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S.I.: ADVANCED MODELS FOR SUPPLY CHAIN FINANCE

Supply chain financing using blockchain: impacts on supply chains selling fashionable products

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Abstract

Today, supply chain finance is a very important topic. Traditional supply chains rely on banks to support the related financing activities and services. With the emergence of blockchain technology, more and more companies in different industries have considered using it to support supply chain finance. In this paper, we study supply chain financing problems in supply chains selling fashionable products. Modeling under the standard newsvendor problem setting with a single manufacturer and a single retailer employing a revenue sharing contract, we develop analytical models for both the traditional and blockchain-supported supply chains. We derive the optimal contracting and quantity decisions in each supply chain with Nash bargaining between the manufacturer and retailer. We analytically show how the revenue sharing contract can coordinate both types of supply chains. We then compare the optimal systems performances between the two supply chains. We prove that the blockchain-supported supply chain incurs a lower level of operational risk than the traditional supply chain. We have shown that if the service fees by banks are sufficiently high, adopting blockchain technology is a mean-risk dominating policy which brings a higher expected profit and a lower risk for the supply chain and its members. For robustness checking, we examine other commonly seen supply chain contracts and alternative risk measures, and analytically reveal that the results remain valid.

Keywords Blockchain · Supply chain management · Coordination · Mean-risk analysis · Fashionable products

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1 Introduction

In supply chain management, one critical aspect is on supply chain finance. According to Investopedia, we have the following definition for supply chain finance[1]: "Supply chain finance is a set of technology-based business and financing processes that link the various parties in a transaction—buyer, seller, and financing institution—to lower financing costs and improve business efficiency. Supply chain finance provides short-term credit that optimizes working capital for both the buyer and the seller." Problems such as getting enough capitals for production, cash flow analyses, supply chain setting for payment terms (e.g., trade credit or payment period), etc. are commonly present. It is known that supply chain finance is crucial for companies to get financing[2] and even expand the middle market economy.[3]

The traditional supply chain system relies heavily on financial service providers to support its supply chain finance (SCF). Well-established banks and financial service providers[4] play an important role. The common situation faced by the traditional supply chain system is that, in order to have a smooth operation, manufacturers and retailers would seek help from "banks".[5] There is no free lunch and both the manufacturers and retailers need to pay the banks a non-trivial amount of service fees.

Blockchain, also called the distributed ledger, is an information technology which supports many critical functions, including "cryptocurrency" (Chod et al. 2018; Choi 2019; Babich and Hilary 2020; Hastig and Sodhi 2020). Blockchain was first developed in the 1990s,[6] which initially was designed as a "cryptographically secured chain of blocks". Since 2008, bitcoin has emerged as a new form of cryptocurrency and got super popular with the development of the respective financial functions and "tradeable nature". Nowadays, with the development of blockchain technology and the associated cryptocurrency called "bitcoin", supply chain members can financially connect to one another by bypassing the banks and using the cryptocurrency directly. This is what industrialists call "digital supply chain transformation".[7] With blockchain technology, or blockchain in short, the sellers and buyers can save the service fees incurred if they seek help from the traditional banks. However, a substantial operational cost per transaction is needed for blockchain-supported operations.

In the industry, blockchain and cryptocurrency have been used in fashion apparel. Among other functions such as product provenance information disclosure and supply chain traceability, the use of cryptocurrency is still developing. It is reported that the apparel industry has been "testing the use of cryptocurrencies" over the past few years.[8] According to Forbes[10], both the LVMH group (with noble fashion brands such as "Dior" and "Louis Vuitton") as well as a fashion brand in China called "Babyghost" have started to use cryptocurrency and a "branded digital currency", respectively. Reports also indicate that cryptocurrency may

[1] https://www.investopedia.com/terms/s/supply-chain-finance.asp (accessed 29 January 2020).

[2] https://www.forbes.com/sites/forbesbusinessdevelopmentcouncil/2018/04/09/how-supply-chain-finance-is-offering-companies-a-new-cash-source/#64ac727322f1 (accessed 29 January 2020).

[3] https://www.forbes.com/sites/moiravetter/2016/02/17/is-supply-chain-finance-the-solution-to-unlocking-the-middle-market-economy/#545e39e6764d (accessed 29 January 2020).

[4] https://www.tradewindfinance.com/ (accessed 29 January 2020).

[5] To simplify the exposition, we use the term "banks" in the following parts of this paper to represent any financial institutes which can provide supply chain financing for the traditional supply chain systems.

[6] https://101blockchains.com/history-of-blockchain-timeline/ (accessed 17 March 2020).

[7] https://www.forbes.com/sites/stevebanker/2019/09/18/20-things-to-know-about-digital-supply-chain-transformations/#7011e0bb45b1 (accessed 30 January 2020).

[8] https://www.forbes.com/sites/kaleighmoore/2019/09/20/how-an-outdoor-retail-brand-leveraged-cryptocurrency-to-engage-young-consumers/#2992b4374d6b (accessed 17 March 2020).

Table 1 Features of traditional supply chains versus blockchain-supported supply chains in SCF

	Traditional Supply Chains	Blockchain-supported Supply Chains
Supply chain financing	Relies on banks (or other third parties)	Uses cryptocurrency directly between the sellers and buyers
Operational cost	No additional cost per transaction but service fees are needed (to be paid to the banks)	A non-trivial blockchain cost is associated with each transaction (for establishing the hash tags and blocks)

be especially appealing to the Chinese retail market.[9] As a remark, it is crystal clear that supply chains selling fashionable products face a high level of risk owing to the product nature (e.g., high demand volatility, short selling season, etc.). This is especially prominent for the fashion apparel industry in which a lot of brands such as Forever 21, Diesel, Rockport Group, etc. declared bankruptcy in 2019 alone.[10] Thus, considering operational risk is critically important for companies selling fashionable products.

Table 1 shows features of traditional supply chains and blockchain-supported supply chains in SCF. Under the traditional supply chain, the supply chain members rely on the traditional bank for providing financing services which would incur service fees. Under the blockchain-supported supply chain, the supply chain members use cryptocurrency which means they do not need to rely on the traditional bank and hence the respective service fees are no longer needed. However, operations with blockchain are not free and costs are incurred. In short, there is no doubt that blockchain technology helps SCF and may potentially improve operational efficiency (with respect the tradeoffs we described earlier). However, the literature has not adequately explored this issue and this paper aims to fill this gap.

To be specific, motivated by the emergence of blockchain technology, popularity of SCF and the under-explored role played by blockchain for SCF in supply chain operations with fashionable products, we build formal analytical models to investigate the topic. We attempt to theoretically address the following important research questions:

1. How to build analytical models for the traditional supply chain and blockchain-supported supply chain systems selling fashionable products? What are the optimal decisions in each supply chain system?
2. Comparing between the performances of the traditional supply chain and blockchain-supported supply chain systems, how does blockchain technology perform in terms of 'benefit" and "risk"? Are there conditions governing when the blockchain-supported supply chain will dominate the traditional supply chain in both "benefit" and "risk"?
3. How robust are the derived theoretical results, e.g., in terms of different supply chain contracts and risk measure?

To answer the above research questions, we follow the mainstream classic supply chain management literature and build newsvendor problem based supply chain models (to capture the core features of "fashionable products"), one for the traditional supply chain scenario and one for the blockchain-supported supply chain. In order to ensure the supply chain can be realistically coordinated, we consider the presence of a commonly seen revenue sharing contract in the supply chain and the members negotiate under a Nash bargaining scheme. We derive the optimal contract setting and optimal ordering quantity for each supply chain.

[9] https://jingdaily.com/cryptocurrencys-huge-potential-in-chinas-luxury-retail/ (accessed 17 March 2020).

