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The impacts of blockchain adoption in fourth party logistics service quality management

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A B S T R A C T

Blockchain technology has attracted widespread attention due to its advantages of decentralization, as well as non-tampering, transparency, and traceability of information. Fourth-party logistics systems that do not use blockchain incur transaction costs and service quality losses due to the inability to fully control the delivery process, whereas the use of blockchain eliminates the transaction costs and quality losses, but the use of blockchain needs implementation and marginal use costs. To study the conditions for the use of blockchain technology, consider the fourth-party logistics system does not use and uses blockchain technology, and the equilibrium strategies in the two cases are compared. Numerical experiments show that there exists a certain range of blockchain costs which leads to a Pareto improvement in profits for both fourth-party logistics and third-party logistics and an improvement in the quality of logistics services when using blockchain.

1. Introduction

Globalization and the expansion of supply chain networks have made logistics systems increasingly complex, with more members directly or indirectly involved in the supply chain network (Choi et al., 2001; Wang et al., 2022). This complexity creates challenges related to communication and transparency, resulting in inefficiencies in the logistics process. At the same time, the expectations of all participants in the supply chain for transparency, reliability, and service are gradually increasing (Dutta et al., 2020; Xin and Xu, 2022). As logistics supply chains become more and more complex, leading to difficulties in logistics tracking and tracing, and most collaboration is done manually and offline leading to redundancies and errors. Blockchain is gradually emerging as a possible solution to these challenges due to its immutable, decentralized, and traceable characteristics (Centobelli et al., 2022). Blockchain technology has the following advantages in the logistics field: improves supply chain transparency and traceability; reduces process complexity; improves compliance, reduces human errors, lowers transaction costs, and improves operational efficiency (Orji et al., 2020; Pournader et al., 2019). For example, Cainiao uses "second order exchange" blockchain technology to cover key ports, open the data between shipping companies and ports, establish process-oriented collaboration and mutual trust, and establish an order exchange platform that is visible, time-controllable, and risk-preventable. In addition, through blockchain and other information technology, China Storage and Intelligent Transportation has fully collaborated with various links such as warehousing and transportation and constructed a scale and efficient service network system. However, despite the advantages of blockchain technology, there are costs to implement blockchain technology, and the time consumed increases as the complexity of the blockchain increases. Dutta et al. (2020) argued that the cost of using blockchain technology is not cheap and that there should be a selective application of blockchain after considering the economics of implementation. Kumar et al. (2020) provided a systematic approach to measure the economics of blockchain technology adoption from cost and risk perspectives and suggested that blockchain solutions should be used selectively and should not be applied to all business problems. Peck (2017) evaluated the cost-benefit analysis of implementing blockchain technology and the feasibility analysis of scaling up its use in the future. Rimba et al. (2017, 2020)

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demonstrated the importance of computational and storage costs of executing business processes on blockchain can be two orders of magnitude higher than on a common cloud server (Amazon SWF). Therefore, companies and supply chains need to comprehensively analyze the strategic changes in the selection and use of blockchain technologies, accurately estimate their economic outcomes, and assess the impact on the entire supply chain (De Giovanni, 2020).

Currently, the 4PL mainly uses internet logistics platforms to manage delivery, warehousing, and cross-border logistics, and to overcome the limitations of internet logistics, the 4PL can choose to use blockchain technology effectively. Accurate analysis and overall assessment of blockchain applications encompasses both positive advantages and negative impacts on the business, management, operations, supply chain, and stakeholders (Dolgui et al., 2020). On the one hand, the use of blockchain eliminates transaction costs and losses caused by uncontrollability in internet logistics. On the other hand, supply chain members face costs associated with blockchain implementation and management. Therefore, this paper focuses on whether the use of blockchain can benefit both parties and whether blockchain can increase the effort level of 3PL thereby improving the quality of logistics services. To investigate the conditions for the implementation and impact of using blockchain on the quality of logistics services, a game problem of a logistics service supply chain consisting of a 4PL and a 3PL is considered in the case where the 4PL and 3PL act as the dominant players when the logistics system is not used and used blockchain technology, respectively. The sequence of the event is the client seeks logistics services from the 4PL, the 4PL decides on the retail price and offers the 3PL a revenue-sharing contract, and the 3PL decides on the wholesale price and the level of effort to be expended for delivery and performs the actual delivery. When blockchain is not used, each transaction incurs a marginal transaction cost and incurs a loss in service quality due to the inability to fully control the 3PL's delivery process. Therefore, the use of blockchain eliminates the transaction costs and loss of service quality, but there are fixed and marginal usage costs of implementing blockchain. The optimal strategies and the profits of 4PL and 3PL are solved for the case of not using and using blockchain and the results are compared to determine under what conditions it is economically advantageous to implement blockchain and the impact of using blockchain on the quality of logistics services. Numerical experiments show that there exists a range of marginal costs of blockchain such that the use of blockchain gives a Pareto improvement in the profits of both 4PL and 3PL and an improvement in the quality of logistics services.

The paper is organized as follows. Section 2 reviews the literature on blockchain and supply chain management. Section 3 describes the game of not using and using blockchain. Sections 4 and 5 model and solve the game models without and with blockchain, respectively. Section 6 compares and analyzes the equilibrium strategies and profits of the game using numerical experiments. Section 7 concludes the paper with general conclusions. All proof is in the Appendix.

2 Literature review

In terms of the impact of blockchain on supply chain management, Babich and Hilary (2020) identified three research themes of blockchain technology in the field of operations management: information, automation, and tokenization. Many scholars have also focused on the research of blockchain technology in the field of supply chain finance (Dong et al., 2023; Chod et al., 2020; Du et al., 2020), blockchain-enabled traceability in food supply chains (Dong et al., 2023; Saurabh and Dey, 2021; Casino et al., 2021), and the application of smart contracts (Zheng et al., 2020; Zhang et al., 2021). Blockchain technology can also be effectively used for client order process management and to improve the efficiency, traceability, and visibility of orders (Martinez et al., 2019). Biswas et al. (2023) addressed consumer distrust in product quality through blockchain technology, but high energy consumption of blockchain negatively affects the environment, thus using a game theoretic model to investigate the trade-offs between traceability and sustainability for blockchain adoption, which showed that high levels of distrust drive firms to avoid implementing blockchain, and conversely, low levels of distrust can make blockchain an appropriate technology. Keskin et al. (2023) studied the adoption of blockchain technology for retailers in the fresh produce industry to obtain more transparent information about product freshness and quantified the value of using blockchain by comparing it to the case of traditional retailers without blockchain, extending the model and analysis to the case of smart contracts. Chang et al. (2021) used a newsboy model to study the strategic decision-making for the selection of the optimal level of adoption of blockchain technology. De Giovanni (2020) studied a supply chain consisting of suppliers and retailers that can be managed through traditional online platforms or blockchain. The use of blockchain removes all the risks from the supply chain and saves on transaction costs. However, the use of blockchain costs initial implementation investment and variable costs. The results of this study identified the conditions under which blockchain is not worth implementing and the applicability of smart wholesale price contracts and smart revenue-sharing contracts. Zhang et al. (2023) argued that there is a need to balance the benefits and costs associated with the implementation of blockchain and construct a dual-channel supply chain in which the manufacturer sells its products through both direct and retail sales channels. Through the analysis, it was found that the blockchain adoption strategy of the supply chain members depends on the unit blockchain operating cost, direct sales cost, and demand volatility. Shi et al. (2023) summarized the innovative applications of blockchain in different kinds of platforms and investigated the value of different blockchain features in the field of operations management.

In terms of blockchain applications in logistics, Tijan et al. (2019) argued that the introduction of blockchain technology can minimize major challenges in logistics such as order delays, damaged goods, errors, and multiple data entries. Li et al. (2019) proposed a blockchain-enabled workflow operating system for e-commerce logistics services to centrally share heterogeneous logistic resources from different clients. Choi et al. (2019) discussed how the mean-variance methodology can be applied to explore the global supply chain operational risks in the era of blockchain technology. Orji et al. (2020) proposed a technology-organization-environment theoretical framework of key factors affecting the successful adoption of blockchain technology in the cargo logistics industry and prioritized them using an analytical network process, which showed that specific blockchain tool availability, infrastructure, and government policy and support are the three most important factors influencing the adoption of blockchain in the freight logistics industry. Ar et al. (2020) used a quantitative approach to study the feasibility of blockchain technology in the logistics industry based on intuitionistic fuzzy theory, and the decision-making framework enables decision-makers to assess the feasibility of blockchain in logistics operations. It can be seen that the research on blockchain technology in the logistics field regarding the perspective of logistics operation and management is still in a blank state.

3. The model

To study the impact of blockchain in logistics systems on the strategies and profits of 4PL and 3PL, consider the game models of a logistics service supply chain consisting of a 4PL and a 3PL under a logistics system not using blockchain (hereafter referred to as the traditional game) and a logistics system using blockchain (hereafter referred to as the blockchain game) dominated by the 4PL and the 3PL, respectively, and compare and analyze the equilibrium results and profits under the four scenarios. Table 1 summarizes all the notations used in this paper.

Table 1
Summary of notation

Symbol	Definition
λ	Market potential
β	Sensitivity of client demand to price
s	Logistics service quality
k	Sensitivity of client demand to service quality
m	Marginal profit of 4PL
r	Lost quality of logistics service
φ	Revenue sharing parameter
c_t	4PL's marginal transaction cost when not using blockchain
c_d	3PL's marginal delivery cost
c_e	3PL's cost coefficient of effort
c_B	Marginal cost of blockchain
F	Fixed cost of setting up the blockchain
t	Fixed cost of using the blockchain
Decision variables	
p	4PL's unit price of logistics services
w	3PL's wholesale price of logistics services
e	3PL's level of effort

4. Logistics systems not using blockchain

In the traditional game model, the client's demand function is

$$D_t = \lambda - \beta p_t + k s_t$$

where λ is the market potential, which represents the market size. p_t is the unit price of logistics services, $p_t = w_t + m_t$, which indicates that the unit price is the sum of the wholesale price w_t and the marginal profit m_t of 4PL, and β is the client's sensitivity to price. $s_t = (1 - r)e_t$ is the logistics service quality, $r \in (0,1)$ represents service quality lost due to insufficient control of delivery, and k represents the client's sensitivity to service quality. The profit functions for 4PL and 3PL are respectively

$$\Pi_t = \max_{p_t}\big((1-\varphi)p_t - w_t - c_t\big)D_t$$

$$\pi_t = \max_{w_t,e_t}(\varphi p_t + w_t - c_d)D_t - c_e e_t^2$$

where φ is the revenue sharing parameter representing the proportion of revenue that 4PL gives to 3PL, c_t is the marginal transaction cost of 4PL, c_d is the marginal delivery cost of 3PL, $c_e e_t^2$ represents the effort cost of 3PL, c_e is the coefficient of effort cost, and e_t is the effort level of 3PL.

