The buyer in our paper is the decision maker while the supplier is the follower. The sales revenue from the buyer is the main source of repayment. And it repays the bank firstly and pays for the supplier with the left cash. Therefore, the amount and possibility of repayment is key element influencing the participant of the supplier, which displays in the modeling.

2.3. Blockchain application in finance

Blockchain was first presented by Nakamoto in 2008 [38], but it has been applied in various industries, including real estate, healthcare, accounting, finance, and supply chain management [39]. Blockchain is considered as one of the important approaches in FinTech [40,41]. Authors research on blockchain application in payment [42], initial coin offering (ICOs) [43–45], and supply chain finance [4,6,46–50].

Hofmann *et al.* [42] reveal that blockchain can speed up cashflows in supply chain. It has been applied in bills of lading, letters of credit, and factoring and reverse factoring. But they only analyze blockchain by case study, instead of theoretical model or experiments. Chod *et al.* [43] characterize financing of entrepreneurial ventures in initial coin offerings (ICOs) by issuing crypto-tokens based on blockchain platforms. Gan *et al.* [44,45] study blockchain-based startups financing from ICOs backed by future assets and the their operations and regulation. They analyse ICO by theoretical models. But ICO has been restricted in some countries. Its mechanism is quite different from that of digital warehouse receipts backed by inventory in supply chain finance. Babich and Hilary [46] find that blockchain is important to overcome information asymmetry which restricts SMEs' access to finance. Shibuya and Babich [47] find that blockchain can be applied into collateral assets at the higher tiers in a supply chain. Du *et al.* [6] design a supply chain financial service platform for digital warehouse receipts applied in steel industry based on a permissioned blockchain. Chod *et al.* [4] investigate warehouse receipts financing in agriculture supply chains on Bitcoin network. All the transactions are validated and committed by distributed nodes. The blockchain in these articles are mainly used for data storage, no demonstration for transactions of digital asset. Yu *et al.* [48] analyse a traditional SCF model with Platform Undertakes Guarantee (PUG) and a novel SCF strategy with Customer Undertakes Guarantee (CUG) where Pareto improvement exists. Liu *et al.* [49] study operational strategies in supply chain by solving trust problems among supply chain members and the bank by blockchain. They find when the retailer's initial capital is low and the production cost is high, blockchain platform finance is the better for supply chain members. Wang *et al.* [50] research on blockchain application in trade credit to increase supply chain efficiency and participants' profits. The last three works analyse financing strategies based on blockchain, but they don't present the digital trading system to show how digital asset is transferred among participants.

We demonstrate digital warehouse receipt trading process by smart contract and design the trading system on a permissioned blockchain Hyperledger Fabric. Smart contract encapsulates information of digital warehouse receipt and trading rules within the asset's implementation, safeguarding the integrity of its state and behavior. The cryptographically enforced data structure provides guarantees for the valid conditions of digital warehouse receipt's state change, reducing the need for a trust third intermediary in the platform. The transfer of a warehouse receipt occurs only after the underlying infrastructure receives a signed instruction from the warehouse receipt's holder, preventing fraudulent risk in IPF.

Here below is the comparisons between this paper and the related literature in Table 1.

TABLE 1. Comparisons between this paper and works related with blockchain-enabled IPF.

Literature	Factors considered	Assets type	Blockchain application
Barman *et al.* [9]	Carbon emissions	No	
Barman *et al* [10]	Products Quality	No	
Barman *et al.* [11], Mondal and Roy [12], Mondal *et al.* [13]	Sustainability	No	
Paul *et al.* [14]	Credit period	No	
Ali *et al.* [15]	Environments	No	
Iancu *et al.* [23], Alan and Gaur [24]	Contract	Inventory	
Yang and Birge [25]	Demand risk	Inventory	
Li *et al.* [26]	Multi risks	Inventory	
Liu *et al.* [27]	Fraudulent risk	Inventory	
Reindorp *et al.* [32], Wu *et al.* [33], Tang *et al.* [34], Dong *et al.* [37]		Purchase order	
Tunca and Zhu [31], Huang *et al.* [35], Kouvelis and Xu [36]		AR	
Hofmann *et al.* [42]			Reverse secularization
Chod *et al.* [43], Gan *et al.* [44][45]			ICOs
Babich and Hilary [46]			SCF
Shibuya and Babich[47]			Multi-tier SCF
Du *et al.* [6]		Warehouse receipt	SCF
Yu *et al.* [48], Liu *et al.* [49], Wang *et al.* [50]			SCF platform
Chod *et al.* [4]	Enterprise quality	Inventory	SCF
This paper	Fraudulent risk	Inventory	SCF

TABLE 2. Notations.

Parameter	Description
B_0	Supplier's initial capital
θ	Non-fraudulent rate of warehouse receipt
ω_i	Wholesale price in different financing schemes (i is denoted by subscripts cl and ss, where cl denotes traditional IPF scheme, ss denotes blockchain-enabled IPF scheme)
Q_i	Order quantity in different financing schemes (i is denoted by subscripts cl, ss and fb, where cl denotes traditional IPF scheme, ss denotes blockchain-enabled IPF scheme, fb denotes first-best solution scheme)
c	Unit product cost
p	Unit sales price
r_i	Loan interest rate in different financing schemes (i is denoted by subscripts cl and ss, where cl denotes traditional IPF scheme, ss denotes blockchain-enabled IPF scheme)
r_f	Risk-free interest rate
D	Market demand
c_e	Return processing cost per unit
c_g	IoT cost per unit under blockchain-enabled IPF scheme
$F(\cdot)$	Cumulative distribution function of market demand
$f(\cdot)$	Probability density function of market demand
$R = \omega_i \min\{Q_i, D\}$	Repayment for the supplier
$F_R(\cdot)$	Cumulative distribution function of R
$f_R(\cdot)$	Probability density function of R

3. NOTATIONS AND SEQUENCE OF EVENTS IN TRADITIONAL AND BLOCKCHAIN-ENABLED IPF SCHEMES

We assume a supply chain financing network consisting of a supplier (herein referred to as "he"), a big buyer (herein referred to as "she"), the warehouse (herein referred to as "it") and a financial institution (herein referred to as "bank"). The big buyer purchases products from the supplier while the supplier imports goods from his upstream supplier abroad. Their payment terms are all in cash on delivery at warehouse. Usually, the supplier needs to wait for some time before delivering the goods to the buyer since large buyers strictly control the warehousing time of goods due to cost control. We assume the supplier has initial budget B_0 but is not sufficient for payment. So the supplier pledges the inventory to the bank once the goods arrives at the warehouse to get loan since he needs to pay for the upstream supplier before the repayment back. We assume there is no quality problem of the products. And the warehouse environment can not change the quality condition of products.

The sequence of events are as follows. The big buyer, who is at dominated position in the trade, decides wholesale price ω_i and order quantity Q_i. Then she sends the contract (ω_i, Q_i) to the supplier, where the subscripts i is cl for traditional IPF scheme, ss for blockchain-enabled IPF scheme or fb for the first-best solution scheme. The order quantity and wholesale price are high enough for the supplier to accept the contract. It is common for big buyers to decide wholesale price and order quantity in business when a small supplier faces with a big buyer who is with strong market power. For example, Chinese suppliers are willing to establish business relationship with Walmart even if they can get very low profits, because they pay less to get money back [51]. The supplier's initial budget B_0 is not sufficient to cover the product procurement cost cQ_i. So the supplier has to get a loan amount $cQ_i - B_0$ from the bank by inventory pledge when the goods arrives at the designated warehouse. The supplier applies for the loan by pledging warehouse receipt issued by the warehouse receipt in favor of the supplier to the bank. The bank verifies the warehouse receipt and releases loan amount

$cQ_i - B_0$ to the supplier. The bank charges fair interest and uses competitive interest rate setting [4, 31] by considering the non-fraudulent rate of warehouse $\theta \in [0, 1]$ and the variable market demand D of the buyer in the sales season. The interest rate from the bank is r_i , i is denoted by subscripts cl and ss. Denote the risk-free rate by r_f, which means the bank could not make extra profits from loan other than investing in risk-free assets. After obtaining loan, the supplier pays cQ_i for his procurement order. The buyer sells products at unit price p which is exogenous. When the market demand D is realized, the supplier pays for the sold products and returns all unsold or damaged products to the supplier in full refund. The buyer needs to pay for a return processing cost per unit at c_e. The return policy is commonly used by some big buyers with strong market power [31]. They also use the policy to avoid high product defective rate. The supplier repays the bank to release the pledged inventory. All description of parameters are in Table 2.

The general sequences of events in traditional IPF (see Fig. 1) and blockchain-enabled IPF (see Fig. 2) schemes are almost the same, but different in some ways. Firstly, the probability of the warehouse receipt fraudulent (repeated pledge) in the two schemes are different. In traditional IPF scheme, the bank can not monitoring the goods in real-time. Most of the time, they even do not go to the warehouse for regular inspection of pledged goods since goods in different industries are in large amounts which is hard for manual work. As a result, the bank reflects their fraudulent risk control of warehouse receipt in different industries by interest rate. We assume the warehouse receipt non-fraudulent rate is θ. If the warehouse receipt is non-fraudulent, the buyer pays for the supplier. Similarly, the bank can get back the principle with interest. But if fraudulent warehouse receipt happens, the supplier delivers nothing to the buyer and gets no payment back. The supplier and the bank lose all. After that, the event will enter into the judicial proceedings, which is not discussed in this paper. While in blockchain-enabled IPF, no fraudulent mentioned above will happen. Since the supplier and the bank can monitor the movement of the pledged goods. But the supplier is required to pay for c_g per unit for hardware of IoT so that the real-time information of the goods can be uploaded to blockchain for bank's and supplier's verifications. This will be reflected in models. Secondly, the information the bank can get are different in two schemes. In traditional IPF, the bank can only get the loan application contract and paper warehouse receipt directly from the supplier and warehouse. It is hard for the bank to control the movements of warehouse receipts and goods. While in blockchain-enabled IPF, some trade details, including waybill, warehouse warrant, warehouse receipt pledge and transfer contracts, can be updated into blockchain. Some critical terms can be encoded by protocol in advance and be processed by consensus of relevant participants. This can be sure that there is only one digital warehouse receipt with warehouse as the issuer and the supplier as the holder. In this way, the fraudulent warehouse receipt can be avoided. This will be reflected in the experiment procedure.

