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Can blockchain help food supply chains with platform operations during the COVID-19 outbreak?

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ABSTRACT

Food selling platforms are facing both challenges and opportunities during the COVID-19 outbreak as the enforcement of social distancing protocols has pushed consumers with serious health and safety concerns to shop online. Observing that platforms and their suppliers have adopted blockchain technologies and linked selected information nodes separately to foster consumers' trust, we establish a game-theoretic model to study the operations decisions and blockchain adoption strategies for a food supply chain consisting of one platform and one supplier. We explore the values and impacts of blockchain on the retailing platform, supplier, and consumers, respectively. An all-win situation is achieved when both members of the supply chain adopt blockchain. We further propose that not all prevalent supply chain contracts can achieve supply chain coordination in the presence of blockchain. In extended studies, we examine the incentives of the supply chain members' blockchain implementation with consideration of the fixed cost of such adoption, product infection, and tampered information.

1. Introduction

1.1. Background and motivation

With the development of e-commerce, we have witnessed a boom of platform operations in many industries all over the world. Amid the emergence of cold chain technology, platforms, such as Amazon, Alibaba, and JD.com, are further prospered by expanding their food selling business scopes. For example, these platforms have conducted long-distance and even cross-border sales of agricultural products, including seafood, eggs, milk, fruits, and meat. However, such innovative business model is challenged by the COVID-19 outbreak (Choi, 2021). Although the enforcement of social distancing protocols has pushed their demands to an online context, consumers now have serious health and safety concerns about the origins of their food and cold chain logistics, where the virus can survive for extended periods (McKinsey & Company, 2020). For instance, several workers were infected by processing cold chain food in Fresh Hema, an omni-channel retailer owned by Alibaba that is partially operating through online platforms. Immediately thereafter, the imported frozen meat and seafood sold through

Fresh Hema were heavily targeted for testing. A total of 9,989 samples from 12 affiliated warehouses and processing facilities were collected and tested¹. Even though such reaction was deemed appropriate, Fresh Hema greatly suffered from the substantial testing costs and dramatic decrease in consumer demand. With the increasing worries of consumers about their health and safety, the imports of seafood products in China decreased by 19.6% in 2020².

To foster consumers' trust and extricate from difficulties during COVID-19 pandemic, the traceability and transparency of supply chains have become important to the survival of firms (Emerson, 2020). Many platforms have leveraged the capability of digital technologies, among which blockchain technology is widely adopted and preferred by platforms (Parker et al., 2016; Constantinides et al., 2018; Choi et al., 2020a). On the one hand, many food selling platforms are established based on e-commerce, which provides a suitable environment to adopt digital technologies. On the other hand, due to the traceability of reliable and trustworthy information supported by blockchain, platforms can trace and efficiently identify products that are potentially infected. The advantages of blockchain features enable platforms and their upstream suppliers to get through difficult times.

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¹ <https://www.producerreport.com/article/hema-workers-shenzhen-test-positive-covid-19-21-stores-close> (accessed March 23, 2021)

² <http://www.customs.gov.cn/customs/302249/zfxgk/2799825/302274/302277/302276/3516042/index.html/> (accessed 5 February 2021)

In industrial practice, platforms adopt blockchain in distribution and logistics, and some of their suppliers have participated in such adoption by linking some information nodes to blockchain. After the COVID-19 outbreak, Alibaba timely launched blockchain for its Tmall e-commerce platform based on a cold chain traceability system. As shown in Fig. 1.1, all information during the distribution and retailing logistics in China is traced and linked to blockchain called Antchain adopted by Alibaba. Unlike giant supermarkets (e.g., Walmart) that offer blockchain solutions to their suppliers for traceable and reliable information, platforms usually link their own logistics and distribution information to blockchain only. Tmall rarely provides tracing services for the origin of its food imports, except for some agricultural products that are sourced from Australia and New Zealand. Fig. 1.1 also indicates that Antchain does not necessarily provide upstream information of its food supply chain, such as source origin and production information.

Suppliers' self-verification by participating in blockchain projects is widely observed. For instance, a famous food supplier, Nestle, involves itself in blockchain implementation with its downstream retailers, such as Amazon. Nestle also collaborates with its upstream partners to achieve supply chain transparency, which enables consumers to track their products from the farm to consumption through the blockchain³. However, blockchain is not free lunch. The complexity of this technology and substantial adoption costs fetter its implementation in firms (Choi et al., 2020b). Other controversial issues also drive the hesitation of firms to involve themselves in blockchain projects, such as privacy and high corrigenda costs for information disclosure because mistakes are recorded forever (López and Farooq, 2020; Choi et al., 2020a). Some suppliers even publicly announce their rejection of blockchain solutions⁴.

1.2. Research questions and major findings

Motivated by the challenges faced by food supply chains and platform operations during the COVID-19 epidemic, we conduct an analytical analysis with the goal of addressing the following questions:

- (1) What are the optimal operations decisions for the retailing platform and supplier with and without blockchain implementation?
- (2) When do the retailing platform and supplier gain incentives to adopt blockchain? Will the blockchain implementation achieve an all-win situation for the platform, supplier, and consumers?
- (3) Can the platform and supplier achieve supply chain coordination by signing a supply chain contract? What is the impact of blockchain adoption on supply chain coordination?
- (4) How robust are the findings when we generalize the models with different considerations, such as (a) fixed cost of blockchain adoption, (b) product infection, and (c) dishonest behaviors of suppliers with blockchain?

We use a setting under which both the retailing platform and supplier have the option to adopt blockchain, which relieves the consumers' health-safety concerns for products. By exploring the answers to the research questions, we theoretically derive several managerial insights from the analytical results. After deriving the optimal wholesale and retail prices without and with blockchain adoption, we present the values and impacts of blockchain on the retailing platform, supplier, and consumers, respectively. Blockchain is most beneficial for the platform, supplier, and consumers when both members of the supply chain adopt such technology. We further develop a centralized supply chain and show that it has no incentive to adopt blockchain when the adoption cost

is relatively low. As a result, the decentralized supply chain outperforms the centralized one. Focused on a scenario where the centralized supply chain is motivated to adopt blockchain, we examine the prevalent supply chain contracts in the presence of blockchain. It is shown that the two-part tariff and profit sharing contracts can achieve supply chain coordination with blockchain, whereas the cost sharing and revenue sharing contracts fail to do so.

In extended studies, we first check the robustness of the main results by considering the fixed cost of blockchain adoption. Second, we examine what will happen if an infection occurs with a certain probability during the pandemic. We propose that at least one of the supply chain members has the incentive to adopt blockchain. Third, we investigate the impact of supplier's dishonest behaviors, such as tampering with information before linking to blockchain. Our result indicates that the incentives of the supply chain members' blockchain implementation highly depend on the penalty costs they incur after an infected product is detected.

The rest of this paper is organized as follows. In Section 2 we review related studies in the literature. Section 3 presents 4 basic models of blockchain implementation in a supply chain. Section 4 outlines the incentives of adopting blockchain for the retailing platform and supplier, respectively. In section 5, we examine whether the prevalent supply chain contracts can achieve coordination with blockchain adoption. We explore the extended studies in Section 6 with considerations of the fixed cost of blockchain adoption, product infection, and dishonest behaviors of suppliers with blockchain. Section 7 concludes the paper. All mathematical proofs are provided in the Appendix.

2. Literature review

This paper contributes to three streams of literature on operations management (OM) and supply chain management (SCM), namely, the implementation of blockchain in the OM/SCM field, SCM under disasters, and supply chain coordination with different contracts.

Studies on blockchain technology highlight the advances and features of blockchain implementation in operations management (Hawlitschek et al., 2018; Shi et al., 2021b; Treiblmaier and Sillaber, 2021). Choi (2019) elaborates an early study about blockchain adoption for platforms by building analytical models for traditional retail network operations and a blockchain-supported platform. In addition, the impacts of blockchain adoption are evaluated for diamond authentication and certification. Pun et al. (2021) explore the value of blockchain in combatting a counterfeiter and find that blockchain should be adopted when either the counterfeit quality is medium or consumers hold intermediate distrust about products in the market. Choi et al. (2020a) investigate the pricing and information disclosure decisions within blockchain-supported rental platforms. Niu et al. (2021) indicate that the blockchain-based authentication of product quality information fosters consumer trust. Jonker (2019) identifies lack of consumer demand as the greatest barrier in the adoption of crypto-payments by online retailers even though these retailers show substantial interest to adopt cryptocurrency based on blockchain. Choi and Luo (2019) discuss the data quality issues in sustainable fashion supply chain operations with blockchain adoption. They show that blockchain may improve social welfare yet harm the supply chain profit. By analyzing the behaviors of consumers and agents through blockchain, Choi et al. (2020b) formulate a pricing policy and wage design for an on-demand service platform with risk-sensitive consumers. Focused on the food supply chains with health-safety concerns, we capture the traceability and transparency of reliable information supported by blockchain implementation.