4.1 The model dominated by 4PL

In this scenario, the logistics market is controlled by a large 4PL, and the scenario is modeled as a typical Stackelberg game in which the 4PL is the leader and the 3PL is the follower. The 4PL decides the unit price of the logistics service p, the 3PL decides the logistics service wholesale price w, and the level of effort e. The timing of the events is as follows: (i) the client seeks the logistics service from the 4PL, the 4PL sets the unit price p of the logistics service and offers the 3PL a revenue sharing contract; (ii) the 3PL decides the wholesale price w and the delivery effort e of the logistics service and delivers. Therefore, the equilibrium outcome of the game when the 4PL dominates in the traditional game is shown in Lemma 1.

Lemma 1 In the traditional game, the optimal strategy and the profits of 4PL and 3PL are

$$m_{t1}^* = \frac{\left(4\beta c_e\lambda - k^2(1-r)^2(\lambda+\beta c_t)\right)(\varphi+1)^2 + 4\beta^2 c_e\left(c_t(1+\varphi)-c_d\right) + k^2(1-r)^2\beta c_d\left(1-\varphi^2\right)}{2\beta\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)},$$

$$w_{t1}^* = \frac{k^2(1-r)^2(1+\varphi)\left(\lambda\varphi+\beta\left(c_t\varphi+c_d(\varphi-2)\right)\right)+2\beta c_e\lambda\left(1-2\varphi^2-2\varphi\right)+2\beta^2 c_e(3c_d-c_t-2c_t\varphi)}{2\beta\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)},$$

$$e_{t1}^* = \frac{k(\varphi+1)(1-r)\left(\lambda-\beta(c_d+c_t)\right)}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)},$$

$$p_{t1}^* = \frac{2\beta c_e\lambda(3+2\varphi)+2\beta^2 c_e(c_d+c_t)-k^2(1-r)^2(\varphi+1)\left(\lambda+\beta(c_d+c_t)\right)}{2\beta\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)},$$

$$D_{t1}^* = \frac{\left(k^2 r(1-r)(\varphi+1)+2\beta c_e\right)\left(\lambda-\beta(c_d+c_t)\right)}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)},$$

$$\Pi_{t1}^* = \frac{c_e\left(\lambda-\beta(c_d+c_t)\right)^2}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)},$$

$$\pi_{t1}^* = \frac{c_e(\varphi+1)\left(\lambda-\beta(c_d+c_t)\right)^2\left(4\beta c_e-k^2(1-r)^2(\varphi+1)\right)}{4\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)^2}.$$

The conditions $\lambda > \beta(c_t + c_d)$ and $2\beta c_e(\varphi + 2) > k^2(1-r)^2(\varphi+1)$ need to be satisfied to ensure that the strategy is feasible for the model and that the profits are positive. The condition $\lambda > \beta(c_t + c_d)$ indicates that a sufficiently high market size is required for the execution of the transaction, and the condition $2\beta c_e(\varphi + 2) > k^2(1-r)^2(\varphi+1)$ indicates that there is a relationship between the client's price sensitivity β and the service quality sensitivity k.

In the traditional game, the transaction cost c_t and the loss r due to the lack of control over service quality represent the inefficiency of the transaction. According to Lemma 1, the effects of transaction inefficiencies c_t and r on the behavior of 4PL and 3PL in the traditional game are further analyzed to obtain Corollary 1.

Corollary 1 In the traditional game, the effects of transaction cost c_t and service quality loss r on strategy and profit are as follows:

(i) The 3PL's effort level e_t^*, the wholesale price of logistics services w_{t1}^*, and the unit price of logistics services p_{t1}^* are monotonically decreasing with respect to transaction costs c_t and r.
(ii) The client's demand D_{t1}^* is monotonically decreasing concerning the transaction cost c_t, and the client's demand varies concerning the loss r as follows: when $r < \frac{\varphi}{2(\varphi+1)}$ and $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{\varphi-2r(\varphi+1)}$, $\frac{\partial D_{t1}^*}{\partial r} > 0$; when $r < \frac{\varphi}{2(\varphi+1)}$ and $\frac{k^2(1-r)^2(\varphi+1)}{\varphi+2} < 2\beta c_e < \frac{k^2(1-r)^2(\varphi+1)}{\varphi-2r(\varphi+1)}$, or when $\frac{\varphi}{2(\varphi+1)} < r < 1$, $\frac{\partial D_{t1}^*}{\partial r} < 0$.
(iii) The 4PL's profit Π_{t1}^* is monotonically decreasing concerning the transaction cost c_t and loss r. 3PL's profit is monotonically decreasing concerning the transaction cost c_t and varies concerning r as follows: when $\frac{k^2(1-r)^2(\varphi+1)}{\varphi+2} < 2\beta c_e < \frac{k^2(1-r)^2(\varphi+1)}{2-\varphi}$, $\frac{\partial \pi_{t1}^*}{\partial r} > 0$ and $\frac{\partial \pi_{t1}^*}{\partial r} < 0$ when $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{2-\varphi}$.

According to Corollary 1(i), as the transaction cost c_t increases, the 3PL reduces the effort exerted in delivery, and thus the transaction cost has a disincentive effect on the effort exerted by the 3PL. In addition, the increase in service quality loss r during the delivery process causes a decrease in service quality and leads to a decrease in the attractiveness of the logistics service to the client, thus the 3PL plans to exert less effort. Transaction costs c_t and losses r lead to lower wholesale prices offered by the 3PL because the 3PL offsets the demand reduction and balances the overall inefficiency caused by uncertain delivery services by lowering wholesale prices. In addition, lower service quality caused by the reduction in 3PL's effort level hurts sales volume, and 3PL balances the impact on demand losses by lowering wholesale price.

From Corollary 1(ii), it can be found that an increase in transaction cost c_t reduces the convenience of trading and leads to a decrease in demand. In addition, an increase in the loss of service quality r in the delivery process affects client demand as follows: when the loss of service quality is small and the client is more price sensitive, demand increases as the loss increases. This is because, as the loss increases, the unit price of logistics services is decreases, and when the client's sensitivity to the unit price of logistics services is high, the number of clients attracted by the price reduction is more than the number of clients reduced by the quality reduction. On the contrary, when the loss is small and the client's price sensitivity is low, the demand decreases as the loss increases, this is because as the loss increases, the unit price of logistics services decreases, when the client's sensitivity to the unit price of logistics services is low, the number of clients attracted by the decrease in price is less than the number of clients reduced by the decrease in quality. Finally, when losses are high, as losses increase, the quality of logistics services affects clients to a greater extent than the unit price affects clients, so the quantity demanded by clients decreases as losses increase.

From Corollary 1(iii), it can be seen that transaction cost c_t and service quality loss r hurt the economic efficiency of 4PL and that the increase in transaction cost reduces the profit of 3PL. In addition, the effect of transaction losses on the profit of 3PL is as follows: when the client's sensitivity to price is low, with the increase of losses, the profit of 3PL increases; when the client's sensitivity to price is high, with the increase of losses, the profit of 3PL decreases. This is because as losses increase, all decision variables decrease, but when clients are less sensitive to price, the decrease in the 3PL's revenue is less than the decrease in their costs, so the 3PL's profits increase; while when clients are more sensitive to price, the decrease in the 3PL's revenue is greater than the decrease in their costs, so the 3PL's profits decrease.

4.2 The model dominated by 3PL

In this case, a 4PL and a strong 3PL form a typical Stackelberg game, in which the 3PL is the leader and the 4PL is the follower. The sequence of decision-making is: the 3PL decides the wholesale price and effort level of logistics services, and then the 4PL decides the retail price. Therefore, when the 3PL dominates in the traditional game without using blockchain technology, the equilibrium of the game is shown in Lemma 2.

Lemma 2 In the traditional game, the optimal strategies as well as the profits of 4PL and 3PL are, respectively

$$w_{t2}^* = \frac{k^2(1-r)^2\left(c_t\varphi - c_d(1-\varphi)\right) + 4\beta c_e\left(c_d(1-\varphi) - c_t\right) + 4c_e\lambda(1-\varphi)^2}{4\beta c_e(2-\varphi) - k^2(1-r)^2},$$
$$e_{t2}^* = \frac{k(1-r)(\lambda - \beta(c_d + c_t))}{4\beta c_e(2-\varphi) - k^2(1-r)^2},$$
$$p_{t2}^* = \frac{2\lambda c_e(3-2\varphi) - \left((1-r)^2k^2 - 2\beta c_e\right)(c_d + c_t)}{4\beta c_e(2-\varphi) - k^2(1-r)^2},$$
$$D_{t2}^* = \frac{2\beta c_e(\lambda - \beta(c_d + c_t))}{4\beta c_e(2-\varphi) - k^2(1-r)^2},$$
$$\Pi_{t2}^* = \frac{4\beta {c_e}^2(1-\varphi)(\lambda - \beta(c_d + c_t))^2}{\left(4\beta c_e(2-\varphi) - k^2(1-r)^2\right)^2},$$
$$\pi_{t2}^* = \frac{c_e(\lambda - \beta(c_d + c_t))^2}{4\beta c_e(2-\varphi) - k^2(1-r)^2}.$$

Conditions $4\beta c_e(2-\varphi) > k^2(1-r)^2$ and $\lambda > \beta(c_t + c_d)$ ensure that the strategy and profit are positive, where condition $4\beta c_e(2-\varphi) > k^2(1-r)^2$ indicates that a certain relationship needs to be satisfied between the client's price sensitivity β and service quality sensitivity k. Condition $\lambda > \beta(c_t + c_d)$ suggests that transaction execution requires a sufficiently high market size.

In the traditional game, the transaction cost c_t and the loss r caused by the lack of control over service quality represent the inefficiency of the transaction. According to Lemma 2, Corollary 2 can be obtained, which focuses on analyzing the effects of the inefficiency factors c_t and r of transactions on the behavior of 4PL and 3PL in the traditional game.

