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Supply chain information coordination based on blockchain technology: A comparative study with the traditional approach

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A B S T R A C T

Blockchain technology has subverted traditional supply chain operational models and transformed information interactions along supply chains. This paper examines the impact of blockchain technology on supply chain information collaboration and operating costs. This paper develops a three-level supply chain model based on blockchain technology that incorporates retailer sensitivity to information. First, the manufacturer's profit function is developed, and the optimal information-sharing quantity and supply chain pricing decisions are analysed. Then, cost models for both the traditional supply chain and the novel supply chain using blockchain technology are developed and the impact of blockchain technology on supply chain operating costs is determined. The results demonstrate that blockchain technology can effectively reduce supply chain operating costs. In addition, this study has an interesting finding that if blockchain adoption is valuable for the supply chain, the quantity of information-sensitive should be moderate. Too many or too few information-sensitive retailers can reduce the value of the blockchain's use. This is because blockchain is implementation will increase the privacy concerns of supply chain companies.

A R T I C L E I N F O

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1. Introduction

One of the most prominent advantages of the blockchain is its ability to increase data interactivity [1]. Companies can more easily share information and data with manufacturers and suppliers by employing blockchain technology [2, 3]. The transparency of the blockchain can also reduce delays by preventing products from stalling on the supply chain [4]. With blockchain-based supply chains, every product can be tracked in real time. At present, there are many applications of blockchain technology in the supply chain, for example, cold chain logistics and transportation [2]. Blockchain technology can also solve the problem of verifying the transportation conditions of food because it enables the real-time tracking of the production and sales process of products from the source. In coffee, pharmaceutical, and automotive supply chains, for example, blockchain technology has exhibited excellent performance.

Due to technical limitations, traditional supply chain management has always experienced some managerial drawbacks. For example, in traditional supply chain management, the data streams are more dispersed. Supply chains often employ enterprise resource planning (ERP) systems that are usually only used for submitting orders and completing transactions; they cannot be extended to other functions such as data collection, induction, and analysis. The non-circulation of information on the supply chain affects the fluency of supply chain operations.

Supply chain information collaboration refers to the integration of information between members of the supply chain with Internet technology. Its goal is to achieve the real-time sharing and transmission of operational and market data [5]. However, the degree of information coordination in traditional supply chains is low and the compatibility of information technology between various enterprises is weak. Furthermore, differences in enterprise size and financial strength negatively impact technological compatibility. Another important factor that influences supply chain information collaboration is the existence of weak trust relationships between members of the supply chain. Blockchain technology can effectively alleviate these problems and promote more efficient supply chain information collaboration.

However, there are important issues to address concerning the use of blockchain technology with supply chains. First, what are the boundaries of supply chain information-sharing? Although the blockchain can guarantee information privacy, complete information transparency might not be conducive to an enterprise's strategic decisions. Secondly, what impact does a company's information sensitivity have on supply chain operations? Will information sensitivity hinder the broad application of blockchain technology? Finally, the application of blockchain technology requires capital investment, but will this technology ultimately reduce supply chain operating costs?

Motivated by observing supply chain operations with blockchain technology and clarifying the general supply chain operating rules, in this paper, we analytically explore the effect of blockchain technology on supply chain collaboration considering the operation costs, information-sensitivity level, and optimal supply chain price strategy. We develop a supply chain profit model and a supply chain cost model to investigate the effect of the blockchain on information coordination along supply chains. To capture the characteristics of supply chain operation based on blockchain technology, we consider the information-sensitivity level of, and supply chain information-sharing quality among, supply chain members. Finally, we examine the impact of blockchain technology on supply chain costs. Having analysed the model, we derive some critical results on various issues regarding blockchain-based supply chain operation and formulate managerial insights drawn from our findings.

This original study makes two crucial contributions. First, to the best of our knowledge, this is the first analytical study that presents the impact of platform operation on supply chain operation costs when blockchain technology is employed. Second, we enlarged the current literature on the blockchain and supply chains by capturing the features of information sensitivity. The information sensitivity of supply chain members will affect the investment in blockchain technology for the supply chain.