Antonucci et al. (2019) present an overview of the scientific literature on the use of blockchain in the agri-food sector. Among the stream of literature which investigates the benefits of blockchain traceability, Kamble et al. (2019) find that traceability is the most significant driver of blockchain technology implementation in the agriculture supply

³ <https://aws.amazon.com/cn/managed-blockchain/> (accessed 6 March 2021)

⁴ <https://shippingwatch.com/carriers/Container/article10602520.ece> (accessed March 22, 2021)

Fig. 1.1. Food supply chain and information nodes on Antchain.

chain. Some literature conducts case studies to shed spotlight on the traceability and transparency in agriculture and food supply chains due to their blockchain adoption (Casino et al., 2020; Bumbalskas et al., 2020). Rogerson and Parry (2020) argue that blockchain adoption in a food supply chain may improve visibility and enhance consumer trust. In this paper, the key features of blockchain are utilized by both the supplier and retailing platform. We assume that both supply chain members have the option to adopt blockchain according to their needs. We also examine blockchain implementation in a food supply chain in the context of a pandemic and other disasters.

Many studies have examined supply chain management in the face of disasters, centering on various topics such as collaborative prepositioning network for disaster response (Balcik et al., 2019), logistics service design (Kim et al., 2019), temporary facility locations and allocation planning (Liu et al., 2019), use of social media analysis (Yan and Pedraza-Martinez, 2019), and disaster relief inventory management (Ye et al., 2020). More recently, with regard to the COVID-19 epidemic, Guan et al. (2020) establish a global trade modelling framework to analyze the impact of idealized lockdown scenarios on supply chains. Ivanov (2020) examines the impact of the pandemic on supply chain networks and supply chain performance via a simulation-based methodology. Choi (2020a) proposes two innovative models under the COVID-19 epidemic outbreak, namely, the “static service operation” and the “mobile service operation,” and discusses related government subsidies and support. Kaplan (2020) proposes COVID-19 scratch models to support local decisions. Unlike the above literature, given that disasters, such as the COVID-19 outbreak, dramatically reduce the demand for food, our research aims at unveiling how blockchain technology can be utilized to foster consumers’ trust and improve profits from the perspective of supply chains.

This paper also relates to the issues of supply chain coordination. Cachon (2003) introduces different supply chain coordination contracts in detail. Wei and Choi (2010) discuss wholesaling and profit sharing contracts under a mean-variance framework. Chen et al. (2017) examine the role of wholesale and two-part tariff contracts in sustainable supply chain management from a power perspective. Considering sustainable investment, Shi et al. (2020) find that two-part tariff and revenue-sharing contracts cannot achieve supply chain coordination, while bargaining contracts can do so. The existing works that investigate the impact of blockchain implementation on supply chain coordination with contracts are rare, except Choi (2020b), Ferrer-Gomila et al. (2019), Cai et al. (2021), and Shi et al. (2021a). Specifically, Choi (2020b) examines the blockchain-based supply chain financing problem and finds that revenue sharing contracts, profit sharing contracts, and two-part tariff contracts can all achieve coordination. On the basis of blockchain implementation, Ferrer-Gomila et al. (2019) propose a novel solution for contract signing, which contributes to classic problems, such

as double spending and fairness. Cai et al. (2021) explore the platform operations supported by blockchain technology to improve supply contracts and avoid moral hazard issues. Focused on copycat issues, Shi et al. (2021a) highlight the effects of blockchain adoption on supply chain coordination with prevalent contracts. In this paper, we further study how food supply chain coordination is affected by the blockchain implementation, which can effectively earn consumers’ trust yet has substantial costs.

3. Model setting

We consider a food supply chain system comprising one retailing platform (she) and one supplier (he), who are indexed by R and S , respectively. The supplier incurs a unit cost c for the product procurement and sells this product to the platform via a wholesale contract at a unit wholesale price w . The platform then sells this product to the market at a unit retail price p , with $p > w > c$. For a consumer in the market, his/her valuation towards the product under normal circumstances is denoted by v , which is a continuous variable and follows a density function $f(v)$. We assume that v follows a uniform distribution in the range of 0 and 1.

In the presence of the pandemic, the whole supply chain faces an infection risk. For example, the source areas may be experiencing a COVID-19 outbreak, thus exposing the product to an infection risk during the logistics process. This case is especially true under the scenario with cold chain transportation. Facing the infection risk, consumers become concerned about the safety of the product. The disutility of purchasing a product due to these concerns is denoted by $\bar{\theta}$, where $\bar{\theta} \in [0, 1]$.

Upon acknowledging these concerns, both the supplier and platform have the incentive to invest in “health-safety” issues. One efficient approach for addressing these concerns is adopting blockchain given its information transparency and traceability. In real-world scenarios, firms do not always link all information nodes to blockchain because such technology has a substantial variable cost (Shi et al., 2021a). To capture this feature, we assume that the supplier and platform have the option to link partial information to blockchain, which in turn blunts consumers’ worries of infection. We define the decrement in a consumer’s disutility due to information disclosure through blockchain as θ_i , where $i \in \{R, S\}$. We consider θ_i a decision variable that represents the amount of information or the number of information nodes linked to blockchain essentially. Accordingly, we use θ_S and θ_R to denote the amount of information linked to blockchain by the supplier and platform, respectively. In order to reduce the consumers’ health-safety concerns and

stimulate demands, firms have incentives to disclose their adoption of blockchain on official websites⁵. On the basis of the observation of information nodes linked to blockchain (if any), the utility perceived by a consumer who has valuation v of the product and is concerned about being infected can be formulated as:

$$u = v - (\bar{\theta} - \theta_R - \theta_S) - bp, \quad (3.1)$$

where $b > 0$ is the price sensitivity of the product. The implementation of the blockchain does not directly influence the product characteristics and price sensitivity but positively affects the utility by fostering consumers' trust. A consumer will purchase a product only when the utility is non-negative. We normalize market size to 1 and assume that the market demand is deterministic. The demand function can then be formulated as follows:

$$D = \int_{(\bar{\theta} - \theta_R - \theta_S) + bp}^1 f(v)dv = 1 - (\bar{\theta} - \theta_R - \theta_S) - bp. \quad (3.2)$$

Without loss of generality, the blockchain adoption is not free and positive correlated with θ_i , where $i \in \{R, S\}$. We assume that the cost associated with the blockchain is scaled by the coefficient λ . This cost represents the need to establish hashtags, build the block, and link information nodes to the blockchain (Choi et al., 2020b). The blockchain implementation cost is then defined as:

$$I_i(\theta_i) = \lambda \frac{\theta_i^2}{2}. \quad (3.3)$$

where $i \in \{R, S\}$. Equation (3.3) indicates that the adoption cost of blockchain is convex and increasing in θ_i . It implies that a greater number of information nodes linked to blockchain corresponds to a higher adoption cost (Shi et al., 2021a). Although substantial, the fixed cost of blockchain technology is usually viewed as a sunk cost, which is omitted from real operations (Choi et al., 2020b). Following the literature, we exclude the fixed cost of blockchain implementation from our basic model but consider such cost in our robustness checks as an extension. To avoid trivial outcomes, we assume that the coefficient cost is sufficiently substantial (i.e., $\lambda b > \frac{3}{8}$) (Dong et al., 2016; Shi et al., 2020).

The decision sequence can be divided into two inter-related stages, namely, the blockchain adoption and operations subgames. In the blockchain adoption subgame, which takes place before the pricing and ordering decisions are made, the supplier and platform decide whether to adopt blockchain and simultaneously determine the amount of information linked to blockchain (i.e., θ_S and θ_R). In the operations subgame, we consider a Stackelberg game wherein the supplier is the leader and the platform is the follower (Shi et al., 2021a). At this stage, the supplier initially decides the wholesale price (w) and offers the platform a wholesale contract. Afterward, the platform determines the retail price (p) in response to the given wholesale price.