Corollary 2 In the traditional game, the effects of transaction cost c_t and service quality loss r on strategy as well as profit are as follows:

(i) 3PL's effort level e_{t2}^*, client's demand D_{t2}^*, wholesale price of logistics service w_{t2}^*, 4PL's profit Π_{t2}^* and 3PL's profit π_{t2}^* are monotonically decreasing with respect to the transaction cost c_t and loss r.
(ii) The unit price of logistics services p_{t2}^* is monotonically decreasing concerning the loss r. p_{t2}^* with respect to transaction cost c_t varies as follows: $\frac{\partial p_{t2}^*}{\partial c_t} < 0$ when $\frac{k^2(1-r)^2}{2(2-\varphi)} < 2\beta c_e < k^2(1-r)^2$; and $\frac{\partial p_{t2}^*}{\partial c_t} > 0$ when $2\beta c_e > k^2(1-r)^2$.

According to Corollary 2(i), as the transaction cost c_t increases, the 3PL reduces the effort made, and thus the transaction cost has a disincentive effect on the effort made by the 3PL. In addition, the increase in service quality loss r during the delivery causes a decrease in service quality, resulting in the logistics service being less attractive to clients, and therefore the 3PL intends to exert less effort. An increase in transaction cost c_t reduces the convenience of transaction resulting in a decrease in demand and an increase in service quality loss similarly reduces the amount of demand from clients. For the 3PL, the lower quality of service caused by the reduction in level of effort is known to hurt demand, and thus the 3PL offsets the demand reduction and balances the overall inefficiency caused by the uncertainty of delivery service by reducing the wholesale price. Transaction costs c_t and service quality losses r hurt the economic efficiency of 4PL and 3PL, because as transaction costs and losses increase, the reduction in demand leads to a reduction in profits for both parties.

Corollary 2(ii) shows that for the 4PL, when clients are less sensitive to service quality, the 4PL offsets the decrease in demand caused by the increase in transaction costs by increasing the retail price, and when clients are more sensitive to service quality, it prevents the loss caused by the sharp decrease in client demand due to the decrease in service quality by reducing the retail price.

5. Logistics systems using blockchain

This section examines the strategic choice of 4PL and 3PL as leaders in the logistics supply chain when the logistics system uses blockchain, respectively.

5.1 The model dominated by 4PL

In the game using blockchain, the client's demand function is

$$D_B = \lambda - \beta p_B + k s_B$$

where s_B is the quality of logistics service, and assumed that $s_B = e_B$, which indicates that the quality of logistics service in the blockchain game depends entirely on the level of effort of the 3PL. Referring to Liu et al. (2018), it is assumed that the unit price of logistics service $p_B = w_B + m_B$, which indicates that the unit price of logistics service is the sum of the wholesale price w_B and the marginal profit m_B of 4PL.

The profit functions of 4PL and 3PL are respectively

$$\Pi_B = \max_{p_B}\big((1-\varphi)p_B - w_B - c_B\big)D_B - F$$
$$\pi_B = \max_{w_B, e_B}(\varphi p_B + w_B - c_d)D_B - c_e e_B^2 - t$$

where φ is the revenue sharing parameter, c_B is the marginal cost of using the blockchain, and F is the fixed cost to implement the blockchain. t is the cost of using the blockchain by the 3PL, e.g., the cost of training employees to use blockchain.

In the 4PL-dominated blockchain game, the equilibrium of the game is shown in Lemma 3.

Lemma 3 In the blockchain game, the optimal strategies as well as the profits of 4PL and 3PL are respectively,

$$m_{B1}^* = \frac{(4\beta c_e\lambda - k^2\lambda - k^2\beta c_B)(\varphi+1)^2 + 4\beta^2 c_e(c_B(\varphi+1) - c_d) + k^2\beta c_d(1-\varphi^2)}{2\beta\big(2\beta c_e(\varphi+2) - k^2(\varphi+1)\big)},$$
$$w_{B1}^* = \frac{\big((\lambda+\beta c_B)\varphi + \beta c_d(\varphi-2)\big)k^2(\varphi+1) + 2\beta c_e\big(3\beta c_d - \beta c_B(2\varphi+1) + \lambda(1-2\varphi-2\varphi^2)\big)}{2\beta\big(2\beta c_e(\varphi+2) - k^2(\varphi+1)\big)},$$
$$e_{B1}^* = \frac{k(\varphi+1)\big(\lambda - \beta(c_B+c_d)\big)}{2\big(2\beta c_e(\varphi+2) - k^2(\varphi+1)\big)},$$
$$p_{B1}^* = \frac{2\beta c_e\big(\lambda(3+2\varphi) + \beta(c_B+c_d)\big) - k^2(\varphi+1)\big(\lambda + \beta(c_B+c_d)\big)}{2\beta\big(2\beta c_e(\varphi+2) - k^2(\varphi+1)\big)},$$
$$D_{B1}^* = \frac{\beta c_e\big(\lambda - \beta(c_B+c_d)\big)}{2\beta c_e(\varphi+2) - k^2(\varphi+1)},$$
$$\Pi_{B1}^* = \frac{c_e\big(\lambda - \beta(c_B+c_d)\big)^2}{2\big(2\beta c_e(\varphi+2) - k^2(\varphi+1)\big)} - F,$$
$$\pi_{B1}^* = \frac{c_e\big(4\beta c_e(\varphi+1) - k^2(\varphi+1)^2\big)(\beta(c_B+c_d) - \lambda)^2 - 4t\big(2\beta c_e(\varphi+2) - k^2(\varphi+1)\big)^2}{4\big(2\beta c_e(\varphi+2) - k^2(\varphi+1)\big)^2}.$$

Conditions $2\beta c_e(\varphi+2) > k^2(\varphi+1)$ and $\lambda > \beta(c_B + c_d)$ ensure that the blockchain model has positive strategies and profits. Condition $2\beta c_e(\varphi+2) > k^2(\varphi+1)$ denotes the magnitude of the relationship that needs to be satisfied between the client's sensitivity to price and sensitivity to the quality of logistics services. The condition $\lambda > \beta(c_B + c_d)$ indicates that the implementation of blockchain technology requires a sufficiently high market opportunity.

Corollary 3 In the blockchain game, the effects of the blockchain marginal cost c_B on the optimal strategy as well as the profit: the effort level of 3PL e_{B1}^*, the wholesale price w_{B1}^* of the logistics service provided by 3PL, and the profits of both 4PL and 3PL are monotonically decreasing concerning the blockchain marginal cost c_B. The retail price of the logistics service p_{B1}^* set by 4PL varies with respect to the blockchain marginal cost c_B as: $\frac{\partial p_{B1}^*}{\partial c_B} < 0$ when $\frac{k^2(\varphi+1)}{\varphi+2} < 2\beta c_e < k^2(\varphi+1)$; and $\frac{\partial p_{B1}^*}{\partial c_B} > 0$ when $2\beta c_e > k^2(\varphi+1)$.

When clients are more sensitive to service quality, the retail price decreases as the marginal cost of using the blockchain increases; when clients are less sensitive to quality, the retail price increases as the marginal cost of using the blockchain increases. This is because when the client's sensitivity to quality is low, the value brought by using blockchain is low, and as the cost of using blockchain increases, the 4PL needs to increase the retail price to compensate for the loss of revenue.

5.2 The model dominated by 3PL

In this case, the 4PL and the strong 3PL form a typical Stackelberg game, in which the 3PL is the leader and the 4PL is the follower, and the sequence of decision-making is as follows: the 3PL decides on the wholesale price of the logistics service and the level of effort, and then the 4PL decides on the retail price. As the leader of the logistics system, the 3PL leads the application and implementation of the blockchain technology, and the implementation cost of the blockchain is F, while the 4PL as a follower incurs the cost of using the blockchain such as the training cost t of using the blockchain. Assuming that there is no difference in the implementation of the blockchain technology by the 4PL or the 3PL, then the client's logistic service demand function is identical to the demand function of the blockchain system dominated by the 4PL.

In the game using blockchain, the client's demand function is

$$D_B = \lambda - \beta p_B + k s_B$$

where s_B is the logistics service quality, assuming that $s_B = e_B$, which indicates that the logistics service quality in the blockchain game depends entirely on the effort level of 3PL.

The profit functions of 4PL and 3PL are respectively,

$$\Pi_B = \max_{p_B}\big((1-\varphi)p_B - w_B\big)D_B - t$$
$$\pi_B = \max_{w_B,e_B}(\varphi p_B + w_B - c_d - c_B)D_B - c_e e_B^2 - F$$

where φ is the revenue sharing parameter, F is the fixed cost spent by the 3PL to implement blockchain technology, which is entirely covered by the 3PL, and c_B is the marginal cost for the 3PL to use the blockchain. t is the fixed cost for the 4PL to use the blockchain, which includes the cost of training employees to use the blockchain and so on.

In the blockchain game dominated by 3PL, the equilibrium of the game is shown in Lemma 4.

Lemma 4 In the blockchain game, the optimal strategies as well as profits of 4PL and 3PL are respectively,

$$e_{B2}^* = \frac{k\big(\lambda-\beta(c_d+c_B)\big)}{4(2-\varphi)\beta c_e-k^2}$$
$$w_{B2}^* = (1-\varphi)\frac{4(1-\varphi)\lambda c_e+\big(4\beta c_e-k^2\big)(c_d+c_B)}{4(2-\varphi)\beta c_e-k^2}$$
$$p_{B2}^* = \frac{2(3-2\varphi)c_e\lambda-\big(k^2-2\beta c_e\big)(c_d+c_B)}{4(2-\varphi)\beta c_e-k^2}$$
$$\Pi_{B2} = \frac{4(1-\varphi)\beta c_e^2\big(\lambda-\beta(c_d+c_B)\big)^2}{(4(2-\varphi)\beta c_e-k^2)^2} - t$$
$$\pi_{B2} = \frac{c_e\big(\lambda-\beta(c_d+c_B)\big)^2}{4(2-\varphi)\beta c_e-k^2} - F$$

Conditions $4(2-\varphi)\beta c_e > k^2$ and $\lambda > \beta(c_B + c_d)$ need to be satisfied, which ensures that the strategies and profits of both parties are positive under the 3PL dominated blockchain model. Condition $4(2-\varphi)\beta c_e > k^2$ indicates that there is a relationship between client sensitivity to price and sensitivity to logistics service quality. Condition $\lambda > \beta(c_B + c_d)$ indicates that the implementation of blockchain technology requires a high enough market opportunity.

