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Operations strategy for supply chain finance with asset-backed securitization: Centralization and blockchain adoption

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Abstract: Supply chain finance (SCF) is a set of financing processes and technology-based business that links supply chain members, in which innovative financial products and technologies, i.e., asset-backed securitization (ABS) and blockchain, have been widely adopted. We use a game-theoretic approach to study the operations strategy for SCF with ABS. More precisely, we explore the issue of centralization, that is, whether a retailer, as a core company in a decentralized supply chain system, should establish her own originated channel, and the impacts of the blockchain adoption on supply chain systems. We find that the core company should not establish her own originated channel when her main business is to sell high-cost products or when the marginal cost of blockchain implementation is sufficiently large. Besides, when the core company builds her own originated channel, the manufacturer should decrease the wholesale price, but the core company should increase the retail price under certain conditions. Interestingly, both the service rate and interest rate in the financing channel remain unchanged. In addition, we find that the impacts of the blockchain technology on the wholesale price, retail price, and discount of the fund depend on the production cost. However, both the service rate and interest rate always decline when the blockchain technology is introduced, because the market becomes more creditable. Moreover, in both decentralized and centralized systems, all supply chain members' profits are increased if the marginal cost of the blockchain technology is sufficiently low.

Keywords: supply chain, fintech, asset-backed securitization, blockchain technology, centralization.

1. Introduction

While majority of firms in the world are small and medium-sized firms, they play very important roles in the economic development and social stability (Yáñez-Araque et al., 2021). For example, small and medium-sized firms take up a lion share of businesses, i.e., accounting for more than 90 percent of the businesses in China (China Daily, 2020). However, many, if not most, small and medium-sized firms' developments are fettered by capital constraints and cash flow problems (Hui et al., 2016; Chen et al., 2018). In real practices, it is common to loan from banks or other financial institutions which require high-credit debtors and only provide limited loanable funds. It is especially difficult for the small and medium-sized firms to obtain funding from external channels like banks (Zhao et al., 2018; Zhou et al., 2020). Thus, it is necessary to develop innovative financing schemes for the small and medium-sized firms (Ndubisi et al., 2020).

Facing the financing difficulties, we have witnessed a boom of supply chain finance (SCF), within which the financial organizers provide a set of solutions for the capital flow management along supply chains (Tang et al., 2018; Ma et al., 2020). The prevalent SCF products can be divided into two categories: The first one is designed and offered to supply chain members by third-party financial institutions. The other one is the financing between upstream and downstream firms in supply chains (Xiao et. al., 2017; Ding et al., 2020). For example, some retailers provide "advance payment discount" to their manufacturers. In this paper, we consider the second type of the SCF products, i.e., the financing between the upstream and downstream supply chain members.

Amid the burgeoning of SCF, some innovative financial business models and technologies, such as asset-backed securitization (ABS), have emerged and developed in SCF. The ABS is a process in which an originator packages the assets with expected stable cash flow in the future and transfers them to the special purpose vehicle (SPV) through structural restructuring. Thereafter, the SPV transforms the packages into securities that can be sold and circulated in the financial market simultaneously for financing (Bissoondoyal-Bheenick et al., 2015). The value of ABS comes from the receivable securitization, provided by the SPV which assigns account receivable and undertakes risk for investors of the securities, and protecting the creditor through bankruptcy remote. This innovative financing product has become the most important and rapidly developing financial technology product in the financial field in recent years (Higgins and Mason, 2004; Boesel et al., 2018). For example, the issuing scale of Chinese ABS has reached 2.01 trillion till 2018 (Tang et al., 2017).