[10] https://www.thefashionlaw.com/retail-woes-a-bankruptcy-timeline/ (accessed 17 March 2020).

Comparing between the two supply chain systems, we analytically show that the retailer's ordering quantity, and the inventory service level achieved are both lower under the case with the use of blockchain technology. Moreover, the blockchain-supported supply chain definitely yields a smaller level of operational risk compared to the traditional supply chain counterpart. When the service fees incurred by the traditional supply chain for banking service are sufficiently big, the use of blockchain is a mean-risk dominating solution in which the supply chain and its members are guaranteed to benefit in having higher profits and lower risks with the implementation of blockchain technology. If the service fees are not sufficiently big, then implementing blockchain technology is a mean-risk non-inferior solution for the supply chain and its members as it brings a smaller level of operational risk while also a smaller expected profit. To show robustness of the derived findings, we conduct further analyses with respect to different commonly seen supply chain contracts and an alternative downside risk measure.

As a remark, the models we propose in this paper focus specifically on blockchain technology because as of today, only blockchain technology can support cryptocurrency in a secure manner. This directly yields the situation in which the supply chain and its members can conduct transactions by themselves without the need of relying on banks for the transaction and financing services. There are some areas which can be explored further but we will postpone them to the future, e.g., information transparency, product information disclosure, sustainable operations, etc.

The rest of this paper is arranged as follows. We present a brief and concise review of the related literature in Sect. 2. We then build and explore the traditional supply chain model in Sect. 3. We construct the model for blockchain-supported supply chain and derive the corresponding optimal decisions in Sect. 4. We conduct a comparison study between the traditional supply chain and blockchain-supported supply chain in Sect. 5. We check the robustness of theoretical results in Sect. 6. We conclude this study with discussions of managerial insights and future research in Sect. 7. To enhance readability and presentation, a table of notation (Table 2) is prepared in "Appendix (1)" and all proofs are placed in "Appendix (2)".

2 Related literature and contribution statement

The following research areas are closely related to this study. We concisely review them as follows.

2.1 Blockchain in supply chain operations

Blockchain is an emerging technology which was originally associated with the cryptocurrency "bitcoins". Now, it is commonly believed that it would disrupt and revolutionalize the way companies operate in the supply chain. In the literature, Chod et al. (2018) study blockchain technology in the context of supply chain financing. The authors focus on highlighting how blockchain technology can add value supply chain management. Based on the real world case of Everledger, Choi (2019) studies the use of blockchain technology in diamond supply chains. He quantifies the value of blockchain technology based platform using consumer utility based models. Choi et al. (2020b) examine the "rental service platforms" using blockchain technology for "product information disclosure". Choi and Luo (2019) explore the information quality issues for fashion supply chains in the emerging economy.

The authors highlight the importance of blockchain technology and government's regulations. Choi et al. (2019) examine how blockchain technology relates to risk analysis for air-logistics. Wang et al. (2019) discuss in a position paper how blockchain technology may change modern supply chain management. In logistics and transportation, Yang (2019) examines the use of blockchain in maritime shipping operations. Choi et al. (2020d) study the use of blockchain supported social media platforms to enhance social media analytics. Babich and Hilary (2020) propose some critical areas for operations researchers to explore with the use of blockchain. Hastig and Sodhi (2020) study blockchain for "supply chain traceability" and the authors conceptually discuss the respective "critical success factors". Most recently, Choi et al. (2020c) investigate the on-demand service platform in the presence of blockchain technology. The authors focus on studying how a blockchain technology based system can help with identifying risk preference of consumers so that the best arrangement for hired service agents can be made. The above studies have examined blockchain based operations. However, they have not touched some fundamental problems such as how cryptocurrency of blockchain technology can make a difference for operations with the commonly explored newsvendor supply chain systems. This paper fills this gap.

2.2 Supply chain finance

Supply chain finance is a big topic. In the following, we only review some related studies (definitely not comprehensive while they do show some key features related to the field). First, Sarmah et al. (2007) explore the supply chain channel coordination challenge considering credit option. The authors study the "profit sharing" contract and highlight how it can maximize the supply chain performance with financial considerations. Chen and Wang (2012) study the "trade credit (TC) contract with limited liability". The authors model the supply chain system as one with capital constraints and uncover how the TC contract performs. Tang et al. (2017) examine the optimal sourcing problem from manufacturers with risk analysis. The authors consider the case in which there are limited capitals. Most recently, Cai et al. (2019a) study the supply chain finance problem in fashion supply chains. Modeling the optimization objective with the probability measures, the authors reveal how early and late payment schemes would make a difference. Guo and Liu (2020) explore the "cash flow shortage" challenge in mass customization supply chains. There are also a lot of studies which conduct risk analysis in supply chains with or without cash flow analyses. We review them in the next sub-section. As a remark, this paper is different from all these reviewed studies in supply chain finance in which the focal point is on blockchain technology and how it could replace the traditional banking or financing systems in supply chain operations.

2.3 Risk analysis and contracting

Nowadays, risk is a critical component of any operational analyses facing uncertainties and potential losses (Araz et al. 2020a, b; Sun et al. 2020a). After years of exploration, more and more common measures (such as the mean-risk models) have been widely recognized. In the literature, Agrawal and Seshadri (2000) study the presence of a middle-party in the supply chain to facilitate risk management. Chen et al. (2007) employ the expected utility approach to study optimal inventory control problems with risk averse decision makers. Choi and Chow (2008) conduct a mean-risk analysis for supply chains with demand information updating. Buzacott et al. (2011) investigate the option contract using the mean-risk approach with forecast revision. Chiu et al. (2018) investigate the optimal "promotion budget allocation" decision making problem by using the mean–variance portfolio concept. Chiu et al. (2019) conduct a risk analysis to identify the "risk minimizing price-rebate-return" contract for newsvendor supply chain systems. Cai et al. (2019b) study the impacts of "risk-aversion information" and uncover how it affects the optimal pricing decision in the channel. DuHadway et al. (2019) investigate disruptions in the supply chain. The authors propose a systematic scheme for risk management. Rahmani (2019) develops a dynamic supply chain model to study "emergency blood supply" facing disruption risks. Shanker and Satir (2019) study the currency exchange risk with supply chain contracts. Sun et al. (2020a) investigate the operational risk in airlines. The authors highlight how characteristics of flight delays would affect the level of operational risk. Choi et al. (2020a) study the optimal pricing decisions with competing risk sensitive container shipping companies using the mean-risk approach. The authors reveal the benefits of being risk seeking. Most recently, Zhang et al. (2020b) explore a newsvendor supply chain with a risk averse retailer who possesses the "mean–variance-skewness-kurtosis" objectives. For more related studies, refer to Chiu and Choi (2016) and Choi et al. (2019). In this paper, to highlight the performance of blockchain technology, we also employ the mean-risk approach so that we not only can uncover the blockchain's impacts in terms of profit (i.e., the "mean"), but also in terms of operational risk. This gives a more comprehensive picture regarding the true influence of blockchain technology. Moreover, using the mean-risk approach allows us to derive analytically tractable closed-form results which are also intuitive and clear (to both researchers and practitioners). This is why we adopt the mean-risk approach in the analysis of this paper.

As a remark, in this paper, we consider the case when the supply chain is internally coordinated by a supply chain contract under the Nash bargaining framework (Shi et al. 2020; Choi and Guo 2020). In other words, the supply chain is optimized and its agents share the optimal supply chain profit with respect to their bargaining power. In the literature, supply chain contracts such as two-part-tariff (Oi 1971), revenue sharing (Gerchak and Wang 2004), and returns (Webster and Weng 2000) have been well-explored. See Cachon (2003) for more studies on this topic.