Assumption 1. *Assume any amount above* $cQ_i - B_0$ *is not economical since we assume the supplier is restricted to invest in other opportunities except for the order [4].*

Assumption 2. *Assume the supplier is not allowed to deliver the products dividends, and the buyer is not allowed to repay the bank and the supplier dividends. The buyer uses the sales revenue as the payment and repayment for the supplier and the bank due to self-liquidation trade finance theory [52]. It is commonly used in practice in supply chain finance by the bank to control the financing risk maximally.*

Assumption 3. *Assume the market demand distribution has a cumulative distribution function (c.d.f.)* $F(\cdot)$ *and a probability density function (p.d.f.)* $f(\cdot)$*. Define function* $R = \omega_i \min\{Q_i, D\}$ *and denote its c.d.f. and the p.d.f. by* $F_R(\cdot)$ *and* $f_R(\cdot)$*, respectively [31].*

4. Decision models

We present different financing schemes for comparison: traditional IPF and blockchain-enabled IPF schemes, and the first-best solution as the benchmark. Although there are more than three participants in the schemes, the critical participants who influence the financing decisions in the IPF are the supplier, the bank and the buyer. So we only discuss their decisions and profits in this paper.

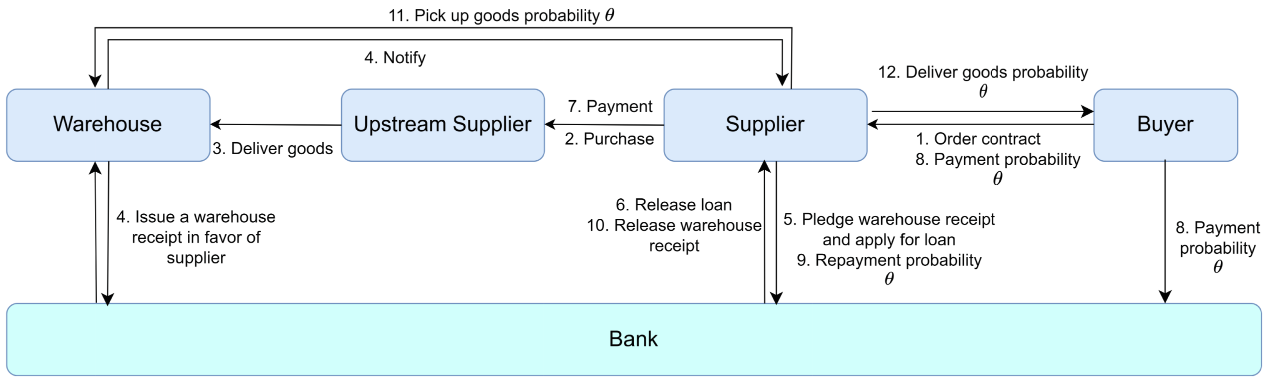


FIGURE 1. Traditional IPF.

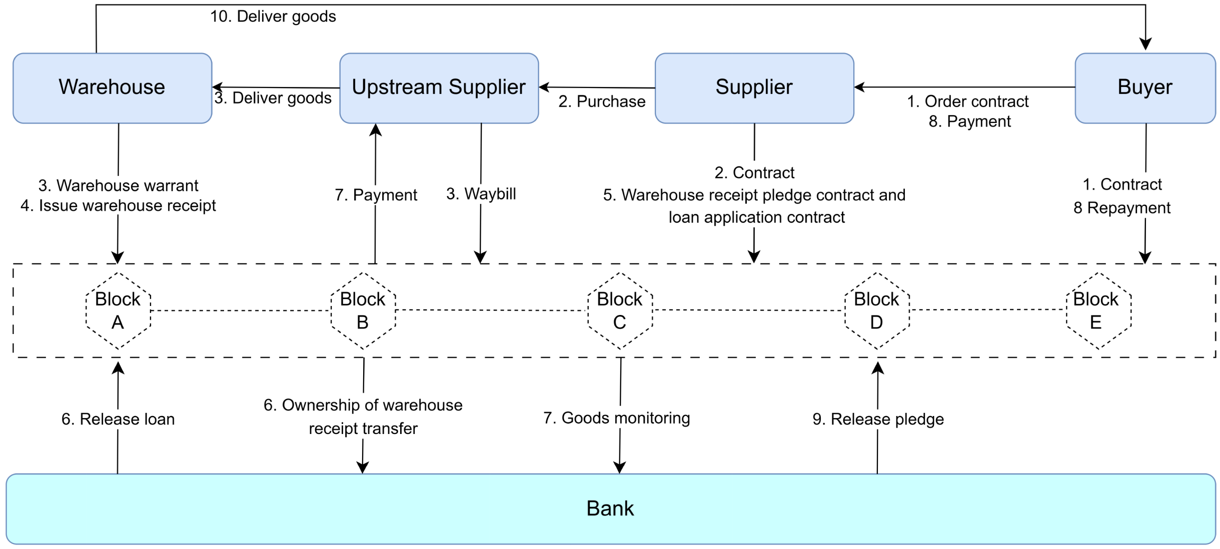


FIGURE 2. Blockchain-enabled IPF.

4.1. Traditional IPF

The traditional IPF scheme is denote by cl. The decisions follow the general outline: the buyer offers the contract by deciding wholesale price and order quantity (ω_{cl}, Q_{cl}) at the beginning. The supplier's initial budget B_0 is not sufficient to cover procurement cost cQ_{cl}. He needs to obtain a loan $cQ_{cl} - B_0$ when the goods arrives at the designated warehouse by pledging the inventory to the bank, and pay for the goods when it is delivered to the buyer. The bank evaluates the risk according to industrial risk of warehouse receipt fraudulent and then decides interest rate r_{cl}. The bank makes zero expected profits on the condition that the bank's expected repayment in warehouse receipt non-fraudulent rate should be the same as the payoff from investing in any other risk-free assets, and no repayment otherwise. Denote the risk free interest rate is r_f.

Denote the supplier's expected profits as a function of Q_{cl} and ω_{cl} under traditiona IPF Π_s^{cl}. When there is no fraudulent risk with probability θ, the buyer will repay the bank loan principle plus interest to the extent possible on behalf of the supplier, *i.e.*, the payment of $\min[(cQ_{cl} - B_0)(1 + r_{cl}), \omega_{cl} \min\{Q_{cl}, D\}]$, and pays for the supplier if any extra fund left after paying the bank, *i.e.*, $(\omega_{cl} \min\{Q_{cl}, D\} - (cQ_{cl} - B_0)(1 + r_{cl}))^+$. When there is fraudulent risk with probability $1-\theta$, the supplier delivers nothing to the buyer and gets no payment back, that is 0. What's worse, the supplier loses procurement cost cQ_{cl} has already been paid. The supplier can participate in the trade only when the profits he can get from the trade is more than the profits his initial capital is invested in any risk-free assets investment $B_0(1+r_f)$, which is also called opportunity cost. Or else, this financing scheme will not happen. We use the mathematical notation $[x]^+ = \max\{x, 0\}$.

The supplier's profits under traditional IPF

$$\Pi_s^{cl} = \theta E[(\omega_{cl} \min\{Q_{cl}, D\} - (cQ_{cl} - B_0)(1+r_{cl}))^+] - (1-\theta)cQ_{cl} - B_0(1+r_f). \tag{1}$$

The supplier makes sure that he applies for loan amount $cQ_{cl} - B_0$ to cover the procurement cost. The bank sets interest rate r_{cl} competitively, which means its expected profits from investing the loan amount in risk-free assets is the same as the profits from financing the supplier. Any amount above $cQ_{cl} - B_0$ is not economical since we assume it is restricted for the supplier to invest in other opportunities except for the order. This assumption is consistent with the restriction of use of funds in supply chain finance that the fund from the loan can only be used in the designated order. The competitive interest rate assumption is common in literature on supply chain finance in operation management [4,31], since it is the lowest condition that the bank is willing to participate in the lending. Or else, the bank is unwilling to participate in the lending and the supplier can not complete the trading if there is no other ways for loans. If the warehouse receipt is in non-fraudulent with rate θ, the repayment for the bank is $E[\min\{(cQ_{cl} - B_0)(1+r_{cl}), \omega_{cl} \min\{Q_{cl}, D\}\}]$. If the warehouse receipt is in fraudulent with rate $(1-\theta)$, the repayment is $E[\min\{(cQ_{cl} - B_0)(1+r_{cl}), 0\}]$, which is equals to be 0. The reason is that the bank considers the worst condition if risk happens when setting the interest rate. Once the risk happens, it takes long legal process to get back the loan after reserving as bad debt for liquidation.

The bank's interest rate function under traditional IPF

$$\begin{aligned}(cQ_{cl} - B_0)(1+r_f) = \theta E[&\min\{(cQ_{cl} - B_0)(1+r_{cl}), \omega_{cl} \min\{Q_{cl}, D\}\}] \\ &+ (1-\theta)E[\min\{(cQ_{cl} - B_0)(1+r_{cl}), 0\}].\end{aligned} \tag{2}$$

Define the buyer's expected profits as the function of ω_{cl} and Q_{cl} in traditional IPF scheme as Π_r^{cl}. If there is no fraudulent risk of the warehouse receipt with probability θ, the buyer sales products at p per unit. The unsold items are returned to the supplier with a full refund, but the buyer pays a return processing cost c_e per unit of each returned product. If fraudulent risk of warehouse receipt happens with probability $1-\theta$, the buyer can sell nothing and no repayment done to the supplier. For simplicity, we assume the lost sales value to be 0.

The buyer's profit under traditional IPF

$$\Pi_r^{cl} = \theta\{E[(p - \omega_{cl}) \min\{Q_{cl}, D\}] - c_e(Q_{cl} - D)^+\}. \tag{3}$$

Equation (4) is the constraint condition of supplier's participation in traditional IPF. The supplier only participates in this trade when his expected profits from buyer's contract is no less than 0. Or else, the supplier rejects this order and the buyer's profits from this order is zero.

Constraint condition

$$\begin{aligned}&\max\ \Pi_r^{cl} \\ &\text{s.t. } \Pi_s^{cl} \geq 0.\end{aligned} \tag{4}$$

4.2. Blockchain-enabled IPF

Although traditional IPF has solved SMEs' financing problems in some industries, but the fraudulent risk of warehouse receipt caused by repeated pledges discourages the incentive of the supplier and the bank in financing. Using technologies of IoT and blockchain to control the fraudulent risk of warehouse receipt becomes urgent. In the blockchain, smart contracts allows contract terms to automatically execute by self-enforcement and contingent on a decentralized consensus that is tamper-proof. Specifically, ordering, shipment and financing contractual terms can be written in a series of programmed codes, and executed when redefined contract terms are verified, and a function is triggered. In this way, blockchain technology ensures the uniqueness and effectiveness of assets. Furthermore, data gathered by IoT devices can be updated to the blockchain to enable trusted participants to monitor the status of goods. For example, UPS and FedEx developed blockchain pilot projects to enhance their logistics systems. Participants can integrate IoT with blockchain to improve business processes and risk control by paying cost. The blockchain-enabled IPF scheme is denoted by ss.