Corollary 4 In the blockchain game, the effect of blockchain marginal cost c_B on the optimal strategy as well as profit is respectively,

(i) 3PL's effort level e_{B2}^*, the profits of both 4PL and 3PL are monotonically decreasing concerning the blockchain marginal cost c_B.
(ii) The retail price of logistics service p_{B2}^* set by 4PL varies with respect to the blockchain marginal cost c_B as $\frac{\partial p_{B2}^*}{\partial c_B} = \frac{-(k^2-2\beta c_e)}{4(2-\varphi)\beta c_e-k^2}$, then $\frac{\partial p_{B2}^*}{\partial c_B} < 0$ when $2\beta c_e < k^2 < 4(2-\varphi)\beta c_e$; $\frac{\partial p_{B2}^*}{\partial c_B} > 0$ when $0 < k^2 < 2\beta c_e$.
(iii) The wholesale price of logistics service w_{B2}^* varies with respect to the blockchain marginal cost c_B as $\frac{\partial w_{B2}^*}{\partial c_B} = \frac{(1-\varphi)(4\beta c_e-k^2)}{4(2-\varphi)\beta c_e-k^2}$, then when $4\beta c_e < k^2 < 4(2-\varphi)\beta c_e$, $\frac{\partial w_{B2}^*}{\partial c_B} < 0$; when $0 < k^2 < 4\beta c_e$, $\frac{\partial w_{B2}^*}{\partial c_B} > 0$.

It can be seen that when the client's sensitivity to the quality of logistics services is high, the retail and wholesale prices decrease with the marginal cost of using the blockchain; when the client's sensitivity to the quality is low, the retail and wholesale prices increase with the marginal cost of using the blockchain. This is because when clients are less sensitive to the quality of logistics services, the value brought by using blockchain is lower, and as the cost of using blockchain increases, the 4PL and 3PL need to increase retail and wholesale prices, respectively, to compensate for the loss of revenue.

6. Comparative analysis

To compare the equilibrium of the traditional game and the blockchain game, numerical analysis is performed in this section. It mainly analyzes the change of effort level e and wholesale price w of 3PL, retail price p of 4PL, profit Π and π of both parties and system profit with parameter c_B in the blockchain game. The values of the setup parameters are as follows: $\lambda = 3$, $\beta = 2$, $k = 1$, $c_e = 1$, $c_d = 0.01$, $c_t = 0.04$, $\varphi = 0.2$, $r = 0.02$, $t = 0.02$, $F = 0.1$, $c_B \in [0,0.6]$, with the parameter settings referring to De Giovanni (2020) and ensuring that the results of both games are meaningful.

6.1 Analysis of effort level and service quality

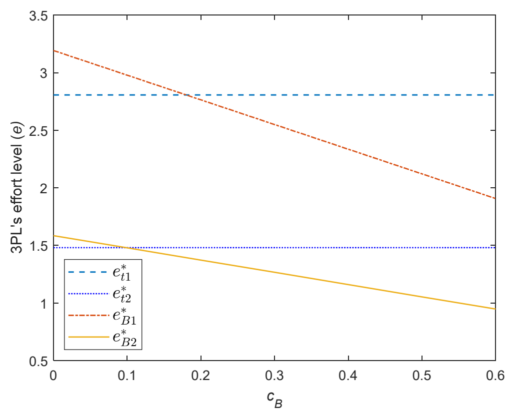

Fig. 1. 3PL's efforts level in traditional game and blockchain game

Fig. 1 shows the change in 3PL's effort level with the marginal cost of using blockchain in the traditional and blockchain game. The effort level of 3PL in the blockchain game gradually decreases in the marginal cost of blockchain c_B. When the blockchain marginal cost c_B is small, the use of blockchain technology will make the 3PL's effort level higher than that in the traditional game, and because the logistics service quality in the traditional game and the blockchain game are $s_t = (1 - r)e_t$ and $s_B = e_B$, respectively, the logistics service quality in the blockchain game is higher than that in the traditional game when the blockchain marginal cost is low.

6.2 Analysis of price and sales

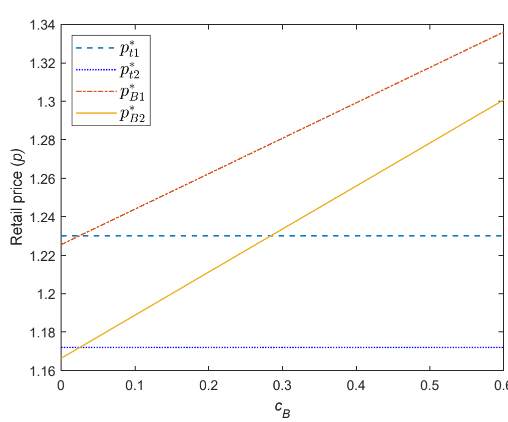

Fig. 2. Retail price of logistics service in the traditional game and blockchain game

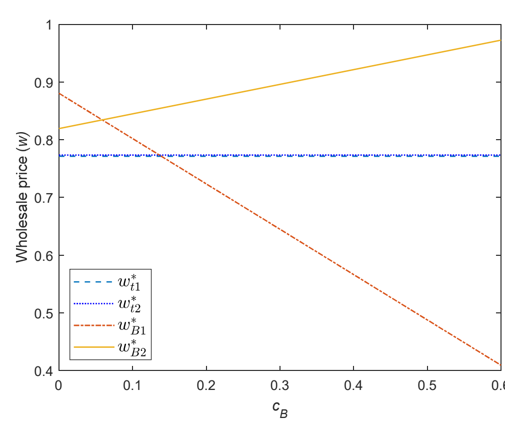

Fig. 3. Wholesale price of logistics service in the traditional game and blockchain game

Figs. 2-4 represent the change in retail price of logistics services of 4PL, the wholesale price of logistics services of 3PL, and the client demand with the marginal cost of using the blockchain. From Figs. 2-4, there exists blockchain marginal cost c_B such that $p_B > p_t$, $e_B < e_t$, $w_B < w_t$, and $D_B < D_t$. This is because although the use of blockchain removes some of the inefficiencies associated with traditional supply chains and transactions, the higher fixed and variable costs incurred by blockchain applications result in the fact that traditional transaction costs may be partially replaced by blockchain costs, with the result that the use of blockchain may seem unattractive.

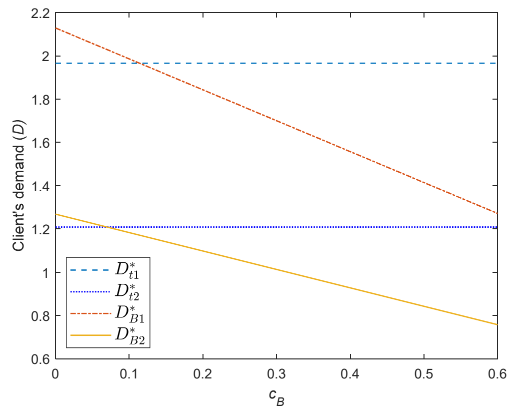

Fig. 4. Demand in the traditional game and blockchain game

Indeed, while the reduction of transaction inefficiencies is an obvious advantage, the presence of blockchain costs means that the 4PL charges higher prices, with the result that logistics service becomes less attractive to clients. As a result, there is less demand from clients, which leads to a reduction in 3PL's efforts towards delivery, leading to a deterioration in overall demand. In addition, as can be seen in Fig. 4, the use of blockchain by 4PL can increase demand when the marginal cost of blockchain c_B is small, this is because the use of blockchain effectively removes inefficiencies, such as quality loss and transaction costs, which exist in the traditional supply chain business process.

6.3 Analysis of profit

Figs. 5-6 represent the changes in the profits of 4PL and 3PL concerning the blockchain marginal cost, respectively. The profits of both 4PL and 3PL decrease in the marginal cost of blockchain and that there exists a range of marginal costs of blockchain that makes the blockchain technology beneficial to both 4PL and 3PL, i.e., there exists a region of Pareto improvement in which the profits of both parties are increased. In addition, there exists a range of marginal costs where both parties are worse off after the implementation of the blockchain, and the profits of both parties are negatively affected by the cost of the blockchain. This result is mainly caused by the variable costs incurred by transactions within the blockchain, and while they reduce traditional transaction costs, they also bring new variable costs in terms of data size and volume as well as protecting the transaction, making the blockchain economically unattractive. Therefore, companies implementing blockchain should first evaluate the marginal costs, and when these costs are high, only the reduction in transaction costs cannot justify its adoption. If the marginal costs of blockchain are affordable, supply chain members may improve economically by eliminating quality of service losses and transaction costs.

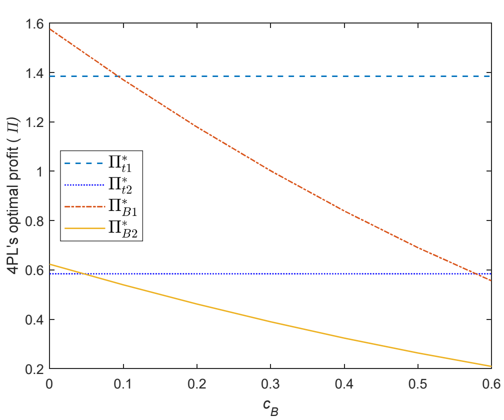

Fig. 5. 4PL's profits in the traditional game and blockchain game

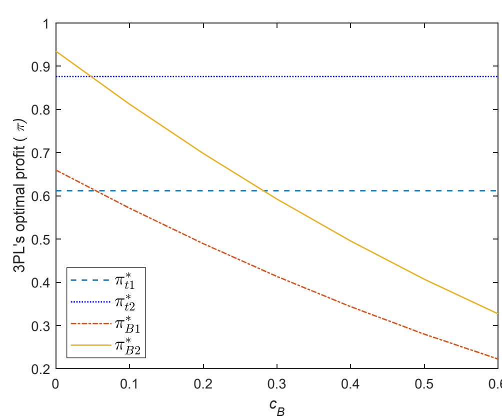

Fig. 6. 3PL's profits in the traditional game and blockchain game

6.4 Analysis of sharing parameter

Figs. 7-10 represent the impact of the revenue sharing parameter on the effort level of the 3PL, the profit of the 4PL, 3PL, and the system, respectively. The parameters are fixed as $F = 0.1$, $c_B = 0.01$, $\varphi = [0,0.5]$, and the rest of the parameters are the same as in the previous section. As can be seen from Fig. 7, the effort level of the 3PL is gradually increasing in the revenue share parameter, this is because the 4PL offering the revenue-sharing contract allows the 3PL to receive increased revenue from improved service quality, so the more sharing parameter the 4PL has, the more it promotes the 3PL to make effort.