2.4 Contribution statement

SCF is an important topic and blockchain technology is known to be a practical and important technological advance which can help. This paper is among the first batch of studies which attempts to uncover the impact brought by blockchain technology for common supply chain systems. The findings are all derived in closed-form and contribute to the supply chain management literature. Many practical implications and managerial insights are also generated which can provide valuable guidance to industrialists and operations managers on the impacts brought by blockchain technology for SCF.

3 Traditional supply chains

In this paper, we consider a supply chain system selling a fashionable product (e.g., fashion apparel) which exhibits a few properties: The product is only sold over a short selling season by the retailer at a unit retail price r. Product leftover by the end of the selling season is cleared at a unit salvage value v. Demand for the fashionable product over the season, denoted by x, is uncertain and follows a probability density function $f(x)$ and cumulative distribution function $F(x)$. The retailer gets the product from the manufacturer under a revenue sharing contract (P.S.: We will examine and discuss other supply chain contracts in Sect. 6) in which the manufacturer offers a unit wholesale price w and charges the retailer a share of revenue, denoted by $0 \le \alpha \le 1$, for each unit of product sold during the regular selling season.

The two supply chain members possess bargaining powers. The manufacturer's bargaining power is $0 < \lambda < 1$ whereas the retailer's bargaining power is $1 - \lambda$. We consider the Nash bargaining scheme. In the supply chain, the manufacturer and retailer first negotiate for the supply chain contracting terms (i.e., w and α). After that, the retailer determines the optimal ordering quantity q. In order to support SCF of the supply chain operations, the manufacturer and retailer have to pay service fees to the bank, which are represented by T_M and T_R, respectively. These costs are treated as fixed service fees which are independent of the ordering quantity. Usually, these fixed service fees relate to the business scales of the manufacturer and retailer.

Under the revenue sharing contract, with the ordering quantity q, the retailer's profit function (which is random and hence we denote it with a "~") is expressed as follows:

$$\tilde{\Pi}_R(q) = ((1-\alpha)r - w)q - ((1-\alpha)r - v)\max(q - x, 0) - T_R. \tag{3.1}$$

From (3.1), we can easily obtain the retailer's expected profit in the following:

$$\Pi_R(q) = ((1-\alpha)r - w)q - ((1-\alpha)r - v)\int_0^q (q - x)f(x)dx - T_R. \tag{3.2}$$

It is easy to find that $d\Pi_R(q)/dq = ((1-\alpha)r - w) - ((1-\alpha)r - v)F(q)$ and $d^2\Pi_R(q)/dq^2 = -((1-\alpha)r - v)f(q) < 0$. Thus, $\Pi_R(q)$ is a concave function and the retailer's optimal ordering quantity is found by the first order condition: $q_R^* = \arg_q\{d\Pi_R(q)/dq = 0\}$, and we have:

$$q_R^* = F^{-1}[((1-\alpha)r - w)/((1-\alpha)r - v)]. \tag{3.3}$$

For the manufacturer and supply chain, we can also derive the respective profit and expected profit functions as follows:

$$\tilde{\Pi}_M(q) = (w - m)q + \alpha r(q - \max(q - x, 0)) - T_M, \tag{3.4}$$

$$\Pi_M(q) = (w - m)q + \alpha r\left(q - \int_0^q (q - x)f(x)dx\right) - T_M, \tag{3.5}$$

$$\tilde{\Pi}_{SC}(q) = (r - m)q - (r - v)\max(q - x, 0) - T_R - T_M, \tag{3.6}$$

$$\Pi_{SC}(q) = (r - m)q - (r - v)\int_0^q (q - x)f(x)dx - T_R - T_M. \tag{3.7}$$

It is also straightforward to find that $\Pi_{SC}(q)$ is concave and hence the optimal product quantity for the traditional supply chain can be obtained by solving the first order condition: $q_{SC}^* = \arg_q\{d\Pi_{SC}(q)/dq = 0\}$, and we have:

$$q_{SC}^* = F^{-1}[(r - m)/(r - v)] = F^{-1}[s], \tag{3.8}$$

where

$$s = (r - m)/(r - v). \tag{3.9}$$

Note that (3.9) is commonly known as the inventory service level which reflects the chance of "no stockout" of the product during the season (with respect to the quantity q_{SC}^*).

Define:

$$\Pi_{SC}^* = \Pi_{SC}(q_{SC}^*). \tag{3.10}$$

Now, we consider the optimal contract setting and we follow the Nash bargaining framework (Shi et al. 2020; Choi and Guo 2020). First, we define the Nash bargaining product $NBP = (\Pi_R)^{1-\lambda}(\Pi_M)^{\lambda}$. Then, the optimal "Nash bargaining solution" that both the retailer and manufacturer are happy with is found by solving Problem (TSC), where TSC stands for the "traditional supply chain"[11]:

$$\textbf{Problem (TSC)}\ Max\ NBP = (\Pi_R)^{1-\lambda}(\Pi_M)^{\lambda} \tag{3.11}$$

$$\text{Subject to } \Pi_R + \Pi_M \leq \Pi_{SC}^*. \tag{3.12}$$

With Problem (TSC), we can derive the optimal contracting parameters which can coordinate the traditional supply chain system as well as divide the channel profit in the proportion with respect to the bargaining powers of supply chain members. Here, coordination means the retailer's optimal ordering quantity will be the same as the supply chain system's optimal product quantity, and the optimal supply chain's expected profit is divided based on the Nash bargaining solution with respect to the bargaining powers of the retailer and manufacturer.

Proposition 3.1 *Under the traditional supply chain model, supply chain coordination under Nash bargaining can be achieved by setting the following:* $\alpha = \{\alpha^* \equiv 1 - H(q_{SC}^*)\}$ *and* $w = \{w^* \equiv sv + (1-s)rH(q_{SC}^*)\}$, *where* $H(q_{SC}^*) = \frac{(1-\lambda)\Pi_{SC}^* + T_R + v(sq_{SC}^* - \int_0^{q_{SC}^*} F(x)dx)}{r(sq_{SC}^* - \int_0^{q_{SC}^*} F(x)dx)}$.

Proposition 3.1 shows the way to coordinate the supply chain using the revenue sharing contract. A few findings can be observed: (1) The optimal contract setting is unique because we have the Nash bargaining framework. (2) The optimal wholesale price appears to be a "weighted average" between the salvage value and $H(q_{SC}^*)$. (3) The revenue sharing ratio depends on $H(q_{SC}^*)$. The retailer with a larger bargaining power (i.e., $(1-\lambda)$ is larger) will lead to a larger $H(q_{SC}^*)$. This directly implies a larger optimal wholesale price (as $w^* = sv + (1-s)rH(q_{SC}^*)$) while a smaller revenue share ratio.

4 Blockchain-supported supply chains

When the supply chain is supported by blockchain technology, every transaction incurs a unit blockchain operational cost b. This cost refers to the need to establish the hash tags, build the block, put it into the blockchain and settle the payment in cryptocurrency.