The decisions follow the general outline: the buyer offers the contract (ω_{ss}, Q_{ss}) to the supplier. The buyer sets the wholesale price high enough for the supplier to accept the contract. The order contract is updated on blockchain by smart contract. The supplier's initial budget B_0 is not sufficient to cover procumbent cost cQ_{ss}. He needs to obtain a loan $cQ_{ss} - B_0$ when the goods arrives at the designated warehouse by pledging the inventory to the bank, and pays for the goods when it is delivered to the buyer. The waybill and warehouse warrant are uploaded into blockchain. The warehouse issues digital warehouse receipt in favor of the supplier on blockchain. The supplier pledges the warehouse receipt to the bank. All the process are programmed in the smart contract, and each process is verified by participants. The bank sets the interest rate r_{ss} competitively only by considering the buyer's variable market demand D since there is no fraudulent risk of digital warehouse receipt in this scheme. Denote the risk-free rate by r_f. The risk-free assets investment assumption is the same as that in the traditional IPF.

Denote the buyer's expected profits in this case by Π_s^{ss}. Since there is no fraudulent risk, so the interest rate priced by the bank and the repayment amount from the buyer are different from those under traditional IPF. the buyer will repay the bank (the first-right creditor) loan principle plus interest to the most extent and then pays for the supplier (the second-right creditor) $[\omega_{ss}\min\{Q_{ss}, D\} - (cQ_{ss} - B_0)(1 + r_{ss})]^+$ if any left. In blockchain-enabled IPF scheme, the supplier needs to pay $c_g Q_{ss}$ as IoT cost for all the products so that the stakerholders can monitor the movement of the goods in the warehouse. The after sales policy and opportunity cost are the same as those in traditional IPF.

The supplier's profits under blockchain-enabled IPF

$$\Pi_s^{ss} = E[(\omega_{ss}\min\{Q_{ss}, D\} - (cQ_{ss} - B_0)(1 + r_{ss}) - c_g Q_{ss})^+] - B_0(1 + r_f). \tag{5}$$

With initial capital B_0, the supplier borrows enough loan $cQ_{ss} - B_0$ to cover its procurement cQ_{ss}. The bank sets a competitive interest rate r_{ss} on the condition that the bank's expected repayment from the buyer should be the same as the payoff from investing in any other risk-free assets. Since no fraudulent risk of the digital warehouse receipt shall be considered by the bank and the bank monitors all the movements on blockhain to implement risk control.

The bank's interest rate function under blockchain-enabled IPF

$$(cQ_{ss} - B_0)(1 + r_f) = E[\min\{(cQ_{ss} - B_0)(1 + r_{ss}), \omega_{ss}\min\{Q_{ss}, D\}\}]. \tag{6}$$

Define the buyer's expected profits in blockchain-enabled IPF scheme as Π_r^{ss}. In this scheme, the supplier can deliver goods on time, the buyer receives a revenue p per unit. The unsold item is returned to the supplier with a full refund, but the buyer pays for return processing cost c_e for each item. We assume the lost sales value to be zero.

The buyer's profits under blockchain-enabled IPF

$$\Pi_r^{ss} = E[(p - \omega_{ss}) \min\{Q_{ss}, D\}] - c_e(Q_{ss} - D)^+. \tag{7}$$

Equation (8) is the constraint condition of supplier's participation in blockchain-enabled IPF. The supplier only participates in this trade when the supplier's expected profits from buyer's contract is no less than 0. Or else, the supplier will reject this order and the retailer's profits from this order is zero.

Constraint condition

$$\begin{aligned} &\max \Pi_r^{ss} \\ &\text{s.t. } \Pi_s^{ss} \geq 0. \end{aligned} \tag{8}$$

4.3. The first-best solution

Lastly, we formulize the first-best case as the benchmark, that is the centralized decision of the supply chain that all participants are integrated as one. In this case, there is no financial constraint, no products return, no monitoring cost, no fraudulent risk and participant incentive compatibility for the participants. No trade friction exists in the first-best case.

The supply chain profits

$$\Pi_{fb} = E[(p - c) \min\{Q_{fb}, D\}] - cQ_{fb}(1 + r_f). \tag{9}$$

We use the first-best quantity and supply chain profits under full efficiency as the benchmark for that under traditional inventory financing and blockchain-based inventory financing to illustrate how the financing schemes influence supply chain efficiency and decisions in the following paper.

5. Equilibrium analysis

Proposition 1. *Since* $\frac{\mathrm{d}^2\Pi_r^{cl}}{\mathrm{d}Q_{cl}^2}$ *is concave,* Q_{cl}^* *is maximized when solving its first condition.* ω_{cl}^* *is related with* Q_{cl}^**. For the traditional IPF scheme, the unique equilibrium for the buyer's decision is* $(Q_{cl}^*, \omega_{cl}^*)$*, that*

$$Q_{cl}^* = F^{-1}\left(1 - \frac{\theta c_e + c(1 + r_f)}{\theta(p + c_e)}\right) \tag{10}$$

$$\omega_{cl}^* = \frac{cQ_{cl}^*(1 + r_f) + (1 - \theta)cQ_{cl}^*}{\theta E \min\{Q_{cl}^*, D\}} \tag{11}$$

and $r_{cl}^* > \frac{1+r_f}{\theta} - 1$ *is the unique solution for* r_{cl} *to the equation*

$$\frac{(cQ_{cl}^* - B_0)(1 + r_f)}{\theta} = \int_0^{(cQ_{cl}^* - B_0)(1+r_{cl})} z f_R(z)\,\mathrm{d}z + (cQ_{cl}^* - B_0)(1 + r_{cl})(1 - F_R((cQ_{cl}^* - B_0)(1 + r_{cl}))). \tag{12}$$

As Proposition 1 states, given the loan amount required by the supplier, the bank sets competitive interest rate r_{cl}^* as given in equation (2), which is translated into equation (11) as stated above. The interest rate r_{cl}^* is correlated with non-fraudulent rate θ. r_{cl}^* is always more than risk-free investment interest rate r_f as (12) shows. The supplier participates in the trade under constraint in binding (4). Besides, the buyer sets the order quantity Q_{cl}^* and the wholesale price ω_{cl}^* to maximize her profits in binding (4). Under these conditions, the buyer's profits is optimized, the equilibrium (Q_{cl}^*, ω_{cl}^*) is founded as equations (10) and (11) show.

Corollary 1. *From* (10) *in Proposition 1, sensitivity analysis of parameter* θ*, c and* c_e *in* Q_{cl}^* *are* $\frac{\partial Q_{cl}^*}{\partial \theta} > 0$, $\frac{\partial Q_{cl}^*}{\partial c} < 0$ *and* $\frac{\partial Q_{cl}^*}{\partial c_e} < 0$.

Given other conditions, the optimal order quantity Q_{cl}^* is increasing in non-fraudulent rate θ, since the higher non-fraudulent rate the supplier can achieve, the more confidence the buyer has on the supplier, the buyer's order quantities are increased. Given other conditions, Q_{cl}^* is decreasing in product unit cost c. Since the higher the unit product cost is, the lower the unit profit the buyer can get after selling it. As a result, the buyer has no incentive to order more quantities. Given other conditions, Q_{cl}^* is decreasing in return processing cost for each unit product c_e. Since the higher the return processing cost for each unit product, the lower the unit profit the buyer can get if not selling it out, the buyer becomes conservative when ordering the quantities.

Corollary 2. *Since the supplier participants in the trade if and only if the supplier can get positive profits from the trade, that is* $c(1 + r_f) + (1 - \theta)c < \omega_{cl}^* \theta \bar{F}(Q_{cl}^*)$ *in traditional IPF scheme.*

$\bar{F}(Q_{cl}^*)$ represents the probability that the buyer sells all the products when the market demand D is larger than the optimal order quantity Q_{cl}^*. The repayment to the supplier is under the condition that the warehouse receipt is non-fraudulent, the products are delivered to the buyer, as well as the buyer has sold out the products, so that the repayment probability is $\theta\bar{F}(Q_{cl}^*)$. The repayment $\omega_{cl}^*\theta\bar{F}(Q_{cl}^*)$ shall be higher than the sum of the principle of the unit products cost with interest in risk-free investment $c(1 + r_f)$ and the loss of the cost when the fraudulent risk of warehouse receipt happens and the supplier can not deliver the products with probability $(1 - \theta)c$.

Corollary 3. *From* (11) *in Proposition 1 and Corollaries 1 and 2,* $\frac{\partial \omega_{cl}^*}{\partial \theta} < 0$ *and* $\frac{\partial \omega_{cl}^*}{\partial c} > 0$.

Given other conditions, ω_{cl}^* is decreasing in θ, because the higher the non-fraudulent rate of warehouse receipt is, the more quantities the buyer orders. Therefore, the buyer sets a lower wholesale price. Given other conditions, ω_{cl}^* is increasing in c, because the higher the unit product cost, the higher the cost is transferred to the wholesale price, finally it increases the wholesale price.