Given that each firm has the option to adopt blockchain or stick to the original operations mode, we investigate the following scenarios: (1) the N scenario where neither firm adopts blockchain; (2) the R scenario where only the platform adopts blockchain; (3) the S scenario where only the supplier adopts blockchain; and (4) the B scenario where both firms adopt blockchain. Both supply chain members maximize their profits. Let π_i^j denote the profit of firm i under scenario j , where $i \in \{R, S\}$ and $j \in \{N, R, S, B\}$. The subscript indicates the platform (R) and supplier (S), whereas the superscript indicates the scenarios of blockchain adoption, respectively. The profit functions under these scenarios are presented as follows:

(1) Without blockchain (N scenario):

$$\pi_R^N(p) = (p - w)(1 - \bar{\theta} - bp),$$

$$\pi_S^N(w) = (w - c)(1 - \bar{\theta} - bp)$$

(2) Only the platform adopts blockchain (R scenario):

$$\pi_R^R(p, \theta_R) = (p - w)\left(1 - (\bar{\theta} - \theta_R) - bp\right) - \frac{1}{2}\lambda\theta_R^2,$$

$$\pi_S^R(w) = (w - c)\left(1 - (\bar{\theta} - \theta_R) - bp\right)$$

(3) Only the supplier adopts blockchain (S scenario):

$$\pi_R^S(p) = (p - w)\left(1 - (\bar{\theta} - \theta_S) - bp\right),$$

$$\pi_S^S(w, \theta_S) = (w - c)\left(1 - (\bar{\theta} - \theta_S) - bp\right) - \frac{1}{2}\lambda\theta_S^2.$$

(4) Both the supplier and platform adopt blockchain (B scenario):

$$\pi_R^B(p, \theta_R) = (p - w)\left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp\right) - \frac{1}{2}\lambda\theta_R^2,$$

$$\pi_S^B(w, \theta_S) = (w - c)\left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp\right) - \frac{1}{2}\lambda\theta_S^2.$$

In order to show the impact of blockchain adoption on consumers, we define CS^j as the consumer surplus under scenario j , where $j \in \{N, R, S, B\}$. Consumer surplus can be formulated as:

$$CS^j = \int_{\bar{\theta} - \theta_R - \theta_S + bp}^1 \left[v - (\bar{\theta} - \theta_R - \theta_S + bp) \right] f(v)dv, j \in \{N, R, S, B\}.$$

4. Model analysis

We adopt the backward sequential decision approach to solve the problems under each scenario. The profit functions of each firm under the four scenarios are all concave according to their structural properties. Hence, the optimal retail prices, wholesale prices, amount of information linked to blockchain, related profits, and consumer surpluses can be derived. We denote the optimal profits of the platform and supplier as Π_R^j and Π_S^j , respectively, and the optimal decisions, demand, and consumer surplus as w^j , p^j , θ_R^j , θ_S^j , D^j and CS^j , respectively, under each scenario, where $j \in \{N, R, S, B\}$. The optimal decisions and related performances are summarized in Table 4.1.

We then compare the supplier's and platform's optimal profits under the four scenarios based on the information shown in Table 4.1.

Proposition 1.. (a) $\Pi_R^B > \Pi_R^S > \Pi_R^R > \Pi_R^N$. (b) $\Pi_S^B > \Pi_S^S > \Pi_S^R > \Pi_S^N$.

Proposition 1 shows that the adoption of blockchain increases the optimal profits of both the platform and supplier (i.e., $\Pi_R^B > \Pi_R^N$ and $\Pi_S^B > \Pi_S^N$). Therefore, both firms have the incentive to link information nodes to blockchain. It is also notable that both the platform and supplier get free-ride on each other's adoption (i.e., $\Pi_R^S > \Pi_R^N$ and $\Pi_S^R > \Pi_S^N$). However, if only one of these firms can adopt blockchain, then the platform prefers the supplier to do so, while the supplier prefers to adopt it by himself (i.e., $\Pi_R^S > \Pi_R^R$ and $\Pi_S^S > \Pi_S^R$). It implies that the supplier has a stronger incentive to build consumer trust by adopting blockchain for self-verifiability.

With regard to each firm's incentive to join the other's blockchain adoption, both the platform and supplier are willing to join the blockchain project when the other adopts the blockchain (i.e., $\Pi_R^B > \Pi_R^S$ and $\Pi_S^B > \Pi_S^R$). In other words, these firms reach a win-win situation after

⁵ <https://www.nestle.com.cn/> (accessed 24 May 2021)

Table 4.1
Optimal decisions and performances under the four scenarios.

	Model N	Model R	Model S	Model B
D^j	$\frac{(1 - \bar{\theta} - bc)}{4}$	$\frac{2b\lambda(1 - \bar{\theta} - bc)}{(8b\lambda - 1)}$	$\frac{b\lambda(1 - \bar{\theta} - bc)}{4b\lambda - 1}$	$\frac{2b\lambda(1 - \bar{\theta} - bc)}{8b\lambda - 3}$
w^j	$\frac{(1 - \bar{\theta} - bc)}{2b} + c$	$\frac{4\lambda(1 - \bar{\theta} - bc)}{8b\lambda - 1} + c$	$\frac{2\lambda(1 - \bar{\theta} - bc)}{4b\lambda - 1} + c$	$\frac{4\lambda(1 - \bar{\theta} - bc)}{8b\lambda - 3} + c$
p^j	$\frac{3(1 - \bar{\theta} - bc)}{4b} + c$	$\frac{6\lambda(1 - \bar{\theta} - bc)}{8b\lambda - 1} + c$	$\frac{3\lambda(1 - \bar{\theta} - bc)}{4b\lambda - 1} + c$	$\frac{6\lambda(1 - \bar{\theta} - bc)}{8b\lambda - 3} + c$
θ_R^j	—	$\frac{(1 - \bar{\theta} - bc)}{8b\lambda - 1}$	—	$\frac{(1 - \bar{\theta} - bc)}{8b\lambda - 3}$
θ_S^j	—	—	$\frac{(1 - \bar{\theta} - bc)}{4b\lambda - 1}$	$\frac{2(1 - \bar{\theta} - bc)}{8b\lambda - 3}$
Π_R^j	$\frac{(1 - \bar{\theta} - bc)^2}{16b}$	$\frac{\lambda(1 - \bar{\theta} - bc)^2}{2(8b\lambda - 1)}$	$\frac{b\lambda^2(1 - \bar{\theta} - bc)^2}{(4b\lambda - 1)^2}$	$\frac{\lambda(8b\lambda - 3)(1 - \bar{\theta} - bc)^2}{2(8b\lambda - 3)^2}$
Π_S^j	$\frac{(1 - \bar{\theta} - bc)^2}{8b}$	$\frac{8b\lambda^2(1 - \bar{\theta} - bc)^2}{(8b\lambda - 1)^2}$	$\frac{\lambda(1 - \bar{\theta} - bc)^2}{2(4b\lambda - 1)}$	$\frac{2\lambda(4b\lambda - 1)(1 - \bar{\theta} - bc)^2}{(8b\lambda - 3)^2}$
CS^j	$\frac{(1 - \bar{\theta} - bc)^2}{32}$	$\frac{2b^2\lambda^2(1 - \bar{\theta} - bc)^2}{(8b\lambda - 1)^2}$	$\frac{b^2\lambda^2(1 - \bar{\theta} - bc)^2}{2(4b\lambda - 1)^2}$	$\frac{2b^2\lambda^2(1 - \bar{\theta} - bc)^2}{(8b\lambda - 3)^2}$

adopting blockchain under scenario B.

In order to further explain the incentives of adopting blockchain, we compare the optimal decisions and related demands under the four scenarios. For notational purposes, we use $\theta_T^B = \theta_R^B + \theta_S^B$ to denote the total amount of information linked to blockchain under scenario B.

Proposition 2.. (a) $w^B > w^S > w^R > w^N$. (b) $p^B > p^S > p^R > p^N$. (c) If $\frac{3}{8} < \lambda b < \frac{1}{2}$, $\theta_T^B > \theta_S^B > \theta_R^B > \theta_S^S > \theta_R^S$; if $\lambda b \geq \frac{1}{2}$, $\theta_T^B > \theta_S^B > \theta_S^S \geq \theta_R^B > \theta_R^S$. (d) $D^B > D^S > D^R > D^N$.