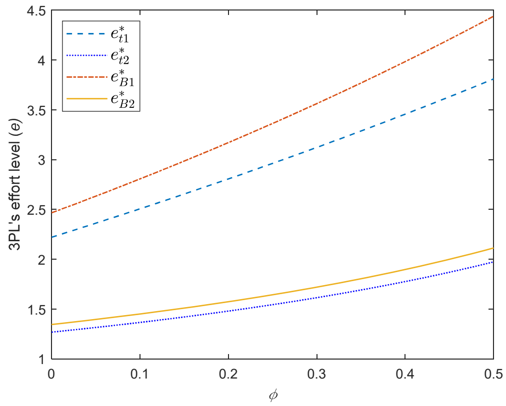

Fig. 7. Effects of sharing parameter on effort level in the traditional game and blockchain game

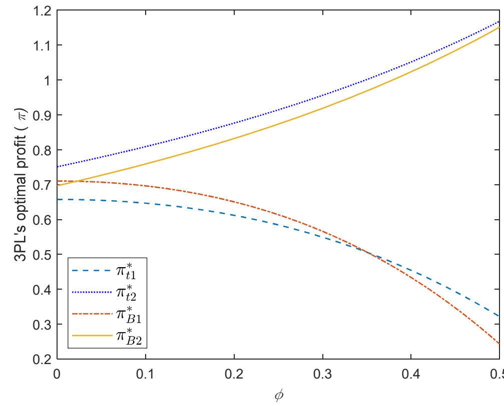

Fig. 8. Effects of sharing parameter on 3PL's profits in the traditional game and blockchain game

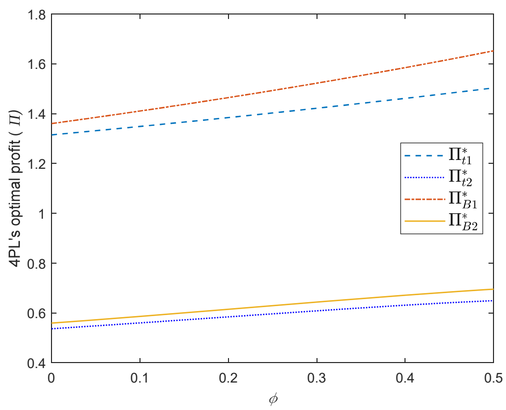

Fig. 9. Effects of sharing parameter on 4PL's profits in the traditional game and blockchain game

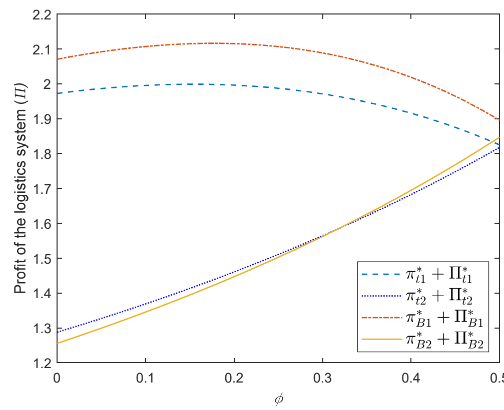

Fig. 10. Effects of sharing parameter on system's profits in the traditional game and blockchain game

From Figs. 8-10, it can be seen that there exists a revenue-sharing parameter that makes the logistics system most profitable, this is because as the sharing parameter increases, the increase in the level of effort makes the logistics efficiency improve and makes the 4PL profit gradually increase, but the increase in the level of effort is accompanied by a significant increase in the cost of effort paid by the 3PL, which leads to a decrease in the profit of the 3PL, so the cost of effort restricts the system efficiency to be further improvement.

7. Conclusions

Blockchain technology has gained a lot of attention due to its advantages of decentralization, tamper-proof information, as well as information transparency and traceability. We consider the game in a logistics service supply chain consisting of a 4PL and a 3PL when the 4PL does not use and uses blockchain. When not using blockchain technology the 4PL has transaction costs in the transaction process and the loss of service quality due to the inability to fully control the 3PL's delivery process. The use of blockchain technology can eliminate transaction costs and the loss of service quality, but there are fixed costs and marginal utilization costs of implementing blockchain. Therefore, we investigate the equilibrium strategies of 4PL in the traditional game and the blockchain game and the conditions under which blockchain is worth implementing. Numerical experiments show that when the marginal cost of blockchain is not too high, the use of blockchain leads to Pareto improvements in both 4PL and 3PL's profits and an improvement in logistics service quality.

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References

Ar, I. M., Erol, I., Peker, I., Ozdemir, A. I., Medeni, T. D., & Medeni, I. T. (2020). Evaluating the feasibility of blockchain in logistics operations: A decision framework. *Expert systems with applications*, *158*, 113543.

Babich, V., & Hilary, G. (2020). OM Forum—distributed ledgers and operations: What operations management researchers should know about blockchain technology. *Manufacturing & Service Operations Management*, *22*(2), 223-240.

Biswas, D., Jalali, H., Ansaripoor, A. H., & De Giovanni, P. (2023). Traceability vs. sustainability in supply chains: The implications of blockchain. *European Journal of Operational Research*, *305*(1), 128-147.

Casino, F., Kanakaris, V., Dasaklis, T. K., Moschuris, S., Stachtiaris, S., Pagoni, M., & Rachaniotis, N. P. (2021). Blockchain-based food supply chain traceability: a case study in the dairy sector. *International Journal of Production Research*, *59*(19), 5758-5770.

Centobelli, P., Cerchione, R., Vecchio, P. D., Oropallo, E., & Secundo, G. (2022). Blockchain technology for bridging trust, traceability and transparency in circular supply chain. *Information & Management*, *59*(7), 103508.

Chang, J., Katehakis, M. N., Shi, J., & Yan, Z. (2021). Blockchain-empowered Newsvendor optimization. *International Journal of Production Economics*, *238*, 108144.

Chod, J., Trichakis, N., Tsoukalas, G., Aspegren, H., & Weber, M. (2020). On the financing benefits of supply chain transparency and blockchain adoption. *Management Science*, *66*(10), 4378-4396.

Choi, T.-M., Wen, X., Sun, X., & Chung, S.-H. (2019). The mean-variance approach for global supply chain risk analysis with air logistics in the blockchain technology era. *Transportation Research Part E: Logistics and Transportation Review*, *127*, 178-191.

Choi, T. Y., Dooley, K. J., & Rungtusanatham, M. (2001). Supply Networks and Complex Adaptive Systems: Control Versus Emergence. *Journal of Operations Management*, *19*, 351-366.

De Giovanni, P. (2020). Blockchain and smart contracts in supply chain management: A game theoretic model. *International Journal of Production Economics*, *228*, 107855.

Dolgui, A., Ivanov, D., Potryasaev, S., Sokolov, B., Ivanova, M., & Werner, F. (2020). Blockchain-oriented dynamic modelling of smart contract design and execution in the supply chain. *International Journal of Production Research*, *58*(7), 2184-2199.

Dong, L., Jiang, P., & Xu, F. (2023). Impact of traceability technology adoption in food supply chain networks. *Management Science*, *69*(3), 1518-1535.

Dong, L., Qiu, Y., & Xu, F. (2023). Blockchain-enabled deep-tier supply chain finance. *Manufacturing & Service Operations Management*, *25*(6), 2021-2037.

Du, M., Chen, Q., Xiao, J., Yang, H., & Ma, X. (2020). Supply chain finance innovation using Blockchain. *IEEE Transactions on Engineering Management*, *67*(4), 1045-1058.

Dutta, P., Choi, T.-M., Somani, S., & Butala, R. (2020). Blockchain technology in supply chain operations: Applications, challenges and research opportunities. *Transportation Research Part E: Logistics and Transportation Review*, *142*, 102067.

Keskin, N. B., Li, C., & Song, J.-S. (2023). The blockchain Newsvendor: Value of freshness transparency and smart contract s. SSRN Working paper. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3915358

Kumar, A., Liu, R., & Shan, Z. (2020). Is Blockchain a silver bullet for supply chain management? Technical challenges and research opportunities. *Decision Sciences*, *51*(1), 8-37.

Li, M., Shen, L., & Huang, G. Q. (2019). Blockchain-enabled workflow operating system for logistics resources sharing in E-commerce logistics real estate service. *Computers & Industrial Engineering*, *135*, 950-969.

Liu, X., Zhang, K., Chen, B., Zhou, J., & Miao, L. (2018). Analysis of logistics service supply chain for the One Belt and One Road initiative of China. *Transportation Research Part E: Logistics and Transportation Review*, *117*, 23-39.

Martinez, V., Zhao, M., Blujdea, C., Han, X., Neely, A., & Albores, P. (2019). Blockchain-driven customer order management. *International Journal of Operations & Production Management*, *39*(6/7/8), 993-1022.

Orji, I. J., Kusi-Sarpong, S., Huang, S., & Vazquez-Brust, D. (2020). Evaluating the factors that influence blockchain adoption in the freight logistics industry. *Transportation Research Part E: Logistics and Transportation Review*, *141*, 102025.

Peck, M. E. (2017). Blockchain world-Do you need a blockchain? This chart will tell you if the technology can solve your problem. *IEEE Spectrum*, *54*(10), 38-60.

Pournader, M., Shi, Y., Seuring, S., & Koh, S. C. L. (2019). Blockchain applications in supply chains, transport and logistics: a systematic review of the literature. *International Journal of Production Research*, *58*(7), 2063-2081.

Rimba, P., Tran, A. B., Weber, I., Staples, M., Ponomarev, A., & Xu, X. (2017). Comparing blockchain and cloud services for business process execution. Paper presented at the IEEE International Conference on Software Architecture (ICSA).

Rimba, P., Tran, A. B., Weber, I., Staples, M., Ponomarev, A., & Xu, X. (2020). Quantifying the cost of distrust: Comparing blockchain and cloud services for business process execution. *Information Systems Frontiers*, *22*(2), 489-507.

Saurabh, S., & Dey, K. (2021). Blockchain technology adoption, architecture, and sustainable agri-food supply chains. *Journal of Cleaner Production*, *284*, 124731.

Shi, X., Yao, S., & Luo, S. (2023). Innovative platform operations with the use of technologies in the blockchain era. *International Journal of Production Research*, *61*(11), 3651-3669.

Tijan, E., Aksentijević, S., Ivanić, K., & Jardas, M. (2019). Blockchain technology implementation in logistics. *Sustainability*, *11*(4), 1185.