Proposition 2. *Since* $\frac{\mathrm{d}^2\Pi_r^{ss}}{\mathrm{d}Q_{ss}^2}$ *is concave,* Q_{ss}^* *is maximized when solving its first condition. For the blockchain-enabled IPF scheme, the unique equilibrium for the buyer's decision is* $(Q_{ss}^*, \omega_{ss}^*)$*, that*

$$Q_{ss}^* = F^{-1}\left(1 - \frac{c_e + c_g + c(1 + r_f)}{p + c_e}\right) \tag{13}$$

$$\omega_{ss}^* = \frac{cQ_{ss}^*(1 + r_f) + c_g Q_{ss}^*}{E\min\{Q_{ss}^*, D\}} \tag{14}$$

and $r_{ss}^* > r_f$ *is the unique solution for* r_{ss} *to the equation*

$$\begin{aligned}(cQ_{ss}^* - B_0)(1 + r_f) = &\int_0^{(cQ_{ss}^* - B_0)(1 + r_{ss})} z f_R(z)\,\mathrm{d}z \\ &+ (cQ_{ss}^* - B_0)(1 + r_{ss})(1 - F_R((cQ_{ss}^* - B_0)(1 + r_{ss}))).\end{aligned} \tag{15}$$

As Proposition 2 states, given the loan amount required by the supplier, the bank sets competitive interest rate r_{ss}^* as given in equation (6), which is translated into (14) as stated above. In blockchain-enabled IPF, there is no fraudulent risk for the supplier. Therefore, the interest rate r_{ss}^* given by the bank is no correlation with fraudulent risk but is always more than risk-free investment interest rate r_f. The supplier does not participate in the trade under constraint in binding (8). Besides, the buyer sets the order quantity Q_{ss}^* and the wholesale price ω_{ss}^* to maximize her profits under binding in (8). Under these conditions, the buyer's profits is optimized, the equilibrium (Q_{ss}^*, ω_{ss}^*) is founded.

Corollary 4. *From (13) in Proposition 2, sensitivity analysis of parameter* c*,* c_g *and* c_e *in* Q_{ss}^* *are* $\frac{\partial Q_{ss}^*}{\partial c} < 0$, $\frac{\partial Q_{ss}^*}{\partial c_g} < 0$*, and* $\frac{\partial Q_{ss}^*}{\partial c_e} < 0$.

Given other conditions, Q^*_{ss} is decreasing in product unit cost c. Since the higher the unit product cost is, the lower unit profits the buyer can get after selling it. The buyer has no incentive to order more quantities. Given other conditions, the order optimal quantity Q^*_{ss} is decreasing in IoT cost c_g for each product. Since the higher the IoT cost paid by the supplier, the higher cost is transferred to the buyer to decrease her profits, the buyer then has no incentive to order more products. Instead, the buyer decreases the order quantity if the IoT cost for each product increases. Given other conditions, Q^*_{ss} is decreasing in the unit return processing cost c_e, since the higher the return processing cost is, the higher the buyer needs to pay. Thus, the return of products largely decreases buyer's profits if unit return processing cost is high. The buyer becomes conservative when giving the order to the supplier.

Corollary 5. *Since the supplier participates in the trade if and only if the supplier can get positive profits from the trade,* $c(1+r_f)+c_g<\omega^*_{ss}\bar{F}(Q^*_{ss})$ *in blockchain-enabled IPF scheme.*

$\bar{F}(Q^*_{ss})$ represents the probability that the buyer sells all the products when the market demand D is larger than the optimal order quantity Q^*_{ss}. The repayment to the supplier is under the condition that the buyer has sold out the products. The repayment $\omega^*_{ss}\bar{F}(Q^*_{ss})$ shall be higher than that the total amount of the unit product cost with interest in risk-free investment $c(1+r_f)$ and unit IoT cost c_g. The supplier would not accept the contract and participate in the trade if he can not get profits from the trade.

Corollary 6. *From* (14) *in Proposition 2 and Corollaries 4 and 5,* $\frac{\partial \omega^*_{ss}}{\partial c}>0$ *and* $\frac{\partial \omega^*_{ss}}{\partial c_g}>0$*.*

Given other conditions, ω^*_{ss} is increasing in unit cost c, because the higher the product cost is, the less quantities the buyer will order. Therefore, the buyer decides a higher wholesale price. Given other conditions, ω^*_{ss} is increasing in c_g, because the higher the unit IoT cost, the higher cost is transferred to the wholesale price, finally it increases the wholesale price.

Proposition 3. *Since* $\frac{\mathrm{d}^2\Pi_{fb}}{\mathrm{d}Q^2_{fb}}$ *is concave,* Q^*_{fb} *is maximized when solving its first condition. For the first-best condition, the optimal order quantity for the supply chain is* Q^*_{fb}*, that*

$$Q^*_{fb}=F^{-1}\left(1-\frac{c(1+r_f)}{p-c}\right). \tag{16}$$

In the first-best condition, there is no capital constraint and no trade friction among the participants, so that the optimal order quantity is only related with unit product cost, unit retail price and risk-free interest rate.

Proposition 4. *Blockchain-enabled IPF has a lower loan interest than that in traditional IPF since* $r^*_{cl}>r^*_{ss}$*.*

Given other conditions, there is no fraudulent risk for the bank when releasing loan in blockchain-enabled IPF scheme. The bank prices interest rate based on risk. Therefore, given the loan amount required by the supplier, the bank sets a lower interest rate under blockchain-enabled IPF scheme than that in traditional IPF scheme due to the decreased fraudulent risk, that is $r^*_{cl}>r^*_{ss}$.

Proposition 5. *For the simplicity of discussion, we discuss* ω_i *on the condition that market demand is stable. There exists a* φ *such that if* $Var[D]<\varphi$, $\omega^*_{cl}>\omega^*_{ss}$ *if and only if* $\theta\in[0,\frac{c}{c_g+c}]$*, and* $\omega^*_{cl}\le\omega^*_{ss}$ *if and only if* $\theta\in(\frac{c}{c_g+c},1]$*.*

The wholesale price in blockchain-enabled IPF scheme can be higher or lower than that in traditional IPF scheme. When demand variability is high, the non-fraudulent rate of warehouse receipt θ is 1, the blockchain-enabled IPF scheme reduces the wholesale price since it reduces the loan interest rate due to risk control. As the non-fraudulent rate θ increases, interest rate decreases and order quantity increases in traditional IPF scheme. The increased loan interest from the borrower's loan covers the increased unit IoT cost for the inventory in blockchain-enabled IPF scheme so that the wholesale price can be lower in traditional IPF scheme than that under blockchain-enabled IPF scheme. When demand variability is low, the order quantity reduction caused by non-fraudulent rate θ is sufficiently low. The supplier also needs to borrow the amount for the order. When the interest rate r_{ss} in blockchain-enabled IPF scheme is lower than r_{cl} in traditional IPF scheme, the wholesale price ω_{ss} is lower than ω_{cl} when the non-fraudulent rate of the warehouse receipt is in the lower and medium levels, that is $\omega_{cl}^* > \omega_{ss}^*$. When the non-fraudulent rate θ is high, the unit IoT cost c_g for the inventory is higher than the interest rate the supplier paid in traditional IPF scheme, and the high unit IoT cost increases the wholesale price, that is $\omega_{cl}^* \leq \omega_{ss}^*$.

Proposition 6. *Blockchain-enabled IPF scheme improves supply chain efficiency since* $Q_{cl}^* \leq Q_{ss}^*$, $\Pi_r^{cl} \leq \Pi_r^{ss}$, *if and only if* $\theta \in [0, \frac{c(1+r_f)}{c_g+c(1+r_f)}]$. *Traditional IPF scheme improves supply chain efficiency since* $Q_{cl}^* > Q_{ss}^*$, $\Pi_r^{cl} > \Pi_r^{ss}$, *if and only if* $\theta \in (\frac{c(1+r_f)}{c_g+c(1+r_f)}, 1]$.

If non-fraudulent rate θ is sufficiently low, the bank is hard to release loan or offers high interest rate to the supplier considering the high fraudulent risk in traditional inventory financing scheme. Traditional inventory financing scheme reduces the efficiency of the supply chain. To control the risk by monitoring the inventory and assure the repayment, the bank will require the supplier to install IoT equipments for the inventory although the it costs c_g for each unit products. The financing cost is low since the blockchain-enabled IPF scheme is considered to be high quality pledge to the bank. As a result, blockchain-enabled IPF scheme improves supply chain efficiency if and only if $\theta \in [0, \frac{c(1+r_f)}{c_g+c(1+r_f)}]$.

If non-fraudulent rate θ is sufficiently high, the bank thinks the fraudulent risk is controllable and get back repayment in high probability, and the loan is in low risk. The supplier can get loan from the bank in a competitive interest rate and delivers goods to the buyers in traditional IPF scheme. But it needs to pay for very high total IoT cost for bank to monitoring the inventory if using blockchain-enabled IPF scheme. Thus, blockchain-enabled IPF scheme is not preferred in this condition. Therefore, traditional IPF scheme improves the supply chain efficiency if and only if $\theta \in (\frac{c(1+r_f)}{c_g+c(1+r_f)}, 1]$.