Proposition 2 indicates that the adoption of blockchain raises the wholesale and retail prices simultaneously. In addition, when only one firm undertakes the blockchain adoption (i.e., scenarios R and S), the supplier attempts to link more information to blockchain, and the increment in demand is more significant under scenario S (i.e., $\theta_S^S > \theta_R^R$ and $D^S > D^R$) than scenario R. This observation in turn explains the impact of blockchain adoption on the optimal decisions of each firm. As a result, both the supplier and platform receive higher profits when the former adopts blockchain than the latter does so (i.e., $\Pi_R^S > \Pi_R^R$ and $\Pi_S^S > \Pi_S^R$).

We then examine the scenario where both firms adopt blockchain. Under this scenario, the amount of information nodes linked to blockchain reaches its highest level from the supply chain's perspective. In addition, the supplier makes the greatest effort in adopting blockchain. However, the involvement of the platform under this scenario depends on the blockchain cost and price sensitivity. Specifically, when the coefficient of blockchain adoption cost is relatively low or when the consumers are less sensitive to retail prices (i.e., $\lambda b < \frac{1}{2}$), the platform prefers to link more information to blockchain under scenario B than the supplier does himself (i.e., $\theta_R^B > \theta_S^S$). **Proposition 2** also implies that the double marginalization amplifies as the number of information nodes linked to blockchain increases. In other words, consumers share the cost of blockchain adoption because of their health-safety concerns essentially. Although they have to pay more due to blockchain adoption, the demands of these consumers increase as the supply chain links more information to blockchain. To further investigate the adoption of blockchain from the consumers' perspective, we compare the consumer surpluses under each scenario and propose the following:

Proposition 3.. $CS^B > CS^S > CS^R > CS^N$

Proposition 3 suggests that the increment in demand dominates the increased retail price that consumers have to pay because the blockchain adoption relieves the health and safety concerns of these consumers. The value of blockchain for consumers is the most significant under scenario B. Therefore, Propositions 1 and 3 imply that an all-win situation is

achieved under scenario B where the supplier, platform, and consumers all benefit from the two firms' involvement in blockchain adoption. This result drives us to focus on scenario B and investigate how the performances of each firm can be further improved through their cooperation.

5. Supply chain coordination with blockchain adoption

We have conducted analysis of blockchain adoption based on a decentralized supply chain. As shown in **Section 4**, both members of the supply chain have incentives to be involved in blockchain adoption. Accordingly, we view scenario B as a benchmark and denote the total profit of the decentralized supply chain under scenario B as $\Pi_{SC}^B = \Pi_R^B + \Pi_S^B$. In this section, we establish the supply chain coordination with blockchain adoption by regarding the supply chain as a centralized decision-making system, which is denoted by superscript C. Acting as a whole system, the centralized supply chain decides the retail price (i.e., p) and the downstream/upstream information linked to blockchain (i.e., θ_R and θ_S , respectively). It is straightforward to represent the profit of the centralized supply chain with blockchain adoption as follows:

$$\pi_{SC}^C(p, \theta_R, \theta_S) = (p - c) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2} \lambda (\theta_R^2 + \theta_S^2)$$

The profit of the centralized supply chain is a concave function. We have the following lemma:

Lemma 1.. The centralized supply chain has the incentive to adopt blockchain if and only if $\lambda b > 1$ and has no incentive to do so if $\frac{3}{8} < \lambda b \leq 1$. The optimal decisions and related performances are summarized in **Table 5.1**.

On the basis of **Lemma 1**, we compare the optimal profits of the centralized and decentralized supply chains.

Proposition 4.. (a) The decentralized supply chain with blockchain outperforms the centralized supply chain if $\frac{3}{8} < \lambda b \leq 1$. (b) The centralized supply chain outperforms the decentralized supply chain in the presence of blockchain adoption if $\lambda b > 1$.

Proposition 4 presents a very important and interesting result. It indicates that blockchain implementation helps the decentralized supply chain outperform the centralized system when the blockchain related cost is relatively low or when consumers are less sensitive to retail price (i.e., $\frac{3}{8} < \lambda b \leq 1$). If this condition holds, then the centralized supply chain has no incentive to adopt blockchain. This counterintuitive result can be ascribed to the following casual chain. The centralized supply chain system tends to link more information nodes to blockchain with a

Table 5.1

Optimal decisions and performances of the centralized supply chain.

	D^C	p^C	$\theta_R^C = \theta_S^C$	Π_{SC}^C	CS^C
$\frac{3}{8} < \lambda b \leq 1$	$\frac{(1 - \bar{\theta} - bc)}{2}$	$\frac{(1 - \bar{\theta} - bc)}{2b} + c$	—	$\frac{(1 - \bar{\theta} - bc)^2}{4b}$	$\frac{(1 - \bar{\theta} - bc)^2}{8}$
$\lambda b > 1$	$\frac{b\lambda(1 - \bar{\theta} - bc)}{2b\lambda - 2}$	$\frac{\lambda(1 - \bar{\theta} - bc)}{2b\lambda - 2} + c$	$\frac{(1 - \bar{\theta} - bc)}{2b\lambda - 2}$	$\frac{\lambda(1 - \bar{\theta} - bc)^2}{4(b\lambda - 1)}$	$\frac{b^2\lambda^2(1 - \bar{\theta} - bc)^2}{2(2b\lambda - 2)^2}$

sufficiently small value of λb , which relieves the consumers' worries and allows the supply chain to significantly raise its retail price. As a result, consumers are driven out of the market due to the high price, and the centralized supply chain has no incentive to adopt blockchain. Therefore, the decentralized supply chain outperforms the centralized system due to the value of blockchain. Throughout the rest of this paper, when discussing supply chain coordination, we assume that the blockchain adoption cost is sufficiently high (i.e., $\lambda b > 1$), which implies that $\Pi_{SC}^C > \Pi_{SC}^B$.

Table 5.1 further compares the optimal decisions and consumer surpluses between the centralized and decentralized supply chains with consideration of blockchain adoption.

Corollary 1.. (a) If $1 < \lambda b < \frac{9}{4}$, $p^C > p^B$; if $\lambda b \geq \frac{9}{4}$, $p^C \leq p^B$. (b) $\theta_T^C > \theta_T^B$. (c) $D^C > D^B$. (d) $CS^C > CS^B$.

Corollary 1 indicates that more information is linked to blockchain in the centralized supply chain (i.e., $\theta_T^C > \theta_T^B$). The demand then increases due to the reduced concerns over infection (i.e., $D^C > D^B$). It is worth to notice that the optimal retail price is higher in the centralized supply chain if $1 < \lambda b < \frac{9}{4}$. It implies that when the cost of blockchain adoption is relatively low or when consumers are less sensitive to price, the centralized supply chain can charge a higher retail price with an amplified demand and efficient blockchain involvement.

On the basis of **Proposition 4** and **Corollary 1**, it is valuable to further explore the supply chain coordination from the perspectives of firms and consumers. Afterward, we verify whether the commonly used contracts can achieve coordination in the presence of blockchain. We also examine different supply chain contracts, including cost sharing (CS), revenue sharing (RS), two-part tariff (TT), and profit sharing (PS) contracts, respectively. For notational purposes, we use superscript j to indicate the type of contract, where $j \in \{CS, RS, TT, PS\}$.

5.1. Cost sharing contract

Under a CS contract, the total cost of blockchain adoption is shared by the platform and supplier with proportions η and $(1 - \eta)$, respectively, where $\eta \in [0, 1]$. The platform shoulders $\frac{1}{2}\lambda\eta(\theta_R^2 + \theta_S^2)$, whereas the supplier takes the remaining cost (i.e., $\frac{1}{2}\lambda(1 - \eta)(\theta_R^2 + \theta_S^2)$). The profit functions are presented as follows:

$$\pi_R^{CS} = (p - w) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2}\lambda\eta(\theta_R^2 + \theta_S^2)$$

$$\pi_S^{CS} = (w - c) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2}\lambda(1 - \eta)(\theta_R^2 + \theta_S^2)$$

By examining the supply chain coordination under the CS contract, we derive the following proposition.

Proposition 5.. In the presence of blockchain adoption, the supply chain fails to be coordinated under the cost sharing contract.

Proposition 5 suggests that the supply chain cannot be coordinated by the CS contract, which can be explained by the motivation to adopt blockchain from the platform's perspective. Although signing a coordination contract leads to the increased demand and retail price, the platform undertakes much of the cost for blockchain adoption, which

exceeds the cost occurred in the decentralized supply chain, thereby hurting the platform's profit.