Similar to the traditional supply chain, we can derive the profit and expected profit functions for the retailer, manufacturer, and supply chain as follows. Note that we use a superscript B to denote the functions and decisions associated with blockchain.

$$\tilde{\Pi}_R^B(q) = [(1-\alpha)r - b]\min(x, q) - wq - (v - b)\max(q - x, 0), \tag{4.1}$$

$$\Pi_R^B(q) = ((1-\alpha)r - b - w)q - ((1-\alpha)r - v)\int_0^q (q - x)f(x)dx, \tag{4.2}$$

$$\tilde{\Pi}_M^B(q) = (w - m)q + \alpha r(q - \max(q - x, 0)) - bq, \tag{4.3}$$

[11] Note that the Nash bargaining (Choi and Guo 2020) is the most common and well-established way to explore two-player bargaining games. In the supply chain contracting literature, if we employ the Stackelberg game without considering bargaining power, the leader will actually take the lion share of profit in the supply chain and leave behind the minimum required profit for the follower, no matter whether it is much more powerful or just slightly more powerful than the follower (e.g., see Chiu et al. 2011). This is not realistic and hence we use the Nash bargaining model in this paper.

$$\Pi_M^B(q) = (w - m - b)q + \alpha r\left(q - \int_0^q (q - x)f(x)dx\right), \tag{4.4}$$

$$\tilde{\Pi}_{SC}^B(q) = (r - m - 2b)q - (r - v)\max(q - x, 0), \tag{4.5}$$

$$\Pi_{SC}^B(q) = (r - m - 2b)q - (r - v)\int_0^q (q - x)f(x)dx. \tag{4.6}$$

From (4.1)–(4.6), a few remarks deserve attention. First, in the blockchain-supported supply chain, the service fees T_M and T_R no longer exist while a unit blockchain operational cost b is incurred. For the retailer, the blockchain operational cost is needed for each product sold (in both the regular and salvage periods). For the manufacturer, the blockchain operational cost is needed for every unit of product produced and supplied. Thus, in the supply chain, we have "2b" as each product incurs the blockchain operational cost twice, one at the manufacturer side and one at the retailer side.

It is easy to find that $\Pi_R^B(q)$ and $\Pi_{SC}^B(q)$ are concave and the optimal quantities which maximize them are given as follows:

$$q_R^{B*} = F^{-1}[((1 - \alpha)r - w - b)/((1 - \alpha)r - v)], \tag{4.7}$$

$$q_{SC}^{B*} = F^{-1}[(r - m - 2b)/(r - v)] = F^{-1}\left[s^B\right], \tag{4.8}$$

where

$$s^B = (r - m - 2b)/(r - v). \tag{4.9}$$

Define:

$$\Pi_{SC}^{B*} = \Pi_{SC}^B\left(q_{SC}^{B*}\right). \tag{4.10}$$

Similar to the traditional supply chain case, we also build the Nash bargaining model (P.S.: BSC represents "blockchain-supported supply chain":

$$\textbf{Problem (BSC)}\ \text{Max}\ NBP^B = \left(\Pi_R^B\right)^{1-\lambda}\left(\Pi_M^B\right)^{\lambda} \tag{4.11}$$

$$\text{Subject to}\ \Pi_R^B + \Pi_M^B \le \Pi_{SC}^{B*}. \tag{4.12}$$

We have Proposition 4.1 which shows the optimal contract parameter setting under Nash bargaining to achieve supply chain coordination.

Proposition 4.1 *Under the blockchain-supported supply chain model, supply chain coordination under Nash bargaining can be achieved by setting the following:* $\alpha^B = \{\alpha^{B*} \equiv 1 - H^B(q_{SC}^{B*})\}$ *and* $w^B = \{w^{B*} \equiv s^B v + (1 - s^B)rH^B(q_{SC}^{B*})\}$, *where* $H^B(q_{SC}^{B*}) = \frac{(1-\lambda)\Pi_{SC}^{B*} + v(s^B q_{SC}^{B*} - \int_0^{q_{SC}^{B*}} F(x)dx)}{r(s^B q_{SC}^{B*} - \int_0^{q_{SC}^{B*}} F(x)dx)}$.

Proposition 4.1 is very similar in format as the conditions in Proposition 3.1. It shows the way to coordinate the supply chain using the revenue sharing contract. The interpretations of results are basically the same as the ones for Proposition 3.1 and hence we omit them for the sake of brevity.

5 Impacts of using blockchain for SCF

5.1 Product quantities and inventory service levels

In Sects. 3 and 4, we have explored the traditional supply chain and blockchain-supported supply chain. We now compare the results derived under the two supply chain systems. First of all, we present the comparisons of optimal product quantities and the corresponding inventory service levels. The results are summarized in Proposition 5.1.

Proposition 5.1 *(a) Product quantities:* $q_{SC}^{B*} < q_{SC}^{*}$ *(b) Inventory service levels:* $s^{B} < s$.

Proposition 5.1 is a neat result. It indicates that with blockchain technology, the optimal product quantity (i.e., the quantity of product to be produced, shipped and sold to the market in the supply chain) and the corresponding inventory service level are both reduced with the use of blockchain technology. Observe that as inventory service level relates to consumer welfare, here, the use of blockchain technology actually yields a smaller inventory service level. From the inventory service perspective, using blockchain for SCF is hence not good to the consumers.

As a remark, we only need to compare the optimal product quantities and inventory service levels of the supply chain system's level, instead of retailer's level, because it is always optimal for the retailer and manufacturer to establish the coordinated supply chain under Nash bargaining. As such, we need not repeat the analysis again because if it is optimal for the supply chain, it will also be optimal for the manufacturer and retailer.

A reduced product quantity and inventory service level may or may not benefit the supply chain in terms of profit as well as risk. As a consequence, in the next sub-section, we explore "benefit" and "risk" associated with the use of blockchain technology.

5.2 Benefits and risks

To explore the benefit and risk of using blockchain technology, we need the respective performance measures. For benefit, we directly employ the expected profit as the performance measure. In the basic model, we employ the variance of profit as the performance measure for risk. Inherited from financial engineering and portfolio management, note that the variance of profit is commonly used nowadays for operational analyses. The use of variance of profit has the beauty of being analytically tractable and intuitive (even though it is not perfect, see Sect. 6.2).

From Sects. 3 and 4, we have the following:

$$\Pi_{SC}^{*} = (r-m)q_{SC}^{*} - (r-v)\int_{0}^{q_{SC}^{*}} \left(q_{SC}^{*} - x\right) f(x)dx - T_R - T_M, \tag{5.1}$$

$$\Pi_{SC}^{B*} = (r-m-2b)q_{SC}^{B*} - (r-v)\int_{0}^{q_{SC}^{B*}} \left(q_{SC}^{B*} - x\right) f(x)dx. \tag{5.2}$$

From Proposition 5.1, we represent q_{SC}^{*} as follows:

$$q_{SC}^{*} = q_{SC}^{B*} + \delta, \tag{5.3}$$

$$\text{where } \delta > 0. \tag{5.4}$$

For a notational purpose, we define the following which represents the total service fees charged to the supply chain by the bank:

$$T_{SC} = T_R + T_M. \tag{5.5}$$

Now, we define the *expected benefit of using blockchain technology for the supply chain* (EBB_{SC}) as follows:

$$EBB_{SC} = \Pi_{SC}^{B*} - \Pi_{SC}^{*}. \tag{5.6}$$

From (5.6), we can easily derive Proposition 5.2.

Proposition 5.2 $EBB_{SC}\begin{pmatrix} > \\ = \\ < \end{pmatrix}0$ if and only if $T_{SC}\begin{pmatrix} > \\ = \\ < \end{pmatrix}(r-m)\delta + 2bq_{SC}^{B*} - (r-v)\int_0^{\delta} F(x)dx$.

Proposition 5.2 carries a very good meaning. First, it shows that when the service fees to pay for the traditional banking services are sufficiently high, the expected benefit of using blockchain technology for the supply chain becomes positive because the money saving from waiving these service fees is high. On the contrary, if the service fees are not high, as using blockchain technology incurs a non-trivial operational cost, the expected benefit of using blockchain technology for the supply chain becomes negative which means it is not beneficial to implement blockchain technology.