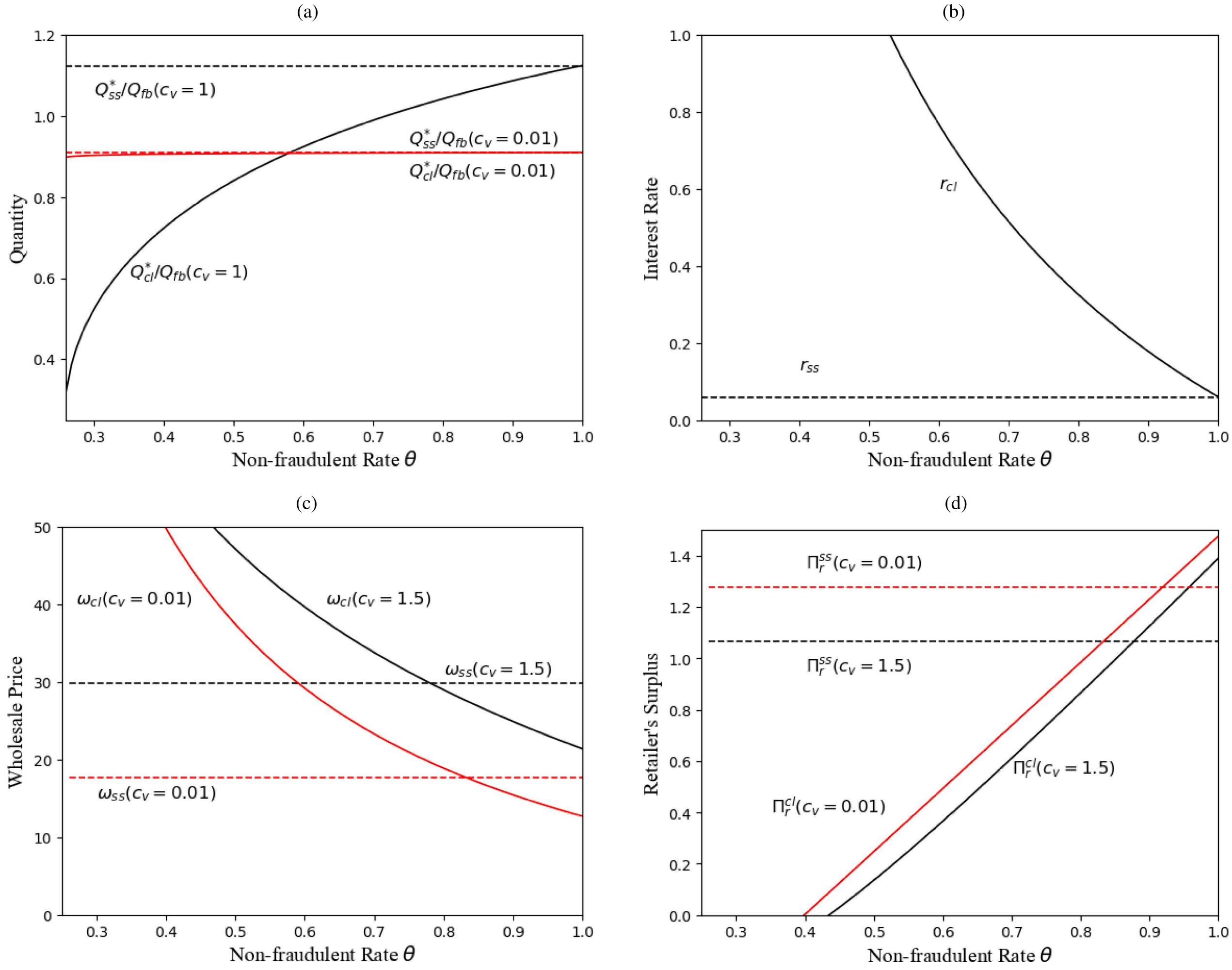
6. Numerical study

In this section, we conduct a numerical study to demonstrate the results derived in the previous section are robust. In all panels of Figure 3, we let the parameters values $p = 50$, $c = 12$, $r_f = 0.06$, $c_e = 6$, $c_g = 5$, $B_0 = 100$. The market demand follows a log-normal distribution with log-mean $\mu = 0.5$. c_v presents the Coefficient of Variation for the logarithm of the market demand distribution, σ/μ, where σ is the log-standard deviation of the market demand distribution. We give $c_v = 0,01$, $c_v = 1$, $c_v = 1.5$ in different panels to test the robustness of the results. $c_v = 1$ and $c_v = 1.5$ mean demand variability is high while $c_v = 0,01$ means demand variability is low. Refer to Tunca and Zhu [31] for the values in all panels.

In panel (a) in Figure 3, in traditional inventory financing, the optimal order quantity Q_{cl}^* increases in non-fraudulent rate θ, since the higher the non-fraudulent rate is, the more confidence the supplier gives to the buyer to increase the order quantity no matter when the demand variability is high ($c_v = 1$) or low ($c_v = 0,01$), which is consistent with our conclusion in Corollary 1. But in blockchain-enabled IPF, the optimal order quantity Q_{ss}^* is constant and not related with non-fraudulent rate θ no matter when the demand variability is high ($c_v = 1$) or low ($c_v = 0,01$), since there is no fraudulent risk of the digital warehouse receipt on blockchain.

In panel (b) in Figure 3, given the loan amount required by the supplier, the interest rate under blockchain-enabled IPF scheme is lower than that in traditional IPF scheme since the fraudulent risk is decreased, that is $r_{cl}^* > r_{ss}^*$, which shows the fraudulent risk is a key factor that the banks considers when setting the interest rate. This result is consistent with our conclusion in Proposition 4.

In panel (c) in Figure 3, when demand variability is high (that is when the coefficient of variation for the log-demand is $c_v = 1.5$), the non-fraudulent rate of warehouse receipt θ is 1, the wholesale price is reduced since the loan interest rate is reduced due to risk control in the blockchain-enabled IPF scheme. When demand variability



Notes: Panel (a) illustrates the order quantity ration with respect to the first best under each financing schemes. Panel (b) illustrates the interest rate under each financing schemes.Panel (c) shows the wholesale price for varying non-fraudulent rate θ. Panel (d) shows the buyer's surplus in each financing schemes in different market demands.

FIGURE 3. Comparison of the Equilibrium Outcomes for Financing through Traditional Inventory and Blockchain-enabled Inventory.

is low (that is $c_v = 0.01$), the reduction of order quantity caused by non-fraudulent rate θ is sufficiently low. This result is consistent with our conclusion in Proposition 5.

In panel (d) in Figure 3, the buyer's surplus increases quickly when the non-fraudulent rate θ increases in both $c_v = 0.01$ and $c_v = 1.5$. The buyer's surplus is higher when $c_v = 0.01$ than that when $c_v = 1.5$ since the stability of market demand is the guarantee of the buyer's profit. It can be concluded that the non-fraudulent rate and stability of market demand are critical elements for buyer's surplus. Buyer's surplus in traditional IPF scheme is higher than that in blockchain-enabled IPF scheme only when the non-fraudulent rate θ is sufficiently high. Since the supplier's surplus is 0, the buyer's surplus reflects the supply chain efficiency. This result is consistent with our conclusion in Proposition 6.

7. EXPERIMENTS

In order to demonstrate how the blockchain enables the digital warehouse receipt non-fraudulent and visible for related participants, we design a digital warehouse receipt trading system on Hyperledger Fabric with privacy protection mechanism. In the experiment, we denote the warehouse, the supplier and the buyer as A, B and C, respectively. We assign the data needed for the simulation experiments to explain the rationality of the experimental process. The code used in this paper is available online in Github repository like [53].

7.1. Deployment procedure

The warehouse issues a digital warehouse receipt (see Fig. 4). If the warehouse is to issue a digital warehouse receipt with the inventory from the supplier, it generates a digital asset mapped from the inventory. The contents of the digital warehouse receipt, including class, current state, issuer name, paper number, issue date time, maturity date time, face value of the warehouse receipt, MSPID of organization and owner name, are verified by the supplier and the bank, and recorded on Hyperledger Fabric. After verification, the digital asset's state is for trading.

```
----------------------------------------------------issue----------------------------------------------------------------------
Connect to Fabric gateway.
Use network channel: mychannel.
Use warehouse receipt smart contract.
Submit warehouse receipt issue transaction.
Process issue transaction response.{"class":"warehouse receipt","currentState":1,"issuer":"A","paperNumber":"00001","issueDate
Time":"2023-04-28","maturityDateTime":"2024-04-27","faceValue":500000,"mspid":"Org1MSP","owner":"A"}
A warehouse receipt : 00001 successfully issued for value 500000
Transaction complete.
Disconnect from Fabric gateway.
Issue program complete.
```

FIGURE 4. Issuing a digital warehouse receipt.

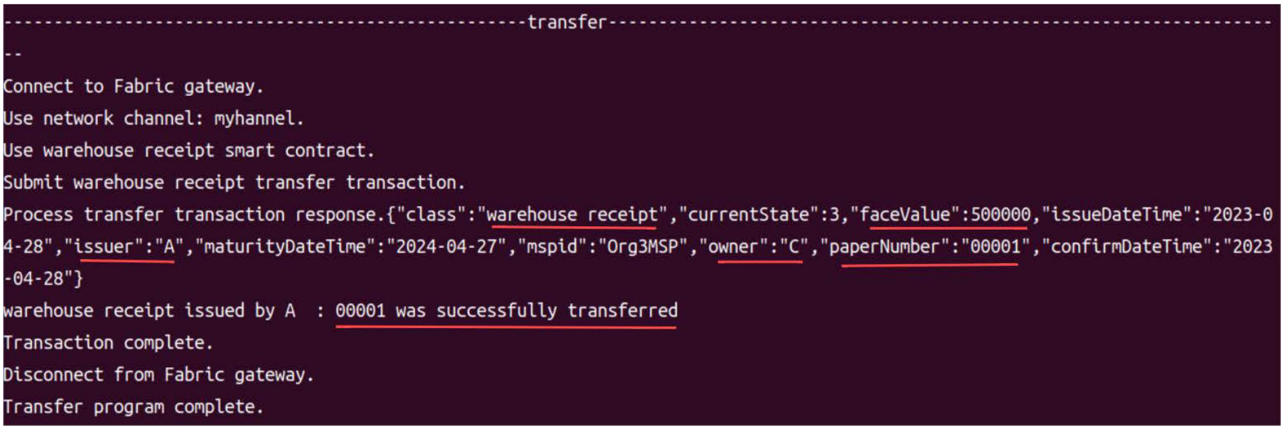
The supplier buys the digital warehouse receipt (see Fig. 5). The supplier invokes the smart contract for buying the digital warehouse receipt. The warehouse transfers the digital warehouse receipt to the supplier, the warehouse adds the warehouse receipt to supplier's account by inserting cryptographic hash of the warehouse receipt into the block representing the supplier's account. The warehouse, the supplier and the bank, who are the three nodes in channel, must sign the new data structure which reflects the success of adding the warehouse receipt to the supplier's account. The three nodes send the signed updated block to the server, verify and commit it to permissioned blockchain framework Hyperledger Fabric. Once the server witnesses the commitment to Fabric, the three nodes (the warehouse, the supplier and the bank) can query from the server for the path to the warehouse receipt. Thus, the supplier and the warehouse can present and share the path as the proof of the issued digital warehouse receipt with others.