There are two types of ABSs in supply chain systems. The first one is called decentralized system in which a core company seeks an originator to provide the fund to the upstream manufacturers or suppliers. For instance, JD Finance issued a financing project, in which, an originator, called Shanghai BangHui, provides a fund to the upstream manufacturers of JD.com through the principle of ABS. Wechain, a subsidiary of Tencent, is committed to building a financial service platform with ABS. As in a decentralized system, it cooperates with external banks and securities companies to package the assets into ABS products and finally distribute to investors (The Paypers, 2019). The other one is a centralized system in which the core company acts as an originator and directly finances upstream manufacturers. For instance, Xiaomi sets up a self-supporting originator, which manages the underlying assets as the original equity owner and transfers to SPVs (Xiaomi Corporation, 2019). Observing the two types of SCF with ABS, it is unknown that which type is better for supply chain members.

In addition, controversial issues in the adoption of ABS, such as information asymmetry, inaccurate rating, and poor product liquidity cannot be ignored (Chesney et al., 2020). Though financing risk can be reduced due to the bankruptcy remote in ABS, the market risk faced by the retailer cannot be eliminated by the innovative financial tool. When the retailer is defeated in the market, the originator's accounts receivable becomes bad debt, and it still needs to pay the principal to the SPV for investor protect. Therefore, the originator is motivated to supervise the underlying capital chain and make sure that the supply chain members fully utilize the fund for their operations. It is well known that features, such as transparency, traceability, and permanent record, supported by blockchain technology can improve the credibility of supply chain finance and help the originator supervise the underlying capital chain. In real practice, blockchain technology has been extensively implemented in the financial sector due to the growth of bitcoin and cryptocurrency (Wamba et al., 2018; Chod et al., 2020). The adoption of blockchain enables the acceleration and simplification of cross border payments, and revolutionizes share trading, identity management, and money management in the financial sector (Dutta et al., 2020). For example, Ant group uses blockchain technology to digitize the accounts receivable of core companies, which not only solves some existing financing problems in supply chains, but also reduces the potential risk of SCF (Li et al., 2021). Meanwhile, many traditional financial institutions actively adopt blockchain technology when establishing financial service platforms (Higginson et al., 2019). Due to the reliability of the underlying fund ensured by blockchain, originators now have incentives to adopt this technology and authorize the downstream SPV and investors to view the underlying capital chain. However, whether the blockchain technology should be well implemented in supply chains with ABS remains unexplored.

Motivated by the above observations, in this paper we study the operations strategies for the firms in a supply chain with consideration of ABS. We consider that a small and medium-size manufacturer with capital constraint has incentive to search financing service through SCF with ABS. After determining the financing strategy based on ABS, the retailer, acting as the core company, can choose to cooperate with an external originator in a decentralized supply system or establish her own originated channel in a centralized supply system. The originator can decide whether to introduce blockchain technology to reduce risk as mentioned above. We aim to answer the following fundamental research questions:

1. Is it beneficial for the core company to build originated channel based on ABS?
2. What are the impacts of the centralization on the operations decisions?
3. What are the impacts of the blockchain technology on supply chain systems with ABS?

In order to answer the above questions, we establish a game-theoretic model, in which we consider that a capital-constrained manufacturer sells products to consumers through a retailer, who is viewed as the core company in the supply chain. The accounts receivable owed by the manufacturer will be sold to the originator as assets, which will be transferred to a special purpose vehicle (SPV) after packaging and restructuring. Finally, the asset-backed security will be sold to investors in the financing market.

Our results show that, in the absence of blockchain implementation, the profit of the core company in centralized system is higher than that in decentralized system, when the production cost is relatively low. It implies that in this case the core company should build her own originated channel. Meanwhile, the profits of other supply chain members will also be affected by the core company's centralization strategy. Whether centralization is beneficial to other supply chain members depends on the value of production cost. The impacts of centralization on decision variables and profits are similar with and without blockchain. The only difference between the two cases is observed as the additional condition associated with the marginal cost of blockchain adoption. If the marginal cost of blockchain technology is relatively high, then the core company should choose to cooperate with the external originator, even if she can charge a higher retail price. In both cases, whether the core company chooses the centralization or not, the service rate and interest rate are unchanged, implying that the investors are indifferent about who is the originator. However, the return rate on investment will be slightly reduced due to the introduction of blockchain technology, because the market becomes more credible. We find that if the marginal cost of blockchain technology is low enough, the profits of all supply chain members will be improved by the introduction of blockchain.