We organize the paper as follows. Section 2 provides an overall review of the related studies to recognized gaps in the research and appropriately position our work. In Section 3, we draw the problem, develop the model, and make its assumptions. In Section 4, we explore different supply chain models considering blockchain technology. In Section 5, we provide the results of simulation analysis to examine the impact of blockchain technology. Finally, in Section 6, we conclude the results and give some essential suggested topics for future relevant research.

2. Literature review

Blockchain technology has transformed supply chain management. Many articles have discussed these changes [6, 7]. The management of information flows in the supply chain is essential to achieve supply chain coordination [8-10]. In general, modern information technologies are required to achieve information synergy in supply chains [10, 11]. In modern supply chain management, many firms use advanced technologies to increase the transparency and improve the efficiency of supply chain information transfer [12, 13]. Blockchain, as an effective technological tool, can help supply chains achieve synergy goals.

2.1 The impact of blockchain on a supply chain

Our research involves the changes brought about by the application of blockchain technology in supply chain operations management. First, blockchain technology has significantly changed agricultural product supply chains [7]. Figorilli [14] examined the application of blockchain technology in the lumber supply chain. They considered integrating traceable information related to product quality into an online information system and using blockchain technology to record transactional data. Kamble *et al*. [15] analysed the strategy of implementing blockchain technology in the agricultural supply chain to ensure food safety and sustainability. Salah *et al*. [10] believed that blockchain technology can provide creative solutions for improved traceability of agricultural and other food products. The author proposed using smart contracts to trace the soybean transactional process. Behnke *et al*. [16] supposed that, before implementing blockchain technology, the organizational structure of the supply chain must be changed and information-sharing among members must be voluntary. Kumar and Iyengar [18] constructed a rice supply chain system based on the blockchain to ensure its safety during the supply chain management process. The above research has performed a sufficient analysis of the means for ensuring the safety of agricultural product supply chains and information traceability. This is necessary for analysing the combination of blockchain technology and supply chain operation management from a macro perspective.

2.2 Operation of a supply chain with blockchain

Many articles have previously investigated how to use blockchain technology in the supply chain. Perboli *et al.* [19] proposed that the blockchain be regarded as a distributed ledger database that can permanently record transactional information and ensure its security. Dolgui *et al.* [20] designed a new model of smart contracts using dynamic control theory. Tseng *et al.* [21] investigated medical supply chain governance based on blockchain technology. Verhoeven *et al.* [22] explored a supply chain management case based on the blockchain. The authors emphasized that the premise of the application of blockchain technology is to fully understand it. Abeyratne and Monfared [23] reviewed the development status and application of blockchain technology and then explained the value of blockchain technology in the manufacturing supply chain and detailed its use in global supply chain governance. The above research fully explains, from a technical point of view, that blockchain technology ensures the information security of the supply chain. Our research is also related to supply chain information. However, we explore how blockchain technology enhances supply chain collaboration from the perspective of supply chain operating costs.

2.3 Information collaboration in a supply chain with blockchain

Blockchain technology can improve information security on the supply chain, reduce supply chain risk, and increase supply chain flexibility [24-27]. Zhu and Kouhizadeh [28] discussed the fact that blockchain technology effectively prevents the deletion of product information. The blockchain also enhances rational decision-making for product information management. Francisco and Swanson [29] developed a conceptual model to determine how the blockchain increases supply chain transparency. Toyoda *et al.* [30] designed a product trading platform based on blockchain technology by using research on radio frequency identification (RFID) technology. Choi *et al.* [31] explored how blockchain technology reduces the risk of aviation logistics. Fu and Zhu [32] analysed how blockchain technology decreases the supply chain risk of large production enterprises. Min [33] discussed ways to use blockchain technology to enhance supply chain resilience when risk and uncertainty increases. Saberi *et al.* [34] explored how blockchain technology and smart contracts can promote supply chain flexibility and proposed four obstacles to the implementation of blockchain technology. Hu *et al.* [35] designed a blockchain-based smart contract to collaborate in supply chains.