5.2. Revenue sharing contract

Under an RS contract, the revenue is shared by the platform and supplier with proportions γ and $(1 - \gamma)$, respectively, where $\gamma \in [0, 1]$. The profit functions of the platform and supplier are as follows:

$$\pi_R^{RS} = (\gamma p - w) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2}\lambda\theta_R^2$$

$$\pi_S^{RS} = ((1 - \gamma)p + w - c) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2}\lambda\theta_S^2$$

By examining the supply chain coordination under the RS contract with blockchain adoption, we propose the following proposition.

Proposition 6.. In the presence of blockchain adoption, the supply chain fails to be coordinated under the revenue sharing contract.

Proposition 6 suggests that the supply chain with blockchain cannot be coordinated with the RS contract. Although the supplier and platform have incentives to adopt blockchain because of the increased demand, the supplier has to supply the product at a wholesale price that is lower than its cost in order to coordinate the supply chain under this type of contract (i.e., $w = \gamma c < c$). In this case, coordination cannot be achieved.

5.3. Two-Part tariff contract

Under the TT contract, we denote the lump-sum fee paid by the platform as F , which is offered to the supplier in addition to the wholesale price. We formulate the profit functions of the two firms as:

$$\pi_R^{TT} = (p - w) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2}\lambda\theta_R^2 - F,$$

$$\pi_S^{TT} = (w - c) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2}\lambda\theta_S^2 + F$$

With regard to supply chain coordination with blockchain adoption under the TT contract, we propose the following proposition.

Proposition 7.. In the presence of blockchain adoption, the supply chain with blockchain can be coordinated with a two-part tariff contract with the lump-sum payment, retail price, and wholesale price satisfying

$$F^{TT} = \frac{\lambda(96b^3\lambda^3 - 92b^2\lambda^2 + 26b\lambda - 5)(1 - \bar{\theta} - bc)^2}{2(2b\lambda - 2)^2(8b\lambda - 3)^2}, p^{TT} = c + \frac{\lambda(1 - \bar{\theta} - bc)}{2b\lambda - 2} = p^C \text{ and } w^{TT} = c.$$

Under the TT contract, the demand increases due to the blockchain implementation, whereas the retail price is the same as that of the centralized supply chain. However, the benefit obtained from supply chain coordination is completely grabbed by the supplier in the form of a lump-sum fee.

5.4. Profit sharing contract

Under the PS contract, the total supply chain profit is shared by the platform and supplier with proportions φ and $(1 - \varphi)$, respectively, where $\varphi \in [0, 1]$. We formulate the profit functions as:

$$\pi_R^{PS} = \varphi \left[(p - c) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2} \lambda (\theta_R^2 + \theta_S^2) \right],$$

$$\pi_S^{PS} = (1 - \varphi) \left[(p - c) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2} \lambda (\theta_R^2 + \theta_S^2) \right]$$

After checking the supply chain coordination under the PS contract, we propose the following proposition.

Proposition 8.. *In the presence of blockchain adoption, the supply chain can be coordinated with a profit sharing contract with a profit sharing portion*

$$\varphi^{PS} = \frac{2(b\lambda-1)(8b\lambda-1)}{(8b\lambda-3)^2} \text{ and retail price } p^{PS} = c + \frac{\lambda(1-\bar{\theta}-bc)}{2b\lambda-2} = p^C.$$

While the CS and RS contracts fail to coordinate the supply chain in the presence of blockchain adoption, the PS contract, which is a special combination of the two aforementioned contracts, can coordinate the supply chain by achieving Pareto improvement. The platform can receive higher profits due to the increased demand. However, the benefit of coordination is completely grabbed by the supplier, who acts as the leader of the supply chain.

6. Extended studies

In this section, we extend our basic model by considering more issues surrounding blockchain features in the context of the COVID-19 pandemic, including the fixed cost of blockchain adoption, the traceability of blockchain versus product infection, and supplier's dishonest behavior such as tampering with information before linking to blockchain. We check the robustness of our basic results and explore the value of blockchain with these additional considerations.

6.1. Extended model with fixed cost of blockchain implementation

In the basic models, we omit the fixed cost of blockchain adoption which is viewed as a sunk cost. We then check the robustness of our main results by taking the fixed cost into consideration.

We define the fixed cost for the implementation of blockchain technology that occurs to the platform and supplier as Z_R and Z_S , respectively. Afterward, the total cost of blockchain adoption by firm i becomes:

$$I_i(\theta_i) = \frac{1}{2} \lambda \theta_i^2 + Z_i,$$

where $i \in \{R, S\}$ represents the platform and supplier, respectively.

Note that the fixed cost of blockchain implementation affects scenarios R, S, and B, where at least one of the firms adopts this technology. The profit functions of a firm who makes efforts in blockchain adoption under these scenarios are as follows:

(1) The platform's profit under the R scenario:

$$\pi_R^R(p, \theta_R) = (p - w) \left(1 - (\bar{\theta} - \theta_R) - bp \right) - \frac{1}{2} \lambda \theta_R^2 - Z_R.$$

(2) The supplier's profit under the S scenario:

$$\pi_S^S(w, \theta_S) = (w - c) \left(1 - (\bar{\theta} - \theta_S) - bp \right) - \frac{1}{2} \lambda \theta_S^2 - Z_S.$$

(3) The profit of both the supplier and platform under the B scenario:

$$\pi_R^B(p, \theta_R) = (p - w) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2} \lambda \theta_R^2 - Z_R,$$

$$\pi_S^B(w, \theta_S) = (w - c) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2} \lambda \theta_S^2 - Z_S.$$

Based on the profit functions, the fixed cost of blockchain adoption

does not influence the optimal decisions, such as the wholesale price, retail price, and amount of information nodes linked to blockchain. As a result, both demand and consumer surplus are not affected by the fixed cost of blockchain adoption. From the profit functions, it is obvious that both firms' incentives to adopt blockchain decrease in the fixed cost of blockchain adoption. We propose the following to indicate the platform's incentive of blockchain adoption based on a comparison of optimal profits:

Proposition 9.. *The platform's profits under different strategies are compared in Fig. 6.1a: (a) $\Pi_R^B > \Pi_R^S > \Pi_R^R > \Pi_R^N$ if $Z_R < Z_{R,1}$; (b) $\Pi_R^B > \Pi_R^S > \Pi_R^R > \Pi_R^N$ if $Z_{R,1} \leq Z_R < Z_{R,2}$; (c) $\Pi_R^S \geq \Pi_R^B > \Pi_R^R > \Pi_R^N$ if $Z_{R,2} \leq Z_R < Z_{R,3}$; (d) $\Pi_R^S \geq \Pi_R^N \geq \Pi_R^B > \Pi_R^R$ if $Z_R \geq Z_{R,3}$, where $Z_{R,1} = \frac{(1-\bar{\theta}-bc)^2}{16b(8b\lambda-1)^2}$, $Z_{R,2} = \frac{\lambda(16b^2\lambda^2-2b\lambda-1)(1-\bar{\theta}-bc)^2}{2(8b\lambda-3)^2(4b\lambda-1)^2}$, $Z_{R,3} = \frac{(40b\lambda-9)(1-\bar{\theta}-bc)^2}{16b(8b\lambda-3)^2}$ and $Z_{R,1} < Z_{R,2} < Z_{R,3}$.*

Given an increasing demand, the platform always benefits from the supplier's blockchain adoption (i.e., $\Pi_R^S > \Pi_R^R$ and $\Pi_R^B > \Pi_R^R$). This result is consistent with that of the basic model. Moreover, the platform's motivation to join or start the blockchain implementation in the presence/absence of the supplier's blockchain adoption blunts as the fixed cost (i.e., Z_R) increases.