Wang, H.Y., Huang, M., Wang, H.F., Feng, X., & Zhou, Y. (2022). Contract design for the fourth party logistics considering tardiness risk. *International Journal of Industrial Engineering Computations*, *13*(1), 13-30.
Xin, B., & Xu, Y. (2022). Optimal subsidy strategies in a smart supply chain driven by dual innovation. *International Journal of Industrial Engineering Computations*, *13*(4), 557-572.
Zhang, E., Li, M., Yiu, S.-M., Du, J., Zhu, J.-Z., & Jin, G.-G. (2021). Fair hierarchical secret sharing scheme based on smart contract. *Information Sciences*, *546*, 166-176.
Zhang, T., Dong, P., Chen, X., & Gong, Y. (2023). The impacts of blockchain adoption on a dual-channel supply chain with risk-averse members. *Omega-International Journal of Management Science*, *114*, 1-18.
Zheng, Z., Xie, S., Dai, H.-N., Chen, W., Chen, X., Weng, J., & Imran, M. (2020). An overview on smart contracts: Challenges, advances and platforms. *Future Generation Computer Systems*, *105*, 475-491.

Appendix A: Proof of Lemma 1

The profits of 4PL and 3PL are

$$\Pi_t = \max_{p_t}\big((1-\varphi)p_t - w_t - c_t\big)D_t = \max_{p_t}\big((1-\varphi)m_t - \varphi w_t - c_t\big)(\lambda - \beta(m_t + w_t) + k(1-r)e_t)$$
$$\pi_t = \max_{w_t,e_t}(\varphi p_t + w_t - c_d)D_t - c_e e_t^2 = \max_{w_t,e_t}\big((\varphi+1)w_t + \varphi m_t - c_d\big)(\lambda - \beta(m_t + w_t) + k(1-r)e_t) - c_e e_t^2$$

Taking the first-order partial derivatives of the objective function of the 3PL with respect to the wholesale price and the level of effort respectively, we have

$$\frac{\partial \pi_t}{\partial w_t} = (\varphi+1)(\lambda - \beta(m_t + w_t) + k(1-r)e_t) - \beta\big((\varphi+1)w_t + \varphi m_t - c_d\big)$$
$$\frac{\partial \pi_t}{\partial e_t} = k(1-r)\big((\varphi+1)w_t + \varphi m_t - c_d\big) - 2c_e e_t$$

Let $\frac{\partial \pi_t}{\partial w_t} = 0$, $\frac{\partial \pi_t}{\partial e_t} = 0$, the following optimal response function for 3PL is obtained

$$w_t = \frac{(\varphi+1)\big(2c_e\lambda + k^2(1-r)^2(\varphi m_t - c_d)\big) - 2c_e\beta\big((1+2\varphi)m_t - c_d\big)}{(\varphi+1)\big(4c_e\beta - k^2(1-r)^2(\varphi+1)\big)} \tag{A.1}$$
$$e_t = \frac{k(1-r)\big((\varphi+1)\lambda - \beta(m_t + c_d)\big)}{4c_e\beta - k^2(1-r)^2(\varphi+1)} \tag{A.2}$$

Substituting w_t and e_t into the 4PL's profit function Π_t and solving for the derivative with respect to m_t for $\Pi_t(m_t)$, and let $\frac{\partial \Pi_t}{\partial w_t} = 0$ yields

$$m_{t1}^* = \frac{\big(4\beta c_e\lambda - k^2(1-r)^2(\lambda + \beta c_t)\big)(\varphi+1)^2 + 4\beta^2 c_e(c_t(1+\varphi) - c_d) + k^2(1-r)^2\beta c_d(1-\varphi^2)}{2\beta\big(2\beta c_e(\varphi+2) - k^2(1-r)^2(\varphi+1)\big)}$$

Substituting m_{t1}^* into Eqs. (A.1) and (A.2), yields w_{t1}^* and e_{t1}^*, which in turn yields $p_{t1}^* = w_{t1}^* + m_{t1}^*$, $D_{t1}^* = \lambda - \beta p_{t1}^* + k(1-r)e_{t1}^*$, Π_{t1}^* and π_{t1}^*.

Appendix B: Proof of Corollary 1

(i) The partial derivatives of the 3PL's effort level e_{t1}^* concerning the transaction inefficiency parameters c_t and r

$$\frac{\partial e_{t1}^*}{\partial c_t} = \frac{-\beta k(\varphi+1)(1-r)}{2\big(2\beta c_e(\varphi+2) - k^2(1-r)^2(\varphi+1)\big)} < 0$$
$$\frac{\partial e_{t1}^*}{\partial r} = \frac{k(\varphi+1)\big(\lambda - \beta(c_d + c_t)\big)\big(-2\beta c_e(\varphi+2) - k^2(\varphi+1)(1-r)^2\big)}{2\big(2\beta c_e(\varphi+2) - k^2(1-r)^2(\varphi+1)\big)^2} < 0$$

The partial derivative of the wholesale price of logistics services w_{t1}^* with respect to the transaction inefficiency parameter c_t is

$$\frac{\partial w_{t1}^*}{\partial c_t} = \frac{k^2(1-r)^2(1+\varphi)\varphi - 2\beta c_e(1+2\varphi)}{2\big(2\beta c_e(\varphi+2) - k^2(1-r)^2(\varphi+1)\big)},$$

From Lemma 1, it follows that $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{\varphi+2}$ needs to be satisfied to ensure that the solution is positive. From $\frac{\partial w_{t1}^*}{\partial c_t} > 0$, we get $2\beta c_e < \frac{k^2(1-r)^2\varphi(\varphi+1)}{2\varphi+1}$. Also since $\frac{k^2(1-r)^2(\varphi+1)\varphi}{2\varphi+1} < \frac{k^2(1-r)^2(\varphi+1)}{\varphi+2}$, then $\frac{\partial w_{t1}^*}{\partial c_t} < 0$ holds.

The partial derivative of wholesale price w_{t1}^* with respect to r is

$\frac{\partial w_{t1}^*}{\partial r} = \frac{A}{2\beta\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)^2} < 0,$

where $A = \left(-2k^2(1-r)(1+\varphi)\left(\lambda\varphi + \beta\left(c_t\varphi + c_d(\varphi-2)\right)\right)\right)\left(2\beta c_e(\varphi+2) - k^2(1-r)^2(\varphi+1)\right) - \left(k^2(1-r)^2(1+\varphi)\left(\lambda\varphi + \beta\left(c_t\varphi + c_d(\varphi-2)\right)\right) + 2\beta c_e\lambda(1-2\varphi^2-2\varphi) + 2\beta^2 c_e(3c_d - c_t - 2c_t\varphi)\right)2k^2(1-r)(\varphi+1) < 0.$

The partial derivative of the unit price of logistics services p_{t1}^* with respect to the transaction cost c_t is

$\frac{\partial p_{t1}^*}{\partial c_t} = \frac{2\beta c_e - k^2(1-r)^2(\varphi+1)}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)},$

To ensure that the solution is greater than zero, it is necessary to satisfy $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{\varphi+2}$. By $\frac{\partial p_{t1}^*}{\partial c_t} > 0$, we get $2\beta c_e > k^2(1-r)^2(\varphi+1)$. Also since $k^2(1-r)^2(\varphi+1) > \frac{k^2(1-r)^2(\varphi+1)}{\varphi+2}$, then $\frac{\partial p_{t1}^*}{\partial c_t} > 0$ holds.

The partial derivative of the unit price p_{t1}^* with respect to r is

$\frac{\partial p_{t1}^*}{\partial r} = \frac{4k^2(1-r)(\varphi+1)^2\beta c_e\left(-\lambda+\beta(c_d+c_t)\right)}{2\beta\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)^2} < 0.$

(ii) The partial derivatives of the client's demand D_{t1}^* with respect to the transaction costs c_t and r are respectively

$\frac{\partial D_{t1}^*}{\partial c_t} = \frac{-\beta\left(k^2r(1-r)(\varphi+1)+2\beta c_e\right)}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)} < 0,$
$\frac{\partial D_{t1}^*}{\partial r} = \frac{\left(\lambda-\beta(c_d+c_t)\right)k^2(\varphi+1)\left(2\beta c_e\left(\varphi-2r(\varphi+1)\right)-k^2(1-r)^2(\varphi+1)\right)}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)^2}.$

It follows from Lemma 1 that to ensure that the solution is positive, it is necessary to satisfy $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{\varphi+2}$ in the following two cases:

① When $\varphi > 2r(\varphi+1)$, from $\frac{\partial D_{t1}^*}{\partial r} > 0$, we get $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{\varphi-2r(\varphi+1)}$. Also, since $\varphi + 2 - \left(\varphi - 2r(\varphi+1)\right) = 2 + 2r(\varphi+1) > 0$, then $\frac{k^2(1-r)^2(\varphi+1)}{\varphi+2} < \frac{k^2(1-r)^2(\varphi+1)}{\varphi-2r(\varphi+1)}$, and hence, when $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{\varphi-2r(\varphi+1)}$, $\frac{\partial D_{t1}^*}{\partial r} > 0$; when $\frac{k^2(1-r)^2(\varphi+1)}{\varphi+2} < 2\beta c_e < \frac{k^2(1-r)^2(\varphi+1)}{\varphi-2r(\varphi+1)}$, $\frac{\partial D_{t1}^*}{\partial r} < 0$.

② When $\varphi < 2r(\varphi+1)$, $\frac{\partial D_{t1}^*}{\partial r} < 0$.