In this article, unlike previous research, we focus on how blockchain technology can reduce supply chain operating costs and methods to achieve supply chain information collaboration. At the same time, we also consider supply chain pricing decisions when blockchain technology is introduced.

3. Problem statement

Consider a supply chain consisting of two suppliers, a manufacturer, and a group of retailers. The number of information-sensitive retailers is μ, where $0 \leq \mu \leq 1$, and all other actors are information-insensitive. If blockchain technology is introduced into supply chain operations, manufacturers will decide to share α quantity of information to retailers through blockchain technology at cost c_B, where $c_B = k\alpha$ and k is the cost coefficient of information-sharing [25]. If blockchain technology is not introduced, the manufacturer incurs a fixed cost, c_T. The manufacturer purchases raw materials from the two suppliers. The retailer's wholesale price is w_i and manufacturer demand is D_i. Note that $i = B, T$, where B represents a supply chain using blockchain technology and T represents a traditional supply chain. The structure of the supply chain using blockchain technology is illustrated in Fig. 1.

To capture the impact of blockchain technology on supply chain costs, we later consider more complex cost components in Section 4.2. We summarize the notations used throughout this paper in Table 1. Specifically, we consider a monopoly market in which the manufacturer provides a product to retailers and manufacturers can fully meet the needs of all retailers. Without any loss of generality, we assume that retailers are rational actors who make decisions with the goal of achieving the maximum level of profit. In addition, we assume that all members of the supply chain are risk-neutral, which means that the optimal decision of the entire supply chain will not be affected by the risk preferences of suppliers, manufacturers or retailers. These assumptions are not only reasonable, but also help us simplify the problem and get general management enlightenment.

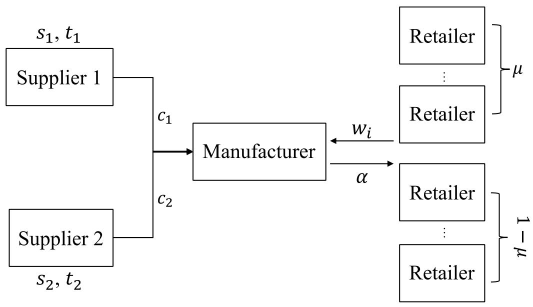

Fig. 1 The structure of a supply chain using blockchain technology

Table 1 Symbols throughout this paper

Symbols	Explanation
D_B	The manufacturer's demand with blockchain technology
D_T	The manufacturer's demand without blockchain technology
d	Basic demand
μ	The proportion of information-sensitive retailers
$1-\mu$	The proportion of information-insensitive retailers
α	The amount of manufacturer information
w_B	The manufacturer's wholesale price with blockchain technology
w_T	The manufacturer's wholesale price without blockchain technology
k	The cost coefficient of information-sharing
c_B	The manufacturer's cost with blockchain technology, $c_B = k\alpha$
c_T	The manufacturer's cost without blockchain technology
β	Price-sensitive coefficient
π_B	The manufacturer's profit with blockchain technology
π_T	The manufacturer's profit without blockchain technology
s_j	The quality of raw materials provided by supplier j
t_j	The arrival time of raw materials
c_j	The storage cost
n	The unit production delay cost

4. The model

In this section, we first develop profit models for two types of supply chains—the traditional supply chain and the blockchain-based supply chain. We first analyse the optimal pricing strategy, the optimal information-sharing quantity, and the optimal profit of the manufacturer under those two conditions and then determine the impact of information-insensitivity on supply chain operation strategy. Next, we compare the operation costs of the two types of supply chains.