We organize the rest of the paper as follows: In Section 2 we review the related literature. In Section 3, we introduce the model setup. In Section 4, we analyze decentralization and centralization systems without blockchain technology. In Section 5, we introduce the blockchain technology. In Section 6, we investigate the impacts of the blockchain technology. In Section 7, we conclude the paper and suggest some future research directions. All the proofs are presented in the Appendix.

2. Literature Review

This work is related to three streams of research in the literature. The first stream is the research on the channel management in supply chains, the second stream focuses on SCF and ABS products, and the third one examines blockchain technology applications in the financial field.

Channel management for supply chain system is widely discussed in the operations management (OM) field (Chang and Harrington, 1998; Chang and Harrington, 2000; Chang and Harrington, 2002; Chang and Harrington, 2003; Shi et al., 2021a). It is common to observe that supply chain systems can be divided into the decentralized and centralized systems in the literature. Many studies show that firms usually prefer a centralized system to a decentralized system in some general settings (Cachon, 2003; Duan and Liao 2013). Meanwhile, there are some papers showing that firms may prefer to be in a decentralized system under certain conditions (McGuire and Staelin, 1983; Moorthy, 1988; Su and Zhang, 2008; Dong et al., 2018). Different from the above studies, which focus on the centralization in OM field by considering supply chain members as a whole system, in this paper we explore the scenario in which the retailer decides whether to act as an originator at the same time when adopting SCF with ABS.

Supply chain finance is one of the main pillars of supply chain management. It provides financial solutions for supply chain members with certain payment conditions (Wutyke et al., 2016; Tseng et al., 2018; Zhu et al., 2019; Song et al., 2020). A large number of studies in SCF have considered the problems such as bank loan, open account credit, letters of credit, and buyer credit (Chauffour and Farole, 2009; Amiti and Weinstein, 2011). The main difference between the above studies and this paper is that we consider an innovative financing product, i.e., ABS, the value and principle of which have been well analyzed (Bhattacharya et al., 2008). As a prevalent innovative financial product (Jiang et al., 2018), ABS enhances the financing flexibility and thus facilitates funding accessibility for all types of borrowers, who suffer from the lack of mortgage diversification (Riddiough, 1997). Yang et al. (2020) provide an overview of the ABS problem and indicate that originators (i.e., leasing companies) play a critical role in determining the issuing price. However, the literature that focuses on the adoption of ABS in SCF is rare. Motivated by the promising development prospects of ABS, in this paper we consider this innovative financing tool within supply chain systems.

Blockchain has a decentralized linked data structure and virtually unlimited applications in various industries (Feng et al., 2019; Choi, 2019; Choi et al., 2020; Berdik et al., 2021). Babich and Hilary (2020) study the value of blockchain technology adoption in operations management. Shen et al. (2021) examine how permissioned blockchain technology combats copycats in the supply chain and how it benefits brand name companies. With the consideration of purchasing agents, Shi et al. (2021c) highlight the effects of blockchain adoption on supply chain coordination with prevalent contracts. Hastig and Sodhi (2020) discuss the business requirements and critical success factors for the adoption of blockchain technology in supply chains. The interested readers may refer to Dutta et al. (2020) and Shi et al. (2021b) for comprehensive reviews of the studies exploring the implementation of blockchain in the operations management field. It is worth noting that blockchain technology is particularly widely adopted in the financial field, including payment, financial regulation, risk prevention and control, securities, credit investigation, and insurance (Ali et al., 2020; Harwick et al., 2020; Kowalski et al., 2021; Babich and Kouvelis, 2018). Chod et al. (2020) identify an important benefit of blockchain adoption by opening a window of transparency into a firm's supply chain, blockchain technology furnishes the ability to secure favorable financing terms at lower signaling costs. Harish et al. (2020) investigates the core constructs of blockchain technology: the tokens and smart contracts, which can be utilized in the digital asset valuation and risk assessment. As mentioned above, blockchain technology can solve many problems in supply chain finance (Choi, 2020; Ahluwalia et al., 2020; Chen and Bellavitis, 2020; Sanka et al., 2021). By considering market credibility problems raised in ABS, we explore the impact of blockchain technology on operations strategy for SCF with ABS in this paper.