We then propose the following to indicate the supplier's incentive of blockchain adoption based on the comparison of optimal profits:

Proposition 10.. *The supplier's profits under different strategies are compared in Fig. 6.1b: (a) $\Pi_S^B > \Pi_S^S > \Pi_S^R > \Pi_S^N$ if $Z_S < Z_{S,1}$; (b) $\Pi_S^B > \Pi_S^S \geq \Pi_S^R > \Pi_S^N$ if $Z_{S,1} \leq Z_S < Z_{S,2}$; (c) $\Pi_S^B > \Pi_S^R > \Pi_S^S \geq \Pi_S^N$ if $Z_{S,2} \leq Z_S < Z_{S,3}$; (d) $\Pi_S^R \geq \Pi_S^B > \Pi_S^S > \Pi_S^N$ if $Z_{S,3} \leq Z_S < Z_{S,4}$, $\Pi_S^R > \Pi_S^N \geq \Pi_S^B > \Pi_S^S$ if $Z_S \geq Z_{S,4}$, where $Z_{S,1} = \frac{\lambda(1-\bar{\theta}-bc)^2}{2(4b\lambda-1)(8b\lambda-1)^2}$, $Z_{S,2} = \frac{(1-\bar{\theta}-bc)^2}{8b(4b\lambda-1)^2}$, $Z_{S,3} = \frac{2\lambda(64b^2\lambda^2-16b\lambda-1)(1-\bar{\theta}-bc)^2}{(8b\lambda-1)^2(8b\lambda-3)^2}$, $Z_{S,4} = \frac{(32b\lambda-9)(1-\bar{\theta}-bc)^2}{8b(8b\lambda-3)^2}$ and $Z_{S,1} < Z_{S,2} < Z_{S,3} < Z_{S,4}$.*

Propositions 9 and 10 are similar: the platform's blockchain adoption is always beneficial to the supplier (i.e., $\Pi_S^B > \Pi_S^S$, $\Pi_R^B > \Pi_R^S$). The supplier's incentive of adopting blockchain depends on the related fixed cost (i.e., Z_S).

In the above propositions, both firms are willing to adopt blockchain technologies to spur demands and improve profits when $Z_R < Z_{R,2}$ and $Z_S < Z_{S,3}$. Scenario B is achieved under this condition. We now turn our discussion to supply chain coordination with blockchain adoption and related fixed cost. Considering the fixed cost of blockchain implementation, the profit of the centralized supply chain becomes as follows:

$$\pi_{SC}^C(p, \theta_R, \theta_S) = (p - c) \left(1 - (\bar{\theta} - \theta_R - \theta_S) - bp \right) - \frac{1}{2} \lambda (\theta_R^2 + \theta_S^2) - Z_R - Z_S$$

Similar to the basic model, the centralized supply chain has the incentive to adopt blockchain if and only if $\lambda b > 1$ and has no incentive to do so if $\frac{3}{8} < \lambda b \leq 1$.

Proposition 11.. (a) *If $\frac{3}{8} < \lambda b \leq 1$, then the decentralized supply chain with blockchain outperforms the centralized supply chain when the fixed cost is sufficiently low (i.e., $Z_R + Z_S < Z_{SC}$). Otherwise, the centralized supply chain outperforms the decentralized supply chain, where $Z_{SC} = \frac{(38b\lambda-16b^2\lambda^2-9)(1-\bar{\theta}-bc)^2}{4b(8b\lambda-3)^2}$.* (b) *If $\lambda b > 1$, then the centralized supply chain outperforms the decentralized supply chain in the presence of blockchain adoption irrespective of the magnitude of fixed cost.*

Proposition 11 shows that the decentralized supply chain with blockchain implementation may outperform the centralized supply chain when the blockchain related costs are sufficiently low (i.e., $\frac{3}{8} < \lambda b \leq 1$ and $Z_R + Z_S < Z_{SC}$). However, it is less likely to meet this condition, after considering the fixed cost of blockchain adoption, which reduces the value of blockchain. The second part of **Proposition 11** is

Fig. 6.1a. The impact of fixed blockchain implementation cost on the platform's profits.

Fig. 6.1b. The impact of fixed blockchain implementation cost on the supplier's profits.

consistent with the results of the comparison between decentralized and centralized supply chains in the basic model.

We now check the robustness of contracts and coordination in a supply chain by considering the fixed cost of blockchain adoption.

Proposition 12.. *The fixed cost of blockchain implementation does not affect the coordination under the cost sharing, revenue sharing, two-part tariff and profit sharing contracts.*

Proposition 12 reveals that the fixed cost of adopting blockchain does not matter when evaluating supply chain coordination under different contracts. The result about supply chain coordination with blockchain in the basic model is solid. The impact of the fixed cost of blockchain implementation is therefore very influential and clear.

6.2. Traceability of blockchain with product infection

During the pandemic, food products may be infected with the COVID-19 virus when they are sourced from risky areas or during the supply and logistic processes. Food products in China are frequently reported to be infected by viruses through various channels⁶. We assume that a product is infected with an ex ante probability of α_I , where $0 \leq \alpha_I \leq 1$. Note that the infected product is not necessarily tested positive when arriving at the end market given that the virus may be eliminated naturally during routine disinfection. In this case, we have two situations. With probability $1 - \beta$, the unsafe product is consumed by the end market without virus detection or outbreak, where $0 \leq \beta \leq 1$. With probability β , the infected product is detected by the market or a third-party inspector. Through contact tracing, the supply chain is held accountable for the infected product. We assume that the whole supply chain system should undertake a penalty cost, which is denoted as M , to dispose the infected product and compensate the consumers.

We use superscripts *IN* and *IB* to represent the infected product scenarios without and with blockchain adoption, respectively. As depicted in Fig. 6.2, in the absence of blockchain, the supplier and platform have to share the penalty cost equally given that the process responsible for the infection is impossible to determine. After adopting blockchain, the supplier and platform can trace the product and achieve self-verifiability. We further assume that an unsafe product is infected during the supply process with probability α_S and is infected during the platform's logistics process with probability $(1 - \alpha_S)$, where $\alpha_S \in [0, 1]$. Since the infected product is accountable with blockchain, the penalty cost M is undertaken by the firm who is responsible for the infection.

Similar to the previous analysis, the demand without blockchain is $D = 1 - \bar{\theta} - bp$. When the supplier and platform get involved in blockchain adoption, the consumers' health-safety concerns are partially relieved, and the demand becomes $D = 1 - (\bar{\theta} - \theta_R - \theta_S) - bp$. The

profit functions of each firm under the two scenarios are as follows:

(1) Without blockchain (IN scenario):

$$\pi_R^{IN}(p) = (p - w)(1 - \bar{\theta} - bp) - \frac{1}{2}\alpha_I\beta M,$$

$$\pi_S^{IN}(w) = (w - c)(1 - \bar{\theta} - bp) - \frac{1}{2}\alpha_I\beta M$$

(2) With blockchain (IB scenario):

$$\pi_R^{IB}(p, \theta_R) = (p - w)(1 - (\bar{\theta} - \theta_R - \theta_S) - bp) - \frac{1}{2}\lambda\theta_R^2 - \alpha_I\beta(1 - \alpha_S)M,$$

$$\pi_S^{IB}(w, \theta_S) = (w - c)(1 - (\bar{\theta} - \theta_R - \theta_S) - bp) - \frac{1}{2}\lambda\theta_S^2 - \alpha_I\beta\alpha_S M.$$

We denote the optimal decisions, profits, and consumer surplus under each scenario as w^j , p^j , θ_R^j , θ_S^j , D^j , Π_R^j , Π_S^j and CS^j , where $j \in \{IN, IB\}$, and summarize them in Table 6.1.

We further define two critical thresholds of the penalty cost M undertaken by the platform and supplier when they are proven responsible

for the infection: $M_{IR} = \frac{(40b\lambda - 9)(1 - \bar{\theta} - bc)^2}{16\alpha_I\beta b \left(\frac{1}{2} - \alpha_S\right) (8b\lambda - 3)^2}$ and $M_{IS} = \frac{(32b\lambda - 9)(1 - \bar{\theta} - bc)^2}{8\alpha_I\beta b \left(\alpha_S - \frac{1}{2}\right) (8b\lambda - 3)^2}$,

respectively. We have the following to highlight the incentives of blockchain adoption based on a comparison of optimal profits.

Proposition 13.. *At least one of the supply chain members has the incentive to adopt blockchain. (a) For the platform, $\Pi_R^{IB} < \Pi_R^{IN}$, if $M > M_{IR}$ and $\alpha_S < \frac{1}{2}$; otherwise, $\Pi_R^{IB} \geq \Pi_R^{IN}$. (b) For the supplier, $\Pi_S^{IB} < \Pi_S^{IN}$, if $M > M_{IS}$ and $\alpha_S > \frac{1}{2}$; otherwise, $\Pi_S^{IB} \geq \Pi_S^{IN}$.*

The condition that triggers the platform to adopt blockchain always holds when $\alpha_S \geq \frac{1}{2}$, but it is opposite for the supplier. When $\alpha_S \leq \frac{1}{2}$, the supplier always has the incentive to adopt blockchain. Therefore, Proposition 13 implies an important result that at least one of the supply chain members has the incentive to adopt blockchain. This proposition also indicates that if the probability of being infected during the supply process is higher than that within the platform's extent of responsibility (i.e., $\alpha_S \geq \frac{1}{2}$), adopting blockchain is always beneficial for the platform (i.e., $\Pi_R^{IB} \geq \Pi_R^{IN}$). In addition, even the logistic processes of the platform are riskier than those of the supplier (i.e., $\alpha_S < \frac{1}{2}$), the platform still has the incentive to adopt blockchain when the penalty cost is relatively low (i.e., $M \leq M_{IR}$) because the adoption increases both the demand and profit margin, which dominate the adoption and contingent penalty costs. A similar result holds for the supplier. Specifically, when the probability of being infected during the supply processes or the penalty cost is relatively low, the supplier is willing to adopt blockchain. Proposition 13 also shows the circumstance where both firms are involved in blockchain adoption, and that is, when the penalty cost is relatively low (i.e., $M \leq \max\{M_{IR}, M_{IS}\}$). The incentives of both the platform and

⁶ <https://www.chinadaily.com.cn/a/202101/16/WS60029122a31024ad0baa30e7.html/> (accessed 5 March 2021)

Fig. 6.2. Models without/with blockchain with consideration of the infected product.