We denote manufacturer demand with a blockchain-based supply chain as Eq. 1 shown:

$$D_B = \mu d + (1-\mu)d\alpha - \beta w_B \tag{1}$$

Total demand comes from all retailers, including both information-sensitive and information-insensitive retailers. However, it will be negatively affected by rising wholesale prices.

We denote manufacturer demand with a traditional supply chain as:

$$D_T = d - \beta w_T \tag{2}$$

These linear demand functions are used extensively in operations management research [36-38]. To simplify the analysis, we consider only the case in which manufacturer demand with the traditional supply chain is negatively affected by an increase in wholesale prices.

To study the impact of blockchain technology on manufacturers' profits, we obtain the profit function of the manufacturer with different supply chains as:

$$\pi_B = (w_B - k\alpha)D_B \tag{3}$$

$$\pi_T = w_T D_T \tag{4}$$

Differentiating Eq. 3 once with respect to w_B and α, respectively, and then considering the first-order condition yields:

$$w_B = \frac{\mu d + (1-\mu)d\alpha + \beta k\alpha}{2\beta} \tag{5}$$

$$\alpha = \frac{(1-\mu)w_B - \mu k}{2(1-\mu)k} \tag{6}$$

Obviously, it is easy to derive the results of the optimal wholesale price $w_B{}^*$ and the optimal amount of manufacturer's information α^* by combining Eqs. 5 and 6.

Differentiating Eq. 4 once with respect to w_T and considering the first-order condition yields the optimal wholesale price of the traditional supply chain, as follows:

$$\pi_T{}^* = \frac{d^2}{4\,\beta} \tag{7}$$

Next, we substitute $w_B{}^*$ and α^* and into Eq. 3, substitute Eq. 7 into Eq. 4, yielding the following result.

Lemma 1: The manufacturer's optimal wholesale price with blockchain technology is $w_B{}^* = \frac{k\mu[d(1-\mu)+\beta k]}{(1-\mu)[3k\beta - d(1-\mu)]}$ and the manufacturer's optimal profit with blockchain technology is $\pi_B{}^* = \frac{k\beta\mu(2(1-\mu)-\beta k)}{(1-\mu)[3k\beta - d(1-\mu)]}$.

Lemma 2: The manufacturer's optimal wholesale price without blockchain technology is $w_T{}^* = \frac{d}{2\,\beta}$ and the manufacturer's optimal profit without blockchain technology is $\pi_T{}^* = \frac{d^2}{4\,\beta}$.

Lemma 3: The optimal amount of manufacturer information $\alpha^* = \frac{\mu[d(1-\mu)-\beta k]}{(1-\mu)[3k\beta - d(1-\mu)]}$.

By analysing the equilibrium solutions of the profit functions of the manufacturers with the different supply chains, we obtain the optimal price decisions of manufacturers and the optimal amounts of manufacturer information.

4.1 The effect of information sensitivity

To investigate how blockchain technology affects supply chain operation, we consider the relationship between information-sensitivity and the manufacturer's optimal equilibrium strategy. The purpose of the introduction of blockchain technology is to achieve supply chain information collaboration. Therefore, on the supply chain, the number of information-sensitive retailers has a meaningful and important influence on a manufacturer's decision to implement blockchain technology.

Analysing the above equilibrium solution yields the following proposition.

Proposition 1: When blockchain technology is employed in a supply chain, the proportion of information-insensitive retailers should be satisfied by $\frac{1}{d} < 1 - \mu < \frac{3}{d}$.

Proposition 1 demonstrates that the quantity of information-sensitive retailers ensures the best information-sharing results within a certain range. In addition, the number of information-sensitive suppliers is related to the basic demand of the manufacturer.

Proposition 2: The manufacturer's optimal wholesale price ${w_B}^*$ increases with the proportion of information-sensitive retailers μ when $k(d\beta - \sqrt{\beta(d+3)}) < t < k(d\beta + \sqrt{\beta(d+3)})$, otherwise, it decreases with μ.