Our work contributes to the extant literature in three folds. First, we consider the ABS, an innovated financial product, and study the financial strategies for the firms in a supply chain with ABS. Second, given the widely adoption of the blockchain technology in financial market, in this paper we conduct a deep analysis on the impact of the blockchain technology on SCF with ABS. Third, we investigate the channel management of supply chain systems and examine whether the core company in the system should build her own originated channel.

3. Decentralized and Centralized SCF with ABS

We consider a supply chain in which a capital-constrained manufacturer (he) sells a single product through a retailer (she) to consumers in an end market. The manufacturer incurs a unit production cost c for production and sells the product at a unit wholesale price w. The retail price set by the retailer is denoted as p, where $p > w > c$. In the product market, we consider that each consumer has a valuation v_c for the product. We assume that v_c is uniformly distributed over $[0,1]$. A consumer will purchase the product if and only if $v_c \geq p$. We normalize the market size to one, which is common in the literature (Shen et al., 2021). Accordingly, we can easily derive that the product demand is $D_c = 1 - p$.

To emphasize the effects of financing capability on the supply chain, the retailer is viewed as the core company. Traditionally, the manufacturer cannot receive the payments from the core company (retailer) until the products are delivered to the retailer. Then, his financial constraints fetter the production and it is widely observed that manufacturers turn to supply chain members for loan. We consider two typical supply chain financing (SCF) schemes supported by asset-backed securitization (ABS), which is commonly adopted in real practices. We name them as decentralized and centralized SCF with ABS, respectively. The key difference between the two SCF schemes is the responsible party for financing the upstream manufacturer: An external originator (resp. the core company herself) is in charge of financing under the decentralized (resp. centralized) SCF scheme.

In the first SCF scheme with ABS, we consider a decentralized system in which the retailer is in cooperation with an originator sponsor (it). Following the practices in the real world, the originator alleviates the manufacturer's capital constraint by providing a loan. The manufacturer, in turn, transfers the accounts receivable from the retailer to the originator in exchange for an immediate fund. Recall that the number of sold products equals the demand (i.e., D_c). Then the amount of accounts receivable is wD_c. To trigger the originator's incentive to get involved in the SCF scheme with ABS, we assume that it requires the manufacturer to offer a discount θ for each product. For the tractability, we model the discount as a linear function, such that the manufacturer eventually receives $w-\theta$ per unit product from the originator.

After receiving the accounts receivable, the originator packages equivalent assets and signs a financial service contract with a Special Purpose Vehicle (SPV) at a service rate r_s. Thereafter, the SPV processes the investment issue to investors at an interest rate r_i. This innovative financing scheme is known as the ABS. To avoid the trivial cases and ensure that the SPV is profitable, we assume that $r_s > r_i$.

It is worth noting that ABS has an important value in realizing risk remoteness between the assets and the originator. Due to the bankruptcy remote supported by ABS, regardless of the success or bankruptcy of the originator (e.g., due to the retailer's selling defeat), the package of assets cannot be preferentially used to repay the debt to the originator. Instead, it is required to remit the invested principal back to the investors by using the cash flow in the assets pool within a specified time. Correspondingly, the originator is able to use the fund raised in the ABS market to generate an extra yield e from each cash flow in the ABS asset pool. According to all the counted countries recorded by World Bank databank, the risk-free rates, which are usually presented by real interest rates, are less than 50% (Word Bank Group, 2021). Thus, we assume that $0 < e < \frac{1}{2}$ to restore the reality. The structure of the decentralized SCF system with ABS is depictured in Figure 1.