Next, we conduct a risk analysis. From (3.6) and (4.5), we have: $\tilde{\Pi}_{SC}(q) = (r-m)q - (r-v)\max(q-x,0) - T_R - T_M$, and $\tilde{\Pi}_{SC}^{B}(q) = (r-m-2b)q - (r-v)\max(q-x,0)$. Taking variance yields the following:

$$V\left[\tilde{\Pi}_{SC}(q)\right] = (r-v)^2 V[\max(q-x,0)], \tag{5.7}$$

$$V\left[\tilde{\Pi}_{SC}^{B}(q)\right] = (r-v)^2 V[\max(q-x,0)], \tag{5.8}$$

where $V[\max(q-x,0)]$ is known to be a monotonic increasing function of q (see Chiu and Choi 2016).

Moreover, we can also derive the variance of profit for the retailer and manufacturer under the traditional supply chain and blockchain-supported supply chain:

$$V\left[\tilde{\Pi}_{M}(q)\right] = (\alpha r)^2 V[\max(q-x,0))], \tag{5.9}$$

$$V\left[\tilde{\Pi}_{M}^{B}(q)\right] = (\alpha r)^2 V[\max(q-x,0))], \tag{5.10}$$

$$V\left[\tilde{\Pi}_{R}(q)\right] = ((1-\alpha)r - v)^2 V[\max(q-x,0))], \tag{5.11}$$

$$V\left[\tilde{\Pi}_{R}^{B}(q)\right] = ((1-\alpha)r - v)^2 V[\max(q-x,0))]. \tag{5.12}$$

From (5.7)–(5.12), we have Proposition 5.3.

Proposition 5.3 $V[\tilde{\Pi}_i^{B}(q_{SC}^{B*})] < V[\tilde{\Pi}_i(q_{SC}^{*})], \forall i \in (R, M, SC)$.

Proposition 5.3 is an important finding. It shows that in the coordinated supply chain system, implementing blockchain technology for SCF is a measure which can *definitely reduce the levels of operational risk* for the supply chain and its members. Thus, if the supply chain members are risk averse, they should welcome the use of blockchain (or at least it is a "non-inferior" measure in the mean-risk domain). This is a critical issue as reducing operational risk is essentially important for business operations under risk. This applies very well to the supply chains selling fashionable products (such as fashion apparel) as demand is highly volatile which brings heavy risk for inventory decisions.

Before we conclude the findings from this sub-section, we present an important definition which relates to "risk" and "benefit" analysis.

Definition 5.1 *(mean-risk dominating; mean-risk non-inferior)*. Under the mean-risk theory, we say a measure (e.g., using blockchain technology) is "mean-risk dominating" if adopting it will lead to a lower operational risk and a higher expected profit (i.e. the "mean") for the supply chain system at the same time. A measure is called "mean-risk non-inferior" if adopting it will either: (1) lead to a lower operational risk and a lower expected profit, or (2) lead to a higher operational risk and a higher expected profit, for the supply chain system at the same time.

Definition 5.1 formally indicates from risk and benefit perspectives, what it means by having a measure which is truly "optimal". To be specific, if we find that a measure is "mean-risk dominating", it means that the respective measure is "truly optimal" in both benefit and risk perspectives. For "mean-risk non-inferior", it means using the measure is neither better nor worse off (compared to the scenario of not using it) in the mean-risk domain. From Propositions 5.2 and 5.3, denoting $\hat{T}_{SC} = (r - m)\delta + 2bq_{SC}^{B*} - (r - v)\int_0^{\delta} F(x)dx$, we have Theorem 5.1.

Theorem 5.1 *Using blockchain technology is a mean-risk dominating solution for the supply chain and its members if and only if $T_{SC} > \hat{T}_{SC}$; otherwise, using blockchain technology is a mean-risk non-inferior solution for the supply chain and its members.*

Theorem 5.1 indicates a very critical finding. For the supply chain and its members, from the SCF perspective, using blockchain technology is a perfectly sound measure if the service fees for banking services are sufficiently large because the mean-risk dominating solution is achieved, i.e., both "benefit" and "risk" are improved. If this is not the case, using blockchain technology is still an efficient solution for them because it can definitely reduce the operational risk even though it may not increase the expected profit (i.e., the mean-risk non-inferior scenario occurs). As a consequence, blockchain technology is definitely a crucial and helpful technological measure for SCF in supply chain systems and supply chain operations managers should never ignore it.

6 Robustness checking

6.1 Other supply chain contracts

In the above analysis, we employ the revenue sharing contract. How about other commonly seen contracts? Essentially, provided that the supply chain contract can coordinate the supply chain in terms of the quantity decision, our analytical results will apply. For example, if the supply chain adopts the profit sharing contract, or returns contract, the results will remain valid.

To be specific, for the returns contract, it has been analytically proven that it generates the same stream of profit (in the newsvendor supply chain with "quantity only" decision) as the revenue sharing contract. The result definitely applies (Cachon and Lariviere 2005). For the profit sharing contract, the result can also be derived (see "Appendix (3)").

As a remark, if we use the two-part-tariff contract in which the manufacturer requests a wholesale price and also a fixed side payment from the retailer, the manufacturer will become riskless under both the traditional and blockchain-supported supply chains. So, the findings under the revenue sharing contract would also apply except for the manufacturer, using blockchain technology or not does not affect its operational risk as it is already riskless.

6.2 Downside risk measure

In Sect. 5, we employ the variance of profit as the performance measure for "operational risk". This is very commonly used in the operations management and operational research literature now (see, e.g., Chiu and Choi 2016; Chiu et al. 2018; Choi et al. 2019). However, the variance of profit is not a perfect measure, especially in the newsvendor model setting owing to the asymmetric nature of the random profit function as a random variable. To be specific, variance by definition includes both upside and downside deviations into its formula. It is commonly known that only the downside "poor" performance should be counted as a negative outcome and contributes to "risk". As such, there are proposals of using the downside-risk measure (Chiu et al. 2019).

Luckily, in the newsvendor model, if we employ the semi-deviation of profit, which is a downside risk measure, as the performance measure for operational risk, our derived results will all remain valid because the semi-deviation of profit exhibits the same feature as the variance of profit, i.e., both being monotonic increasing (see Chiu et al. 2019).

$$SDV\left(\tilde{\Pi}_{SC}(q)\right) = SDV\left[\tilde{\Pi}^{B}_{SC}(q)\right] = (r-v)^2\Phi(q), \tag{6.1}$$

$$SDV\left[\tilde{\Pi}_{M}(q)\right] = SDV\left[\tilde{\Pi}^{B}_{M}(q)\right] = (\alpha r)^2\Phi(q), \tag{6.2}$$

$$SDV\left[\tilde{\Pi}_{R}(q)\right] = SDV\left[\tilde{\Pi}^{B}_{R}(q)\right] = ((1-\alpha)r-v)^2\Phi(q), \tag{6.3}$$

$$\text{where } \Phi(q) = \int_0^{q-\int_0^q F(x)dx} \left(q - \int_0^q F(x)dx - x\right) dF(x). \tag{6.4}$$

We summarize the robustness checking results of Sect. 6 in Theorem 6.1.

Theorem 6.1 *The results derived in Theorem 5.1 remain valid if* (1) *the supply chain contract is changed to be the returns contract, or profit sharing contract;* (2) *the variance of profit performance measure is replaced by the semi-deviation of profit (a downside risk measure).*

Theorem 6.1 clearly shows that the analytical results derived on the use of blockchain technology are valid for different commonly seen supply chain contracts as well as the theoretically more solid (yet more complicated) downside risk performance measure.