Proposition 2 illustrates that the manufacturers' wholesale price is non-monotonically related to the quantity of information-sensitive retailers. When the number of information-insensitive retailers is within a certain range, the more sensitive the retailer is to information, the more pricing power the manufacturer wields. This is because blockchain technology increases the possibility and security of information-sharing. If the retailer is sensitive to information, the more likely he or she is to accept the introduction of blockchain technology into the supply chain. Currently, the manufacturer has strong bargaining power.

Proposition 3: The manufacturer's optimal profit ${\pi_B}^*$ increases with the proportion of information-sensitive retailers μ when $t < \frac{2d+3k^2\beta}{2\beta k}$, otherwise, it decreases with μ.

Proposition 3 illustrates that the manufacturers' profits are affected non-monotonically by the quantity of information-sensitive retailers. When the number of information-insensitive supply chains is small, the more sensitive retailers are, the more profitable the manufacturer is. If a manufacturer wants to increase profits by using blockchain technology, it is necessary to consider not only the retailer's information sensitivity, but also the number of downstream information-sensitive retailers.

4.2 The effect on cost

In Section 4.1, we intentionally ignored the manufacturer's cost because the impact of blockchain technology on supply chain cost is comprehensive. In this section, we specifically discuss manufacturer cost.

In a traditional supply chain, we consider a case in which there are two suppliers that provide raw materials s_j (where $j = 1, 2$) to the manufacturer. However, because of delayed supply and undisclosed information, the manufacturer cannot receive those two suppliers' raw materials at the same time, which leads to production delays. The arrival time of each raw material is t_j (where $j = 1, 2$). Moreover, the manufacturer will incur storage cost c_j (where $i = 1, 2$) for the raw material arriving first and unit production delay cost n for the raw material arriving second.

Consequently, we obtain the total cost c_T to the manufacturer under the condition of using a supply chain without blockchain technology, as follows.

$$c_T = \begin{cases} nt_1, & if\ t_1 > t_2. \\ nt_2, & if\ t_1 < t_2. \\ n(D_T - s_1)^+, & if\ s_1 < s_2. \\ n(D_T - s_2)^+, & if\ s_1 > s_2. \\ (s_i - \min(s_i, D_T))^+ \sum_{i=1}^{2} c_i, & \\ (t_1 - t_2)^+ \sum_{i=1}^{2} c_i s_i, & \\ s_i, t_i, c_i > 0. & \end{cases} \tag{8}$$

In Eq. 8, the first and second items represent the production delay costs. The third and fourth items denote the out-of-stock costs. Note that the above two kinds of costs are caused by the differential between the arrival times of the two suppliers' raw materials. The fifth item is the cost of storing surplus materials. The sixth item is the total storage cost for the raw materials that arrive first. The last item is the constraint to ensure that the model has practical meaning.

Next, we investigate a supply chain using blockchain technology. When the blockchain technology is employed by the supply chain, the manufacturer and supplier can each obtain complete information. The two suppliers can then supply the manufacturer at the same time, thus eliminating the storage cost for the material that arrives first and the cost of storing surplus materials.

Consequently, we obtain the total cost c_B to the manufacturer under the condition of using the blockchain-based supply chain, as follows.

$$c_B = \begin{cases} nt_1, & if\ t_1 > t_2. \\ nt_2, & if\ t_1 < t_2. \\ n(D_T - s_1)^+, & if\ s_1 < s_2. \\ n(D_T - s_2)^+, & if\ s_1 > s_2. \\ (\min\ s_i - D_T)^+ \sum_{i=1}^{2} c_i, & \\ s_i, t_i, c_i > 0. & \end{cases} \tag{9}$$

In Eq. 9, the first four items are same as Eq. 8. Since the two suppliers have achieved a coordinated supply, the fifth item represents the storage cost for surplus materials. The last item is the constraint to ensure that the model has practical meaning.

After analysing the total costs of the two supply chains, Lemma 4 is provided, as follows.