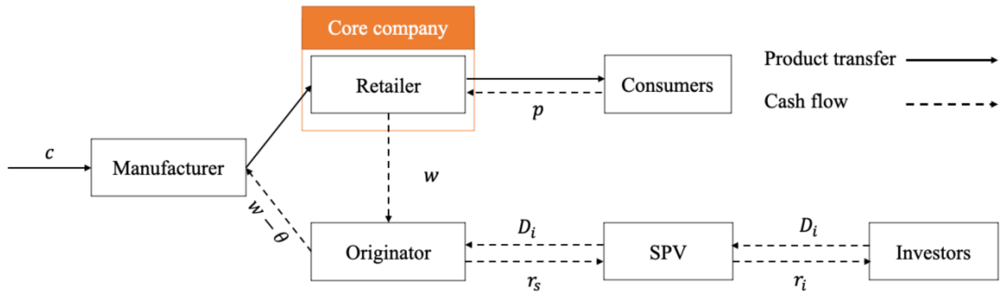

Figure 1. Structure of the decentralized system.

In the second supply chain financing scheme, we consider a centralized system in which the retailer establishes her own originated channel to finance the upstream manufacturer. Differing from the first SCF scheme, in the centralized system, the upstream manufacturer does not need to pay the unit discount of the accounts receivable θ to the core company, because the source of the money associated with accounts receivable is actually from the retailer. At this time, there is a tradeoff for the core company to decide: Whether to build her own originated channel. The structure of the centralized system is depictured in Figure 2. Note that acting as an originator at the same time, the core company signs a financial contract with SPV for ABS service as the originator does in the decentralized system.

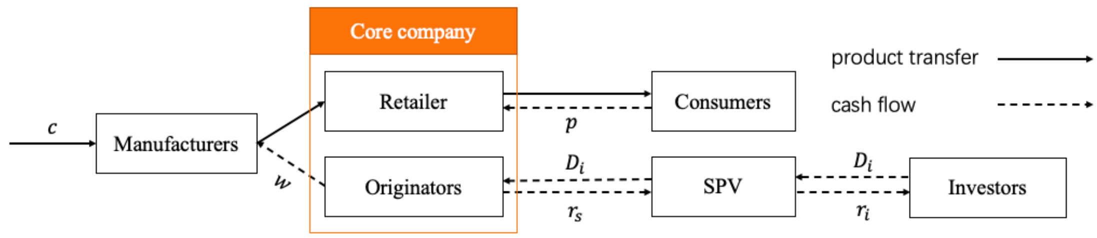

Figure 2. Structure of the centralized system.

For the core company, it is possible that she may fail to defray the accounts payable to the originator. To model this feature, we let β_n denote the market credibility of the core company. With probability β_n, the company is able to perform the accounts payable within the contract period to the originator. Otherwise, she fails to do so with probability $1 - \beta_n$, and then the accounts payable becomes a bad debt. In this paper, we do not consider the malicious default behavior of the core company, by assuming that the market credibility is exogenous. By analyzing the data of the World Bank on the index of bank non-performing loans to total growth loans (%) in the past 20 years, we can find that the index decreases in the development level of the country. In some developing countries, like Ukraine and Equatorial Guinea, the index is up to 50% (World Bank Group, 2021). Therefore, in order to ensure that the model can accurately reflect the social phenomena, we assume that $\beta_n > \frac{1}{3}$.