(iii) The partial derivatives of the profits of 4PL and 3PL with respect to the transaction costs c_t and loss r are respectively

$$\frac{\partial \Pi_{t1}^*}{\partial c_t} = \frac{-2\beta c_e\left(\lambda-\beta(c_d+c_t)\right)}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)} < 0,$$
$$\frac{\partial \Pi_{t1}^*}{\partial r} = -\frac{c_e\left(\lambda-\beta(c_d+c_t)\right)^2 k^2(1-r)(\varphi+1)}{\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)^2} < 0,$$
$$\frac{\partial \pi_{t1}^*}{\partial c_t} = \frac{-\beta c_e(\varphi+1)\left(\lambda-\beta(c_d+c_t)\right)\left(4\beta c_e-k^2(1-r)^2(\varphi+1)\right)}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)^2} < 0,$$
$$\frac{\partial \pi_{t1}^*}{\partial r} = \frac{c_e(\varphi+1)^2\left(\lambda-\beta(c_d+c_t)\right)^2 k^2(1-r)\left(-2\beta c_e(2-\varphi)+k^2(1-r)^2(\varphi+1)\right)}{2\left(2\beta c_e(\varphi+2)-k^2(1-r)^2(\varphi+1)\right)^3},$$

From Lemma 1, it follows that $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{\varphi+2}$ needs to be satisfied to ensure that the solution is positive. From $\frac{\partial \pi_{t1}^*}{\partial r} > 0$, we get $2\beta c_e < \frac{k^2(1-r)^2(\varphi+1)}{2-\varphi}$. Also, since $\frac{k^2(1-r)^2(\varphi+1)}{2-\varphi} > \frac{k^2(1-r)^2(\varphi+1)}{\varphi+2}$, then $\frac{\partial \pi_{t1}^*}{\partial r} > 0$ when $\frac{k^2(1-r)^2(\varphi+1)}{\varphi+2} < 2\beta c_e < \frac{k^2(1-r)^2(\varphi+1)}{2-\varphi}$; $\frac{\partial \pi_{t1}^*}{\partial r} < 0$ when $2\beta c_e > \frac{k^2(1-r)^2(\varphi+1)}{2-\varphi}$.

Appendix C: Proof of Lemma 2

The profit functions for 4PL and 3PL are respectively

$$\Pi_t = \max_{p_t}\big((1-\varphi)p_t - w_t - c_t\big)(\lambda - \beta p_t + k(1-r)e_t)$$
$$\pi_t = \max_{w_t,e_t}(\varphi p_t + w_t - c_d)(\lambda - \beta p_t + k(1-r)e_t) - c_e e_t^2$$

Taking the first-order partial derivative of the objective function Π_t with respect to the retail price p_t, we have

$$\frac{\partial \Pi_t}{\partial p_t} = (1-\varphi)(\lambda - \beta p_t + k(1-r)e_t) - \beta\big((1-\varphi)p_t - w_t - c_t\big)$$

Let $\frac{\partial \Pi_t}{\partial p_t} = 0$ to obtain the following optimal response function for 4PL

$$p_t = \frac{(1-\varphi)(\lambda + k(1-r)e_t) + \beta(w_t + c_t)}{2(1-\varphi)\beta} \tag{C.1}$$

Substituting p_t into the 3PL's profit function π_t, we have

$$\pi_t = \max_{w_t,e_t}\left(\frac{(1-\varphi)\varphi(\lambda + k(1-r)e_t) + \beta\varphi c_t + \beta w_t(2-\varphi)}{2(1-\varphi)\beta} - c_d\right)\left(\frac{(\lambda + k(1-r)e_t)}{2} - \frac{\beta(w_t + c_t)}{2(1-\varphi)}\right) - c_e e_t^2$$

Solving for the derivatives for π_t with respect to w_t and e_t respectively, yields

$$\frac{\partial \pi_t}{\partial w_t} = \frac{(2-\varphi)}{2(1-\varphi)}\left(\frac{(\lambda + k(1-r)e_t)}{2} - \frac{\beta(w_t + c_t)}{2(1-\varphi)}\right) - \frac{\beta}{2(1-\varphi)}\left(\frac{(1-\varphi)\varphi(\lambda + k(1-r)e_t) + \beta\varphi c_t + \beta w_t(2-\varphi)}{2(1-\varphi)\beta} - c_d\right)$$
$$\frac{\partial \pi_t}{\partial e_t} = \frac{\varphi k(1-r)}{2\beta}\left(\frac{(\lambda + k(1-r)e_t)}{2} - \frac{\beta(w_t + c_t)}{2(1-\varphi)}\right) + \frac{k(1-r)}{2}\left(\frac{(1-\varphi)\varphi(\lambda + k(1-r)e_t) + \beta\varphi c_t + \beta w_t(2-\varphi)}{2(1-\varphi)\beta} - c_d\right) - 2c_e e_t$$

Let $\frac{\partial \pi_t}{\partial w_t} = 0, \frac{\partial \pi_t}{\partial e_t} = 0$, and simplify to get

$$k(1-r)(1-\varphi)(\varphi(\lambda + k(1-r)e_t) + \beta w_t - \beta c_d) - 4(1-\varphi)\beta c_e e_t = 0$$
$$(1-\varphi)^2(\lambda + k(1-r)e_t) = \beta c_t - (1-\varphi)\beta c_d + (2-\varphi)\beta w_t$$

Then

$$w_{t2}^* = \frac{k^2(1-r)^2\big(c_t\varphi - c_d(1-\varphi)\big) + 4\beta c_e(c_d(1-\varphi) - c_t) + 4c_e\lambda(1-\varphi)^2}{4\beta c_e(2-\varphi) - k^2(1-r)^2}$$
$$e_{t2}^* = \frac{k(1-r)(\lambda - \beta(c_d + c_t))}{4\beta c_e(2-\varphi) - k^2(1-r)^2}$$

Substituting w_{t2}^* and e_{t2}^* into Eq. (C.1) further yields

$$p_{t2}^* = \frac{2\lambda c_e(3-2\varphi) - \big((1-r)^2k^2 - 2\beta c_e\big)(c_d + c_t)}{4\beta c_e(2-\varphi) - k^2(1-r)^2}$$
$$\Pi_{t2}^* = \frac{4\beta {c_e}^2(1-\varphi)(\beta(c_d + c_t) - \lambda)^2}{(4\beta c_e(2-\varphi) - k^2(1-r)^2)^2}$$
$$\pi_{t2}^* = \frac{c_e(\beta(c_d + c_t) - \lambda)^2}{4\beta c_e(2-\varphi) - k^2(1-r)^2}$$
$$D_{t2}^* = \frac{2\beta c_e(\lambda - \beta(c_d + c_t))}{4\beta c_e(2-\varphi) - k^2(1-r)^2}$$

The conditions $4\beta c_e(2-\varphi) > k^2(1-r)^2$ and $\lambda > \beta(c_t + c_d)$ ensure that the model's strategy and profits are positive.

Appendix D: Proof of Corollary 2

(i) The partial derivatives of the 3PL's effort level e_{t2}^* with respect to the trading inefficiency parameters c_t and r are, respectively:

$$\frac{\partial e_{t2}^*}{\partial c_t} = \frac{-\beta k(1-r)(\lambda(c_d + c_t))}{4\beta c_e(2-\varphi) - k^2(1-r)^2} < 0,$$
$$\frac{\partial e_{t2}^*}{\partial r} = k\big(\lambda - \beta(c_d + c_t)\big)\frac{-4\beta c_e(2-\varphi) - k^2(1-r)^2}{(4\beta c_e(2-\varphi) - k^2(1-r)^2)^2} < 0,$$

The partial derivatives of the wholesale price of the logistics service w_{t2}^* with respect to the transaction inefficiency parameters c_t and r are $\frac{\partial w_{t2}^*}{\partial c_t} = -\frac{4\beta c_e - \varphi k^2(1-r)^2}{4\beta c_e(2-\varphi)-k^2(1-r)^2}$, then from $4\beta c_e > \frac{k^2(1-r)^2}{2-\varphi}$ and $\frac{1}{2-\varphi} - \varphi = \frac{1}{2-\varphi} - \frac{\varphi(2-\varphi)}{2-\varphi} = \frac{(1-\varphi)^2}{2-\varphi} > 0$, which shows that $4\beta c_e > \varphi k^2(1-r)^2$ holds, and hence $\frac{\partial w_{t2}^*}{\partial c_t} < 0$. In addition, $\frac{\partial w_{t2}^*}{\partial r} = -\frac{8k^2(1-r)(1-\varphi)^2 c_e(\lambda - \beta(c_t+c_d))}{(4\beta c_e(2-\varphi)-k^2(1-r)^2)^2} < 0$.

The partial derivatives of the clinet's demand D_{t2}^* with respect to the transaction costs c_t and r are respectively

$$\frac{\partial D_{t2}^*}{\partial c_t} = \frac{-2\beta^2 c_e}{4\beta c_e(2-\varphi)-k^2(1-r)^2} < 0,$$
$$\frac{\partial D_{t2}^*}{\partial r} = -\frac{4\beta c_e(\lambda-\beta(c_d+c_t))k^2(1-r)}{(4\beta c_e(2-\varphi)-k^2(1-r)^2)^2} < 0.$$

The partial derivatives of the profits of 4PL and 3PL with respect to the transaction costs c_t and r, respectively, are

$$\frac{\partial \Pi_{t2}^*}{\partial c_t} = \frac{-8\beta^2 {c_e}^2(1-\varphi)(\lambda-\beta(c_d+c_t))}{(4\beta c_e(2-\varphi)-k^2(1-r)^2)^2} < 0,$$
$$\frac{\partial \Pi_{t2}^*}{\partial r} = -\frac{16k^2(1-r)\beta {c_e}^2(1-\varphi)(\lambda-\beta(c_d+c_t))^2}{(4\beta c_e(2-\varphi)-k^2(1-r)^2)^3} < 0,$$
$$\frac{\partial \pi_{t2}^*}{\partial c_t} = \frac{-2\beta c_e(\lambda(c_d+c_t))}{4\beta c_e(2-\varphi)-k^2(1-r)^2} < 0,$$
$$\frac{\partial \pi_{t2}^*}{\partial r} = -\frac{2k^2(1-r)c_e(\lambda-\beta(c_d+c_t))^2}{(4\beta c_e(2-\varphi)-k^2(1-r)^2)^2} < 0.$$

(ii) The partial derivatives of the retail price of the logistics service p_{t2}^* with respect to the transaction costs c_t and r are $\frac{\partial p_{t2}^*}{\partial c_t} = \frac{2\beta c_e - k^2(1-r)^2}{4\beta c_e(2-\varphi)-k^2(1-r)^2}$, then from $2\beta c_e > \frac{k^2(1-r)^2}{2(2-\varphi)}$ and $\frac{1}{2(2-\varphi)} - 1 = \frac{1-2(2-\varphi)}{2(2-\varphi)} < 0$, we have when $\frac{k^2(1-r)^2}{2(2-\varphi)} < 2\beta c_e < k^2(1-r)^2$, $\frac{\partial p_{t2}^*}{\partial c_t} < 0$; when $2\beta c_e > k^2(1-r)^2$, $\frac{\partial p_{t2}^*}{\partial c_t} > 0$. In addition, $\frac{\partial p_{t2}^*}{\partial r} = 4k^2 c_e(1-r)(3-2\varphi)\frac{\beta(c_d+c_t)-\lambda}{(4\beta c_e(2-\varphi)-k^2(1-r)^2)^2} < 0$.