Lemma 4**:** Blockchain technology has a great impact on supply chain costs. The cost of the traditional supply chain is c_T and the cost of the blockchain-based supply chain is c_B.

To explore the impact of blockchain technology on supply chain costs in detail, we use the Monte Carlo (MC) method to simulate the costs of the different supply chains.

5. Simulation

We assume that the quality of the raw materials provided by suppliers is denoted as s_j, which is uniformly distributed in [0, 0.3], i.e., $s_1 \sim U[0, 0.3]$ and $s_2 \sim U[0, 3]$. The arrival time of the two different raw materials is denoted as t_j, which is uniformly distributed in [0,0.4], $t_1 \sim U[0, 0.4]$ and $t_2 \sim U[0, 4]$. Using the MC method, we randomly generate 1000 sets s_j and t_2. In addition, let $D_T = 1000$, $c_1 = 100$, and $c_2 = 150$. We consider n ranges from 100 to 180, with an interval of 20. After the simulation, the manufacturer's cost changes are obtained, as shown in Figs. 2 and 3.

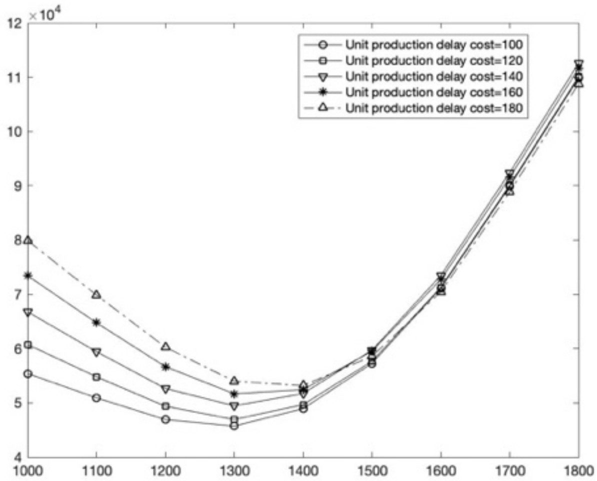

Fig. 2 Changes in manufacturers' costs with traditional supply chains

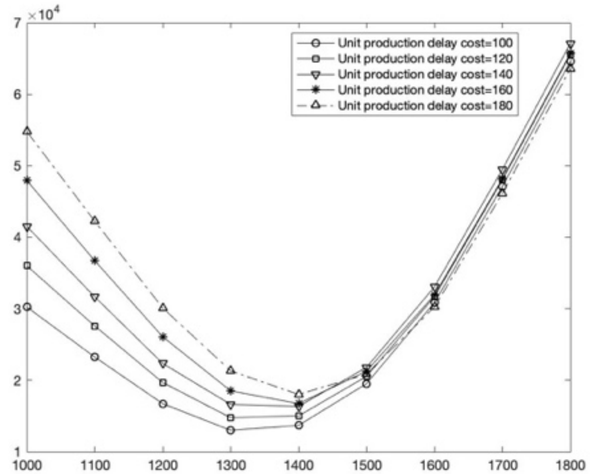

Fig. 3 Changes in manufacturers' costs with blockchain-based supply chains

By simulating the cost models of traditional supply chains and blockchain supply chains, we discover that there is a minimum cost for both types of supply chains under the aversion cost. Moreover, the cost of supply chain changes with delay costs is not monotonous.

The simulation results in Fig. 2 and Fig. 4 show that regardless of the type of supply chain (traditional or blockchain-enabled), an increase in the per unit cost of delay has the potential to increase the total cost of both supply chains. Therefore, manufacturers need to keep a tight rein on the per unit cost of delay. The use of blockchain, on the other hand, increases the transparency of the supply chain and allows the manufacturer to have information on the availability of raw materials. This further illustrates the value of blockchain in collaborating on supply chain information. To better determine how blockchain helps supply chains to achieve information collaboration, we need to compare the total costs of the two supply chains (as shown in Fig. 4).