It is well known that the blockchain technology can improve the credibility of supply chain finance, due to its characteristics such as transparency, traceability, and permanent record. In the presence of blockchain, the originator can authorize the downstream SPV and investors to view the underlying capital chain. As a result, blockchain implementation improves the credibility of the core company from β_n to β_b, where $\frac{1}{3} < \beta_n < \beta_b < 1$. Because of the advantages of blockchain implementation, the originator may have an incentive to adopt the blockchain technology with an additional unit cost c_b of each product. To avoid the trivial outcomes and ensure that the profits of the supply chain's members are non-negative, we further assume that $\beta_b < 1 - \frac{e^2}{8}$, $0 < c < \frac{8\beta_n}{8-e^2}$, and $0 < c_b < \frac{-8c+ce^2+8\beta_b}{8}$. Otherwise, with a sufficiently large β_b, the company can well perform the accounts payable within the contract period to the originator. In this case, it is unnecessary for the core company to decide whether to cooperate with an external originator, because the probability of bad debts is very low. If the unit production cost is too large, i.e., $c > \frac{8\beta_n}{8-e^2}$, then the manufacturer's profit is non-positive. Similar, if the marginal cost of the blockchain technology is too substantial, i.e., $c_b > \frac{-8c+ce^2+8\beta_b}{8}$, then the profit of the originator is non-positive. Therefore, in order to ensure the feasibility of the model, we make the above assumptions. We assume that the fixed cost of the blockchain technology is zero. Note that the fixed cost of blockchain implementation is a sunk cost and the operational decisions will keep unchanged even if we consider a positive fixed cost (Choi et al., 2020).

In the ABS market, a group of potential investors holds a heterogeneous expectation about the return rate for the investment. We denote the investor's expected return rate as v_i and assume that it is uniformly distributed over $[0,1]$. Recall the interest rate of ABS is r_i, then the expected interest rates are $r_i\beta_n$ and $r_i\beta_b$ without and with blockchain adoption, respectively, with the consideration of the core company's market credibility. Then, an investor will invest in the asset-backed security if and only if the expected interest rate is larger than his/her expected return rate v_i. Then the probability that the investors will get involved in the ABS project are $r_i\beta_n$ $(r_i\beta_b)$ without (with) blockchain technology. Note that the asset associated with the accounts receivable in the financial market is wD_c, then the expected cash flow in the asset pool is $D_i = \beta_n r_i w D_c$ in the absence of blockchain. After the adoption of blockchain, it becomes $D_i = \beta_b r_i w D_c$.

We first consider the two systems without blockchain technology in Section 4. And then in Section 5, we extend our model by considering that blockchain technology is adopted in each system. Thus, we investigate four scenarios in this paper. That is, the decentralized system without blockchain technology (N, D), the centralized system without blockchain technology (N, C), the decentralized system with blockchain technology (B, D), and the centralized system with blockchain technology (B, C).

Table 1. Four scenarios investigated in this paper.

	Decentralized system	Centralized system
Without blockchain	(N, D)	(N, C)
With blockchain	(B, D)	(B, C)

In each scenario, we consider two sub-games. The first one is the ABS problem of the originator, SPV, and investors in the financing market. After releasing the capital constraint, the manufacturer and retailer get involved in the operations problem. Let π_m, π_c, π_o, and π_s denote the profits of the manufacturer, core company, originate (if any), and SPV, respectively. We use superscripts to denote the equilibrium outcomes of each scenario. For example, for the scenario (N, D), we use p^{ND}, w^{ND}, θ^{ND}, r_s^{ND}, r_i^{ND}, D_c^{ND}, D_i^{ND}, π_m^{ND}, π_c^{ND}, π_o^{ND}, and π_s^{ND} to denote the selling price of the product, wholesale price of the product, discount of funding, service rate, interest rate, demand of the product in the product market, demand of the investment in the ABS market, profit of the manufacturer, profit of the core company, profit of the originator, and profit of the SPV in equilibrium, respectively. We summarize the major notations used in the paper in Table 2.