The buyer transfers a digital warehouse receipt to the bank for pledge (see Fig. 6). If the supplier seeks to finance from the bank, the supplier transfers a digital warehouse receipt to the bank. He removes the digital warehouse receipt from his account and adds it to the bank's account. Adding and removing the digital warehouse receipt are reflected in the data structures. Thus, the supplier, the bank and the warehouse must sign the new block for the valid transfer records. Then the server witnesses updates to Hyperledger Fabric. Once the server witnesses the commitment to Hyperledger Fabric, the three nodes (the supplier, the bank and the warehouse) can query from the server for the path to the transferred warehouse receipt. Thus, the supplier

```
----------------------------------------------------buy--------------------------------------------------------------------
Connect to Fabric gateway.
Use network channel: mychannel.
Use warehouse receipt smart contract.
Submit warehouse receipt buy transaction.
Process buy transaction response.
A warehouse receipt : 00001 successfully purchased by B
Transaction complete.
Disconnect from Fabric gateway.
Buy program complete.
```

Figure 5. Buying the digital warehouse receipt.

and the bank can present and share the path as the proof of the transferred digital warehouse receipt the bank owns. What is more important, the supplier's previous ownership of the digital warehouse receipt is invalid after consensus by broadcasting the new commitment. It is critical since the supplier can no longer present a correct proof to state that she owns the digital warehouse receipt after it has been transferred to the bank. It is impossible for other systems to achieve this property without the proof from a trusted intermediary. That means the ownership of digital warehouse receipt has been changed to be bank's account.



```
----------------------------------------------------transfer------------------------------------------------------------------
--
Connect to Fabric gateway.
Use network channel: myhannel.
Use warehouse receipt smart contract.
Submit warehouse receipt transfer transaction.
Process transfer transaction response.{"class":"warehouse receipt","currentState":3,"faceValue":500000,"issueDateTime":"2023-0
4-28","issuer":"A","maturityDateTime":"2024-04-27","mspid":"Org3MSP","owner":"C","paperNumber":"00001","confirmDateTime":"2023
-04-28"}
warehouse receipt issued by A  : 00001 was successfully transferred
Transaction complete.
Disconnect from Fabric gateway.
Transfer program complete.
```

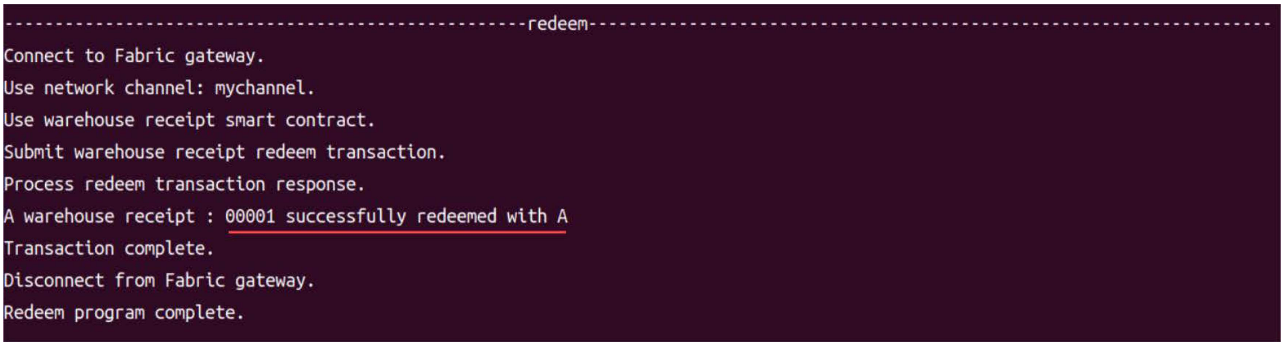
Figure 6. Transferring a digital warehouse receipt.

The warehouse redeems a digital warehouse receipt (see Fig. 7). When the supplier repays the loan principle and interest, the warehouse redeems the digital warehouse receipt from the bank. The warehouse revoke the smart contract for redeeming. The status of the digital warehouse receipt is changed from the bank's account to be the warehouse's account. The transaction is verified by the bank, the warehouse and the supplier. It means the finance has finished and whole transaction procedure has completed.

7.2. Performance test report and test environments

In designing the system, we use hardware and soft environments as list in Table 3.

To understand how the total number of transactions impact on throughput (TPS) and latency of blockchain, we test query transactions number varied from 500, 1000, 3000, 5000 and 10 000, respectively. Figure 8 illustrates



```
----------------------------------------------------redeem----------------------------------------------------
Connect to Fabric gateway.
Use network channel: mychannel.
Use warehouse receipt smart contract.
Submit warehouse receipt redeem transaction.
Process redeem transaction response.
A warehouse receipt : 00001 successfully redeemed with A
Transaction complete.
Disconnect from Fabric gateway.
Redeem program complete.
```

FIGURE 7. Redeeming a digital warehouse receipt.

TABLE 3. Environments for experiment.

Hardware Environments	Software Environments
4-core CPU	Linux Operating System (Ubuntu v22.04.1LTS)
4 GB Memory	VMware v16.2.4
100 GB Storage Space	Apache v2.0
	Fabric v2.4.9
	Docker v1.4.7
	Docker compose v1.29.2
	Go v1.18.1
	Fabric CA v1.5.5
	Git v2.34.1
	Couchdb v3.1.1
	Node.js v18.12.1
	Fabric explorer v1.1.8
	Caliper v0.5.0

the performance, mainly throughput and latency, of the query transaction at different send rates. From panel (a) in Figure 8, we can observe that the average latency is around 0.04 s, the minimum latency is 0.01 s, and the maximum latency is less than 0.24 s. The throughput increases from 87 to 149.8 times/second as the number of transactions increases ((b) in Fig. 8). The throughput of assets trading on Bitcoin is around 7 times/second, and on Ethereum is around 25 times/second. Therefore, the digital warehouse receipt trading system have potential for industrial application since the throughput is much higher than throughput of assets trading on Bitcoin and Ethereum networks. In supply chain financing, only designated organizations have the right to view and issue assets since different organizations have different roles in cooperation. Business logics are in sequence orders and each organization has a limited number of trading per day so that the throughout can satisfy the industrial uses. In conclusion, the performance of the blockchain-enabled digital warehouse receipt trading system is applicable for actual supply chain finance business.

8. CONCLUSIONS AND MANAGEMENT INSIGHTS

It is hard to monitor the inventory pledge transactions and verify warehouse receipts which is easy to be fraud by duplicate pledge in SCF. Blockchain can mitigate the shortcomings of the traditional IPF due to its transparency and smart contract. In this research, we use a stochastic demand model to illustrate the rationality of blockchain applied in IPF by considering fraudulent risk. We compare traditional IPF scheme, blockchain-enabled IPF scheme

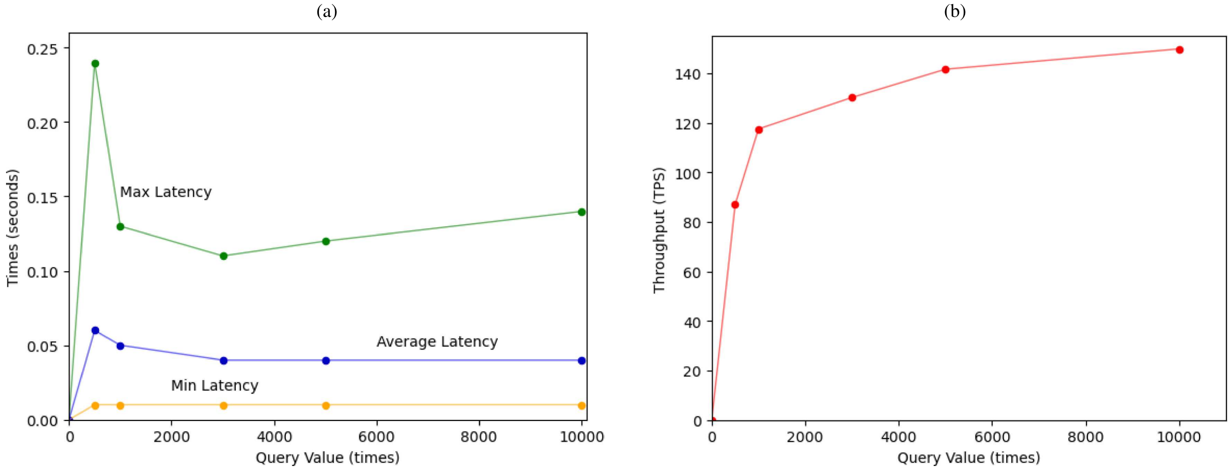


FIGURE 8. Performance test.

with benchmark the first best solution. We have the following result. Firstly, the loan interest rate for the SMEs can be reduced in blockchain-enabled IPF scheme since the bank can avoid the fraudulent risk by IoT devices and blockchain technology. Secondly, the buyer can decrease wholesale price and increase order quantity in blockchain-enabled IPF comparing with traditional IPF when fraudulent risk is higher than a threshold and the market demand is stable. Thirdly, blockchain-enabled IPF would benefit for supply chains if and only if the fraudulent risk is high since the saved loan interest can cover the IoT costs spent in inventory. In this condition, the buyer is better to chose blockchain-enabled IPF scheme. Moreover, we explained how the verification can be achieved by blockchain technology in practice. To demonstrate, we develop protocol to show how the warehouse recept is issued, purchased, transferred and redeemed in a privacy and monitored way on Hyperledger Fabric. When testing the performance of the system by Caliper, it shows that the TPS in the system is more than 80 times per second, which can meet needs of blockchain applications in industry.

Based on the above results, we can get managerial implications as follows. Firstly, the bank can monitor the inventory in a trust way by blockchain technology to reduce the interest rate in inventory pledge financing when the fraudulent risk is high. The financing risk is lower under blockchain-enabled inventory pledge financing since there is no fraudulent risk. The bank can execute some commitment by smart contract so as to improve the repayment on loan. Secondly, the buyer can decrease wholesale price and increases order quantity when giving the order under blockchain-enabled inventory pledge financing scheme. The wholesale price is decreased due to the reduced interest rate in financing. Given the other conditions, the buyer can increase order quantities in each order. Thirdly, the supplier and the warehouse can improve the infrastructure to ensure the authenticity of warehouse receipts. Only when the supplier and the warehouse participate in the financing, the market of inventory pledge financing can be expanded and the supply chain financing efficiency can be improved.

There are also some limitation of this paper. Firstly, our research is suitable for inventory pledge of general products, not for some special products. When pledging inventory of special products in special industries, the financial institutions need to consider other factors. For example, time cycle of product preservation is a key factor for pledging inventory of perishable products. For products with high market volatility, buying insurance or hedging tools needs to be considered to avoid risk in finance. Therefore, the financing theoretical models of some products will be different. Secondly, the system in this paper are only for digital asset issuance after being reviewed by regulators. When the regulator needs to review the issuance information of digital asset before issuance, there must be a corresponding audit mechanism to access to the system.

Future research directions can be extended. Our research are mainly focus on scenario of inventory financing in supply chain with the deploy of blockchain technology. Similarly, blockchain can be deployed in some other scenarios, such as commodities, property and so on. The researches on these scenarios could be quite different because of the different features of the assets and different requirement of users. Moreover, we can further discuss how the supply chain efficiency changes if endogenous default risk exists? What are the results if multi periods and multi products are considered in the extensio.