To study the impact of blockchain technology on supply chain costs, we compared the simulation data of the minimum costs of two supply chains under different delay costs, as illustrated in Fig. 4. The results demonstrate that under any delay cost, the minimum cost of the blockchain supply chain is lower than the minimum cost of the traditional supply chain, which indicates that blockchain technology can effectively reduce supply chain operating costs.

As a whole, the implementation of blockchain has significant value for information collaboration in the supply chain. Our simulation results confirm this value numerically. For blockchain-enabled supply chains, the increased transparency of the supply chain means that manufacturers can produce on demand, order on demand, and do not need higher safety stock levels. Thus, blockchain implementation has practical implications for the efficient collaborative supply chain management.

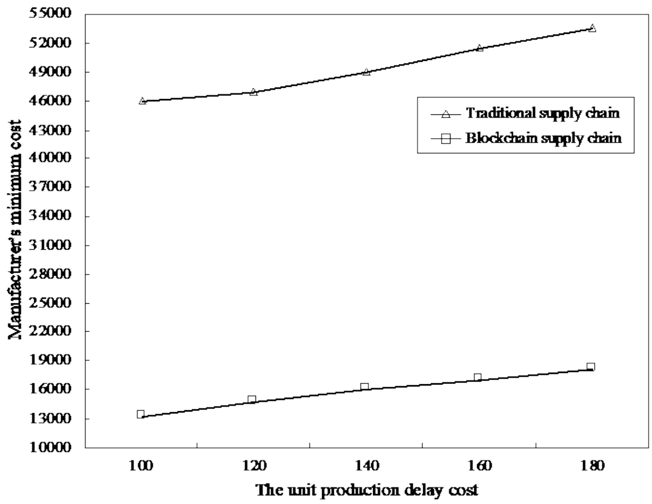

Fig. 4 Comparison of manufacturers' minimum costs with different types of supply chains

6. Conclusion

In traditional supply chains, various entities independently maintain their own supply chain information and the lack of transparency results in higher temporal and informational costs. Blockchain technology has been proven to provide a transparent and reliable unified information platform that is able to reduce logistical costs and trace the entire production and delivery process, thereby improving supply chain management efficiency. In this paper, we considered a three-level supply chain using blockchain technology to analyse the impact of information sensitivity on supply chain operations when blockchain technology was introduced into supply chain management. Our research reached the following conclusions.

- Although the introduction of blockchain technology into the supply chain allows supply chain information to be more effectively shared, it is not the case that the more information is shared, the more beneficial it is to the supply chain. The optimal quality of information-sharing is directly related to the information sensitivity of the supply chain members.
- In the supply chain, there is a non-monotonic relationship between manufacturers' wholesale prices and profits and the number of information-sensitive retailers. Therefore, manufacturers' pricing decisions should consider the cost of information-sharing.
- Simulation research found that blockchain technology could effectively reduce the supply chain operating costs. Therefore, blockchain technology is better used for improving the supply chain governance level.

This study generates insightful guidelines regarding the optimal operational strategies of a supply chain considering blockchain technology, especially when the blockchain technology is introduced into the supply chain, how can the supply chain maintain a reduced operating cost? For further research, it would be interesting to explore a case in which supply chains have different channel structures and determine how blockchain technology affects channel structures. In addition, further research should also consider the impact of information traceability from a management perspective. Another topic we are more interested in is when the members of the supply chain have inconsistent risk appetites for information disclosure, (that is, some members of the supply chain are risk-averse), what should be the optimal decision of the supply chain? In future studies, we will conduct in-depth research on this interesting problem. In addition, future research can consider supply chain risks [38, 39] with blockchain adoption.