Table 2. Notations

Notation	Description
β	The market credibility of the core company
c	The production cost of the manufacturer
c_b	The margin cost of the blockchain technology
e	The extra yield from each cash flow in the ABS asset pool
p	The core company's retail price of the product
w	The wholesale price of the product by the manufacturer
θ	The unit discount of the advanced receivable of the manufacturer to the core company
r_s	The service rate of the originator (or core company) to the SPV
r_i	The interest rate of the SPV to the investors
D_c	Demands of the product in the retail channel
D_i	Expected cash flow in the asset pool
π_m, π_c, π_o and π_s	The profits of the manufacturer, core company, originator and SPV, respectively

4. Without Blockchain Technology

In this section, we consider the decentralized and centralized systems, respectively, in the absence of blockchain implementation.

4.1 Decentralized system without blockchain technology $(\boldsymbol{N}, \boldsymbol{D})$

In this scenario, the event sequence is as follows: The originator first determines the value of discount θ and service rate r_s. Then, the SPV determines the investor's interest rate r_i. When the ABS financing is ensured, the manufacturer determines the wholesale price w, which is followed by the retailer's decision, i.e., the retail price p.

Profits of the originator and SPV from the financing channel are given as follows:

$$\pi_o(\theta, r_s) = D_i(1+e) + \beta_n\big(wD_c - D_i(1+r_s)\big) + (1-\beta_n)(-D_i) - (w-\theta)D_c$$
$$= \beta_n(wD_c - D_i r_s) + D_i\, e - (w-\theta)D_c$$
$$\pi_s(r_i) = \beta_n\big(D_i(1+r_s) - D_i(1+r_i)\big) + (1-\beta_n)(D_i - D_i)$$
$$= \beta_n\big(D_i(1+r_s) - D_i(1+r_i)\big)$$

For the originator, it receives an additional revenue (i.e., $D_i e$), due to the value of cash flow in the asset pool. With probability β_n, the originator eventually receives the accounts payable wD_c from the core company and pays the amount of fund $D_i(1+r_s)$ to the SPV. With probability $1-\beta_n$, the originator's accounts receivable becomes bad debt, however, it still needs to pay the principal D_i to the SPV to protect the rights of investors. The last term $(w-\theta)D_c$ is the amount of fund transferred to the manufacturer.

With probability β_n, the SPV receives the amount of fund $D_i(1+r_s)$ from the originator and thus pays $D_i(1+r_i)$ to the investors. With probability $1-\beta_n$, the SPV receives the principal D_i from the originator, which will be paid to the investors ultimately.

The profit functions of the manufacturer and core company from operations are as follows:

$$\pi_m(w) = (w-\theta-c)D_c$$
$$\pi_c(p) = \beta_n(p-w)D_c$$

The manufacturer earns a wholesale price w, offers a discount θ to the originator, and incurs a production cost c for each demand. The core company obtains the profit $(p-w)D_c$ with probability β_n. Based on our assumption, she suffers from market risk and obtains zero profit with probability $1-\beta_n$.

We solve the problem from backward. In the first step, we solve the operations problem: Given the interest rates r_s and r_i, and discount θ in financing market, we derive the maximum profits of the manufacturer and core company, respectively. In the second step, we substitute the supply chain members' best responses into the profit functions of the originator and SPV, respectively, and solve the financing problem then.