APPENDIX A. INVENTORY PLEDGE FINANCING DECISIONS BASED ON A PERMISSIONED BLOCKCHAIN BY CONTROLLING FRAUDULENT RISK

Proofs of propositions and corollaries

Proof of Proposition 1. We will present the proof for traditional IPF scheme. We firstly solve bank's competitive interest rate setting problem for any given (Q_{cl}, ω_{cl}) by backwards deduction. The bank's competitive interest rate setting equation in traditional IPF scheme is

$$\frac{(cQ_{cl} - B_0)(1 + r_f)}{\theta} = E[\min\{(cQ_{cl} - B_0)(1 + r_{cl}), \omega_{cl} \min\{Q_{cl}, D\}\}]. \tag{A.1}$$

From binding condition in (4), supplier's participant constraint in traditional IPF scheme is

$$\theta(\omega_{cl} E[\min\{Q_{cl}, D\}] - E[\min\{(cQ_{cl} - B_0)(1 + r_{cl}), \omega_{cl} \min\{Q_{cl}, D\}\}]) \geq B_0(1 + r_f) + (1 - \theta)cQ_{cl}. \tag{A.2}$$

Since the buyer's objective function is decreasing in ω_{cl}, (A.2) is binding optimally. Substitute (A.1) into (A.2), we have

$$\omega^*_{cl} \geq \frac{cQ^*_{cl}(1 + r_f) + (1 - \theta)cQ_{cl}}{\theta E \min\{Q^*_{cl}, D\}}. \tag{A.3}$$

Substitute (A.1) and (A.2) into (3), the buyer's profits function in traditional IPF scheme is

$$\begin{aligned}\Pi^{cl}_r &= \theta\{E[(p - \omega_{cl}) \min\{Q_{cl}, D\}] - c_e(Q_{cl} - D)^+\} \\ &= \theta p E[\min\{Q_{cl}, D\}] - cQ_{cl}(1 + r_f) - \theta c_e(Q_{cl} - D)^+ \\ &= \theta p \int_0^{Q_{cl}} \bar{F}(D)\,\mathrm{d}D - cQ_{cl}(1 + r_f) - \theta c_e \int_0^{Q_{cl}} F(D)\,\mathrm{d}D.\end{aligned} \tag{A.4}$$

Also note that,

$$\frac{\mathrm{d}\prod^{cl}_r}{\mathrm{d}Q_{cl}} = \theta p - \theta(p + c_e)F(Q_{cl}) - c(1 + r_f) \tag{A.5}$$

$$\frac{\mathrm{d}^2\prod^{cl}_r}{\mathrm{d}Q^2_{cl}} = -\theta(p + c_e)f(Q_{cl}) < 0 \tag{A.6}$$

$\frac{\mathrm{d}^2\prod^{cl}_r}{\mathrm{d}Q^2_{cl}}$ is concave, by solving its first condition, Q^*_{cl} is maximized at

$$\begin{aligned}Q^*_{cl} &= F^{-1}\left(\frac{\theta p + \theta c_e - \theta c_e - c(1 + r_f)}{\theta(p + c_e)}\right) \\ &= F^{-1}\left(1 - \frac{\theta c_e + c(1 + r_f)}{\theta(p + c_e)}\right).\end{aligned} \tag{A.7}$$

Substitute (A.7) into (A.3), we have

$$\omega^*_{cl} = \frac{cQ^*_{cl}(1 + r_f) + (1 - \theta)cQ_{cl}}{\theta E \min\{Q^*_{cl}, D\}}. \tag{A.8}$$

From (A.1), we can get the unique solution for r_{cl} to the equation

$$\begin{aligned}\frac{(cQ^*_{cl}-B_0)(1+r_f)}{\theta} = &\int_0^{(cQ^*_{cl}-B_0)(1+r_{cl})} z f_R(z)\,\mathrm{d}z \\ &+ (cQ^*_{cl}-B_0)(1+r_{cl})(1-F_R((cQ^*_{cl}-B_0)(1+r_{cl}))).\end{aligned} \tag{A.9}$$

□

Proof of Corollary 1. We analyze the sensitivity of parameters θ, c and c_e in Q^*_{cl}.

$$\frac{\partial Q^*_{cl}}{\partial \theta} = \frac{c(1+r_f)}{\theta^2(p+c_e)(f(Q^*_{cl}))} > 0 \tag{A.10}$$

$$\frac{\partial Q^*_{cl}}{\partial c} = -\frac{1+r_f}{\theta(p+c_e)(f(Q^*_{cl}))} < 0 \tag{A.11}$$

$$\frac{\partial Q^*_{cl}}{\partial c_e} = -\frac{[\theta p - c(1+r_f)]}{\theta(p+c_e)^2(f(Q^*_{cl}))} < 0. \tag{A.12}$$

In traditional IPF scheme, the optimal order quantity Q^*_{cl} is increasing in non-fraudulent rate θ, decreasing in product unit cost c and return processing cost per unit c_e. □

Proof of Corollary 2. Since the supplier participants in the trade if and only if the supplier can get profits, that is

$$\omega^*_{cl}\theta\bar{F}(Q^*_{cl}) - [c(1+r_f) + (1-\theta)cQ_{cl}] > 0. \tag{A.13}$$

□

Proof of Corollary 3. We analyze the sensitivity of parameters θ, and c in ω^*_{cl}. From Corollary 1, $\frac{\partial Q^*_{cl}}{\partial \theta} > 0$,

$$\begin{aligned}\frac{\partial \omega^*_{cl}}{\partial \theta} &= \frac{c(1+r_f+1-\theta)\frac{\partial Q^*_{cl}}{\partial \theta} - \omega^*_{cl}\int_0^{Q^*_{cl}}\bar{F}(D)\,\mathrm{d}D - \omega^*_{cl}\theta\bar{F}(Q^*_{cl})\frac{\partial Q^*_{cl}}{\partial \theta}}{\theta\int_0^{Q^*_{cl}}\bar{F}(D)\,\mathrm{d}D} \\ &= \frac{\frac{\partial Q^*_{cl}}{\partial \theta}[c(1+r_f+1-\theta) - \omega^*_{cl}\theta\bar{F}(Q^*_{cl})] - \omega^*_{cl}\int_0^{Q^*_{cl}}\bar{F}(D)\,\mathrm{d}D}{\theta\int_0^{Q^*_{cl}}\bar{F}(D)\,\mathrm{d}D} < 0.\end{aligned} \tag{A.14}$$

Similarly, from Corollary 1, $\frac{\partial Q^*_{cl}}{\partial c} < 0$,

$$\begin{aligned}\frac{\partial \omega^*_{cl}}{\partial c} &= \frac{c(1+r_f+1-\theta)\frac{\partial Q^*_{cl}}{\partial c} + Q^*_{cl}(1+r_f) - \omega^*_{cl}\theta\bar{F}(Q^*_{cl})\frac{\partial Q^*_{cl}}{\partial c}}{\theta\int_0^{Q^*_{cl}}\bar{F}(D)\,\mathrm{d}D} \\ &= \frac{\frac{\partial Q^*_{cl}}{\partial c}[c(1+r_f+1-\theta) - \omega^*_{cl}\theta\bar{F}(Q^*_{cl})]}{\theta\int_0^{Q^*_{cl}}\bar{F}(D)\,\mathrm{d}D} > 0\end{aligned} \tag{A.15}$$

ω^*_{cl} is decreasing in θ and increasing in c. □

Proof of Proposition 2. We firstly solve bank's competitive interest rate setting problem for any given (Q_{ss}, ω_{ss}) by backwards deduction. The bank's competitive interest rate setting equation in blockchain-enabled IPF scheme is

$$(cQ_{ss}-B_0)(1+r_f) = E[\min\{(cQ_{ss}-B_0)(1+r_{ss}), \omega_{ss}\min\{Q_{ss}, D\}\}]. \tag{A.16}$$

From binding condition in (8), supplier's participant constraint in blockchain-enabled IPF scheme is

$$\omega_{ss} E[\min Q_{ss}, D\}] - E[\min\{(cQ_{ss} - B_0)(1+r_{ss}), \omega_{ss}\min\{Q_{ss}, D\}] - c_g Q_{ss} \geq B_0(1+r_f). \tag{A.17}$$

Since the buyer's objective function is decreasing in ω_{ss}, (A.17) is binding optimally. Substitute (A.16) into (A.17), we have

$$\omega_{ss}^* \geq \frac{cQ_{ss}^*(1+r_f) + c_g Q_{ss}^*}{E\min\{Q_{ss}^*, D\}}\cdot \tag{A.18}$$

Substitute (A.16) and (A.17) into (6), the buyer's profits function in blockchain-enabled IPF scheme is

$$\begin{aligned}\Pi_r^{ss} &= \{E[(p-\omega_{ss})\min\{Q_{ss}, D\}] - c_e(Q_{ss}-D)^+\}\\ &= pE[\min\{Q_{ss}, D\}] - cQ_{ss}(1+r_f) - c_g Q_{ss} - c_e(Q_{ss}-D)^+\\ &= p\int_0^{Q_{ss}} \bar{F}(D)\,\mathrm{d}D - Q_{ss}[c(1+r_f)+c_g] - c_e\int_0^{Q_{ss}} F(D)\,\mathrm{d}D.\end{aligned} \tag{A.19}$$

Also note that,

$$\frac{\mathrm{d}\prod_r^{ss}}{\mathrm{d}Q_{ss}} = p - (p+c_e)F(Q_{ss}) - [c(1+r_f)+c_g] \tag{A.20}$$

$$\frac{\mathrm{d}^2\prod_r^{ss}}{\mathrm{d}Q_{ss}^2} = -(p+c_e)f(Q_{ss}) < 0 \tag{A.21}$$

$\frac{\mathrm{d}^2\prod_r^{ss}}{\mathrm{d}Q_{ss}^2}$ is concave, by solving its first condition, Q_{ss}^* is maximized at

$$\begin{aligned}Q_{ss}^* &= F^{-1}\left(\frac{p-c(1+r_f)-c_g}{(p+c_e)}\right)\\ &= F^{-1}\left(1 - \frac{c_e+c_g+c(1+r_f)}{(p+c_e)}\right)\cdot\end{aligned} \tag{A.22}$$

Substitute (A.22) into (A.18), we have

$$\omega_{ss}^* = \frac{cQ_{ss}^*(1+r_f) + c_g Q_{ss}^*}{E\min\{Q_{ss}^*, D\}}\cdot \tag{A.23}$$

From (A.16), we can get the unique solution for r_{ss} to the equation

$$\begin{aligned}(cQ_{ss}^* - B_0)(1+r_f) = &\int_0^{(cQ_{ss}^*-B_0)(1+r_{ss})} zf_R(z)\,\mathrm{d}z\\ &+ (cQ_{ss}^* - B_0)(1+r_{ss})(1 - F_R((cQ_{ss}^*-B_0)(1+r_{ss}))).\end{aligned} \tag{A.24}$$