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Appendix A

Proof of lemmas: we have $\pi_B = w_B(\mu d + (1-\mu)d\alpha + \beta k\alpha) - \beta {w_B}^2 - \mu dk\alpha - (1-\mu)dk\alpha^2$, differentiating Eq. 3 once with respect to w_B and α, respectively, and then considering the first-order condition yields: $\frac{\partial \pi_B}{\partial w_B} = \mu d + (1-\mu)d\alpha + \beta k\alpha - 2\beta w_B = 0$ and $\frac{\partial \pi_B}{\partial \alpha} = (1-\mu)dw_B - \mu dk - 2(1-\mu)dk\alpha = 0$. Solving this system of equations, the optimal wholesale price as ${w_B}^* = \frac{k\mu[d(1-\mu)+\beta k]}{(1-\mu)[3k\beta - d(1-\mu)]}$ and the optimal amount of manufacturer's information as $\alpha^* = \frac{\mu[d(1-\mu)-\beta k]}{(1-\mu)[3k\beta - d(1-\mu)]}$ are obtained. Thus, the manufacturer's optimal profit with blockchain technology as ${\pi_B}^* = \left(\frac{2\mu\beta k^2}{(1-\mu)[3k\beta-(1-\mu)d]}\right)\left(\frac{\mu d(1-\mu)[3k\beta-d(1-\mu)]}{(1-\mu)[3k\beta-d(1-\mu)]} + \frac{d\mu(1-\mu)[d(1-\mu)-k\beta]}{(1-\mu)[3k\beta-d(1-\mu)]} - \frac{k\mu\beta[d(1-\mu)+\beta k]}{(1-\mu)[3k\beta-(1-\mu)d]}\right) = \frac{k\beta\mu(2(1-\mu)-\beta k)}{(1-\mu)[3k\beta-d(1-\mu)]}$. Similarly, we have $\pi_T = w_T(d - \beta w_T) = w_T d - \beta {w_T}^2$, differentiating Eq. 4 once with respect to w_B and α, respectively, and then considering the first-order condition yields: $\frac{\partial \pi_B}{\partial w_T} = d - 2\,\beta w_T = 0$, then we have the manufacturer's optimal wholesale price without blockchain technology as ${w_T}^* = \frac{d}{2\,\beta}$. Thus, the manufacturer's optimal profit without blockchain technology as ${\pi_T}^* = \left(\frac{2d^2}{4\,\beta} - \frac{d^2}{4\,\beta}\right) = \frac{d^2}{4\,\beta}$.

Proof of Proposition 1: We have $\alpha^* = \frac{\mu[d(1-\mu)-\beta k]}{(1-\mu)[3k\beta-d(1-\mu)]} > 0$, thus, there must be $3k\beta - d(1-\mu) > 0$ and $d(1-\mu) - \beta k > 0$ or $3k\beta - d(1-\mu) < 0$ and $d(1-\mu) - \beta k < 0$. Solving this inequality, we obtain $\frac{1}{d} < 1 - \mu < \frac{3}{d}$.

Proof of Proposition 2: Let $\frac{\partial {w_B}^*}{\partial \mu} = \frac{k\mu\left(3k^2\beta - 2dk\beta(1-\mu) - d^2(\mu-1)^2\right)}{(3k\beta + d(\mu-1))^2(\mu-1)^2} > 0$, yielding $3k^2\beta - 2dk\beta(1-\mu) - d^2(\mu-1)^2 > 0$. Then, let $d(1-\mu) = t$. We thus obtain $k(d\beta - \sqrt{\beta(d+3)}) < t < k(d\beta + \sqrt{\beta(d+3)})$. Note that t represents the quantity of information-insensitive retailers.

Proof of Proposition 3: Let $\frac{\partial {\pi_B}^*}{\partial \mu} = -\frac{k\beta\mu\left(3k^2\beta - 2d(1-\mu)(\mu - 1 + \beta k)\right)}{(3k\beta + d(\mu-1))^2(\mu-1)^2} > 0$, yielding $3k^2\beta - 2d(1-\mu)(\mu - 1 + \beta k) < 0$. Then, let $d(1-\mu) = t$. We thus obtain $t < \frac{2d + 3k^2\beta}{2\beta k}$.