Table 6.1
Optimal decisions and performances under the two scenarios.

	Model IN	Model IB
D^j	$\frac{(1 - \bar{\theta} - bc)}{4}$	$\frac{2b\lambda(1 - \bar{\theta} - bc)}{8b\lambda - 3}$
w^j	$\frac{(1 - \bar{\theta} - bc)}{2b} + c$	$\frac{4\lambda(1 - \bar{\theta} - bc)}{8b\lambda - 3} + c$
p^j	$\frac{3(1 - \bar{\theta} - bc)}{4b} + c$	$\frac{6\lambda(1 - \bar{\theta} - bc)}{8b\lambda - 3} + c$
θ_R^j	—	$\frac{(1 - \bar{\theta} - bc)}{8b\lambda - 3}$
θ_S^j	—	$\frac{2(1 - \bar{\theta} - bc)}{8b\lambda - 3}$
Π_R^j	$\frac{(1 - \bar{\theta} - bc)^2}{16b} - \frac{1}{2}\alpha_I\beta M$	$\frac{\lambda(8b\lambda - 1)(1 - \bar{\theta} - bc)^2}{2(8b\lambda - 3)^2} - \alpha_I\beta(1 - \alpha_S)M$
Π_S^j	$\frac{(1 - \bar{\theta} - bc)^2}{8b} - \frac{1}{2}\alpha_I\beta M$	$\frac{2\lambda(4b\lambda - 1)(1 - \bar{\theta} - bc)^2}{(8b\lambda - 3)^2} - \alpha_I\beta\alpha_S M$
CS^j	$\frac{(1 - \bar{\theta} - bc)^2}{32}$	$\frac{2b^2\lambda^2(1 - \bar{\theta} - bc)^2}{(8b\lambda - 3)^2}$

supplier to adopt blockchain decrease in the probabilities of infection and detection (i.e., α_I and β).

6.3. Blockchain adoption with consideration of dishonest behavior

Although blockchain information cannot be modified after being uploaded, it is reported that organizations may have the incentive to tamper with such information before linking nodes to blockchain⁷. Such dishonest action is increasingly popular among suppliers, who may source their products from unsafe origins. On the basis of observations in practice, we investigate blockchain adoption with consideration of the supplier's dishonest behavior.

We assume that an epidemic breaks out in the supplier's source area with an ex ante probability μ , where $0 \leq \mu \leq 1$. Due to safety concerns, the consumer demand dramatically decreases. Accordingly, the supplier

has a strong motivation to change information about the source area and link such tampered information to blockchain, thereby earning the consumers' trust. We denote the increment in consumer valuation due to replacing a source origin with a safe place as θ_G . Without loss of generality, the supplier incurs an additional cost g per unit product for information tampering. This cost refers to replacing RFID card or revising the label of each product. Eventually, the risky product with tampered information is likely to be detected by the market or leads to a virus outbreak with probability ρ , where $0 \leq \rho \leq 1$ (Plambeck and Taylor, 2016). After detecting the infected product in the market, the contact tracing enables the regulator to find out that the supplier is accountable with probability τ , where $0 \leq \tau \leq 1$. The likelihood that the supplier successfully hides all evidence about his unsafe product is $1 - \tau$. After being detected, the supplier incurs an additional cost denoted as T , such as the damage to his reputation and punishment for information tampering.

We use superscripts *FN* and *FB* to represent those scenarios without and with blockchain adoption, respectively. Fig. 6.3 shows the sequential events under the two scenarios. Similar to Model *IN*, the platform has to share the penalty cost M equally with the supplier when the party at fault is unclear without blockchain. After adopting blockchain, the supplier should pay the penalty cost plus an additional cost (i.e., $M + T$) if his dishonest behavior is discovered. Otherwise, the platform has to pay an equal share of the penalty cost with the supplier, who hides the unsafe source origin successfully.

The demand remains unchanged under scenario *FN* and becomes $D = 1 - (\bar{\theta} - \theta_R - \theta_S - \mu\theta_G) - bp$ under scenario *FB*. Compared with the basic case, the incremental demand resulting from tampered information (i.e., θ_G) occurs when the epidemic outbreak reaches the source origin with probability μ .

The profit functions of each firm under the two scenarios are presented as follows:

(1) Without blockchain (FN scenario):

$$\pi_R^{FN}(p) = (p - w)(1 - \bar{\theta} - bp) - \frac{1}{2}\mu\rho M,$$

$$\pi_S^{FN}(w) = (w - c)(1 - \bar{\theta} - bp) - \frac{1}{2}\mu\rho M.$$

⁷ <https://www.supplychaindive.com/news/blockchain-technology-trust-data-integrity/supply-chain/549139/> (accessed 25 March 2021)

Fig. 6.3. Models without/with blockchain with consideration of the supplier's dishonest behavior.

(2) Both the supplier and platform adopt blockchain (FB scenario):

$$\pi_R^{FB}(p, \theta_R) = (p - w) \left(1 - (\bar{\theta} - \theta_R - \theta_S - \mu\theta_G) - bp \right) - \frac{1}{2} \lambda \theta_R^2 - \frac{1}{2} \mu \rho (1 - \tau) M,$$

Proposition 14.. (a) The platform has no incentive to adopt blockchain if $M < M_{FR}$ and $bg - \frac{2(1-\bar{\theta}-bc)}{\mu} < \theta_G < bg$ but prefers to adopt such technology

$$\pi_S^{FB}(w, \theta_S) = (w - c - \mu g) \left(1 - (\bar{\theta} - \theta_R - \theta_S - \mu\theta_G) - bp \right) - \frac{1}{2} \lambda \theta_S^2 - \mu \rho \tau (M + T) - \frac{1}{2} \mu \rho (1 - \tau) M.$$

We denote the optimal decisions, profits, and consumer surplus under each scenario as w^j , p^j , θ_R^j , θ_S^j , D^j , Π_R^j , Π_S^j , and CS^j , where $j \in \{FN, FB\}$, and summarize them in Table 6.2.

We define two critical thresholds of the penalty cost M undertaken by the platform and supplier, respectively, and then present Proposition 14 based on the comparison of optimal profits.

otherwise. (b) The supplier has no incentive to adopt blockchain if $\frac{1}{2}M + T > M_{FS}$ but prefers to adopt such technology otherwise.

Proposition 14 shows that the platform doesn't always have the incentive to adopt blockchain in the presence of the supplier's dishonest behavior. Specifically, the platform prefers to stick to the status where blockchain technology is not implemented when the increment in demand resulting from tampered information is relatively small (i.e., $\theta_G < bg$) and when the penalty cost resulting from the detection of

$$M_{FR} = \frac{8b\lambda(8b\lambda - 1)(\mu bg - \mu\theta_G) \left[2(1 - \bar{\theta} - bc) + (\mu\theta_G - \mu bg) \right] - (40b\lambda - 9)(1 - \bar{\theta} - bc)^2}{8\mu\rho\tau b(8b\lambda - 3)^2}$$

$$M_{FS} = \frac{(32b\lambda - 9)(1 - \bar{\theta} - bc)^2 + 16b\lambda(4b\lambda - 1)(\mu\theta_G - \mu bg) \left[2(1 - \bar{\theta} - bc) + (\mu\theta_G - \mu bg) \right]}{8\mu\rho\tau b(8b\lambda - 3)^2}$$

Table 6.2
Optimal decisions and performances under the two scenarios.