Appendix D: Proof of Lemma 3

In the 4PL-dominated logistics system, the profit functions of 4PL and 3PL are respectively

$$\Pi_B = \max_{p_B}\big((1-\varphi)p_B - w_B - c_B\big)D_B - F = \max_{p_B}\big((1-\varphi)m_B - \varphi w_B - c_B\big)(\lambda - \beta(m_B+w_B) + ke_B) - F$$
$$\pi_B = \max_{w_B,e_B}(\varphi p_B + w_B - c_d)D_B - c_e e_B^2 - t = \max_{w_B,e_B}\big((\varphi+1)w_B + \varphi m_B - c_d\big)(\lambda - \beta(m_B+w_B) + ke_B) - c_e e_B^2 - t$$

Taking the first-order partial derivatives of the objective function of the 3PL with respect to wholesale price and effort level, respectively, we have

$$\frac{\partial \pi_B}{\partial w_B} = (\varphi+1)(\lambda - \beta(m_B+w_B) + ke_B) - \beta\big((\varphi+1)w_B + \varphi m_B - c_d\big)$$
$$\frac{\partial \pi_B}{\partial e_B} = k\big((\varphi+1)w_B + \varphi m_B - c_d\big) - 2c_e e_B$$

Let $\frac{\partial \pi_B}{\partial w_B} = 0$ and $\frac{\partial \pi_B}{\partial e_B} = 0$ to obtain the following optimal response function for 3PL

$$w_B = \frac{(\varphi+1)\big(2c_e\lambda + k^2(\varphi m_B - c_d)\big) - 2c_e\beta\big((1+2\varphi)m_B - c_d\big)}{(\varphi+1)\big(4c_e\beta - k^2(\varphi+1)\big)} \tag{D.1}$$
$$e_B = \frac{k\big((\varphi+1)\lambda - \beta(m_B+c_d)\big)}{4c_e\beta - k^2(\varphi+1)} \tag{D.2}$$

Substituting w_B and e_B into the 4PL's profit function Π_B, and solving for the derivative of $\Pi_B(m_B)$ with respect to m_B, and let $\frac{\partial \Pi_B}{\partial m_B} = 0$ yields

$$m_{B1}^* = \frac{(4\beta c_e\lambda - k^2\lambda - k^2\beta c_B)(\varphi+1)^2 + 4\beta^2 c_e(c_B(\varphi+1) - c_d) + k^2\beta c_d(1-\varphi^2)}{2\beta\big(2\beta c_e(\varphi+2) - k^2(\varphi+1)\big)}$$

Substituting m_{B1}^* into Eqs. (D.1) and (D.2) yields w_{B1}^* and e_{B1}^*, which in turn yields $p_{B1}^* = w_{B1}^* + m_{B1}^*$, $D_{B1}^* = \lambda - \beta p_{B1}^* + ke_{B1}^*$, Π_{B1}^*, and π_{B1}^*.

Appendix E: Proof of Corollary 3

Solve for the derivative of w_{B1}^* with respect to c_B, we have $\frac{\partial w_{B1}^*}{\partial c_B} = \frac{\varphi k^2(\varphi+1)-2\beta c_e(2\varphi+1)}{2\left(2\beta c_e(\varphi+2)-k^2(\varphi+1)\right)}$. Let $\frac{\partial w_{B1}^*}{\partial c_B} > 0$, then $2\beta c_e < \frac{\varphi k^2(\varphi+1)}{2\varphi+1}$. To guarantee the existence of a solution, it is necessary to satisfy that $2\beta c_e > \frac{k^2(\varphi+1)}{\varphi+2}$, and since $\frac{k^2(\varphi+1)}{\varphi+2} - \frac{\varphi k^2(\varphi+1)}{2\varphi+1} = \frac{k^2(\varphi+1)(1-\varphi^2)}{\varphi+2} > 0$, then $\frac{\partial w_{B1}^*}{\partial c_B} < 0$ holds.

Solving for the derivatives of Π_{B1}^* and π_{B1}^* with respect to c_B, respectively, we have $\frac{\partial \Pi_{B1}^*}{\partial c_B} = \frac{\beta c_e(\beta(c_B+c_d)-\lambda)}{2\beta c_e(\varphi+2)-k^2(\varphi+1)} < 0$, and $\frac{\partial \pi_{B1}^*}{\partial c_B} = \frac{\beta c_e\left(4\beta c_e(\varphi+1)-k^2(\varphi+1)^2\right)(\beta(c_B+c_d)-\lambda)}{2\left(2\beta c_e(\varphi+2)-k^2(\varphi+1)\right)^2} < 0$. Thus, the optimal profits of both 4PL and 3PL are monotonically decreasing with respect to c_B.

Solving for the derivative of p_{B1}^* with respect to c_B, we have $\frac{\partial p_{B1}^*}{\partial c_B} = \frac{2\beta c_e - k^2(\varphi+1)}{2\left(2\beta c_e(\varphi+2)-k^2(\varphi+1)\right)}$. Let $\frac{\partial p_{B1}^*}{\partial c_B} > 0$, then $2\beta c_e > k^2(\varphi+1)$. Also, since $2\beta c_e > \frac{k^2(\varphi+1)}{\varphi+2}$, then we have when $\frac{k^2(\varphi+1)}{\varphi+2} < 2\beta c_e < k^2(\varphi+1)$, $\frac{\partial p_B^*}{\partial c_B} < 0$; when $2\beta c_e > k^2(\varphi+1)$, $\frac{\partial p_{B1}^*}{\partial c_B} > 0$.

Appendix F: Proof of Lemma 4

In the game using the blockchain, when the 3PL is dominant, the profit functions of the 4PL and the 3PL are, respectively, as follows

$$\Pi_{B2} = \max_{p_B}\left((1-\varphi)p_B - w_B\right)(\lambda - \beta p_B + k e_B) - t$$
$$\pi_{B2} = \max_{w_B, e_B}(\varphi p_B + w_B - c_d - c_B)D_B - c_e e_B^2 - F$$

Taking the first order partial derivative of the objective function Π_{B2} with respect to the retail price p_B, we have

$$\frac{\partial \Pi_{B2}}{\partial p_B} = (1-\varphi)(\lambda - \beta p_B + k e_B) - \beta\left((1-\varphi)p_B - w_B\right)$$

Let $\frac{\partial \Pi_{B2}}{\partial p_B} = 0$, we obtain the following optimal response function for 4PL

$$p_B = \frac{(1-\varphi)(\lambda + k e_B) + \beta w_B}{2\beta(1-\varphi)}$$

Substituting p_B into the 3PL's profit function, we have

$$\pi_{B2} = \max_{w_B, e_B}\left(\frac{\varphi(\lambda + k e_B)}{2\beta} + \frac{(2-\varphi)w_B}{2(1-\varphi)} - c_d - c_B\right)\left(\frac{k e_B + \lambda}{2} - \frac{\beta w_B}{2(1-\varphi)}\right) - c_e e_B^2 - F$$

Solving for the derivatives of π_{B2} with respect to w_B and e_B yields

$$\frac{\partial \pi_{B2}}{\partial w_B} = (1-\varphi)(k e_B + \lambda) - \frac{(2-\varphi)\beta w_B}{(1-\varphi)} + \beta(c_d + c_B)$$
$$\frac{\partial \pi_{B2}}{\partial e_B} = \frac{\varphi k}{\beta}(k e_B + \lambda) + k w_B - k(c_d + c_B) - 4 c_e e_B$$

Let $\frac{\partial \pi_{B2}}{\partial w_B} = 0$ and $\frac{\partial \pi_{B2}}{\partial e_B} = 0$ to obtain the following optimal response function for 3PL

$$w_B = \frac{(1-\varphi)^2(k e_B + \lambda) + (1-\varphi)\beta(c_d + c_B)}{(2-\varphi)\beta}$$

which further yields

$$e_{B2}^* = \frac{k\left(\lambda - \beta(c_d + c_B)\right)}{4(2-\varphi)\beta c_e - k^2}$$

$w_{B2}^* = (1-\varphi)\frac{4(1-\varphi)\lambda c_e + (4\beta c_e - k^2)(c_d + c_B)}{4(2-\varphi)\beta c_e - k^2}$

$p_{B2}^* = \frac{2(3-2\varphi)\lambda c_e + (2\beta c_e - k^2)(c_d + c_B)}{4(2-\varphi)\beta c_e - k^2}$

$D_{B2}^* = \lambda - \beta p_B + k s_B = \frac{2\beta c_e(\lambda - \beta(c_d + c_B))}{4(2-\varphi)\beta c_e - k^2}$

$\Pi_{B2}^* = \frac{4(1-\varphi)\beta c_e^2 (\lambda - \beta(c_d + c_B))^2}{(4(2-\varphi)\beta c_e - k^2)^2} - t$

$\pi_{B2}^* = \frac{c_e(\lambda - \beta(c_d + c_B))^2}{4(2-\varphi)\beta c_e - k^2} - F$

Appendix G: Proof of Corollary 4

Solving for the derivatives of e_{B2}^*, Π_{B2}^*, and π_{B2}^* with respect to c_B, we have $\frac{\partial e_{B2}^*}{\partial c_B} < 0$, $\frac{\partial \Pi_{B2}^*}{\partial c_B} < 0$, and $\frac{\partial \pi_{B2}^*}{\partial c_B} < 0$.

The derivative of the retail price of logistics service p_{B2}^* with respect to the marginal cost of blockchain c_B is $\frac{\partial p_{B2}^*}{\partial c_B} = \frac{-(k^2 - 2\beta c_e)}{4(2-\varphi)\beta c_e - k^2}$, then when $2\beta c_e < k^2 < 4(2-\varphi)\beta c_e$, $\frac{\partial p_{B2}^*}{\partial c_B} < 0$; when $0 < k^2 < 2\beta c_e$, $\frac{\partial p_{B2}^*}{\partial c_B} > 0$.

The derivative of the wholesale price of logistics service w_{B2}^* with respect to the marginal cost of blockchain c_B is $\frac{\partial w_{B2}^*}{\partial c_B} = \frac{(1-\varphi)(4\beta c_e - k^2)}{4(2-\varphi)\beta c_e - k^2}$, then when $4\beta c_e < k^2 < 4(2-\varphi)\beta c_e$, $\frac{\partial w_{B2}^*}{\partial c_B} < 0$; when $0 < k^2 < 4\beta c_e$, $\frac{\partial w_{B2}^*}{\partial c_B} > 0$.