7 Concluding remarks, insights, and future research

7.1 Summary

Blockchain technology, with its "gene" in cryptocurrency, has emerged as a major player in supply chain management, especially in supply chain finance (SCF). In this paper, we have developed analytical models to explore the impacts brought by blockchain technology in supply chains. To be specific, we have built two models, one for the traditional supply chain scenario (with the support by traditional banks with service fees) and one for the blockchain-supported supply chain in which the supply chain members conduct transactions between themselves directly using cryptocurrency. For each supply chain, we have derived the optimal contracting scenarios under the Nash bargaining framework. Comparing between the two supply chain systems, we have analytically shown that the retailer's ordering quantity and the inventory service level achieved are both lower under the case with the use of blockchain technology. Moreover, we have revealed that the blockchain-supported supply chain definitely yields a smaller level of operational risk compared to the traditional supply chain counterpart. When the service fees incurred by the traditional supply chain for banking services are sufficiently big, the use of blockchain technology is a *mean-risk dominating solution* which implies that the supply chain as well as its members are all benefited in two dimensions: Having higher expected profits and lower operational risks with the implementation of blockchain technology. However, if the service fees are not sufficiently big, then implementing blockchain technology is still a *mean-risk non-inferior solution* for the supply chain and its members because it brings a smaller level of operational risk while also a smaller expected profit. For research rigor and to show the robustness of the derived results, we have extended the analyses with respect to different commonly seen supply chain contracts and an alternative downside risk measure. We have analytically proven that all the derived results remain valid and robust in these extensions.

7.2 Managerial insights and research implications

After summarizing the research findings, in the following, we discuss the managerial insights and research implications.

7.2.1 No free lunch

Using blockchain technology incurs a cost. In our analysis, we explicitly include the operational cost for using blockchain technology per transaction. This relates to the establishment of hash tags as well as creation of blocks for each transaction when the blockchain system is in place to support cryptocurrency transactions. This cost is known to be non-trivial. Thus, in our analysis, operations managers should pay close attention to it before proceeding to confirm their intention to use blockchain technology.

7.2.2 Traditional banking versus blockchain

In SCF, for traditional supply chains using banking services, service fees must be paid. In our analyses, we consider the situation when both the retailer and manufacturer have to pay a service fee, which can be interpreted as the transactions costs. The service fees can be non-trivial, too. Thus, using blockchain technology is a way to get rid of this kind of banking service fees which potentially can improve supply chain performance.

7.2.3 When to use blockchain technology

From an operational risk perspective, considering the blockchain operational cost as well as the traditional service fees for banking, we have analytically proven that using blockchain technology can reduce operational risk for the supply chain system as well as its members. This is a very important result which proposes that for risk averse operations managers, they should prefer the use of blockchain technology. In addition, if the service fees for traditional banking services are sufficiently large, then using blockchain technology not only reduces operational risk, but also improves expected profit. This is the best situation (i.e., the mean-risk dominating case) and operations managers in the supply chain should vote for using blockchain technology if it is the case. In real world practices, it is widely observed that the service fees for banking supports are in fact substantial. This point explains why a lot of companies are moving towards blockchain technology deployment as it does help a lot.

7.2.4 Consumers

In our analyses, we have shown that using blockchain technology, the optimal product quantity and the corresponding inventory service level in the supply chain will be smaller than the ones under the traditional supply chain. This, unfortunately, may not be a good result for consumers because a lower inventory service directly means a higher chance of stockout. In the future, supply chains and their members should consider providing additional benefits, e.g., product provenance information, with the use of blockchain technology which can lift the consumer welfare in another perspective (which we humbly postpone to future research as it is not the focus of this paper).

7.2.5 Contract types and risk performance measures

We have shown that provided that the supply chain contract can coordinate the channel, our results remain generally robust. For risk performance measures, if we replace the variance of profit by using the downside risk measure such as semi-deviation of profit, the findings and insights remain valid. Thus, operations managers need not worry if they are adopting different kinds of supply chain contracts or using other risk performance measures in their operational analyses and estimations.

7.3 Future research

In this paper, we focus on the fashionable product supply chain and model it using the classic newsvendor model. Consumers are then treated just "as a part of the demand". As inventory service level is reduced at the optimal supply chain quantity with the use of blockchain, consumer welfare is hurt from the perspective of inventory stockout. Future research can hence be conducted to examine whether some measures can be imposed to compensate for it, e.g., via building and exploring a consumer utility based model. Moreover, in the current study, we focus on studying the forward supply chain. Nowadays, environmental sustainability (Govindan et al. 2015; Zhang et al. 2019; Sun et al. 2020b) is critical and how SCF models affect it deserves explorations. As a result, it will also be interesting to study sustainable supply chain operations with the use of blockchain technology for SCF. As a remark, the models that we have explored in this paper focus specifically on blockchain technology (because as of today, only blockchain technology can support cryptocurrency in a secure manner so that supply chain members can conduct transactions by themselves without the need of relying on other banking service agents). However, there are many other areas related to blockchain technology's features which can be explored further. For instance, information transparency (Chod et al. 2018), product information disclosure (Choi et al. 2019), luxury product authentication (Wang et al. 2020), data-driven risk analyses (Araz et al. 2020a, b; Chung et al. 2020), production flexibility with information updating (Zhang et al. 2020a), etc. are all important functions that blockchain technology can support and we will postpone them to future research.

Appendix 1: Notation table

See Table 2.

Table 2 Notation/abbreviation and the respective meanings

Notation/abbreviation	Meaning
M, R, SC	Manufacturer, retailer, supply chain
B	Blockchain
SCF	Supply chain finance
λ	Bargaining power of the manufacturer
$1-\lambda$	Bargaining power of the retailer
T_M, and T_R	Service fees for banking services paid by the manufacturer, and retailer, respectively
T_{SC}	Sum of the service fees for banking services paid by the manufacturer, and retailer (T_R+T_M)
$\tilde{\Pi}_R(q)$, and $\Pi_R(q)$	Retailer's profit, and expected profit functions under the traditional supply chain system
$\tilde{\Pi}_M(q)$, and $\Pi_M(q)$	Manufacturer's profit, and expected profit functions under the traditional supply chain system
$\tilde{\Pi}_{SC}(q)$, and $\Pi_{SC}(q)$	Supply chain's profit, and expected profit functions under the traditional supply chain system
s	Inventory service level achieved in coordinated channel under the traditional supply chain system
q^*_{SC}	Optimal product quantity of the traditional supply chain system
NBP	Nash bargaining product under the traditional supply chain system
b	Unit operational cost for using blockchain
r	Unit retail price
w	Unit wholesale price
α	The revenue share proportion granted to the manufacturer
v	Unit salvage value
$\hat{T}_{SC}$	An important threshold which is defined as: $\hat{T}_{SC}=(r-m)\delta+2bq^{B*}_{SC}-(r-v)\int_0^{\delta}F(x)dx$
$\tilde{\Pi}^B_R(q)$, and $\Pi^B_R(q)$	Retailer's profit, and expected profit functions under the blockchain-supported supply chain system
$\tilde{\Pi}^B_M(q)$, and $\Pi^B_M(q)$	Manufacturer's profit, and expected profit functions under the blockchain-supported supply chain system
$\tilde{\Pi}^B_{SC}(q)$, and $\Pi^B_{SC}(q)$	Supply chain's profit, and expected profit functions under the blockchain-supported supply chain system
s^B	Inventory service level achieved in coordinated channel under the blockchain-supported supply chain system
q^{B*}_{SC}	Optimal product quantity of the blockchain-supported supply chain system
NBP^B	Nash bargaining product under the blockchain-supported supply chain system
$V[\cdot]$	Variance operator
$SDV[\cdot]$	Semi-deviation operator

Appendix 2: All proofs

Proof of Proposition 3.1 First, we have to identify the optimal "Nash bargaining solution", which is found by solving Problem (TSC):

$$\begin{aligned} &Problem\ (TSC)\ \text{Max}\ NBP = (\Pi_R)^{1-\lambda}(\Pi_M)^{\lambda} \\ &\text{Subject to}\ \Pi_R + \Pi_M \leq \Pi_{SC}^{*}. \end{aligned}$$

Our approach follows the standard treatment for Nash bargaining in the literature (e.g., Shi et al. 2020; Choi and Guo 2020). First of all, in order to maximize NBP, the supply chain members should maximize the supply chain's expected profit as far as possible. Under the revenue sharing contract, it is possible and hence the inequity constraint $\Pi_R + \Pi_M \leq \Pi_{SC}^{*}$ becomes an equality constraint $\Pi_R + \Pi_M = \Pi_{SC}^{*}$.