	Model FN	Model FB
D^j	$\frac{(1 - \bar{\theta} - bc)}{4}$	$\frac{2b\lambda(1 - \bar{\theta} + \mu\theta_G - bc - \mu bg)}{8b\lambda - 3}$
w^j	$\frac{(1 - \bar{\theta} - bc)}{2b} + c$	$\frac{4\lambda(1 - \bar{\theta} + \mu\theta_G - bc - \mu bg)}{8b\lambda - 3} + c + \mu g$
p^j	$\frac{3(1 - \bar{\theta} - bc)}{4b} + c$	$\frac{6\lambda(1 - \bar{\theta} + \mu\theta_G - bc - \mu bg)}{8b\lambda - 3} + c + \mu g$
θ_R^j	—	$\frac{(1 - \bar{\theta} + \mu\theta_G - bc - \mu bg)}{8b\lambda - 3}$
θ_S^j	—	$\frac{2(1 - \bar{\theta} + \mu\theta_G - bc - \mu bg)}{8b\lambda - 3}$
Π_R^j	$\frac{(1 - \bar{\theta} - bc)^2}{16b} - \frac{1}{2}\mu\rho M$	$\frac{\lambda(8b\lambda - 1)(1 - \bar{\theta} + \mu\theta_G - bc - \mu bg)^2}{2(8b\lambda - 3)^2} - \frac{1}{2}\mu\rho(1 - \tau)M$
Π_S^j	$\frac{(1 - \bar{\theta} - bc)^2}{8b} - \frac{1}{2}\mu\rho M$	$\frac{2\lambda(4b\lambda - 1)(1 - \bar{\theta} + \mu\theta_G - bc - \mu bg)^2}{(8b\lambda - 3)^2} - \mu\rho\tau(M + T) - \frac{1}{2}\mu\rho(1 - \tau)M$
CS^j	$\frac{(1 - \bar{\theta} - bc)^2}{32}$	$\frac{2b^2\lambda^2(1 - \bar{\theta} - bc + \mu\theta_G - \mu bg)^2}{(8b\lambda - 3)^2}$

infected products is relatively low (i.e., $M < M_{FR}$). These two conditions hint that the weak demand stimulated by tampered information and the low penalty for detecting the infection will reduce the platform's incentive for blockchain implementation. Note that the condition for the platform to adopt blockchain becomes more likely to hold as ρ and τ increase, thereby helping the platform achieve self-verifiability through blockchain implementation.

Proposition 14 also indicates that the supplier has the incentive to adopt blockchain when the penalty costs are relatively low (i.e., $\frac{1}{2}M + T \leq M_{FS}$). The incentive blunts as ρ and τ increase, which suggests that the likelihood of being detected and traced for responsibility plays an important role in blockchain implementation of the supplier with dishonest behavior. For regulators, high penalty costs and efficient detection are important approaches that discourage suppliers from tampering with information.

We perform a numerical analysis to clearly illustrate the firms' incentives for blockchain implementation. From **Proposition 14**, the crucial influential parameters are the incremental demand due to the tampered information (i.e., θ_G) and the penalty cost M .

We show the blockchain strategies adopted by the platform and supplier by varying θ_G and M . The numerical example uses the following parameter values initially: $\bar{\theta}=0.5$, $b=0.5$, $c=0.6$, $\lambda=5$, $g=0.4$, $\mu=0.5$, $\rho=0.1$, $\tau=0.1$, $T=2$. We obtain **Fig. 6.4**.

Fig. 6.4 indicates that both firms prefer not to adopt blockchain when θ_G and M are sufficiently small. As the demand increment θ_G increases, the supplier has the incentive to adopt blockchain when the penalty cost is relatively low.

Fig. 6.4. Optimal blockchain adoption strategies of the platform and supplier.

We further compare the optimal operations decisions with/without blockchain adoption considering the supplier's dishonest behavior. Then we have the following proposition.

Proposition 15.. (a) $w^{FB} < w^{FN}$, if $\lambda b < \frac{3}{4}$ and $\theta_G < \frac{2\mu bg(3-4b\lambda)-3(1-\bar{\theta}-bc)}{8b\lambda\mu}$; otherwise, $w^{FB} \geq w^{FN}$. (b) $p^{FB} < p^{FN}$, if $\lambda b < \frac{3}{2}$ and $\theta_G < \frac{4\mu bg(3-2b\lambda)-9(1-\bar{\theta}-bc)}{24b\lambda\mu}$; otherwise, $p^{FB} \geq p^{FN}$.

Unlike the impact of blockchain adoption on the optimal decisions in the basic model, blockchain adoption does not necessarily raise the optimal wholesale and retail prices with consideration of the supplier's information tampering. **Proposition 15** suggests that blockchain implementation reduces the optimal wholesale and retail prices when the tampered information has a relatively small impact on the demand and the cost associated with the blockchain is sufficiently low. This condition becomes more likely to hold as μ increases. This result is rather interesting. The supplier has to drop the wholesale price in the presence of blockchain when the tampered information fails to sufficiently spur demand because the platform suspects a related risk due to the dishonest behavior from the upstream.

7. Conclusion

7.1. Concluding remarks

Under the COVID-19 outbreak, food supply chains have recently faced unprecedented challenges. Due to the e-commerce base of retailing platforms and the features of blockchain, adopting blockchain technology as an efficient solution to these problems becomes a natural choice for food supply chains. Motivated by the widely reported real-world blockchain applications of platforms and suppliers, we have built analytical models to evaluate blockchain implementation in food supply chains. We have considered a food supply chain with a retailing platform and a supplier. Both of them have the option to reduce consumers' health-safety worries by adopting blockchain and linking information nodes. We have derived their pricing and blockchain involvement decisions and compared their incentives for blockchain implementation and related performances. We also have explored supply chain coordination with blockchain adoption. In the extended analysis, we have further studied models with general features, such as fixed cost of blockchain adoption, the possibility of product infection, and supplier's dishonest behaviors. As a concluding remark, we highlight the results we have obtained in relation to our research questions.

- (1) The adoption of blockchain raises the wholesale and retail prices simultaneously. In addition, the double marginalization amplifies as the amount of information linked to blockchain increases, thereby suggesting that consumers share the cost of blockchain adoption to relieve their health and safety concerns.
- (2) The optimal profits of both the platform and supplier are improved by the blockchain implementation. Therefore, both firms have the incentive to link information to blockchain. An all-win situation is achieved under scenario B where the supplier, platform, and consumers all benefit from the two firms' involvement in blockchain adoption.
- (3) If the blockchain adoption cost is relatively low or the consumers are less sensitive to retail prices, then the centralized supply chain has no incentive to adopt blockchain. As a result, the decentralized supply chain outperforms the centralized supply chain. After examining the prevalent supply chain contracts in the presence of blockchain adoption, we have found that the two-part tariff and profit-sharing contracts can achieve supply chain coordination with blockchain adoption, whereas the cost sharing and revenue sharing contracts fail to do so.
- (4) In our extended studies, we have considered the fixed cost of blockchain implementation and found that most of the main

results still hold even if the firms' incentives to adopt such technology are reduced by the fixed cost. We also have examined the traceability of blockchain with consideration of product infection. We have proposed that at least one of the supply chain members has the incentive to adopt blockchain. In addition, we have investigated the impact of supplier's dishonest behaviors, such as tampering with information before linking to blockchain. Our result shows that the incentives of the supply chain members to adopt blockchain depend on the penalty costs they incur after an infected product is detected.

7.2. Future studies

In this paper, both the supplier and platform have the option to either invest in blockchain implementation that uncovers their own sourcing and logistics information or stick to their original operations. We did not consider the innovative business model under which one of the supply chain members adopts blockchain and offers solutions to his/her partners to link related information to blockchain. In future studies, different modes of blockchain implementation and involvement warrant investigation. Another probable direction for future research is to consider the downstream and upstream competitions. Whether the rivals have stronger incentives to adopt blockchain to gain their consumers' trust will be a significant topic to explore. Last but not least, it will also be promising to extend the analysis to cover the role of regulators and governments during the COVID-19 pandemic. In our extended study, we have considered product infection, which may be detected by a third party. Policies implemented by regulators and governments, such as those related to penalties and detection efficiency, also warrant further study.

CRediT authorship contribution statement

Lu Yang: Writing – original draft, Formal analysis, Validation, Writing - review & editing. **Jun Zhang:** Supervision, Formal analysis, Validation, Writing - review & editing, Project administration, Funding acquisition. **Xiutian Shi:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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