□

Proof of Corollary 4. We analyze the sensitivity of parameters, c, c_g and c_e in Q_{ss}^*.

$$\frac{\partial Q_{ss}^*}{\partial c} = -\frac{1+r_f-c_g}{(p+c_e)(f(Q_{ss}^*))} < 0. \tag{A.25}$$

$$\frac{\partial Q_{ss}^*}{\partial c_g} = -\frac{1}{(p+c_e)(f(Q_{ss}^*))} < 0 \tag{A.26}$$

$$\frac{\partial Q_{ss}^*}{\partial c_e} = -\frac{p-c(1+r_f-c_g)}{(p+c_e)^2(f(Q_{ss}^*))} < 0. \tag{A.27}$$

Q_{ss}^* is decreasing in c, c_g and c_e. □

Proof of Corollary 5. Since the supplier participants in and gets profits from the trade if and only if

$$c_g + c(1 + r_f) - \omega^*_{ss}\bar{F}(Q^*_{ss}) < 0. \tag{A.28}$$

□

Proof of Corollary 6. We analyze the sensitivity of parameters, c and c_g in ω^*_{ss}. From Corollary 3, $\frac{\partial Q^*_{ss}}{\partial c} < 0$,

$$\frac{\partial \omega^*_{ss}}{\partial c} = \frac{Q^*_{ss}(1 + r_f) + \frac{\partial Q^*_{ss}}{\partial c}(c_g + c(1 + r_f) - \omega^*_{ss}\bar{F}(Q^*_{ss}))}{\int_0^{Q^*_{ss}} \bar{F}(D)\,\mathrm{d}D} > 0. \tag{A.29}$$

From Corollary 3, $\frac{\partial Q^*_{ss}}{\partial c_g} < 0$,

$$\frac{\partial \omega^*_{ss}}{\partial c_g} = \frac{Q^*_{ss} + \frac{\partial Q^*_{ss}}{\partial c_g}(c_g + c(1 + r_f) - \omega^*_{ss}\bar{F}(Q^*_{ss}))}{\int_0^{Q^*_{ss}} \bar{F}(D)\,\mathrm{d}D} > 0 \tag{A.30}$$

ω^*_{ss} is increasing in c and c_g. □

Proof of Proposition 3. In the first-best condition, we get

$$\begin{aligned} \Pi_{fb} &= E[(p - c)\min\{Q_{fb}, D\}] - cQ_{fb}(1 + r_f) \\ &= E[(p - c)(Q_{fb} - \int_0^{Q_{fb}} F(D)\,\mathrm{d}D)] - cQ_{fb}(1 + r_f). \end{aligned} \tag{A.31}$$

Also note that,

$$\frac{\mathrm{d}\prod_{fb}}{\mathrm{d}Q_{fb}} = (p - c)(1 - F(Q_{fb})) - c(1 + r_f) \tag{A.32}$$

$$\frac{\mathrm{d}^2\prod_{fb}}{\mathrm{d}Q_{fb}} = -(p - c)f(Q_{fb}) < 0 \tag{A.33}$$

$\frac{\mathrm{d}^2\prod_{fb}}{\mathrm{d}Q^2_{fb}}$ is concave, by solving its first condition, Q^*_{fb} is maximized at

$$Q^*_{fb} = F^{-1}\left(1 - \frac{c(1 + r_f)}{p - c}\right). \tag{A.34}$$

□

Proof of Proposition 4. Notice from (A.9), we have

$$\begin{aligned} \frac{(cQ^*_{cl} - B_0)(1 + r_f)}{\theta} &= \int_0^{(cQ^*_{cl}-B_0)(1+r_{cl})} z f_R(z)\,\mathrm{d}z + (cQ^*_{cl} - B_0)(1 + r_{cl})(1 - F_R((cQ^*_{cl} - B_0)(1 + r_{cl}))) \\ &= F_R(z)z\big|_0^{(cQ^*_{cl}-B_0)(1+r_{cl})} - \int_0^{(cQ^*_{cl}-B_0)(1+r_{cl})} F_R(z)\,\mathrm{d}z \\ &\quad + (cQ^*_{cl} - B_0)(1 + r_{cl})(1 - F_R((cQ^*_{cl} - B_0)(1 + r_{cl}))) \\ &= F_R((cQ^*_{cl} - B_0)(1 + r_{cl}))(cQ^*_{cl} - B_0)(1 + r_{cl}) - \int_0^{(cQ^*_{cl}-B_0)(1+r_{cl})} F_R(z)\,\mathrm{d}z \\ &\quad + (cQ^*_{cl} - B_0)(1 + r_{cl})(1 - F_R((cQ^*_{cl} - B_0)(1 + r_{cl}))) \end{aligned}$$

$$\begin{aligned} &= (cQ_{cl}^* - B_0)(1+r_{cl}) - \int_0^{(cQ_{cl}^*-B_0)(1+r_{cl})} F_R(z)\,\mathrm{d}z \\ &< (cQ_{cl}^* - B_0)(1+r_{cl}). \end{aligned} \tag{A.35}$$

From (A.35), we have

$$r_{cl}^* > \frac{1+r_f}{\theta} - 1. \tag{A.36}$$

Similarly,

$$r_{ss}^* > r_f. \tag{A.37}$$

From (A.9), we have

$$\begin{aligned} \frac{1+r_f}{\theta(1+r_{cl})} &= 1 - \frac{\int_0^{(cQ_{cl}^*-B_0)(1+r_{cl})} F_R(z)\,\mathrm{d}z}{(cQ_{cl}^*-B_0)(1+r_{cl})} \\ &= 1 - \bar{F}_R(z). \end{aligned} \tag{A.38}$$

From (A.24), we have

$$\begin{aligned} \frac{1+r_f}{(1+r_{ss})} &= 1 - \frac{\int_0^{(cQ_{ss}^*-B_0)(1+r_{ss})} F_R(z)\,\mathrm{d}z}{(cQ_{ss}^*-B_0)(1+r_{ss})} \\ &= 1 - \bar{F}_R(z). \end{aligned} \tag{A.39}$$

From (A.38) and (A.39), we have $\frac{1+r_f}{\theta(1+r_{cl}^*)} = \frac{1+r_f}{(1+r_{ss}^*)}$. Since $\theta \in [0,1]$, we get

$$r_{cl}^* > r_{ss}^*. \tag{A.40}$$

From (A.36), (A.37) and (A.40), we have

$$r_{cl}^* > r_{ss}^* > r_f. \tag{A.41}$$

□

Proof of Proposition 5. In traditional IPF scheme,

$$F(Q_{cl}^*) = \int_0^{Q_{cl}^*} f(D)\,\mathrm{d}D = 1 - \frac{\theta c_e + c(1+r_f)}{\theta(p+c_e)} > 0 \tag{A.42}$$

the right side of (A.41) is independent of $Var[D]$. There exists a $\varphi > 0$ such that if $Var[D] < \varphi$, then $Var[D] \to 0$, for any $D \neq E[D]$, $f(D) \to 0$. Hence, $\lim_{Var[D]\to 0}(Q_{cl}^*) = E[D]$. Similarly, $\lim_{Var[D]\to 0}(Q_{ss}^*) = E[D]$. Further, as $Var[D] \to 0$, $D \xrightarrow{p} E[D]$ as well,

$$\lim_{Var[D]\to 0} E[\min\{Q_{cl}^*, D\}] = E[D]. \tag{A.43}$$

Similarly, we have

$$\lim_{Var[D]\to 0} E[\min\{Q_{ss}^*, D\}] = E[D]. \tag{A.44}$$

Substitute (A.42) and (A.43) into (10) and (13), we have

$$\lim_{Var[D]\to 0}(\omega_{cl}^{*}-\omega_{ss}^{*}) = \frac{(1-\theta)c-\theta c_g}{\theta}. \tag{A.45}$$

By (A.44), $\omega_{cl}^{*} > \omega_{ss}^{*}$ if and only if $\theta \in [0, \frac{c}{c_g+c}]$, which means the wholesale price under traditional IPF scheme is higher than that under blockchain-enabled IPF scheme, because if the fraudulent of warehouse receipt happens in traditional IPF scheme, the principle and risk-free interest of cost for the product is higher than the IoT cost under non-fraudulent condition in blockchain-enabled IPF scheme. Otherwise, $\omega_{cl}^{*} \leq \omega_{ss}^{*}$ if and only if $\theta \in (\frac{c}{c_g+c}, 1]$. □

Proof of Proposition 6. When comparing the equilibrium order quantities, $Q_{ss}^{*} \leq Q_{cl}^{*}$ if and only if $F^{-1}(Q_{ss}^{*}) < F^{-1}(Q_{cl}^{*})$, that is

$$F^{-1}\left(1-\frac{c_e+c_g+c(1+r_f)}{(p+c_e)}\right) < F^{-1}\left(1-\frac{\theta c_e+c(1+r_f)}{\theta(p+c_e)}\right). \tag{A.46}$$

Since $F^{-1}(\cdot)$ is monotonically non-decreasing, (A.45) is satisfied if and only if $\theta \in (\frac{c(1+r_f)}{c_g+c(1+r_f)}, 1]$. Otherwise, $Q_{ss}^{*} > Q_{cl}^{*}$ if and only if $F^{-1}(Q_{ss}^{*}) > F^{-1}(Q_{cl}^{*})$ and $\theta \in [0, \frac{c(1+r_f)}{c_g+c(1+r_f)}]$. We compare the buyer's profits by (A.4) and (A.19), we have

$$\Pi_r^{ss} - \Pi_r^{cl} = (1-\theta)\{E[(p-\omega)]\min\{Q, D\} - c_e(Q-D)^{+}\}. \tag{A.47}$$

The buyer's profits is non-decreasing in Q^{*}. Therefore, $\Pi_r^{cl} < \Pi_r^{ss}$ if and only if $Q_{cl}^{*} \leq Q_{ss}^{*}$ and $\theta \in [0, \frac{c(1+r_f)}{c_g+c(1+r_f)}]$. $\Pi_r^{cl} > \Pi_r^{ss}$ if and only if $Q_{cl}^{*} > Q_{ss}^{*}$ and $\theta \in (\frac{c(1+r_f)}{c_g+c(1+r_f)}, 1]$. □

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Data availability statement

The name of repository is Github, link is `https://github.com/zhanglivy/WarehouseReceiptDoubleChannel/tree/main` [53].

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