Putting $\Pi_M = \Pi_{SC}^{*} - \Pi_R$,

$$\begin{aligned} \frac{\partial NBP}{\partial \Pi_R} &= \frac{\partial\left[(\Pi_R)^{1-\lambda}\left(\Pi_{SC}^{*} - \Pi_R\right)^{\lambda}\right]}{\partial \Pi_R} \\ &= -(\Pi_R)^{1-\lambda}\left[\lambda\left(\Pi_{SC}^{*} - \Pi_R\right)^{\lambda-1}\right] + (1-\lambda)(\Pi_R)^{-\lambda}\left(\Pi_{SC}^{*} - \Pi_R\right)^{\lambda} \\ &= \left(\Pi_{SC}^{*} - \Pi_R\right)^{\lambda-1}(\Pi_R)^{-\lambda}\left\{-\lambda\Pi_R + (1-\lambda)\left(\Pi_{SC}^{*} - \Pi_R\right)\right\} \\ &= \left(\Pi_{SC}^{*} - \Pi_R\right)^{\lambda-1}(\Pi_R)^{-\lambda}\left\{((1-\lambda)\Pi_{SC}^{*} - \Pi_R\right\}. \end{aligned}$$

$\frac{\partial NBP}{\partial \Pi_R} = 0$ implies

$$\Pi_R^{*} = (1-\lambda)\Pi_{SC}^{*}. \tag{A1}$$

Similarly, putting $\Pi_R = \Pi_{SC}^{*} - \Pi_M$, we can compute and solve $\frac{\partial NBP}{\partial \Pi_M} = 0$, which yields:

$$\Pi_M^{*} = \lambda\Pi_{SC}^{*}. \tag{A2}$$

Second, to achieve supply chain coordination under the traditional supply chain system, we need to make $q_R^{*} = q_{SC}^{*}$, which implies:

$$F^{-1}[((1-\alpha)r - w)/((1-\alpha)r - v)] = F^{-1}[s]. \tag{A3}$$

Rearranging terms, (A3) becomes:

$$w = (1-\alpha)(1-s)r + vs. \tag{A4}$$

From (3.2), we have: $\Pi_R(q) = ((1-\alpha)r - w)q - ((1-\alpha)r - v)\int_0^q (q-x)f(x)dx - T_R$. When (A4) holds, we have:

$$\begin{aligned} \Pi_R\left(q_{SC}^{*}\right) &= ((1-\alpha)r - w)q_{SC}^{*} - ((1-\alpha)r - v)\int_0^{q_{SC}^{*}} \left(q_{SC}^{*} - x\right)f(x)dx - T_R \\ &= ((1-\alpha)r - w)q_{SC}^{*} - ((1-\alpha)r - v)\int_0^{q_{SC}^{*}} F(x)dx - T_R. \end{aligned} \tag{A5}$$

Combining (A5) and (A1), we have:

$$((1-\alpha)r - w)q_{SC}^{*} - ((1-\alpha)r - v)\int_0^{q_{SC}^{*}} F(x)dx - T_R = (1-\lambda)\Pi_{SC}^{*}. \tag{A6}$$

Putting (A4) into (A6) gives:

$$((1-\alpha)r-[(1-\alpha)(1-s)r+vs])q_{SC}^{*}-((1-\alpha)r-v)\int_{0}^{q_{SC}^{*}}F(x)dx-T_R=(1-\lambda)\Pi_{SC}^{*}. \tag{A6}$$

Solving (A6) gives:

$$\alpha=\left\{\alpha^{*}\equiv 1-H\left(q_{SC}^{*}\right)\right\}, \tag{A7}$$

where $H(q_{SC}^{*})=\frac{(1-\lambda)\Pi_{SC}^{*}+T_R+v(sq_{SC}^{*}-\int_0^{q_{SC}^{*}}F(x)dx)}{r(sq_{SC}^{*}-\int_0^{q_{SC}^{*}}F(x)dx)}$.

Then, putting (A7) into (A4) yields:

$$w=\left\{w^{*}\equiv vs+(1-s)rH\left(q_{SC}^{*}\right)\right\}. \tag{Q.E.D.}$$

Proof of Proposition 4.1 Similar to Proposition 3.1, first, we have to find the optimal "Nash bargaining solution", which is found by solving Problem (BSC):

$$\textit{Problem (BSC)}\ \text{Max}\ NBP^{B}=\left(\Pi_R^{B}\right)^{1-\lambda}\left(\Pi_M^{B}\right)^{\lambda}$$
$$\text{Subject to}\ \Pi_R^{B}+\Pi_M^{B}\le\Pi_{SC}^{B*}.$$

The solution can be found using the same approach as in the proof of Proposition 3.1:

$$\Pi_R^{B*}=(1-\lambda)\Pi_{SC}^{B*}, \tag{A8}$$

$$\Pi_M^{B*}=\lambda\Pi_{SC}^{B*}. \tag{A9}$$

Second, to achieve supply chain coordination under the blockchain-supported supply chain system, we need to make $q_R^{B*}=q_{SC}^{B*}$, which implies:

$$F^{-1}[((1-\alpha)r-w-b)/((1-\alpha)r-v)]=F^{-1}\left[s^{B}\right]. \tag{A10}$$

From (A10), we have the following:

$$w=(1-\alpha)\left(1-s^{B}\right)r-b+vs^{B}. \tag{A11}$$

From (4.2), we have: $\Pi_R^{B}(q)=((1-\alpha)r-b-w)q-((1-\alpha)r-v)\int_0^{q}(q-x)f(x)dx$. Thus, at the coordinated supply chain, we have:

$$\begin{aligned}\Pi_R^{B}\left(q_{SC}^{B*}\right)&=((1-\alpha)r-b-w)q_{SC}^{B*}-((1-\alpha)r-v)\int_0^{q_{SC}^{B*}}\left(q_{SC}^{B*}-x\right)f(x)dx\\&=((1-\alpha)r-b-w)q_{SC}^{B*}-((1-\alpha)r-v)\int_0^{q_{SC}^{B*}}F(x)dx.\end{aligned} \tag{A12}$$

Putting (A12) into (A8), we have:

$$((1-\alpha)r-b-w)q_{SC}^{B*}-((1-\alpha)r-v)\int_0^{q_{SC}^{B*}}F(x)dx=(1-\lambda)\Pi_{SC}^{B*}. \tag{A13}$$

Substituting (A11) into (A13) and solving for α gives:

$$\alpha^{B}=\left\{\alpha^{B*}\equiv 1-H^{B}\left(q_{SC}^{B*}\right)\right\}, \tag{A14}$$

$$\text{where } H^B\left(q_{SC}^{B*}\right) = \frac{(1-\lambda)\Pi_{SC}^{B*} + v\left(s^B q_{SC}^{B*} - \int_0^{q_{SC}^{B*}} F(x)dx\right)}{r\left(s^B q_{SC}^{B*} - \int_0^{q_{SC}^{B*}} F(x)dx\right)}. \tag{A15}$$

Putting (A15) into (A11) gives:

$$w^B = \left\{w^{B*} \equiv vs^B + \left(1-s^B\right)rH^B\left(q_{SC}^{B*}\right)\right\}. \tag{Q.E.D.}$$

Proof of Proposition 5.1
We first prove part (b) and then part (a).

(b) Inventory service levels:

By definition, we have: $s^B = (r-m-2b)/(r-v)$ and $s = (r-m)/(r-v)$. Since b is the unit operational cost for blockchain technology and it is positive, it is obvious that: $s^B < s$.

(a) Product quantities:

From Sect. 3 and Sect. 4, we have:

$$q_{SC}^* = F^{-1}[(r-m)/(r-v)] = F^{-1}[s],$$

$$q_{SC}^{B*} = F^{-1}[(r-m-2b)/(r-v)] = F^{-1}\left[s^B\right].$$

Since $F^{-1}[.]$ is increasing in its argument,$s^B < s$ implies $q_{SC}^{B*} < q_{SC}^*$. (Q.E.D.)

Proof of Proposition 5.2
By definition, we have the following:

$$q_{SC}^* = q_{SC}^{B*} + \delta, \tag{A16}$$

where $\delta > 0$,

$$\begin{aligned}\Pi_{SC}^* &= (r-m)q_{SC}^* - (r-v)\int_0^{q_{SC}^*}\left(q_{SC}^* - x\right)f(x)dx - T_R - T_M \\ &= (r-m)q_{SC}^* - (r-v)\int_0^{q_{SC}^*} F(x)dx - T_R - T_M,\end{aligned} \tag{A17}$$

$$\begin{aligned}\Pi_{SC}^{B*} &= (r-m-2b)q_{SC}^{B*} - (r-v)\int_0^{q_{SC}^{B*}}\left(q_{SC}^{B*} - x\right)f(x)dx \\ &= (r-m-2b)q_{SC}^{B*} - (r-v)\int_0^{q_{SC}^{B*}} F(x)dx.\end{aligned} \tag{A18}$$

Putting (A16) into (A17) gives:

$$\Pi_{SC}^* = (r-m)\left(q_{SC}^{B*} + \delta\right) - (r-v)\int_0^{q_{SC}^{B*}+\delta} F(x)dx - T_R - T_M. \tag{A19}$$

Putting (A19) and (A18) into $EBB_{SC} = \Pi_{SC}^{B*} - \Pi_{SC}^*$ and simplifying, we have the following:

$$\begin{aligned}EBB_{SC} &= T_R + T_M + (r-m)\delta - (r-v)\int_0^{\delta} F(x)dx - 2bq_{SC}^{B*} \\ &= T_{SC} + (r-m)\delta - (r-v)\int_0^{\delta} F(x)dx - 2bq_{SC}^{B*}.\end{aligned} \tag{A20}$$

It is hence easy to find that:

$$EBB_{SC}\begin{pmatrix}>\\=\\<\end{pmatrix}0 \text{ if and only if } T_{SC}\begin{pmatrix}>\\=\\<\end{pmatrix}(r-m)\delta+2bq_{SC}^{B*}-(r-v)\int_0^{\delta}F(x)dx.$$

(Q.E.D.)

Proof of Proposition 5.3
The proof is straightforward. First, note that from Proposition 5.1, we have: $q_{SC}^{B*} < q_{SC}^{*}$. Second, observe that the variance of profit functions are all increasing in quantity q. Directly substituting the optimal product quantities into the respective variance of profit functions generates the result:

$$V\left[\tilde{\Pi}_i^B\left(q_{SC}^{B*}\right)\right] < V\left[\tilde{\Pi}_i\left(q_{SC}^{*}\right)\right], \quad \forall i \in (R, M, SC). \qquad \text{(Q.E.D.)}$$

Proof of Theorem 5.1
Observe that $\hat{T}_{SC}=(r-m)\delta+2bq_{SC}^{B*}-(r-v)\int_0^{\delta}F(x)dx$. From Proposition 5.2, we have: $EBB_{SC}\begin{pmatrix}>\\=\\<\end{pmatrix}0$ if and only if $T_{SC}\begin{pmatrix}>\\=\\<\end{pmatrix}\hat{T}_{SC}$. Thus, we have the following two cases:

When $T_{SC} > \hat{T}_{SC}$, we have $EBB_{SC} > 0$, which means using blockchain technology benefits the supply chain and also its members in terms of expected profit. As using blockchain technology always reduces the operational risk (Proposition 5.3), we have "using blockchain technology is a mean-risk dominating solution for the supply chain and its members if and only if $T_{SC} > \hat{T}_{SC}$".

When $T_{SC} \le \hat{T}_{SC}$, we have $EBB_{SC} \le 0$, which means using blockchain technology hurts the supply chain and also its members in terms of expected profit. As using blockchain technology always reduces the operational risk (Proposition 5.3), we know that using blockchain technology is a mean-risk non-inferior solution for the supply chain and its members for this case. (Q.E.D.)

Proof of Theorem 6.1
For (1): Directly from the discussions that if the supply chain contract is changed to be the two-part-tariff contract, returns contract, or profit sharing contract, we can still achieve the coordinated optimal supply chain in the same way as the revenue sharing contract. As a result, the corresponding results also hold.

For (2): Note that the semi-deviation of profit (a downside risk measure) exhibits the same monotonic increasing property as the variance of profit. As such, we have the following:

$$SDV\left[\tilde{\Pi}_i^B\left(q_{SC}^{B*}\right)\right] < SDV\left[\tilde{\Pi}_i\left(q_{SC}^{*}\right)\right], \quad \forall i \in (R, M, SC),$$

which completes the proofs. (Q.E.D.)

Appendix 3: Other contracts

The profit sharing contract

Under the profit sharing contract, the manufacturer supplies the product to the retailer at a wholesale price w and also shares a proportion $0 \le \theta \le 1$ of the retailer's profit. It is easy to find that the following arrangement can achieve coordination of the supply chain:

Proposition A3.1 *Using the profit sharing contract: (a) Under the traditional supply chain model, supply chain coordination under Nash bargaining can be achieved by setting the following:* $w = m$ *and* $\theta = \lambda$. *(b) Under the blockchain-supported supply chain model, supply chain coordination under Nash bargaining can be achieved by setting the following:* $w = m + 2b$ *and* $\theta = \lambda$.

Once the supply chain can be coordinated by using the profit sharing contract, all remaining analyses can be conducted and we can see that the results would remain valid.

The two-part-tariff contract

Under the two-part-tariff contract, the manufacturer supplies the product to the retailer at a wholesale price w and also gets a side-payment of G from the retailer. It is direct to find that the following arrangement can achieve coordination of the supply chain:

Proposition A3.2 *Using the two-part-tariff contract: (a) Under the traditional supply chain model, supply chain coordination under Nash bargaining can be achieved by setting the following:* $w = m$ *and* $G = \lambda \Pi_{SC}^{*}$. *(b) Under the blockchain-supported supply chain model, supply chain coordination under Nash bargaining can be achieved by setting the following:* $w = m + 2b$ *and* $G = \lambda \Pi_{SC}^{B*}$.

Once the supply chain can be coordinated, all the remaining analyses for the supply chain systems can be conducted and we can see that the results would remain valid (except for the manufacturer, there is no risk under both the traditional and blockchain-supported supply chains, and hence using blockchain technology does not reduce the operational risk for the manufacturer).

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