Lemma 1. *The equilibrium outcomes in the scenario (N, D) are given in Table 3.*

Table 3: Equilibrium outcomes in the scenario $(\boldsymbol{N}, \boldsymbol{D})$

Retail price	$p^{ND} = \frac{3}{4} + \frac{2(1+c)}{8+e^2+8\beta_n}$
Wholesale price	$w^{ND} = \frac{1}{2} + \frac{4(1+c)}{8+e^2+8\beta_n}$
Discount of funding	$\theta^{ND} = -c + \frac{8(1+c)}{8+e^2+8\beta_n}$
Service rate	$r_s^{ND} = \frac{e}{2\beta_n}$
Interest rate	$r_i^{ND} = \frac{e}{4\beta_n}$
Demand of the product	$D_c^{ND} = \frac{1}{4} - \frac{2(1+c)}{8+e^2+8\beta_n}$
Cash flow in the ABS asset pool	$D_i^{ND} = \frac{e}{32} - \frac{2(1+c)^2 e}{(8+e^2+8\beta_n)^2}$
Manufacturers' profit	$\pi_m^{ND} = \frac{(-8c+e^2+8\beta_n)^2}{8(8+e^2+8\beta_n)^2}$
Core company's profit	$\pi_c^{ND} = \frac{\beta_n(-8c+e^2+8\beta_n)^2}{16(8+e^2+8\beta_n)^2}$
Originator's profit	$\pi_o^{ND} = \frac{(-8c+e^2+8\beta_n)^2}{64(8+e^2+8\beta_n)}$
SPV's profit	$\pi_s^{ND} = \frac{e^2(-8c+e^2+8\beta_n)\big(8c+e^2+8(2+\beta_n)\big)}{128(8+e^2+8\beta_n)^2}$

Focused on the capital needed for production, we examine the impact of production cost on the optimal decisions and profits, respectively. From Lemma 1, it is intuitive that both the optimal wholesale price and retail price are increasing in production cost due to the marginalization. As a result, the product demand decreases in production cost, which may relieve the capital constraint at certain extent. It helps explain the observation that the originator attempts to decrease the discount, as the production cost increases.

Lemma 1 also indicates that the optimal operations decisions (i.e., p^{ND} and w^{ND}) decrease in the extra yield e and the market credibility β_n, which are positive indicators in the financing market. It hints that the supply chain members tend to raise price decisions for a higher profit margin, when the financing indexes are not favorable. Accordingly, the product demand D_c^{ND} increases in the two key parameters. For the financing decisions, both the optimal service rate and interest rate of ABS (r_s^{ND} and r_i^{ND}) increases in e but decreases in β_n. The SPV raises the interest rate for the investors when the market credibility is low, which also leads the originator to issue securities to the SPV at a high service rate to induce the SPV's involvement.

Next, we conduct the sensitivity analysis of the members' performance in the system. Though the increment of production cost benefits the manufacturer by increasing the wholesale price and decreasing the discount, its negative impact on the product demand dominates the benefit and hurts the manufacture's profit eventually. Hence, all in all, the manufacturer should make efforts to reduce the production cost for profit improvement. The manufacturer is also suggested to cooperate with an originator with high extra yield of the fund (i.e., e) and a core company with high market credibility (i.e., β_n), although the two crucial factors in financing market cannot be determined by him directly.

For the core company's optimal profit, it follows the same pattern. Facing high market risk represented by a low market credibility, the retailer attempts to grab the profit by raising the retail price for a higher profit margin. Then, the product demand drops as a result, which plays a dominating role in profit. Then, the core company's profit reduces as the market credibility decreases.

The originator's optimal profit decreases in the production cost, but increases in the extra yield and market credibility. The extra yield affects the optimal discount and service rate promised to the SPV in opposite directions. As both the product demand and cash flow in the ABS asset pool decrease in production cost and increase in the market credibility, it leads to the increment of the originator's profit as a result. Thus, the originator should choose to cooperate with a manufacturer with low production cost and a core company with high market credibility.

The impacts of key parameters on the SPV's optimal profit are similar. Partial of the SPV's profit depends on the gap between the service rate signed with the upstream originator and the interest rate signed with downstream investors, which increases in the extra yield. It implies that the SPV should cooperate with originator who can make better use of the return fund. Then, with the consideration of market risk and credibility, the SPV's profit is positively related to the market credibility naturally.

4.2 Centralized system without blockchain technology $(\boldsymbol{N}, \boldsymbol{C})$

In this subsection, we consider that the core company acts as the retailer and originator at the same time. Then the event sequence is as follows: First, the core company decides the service rate to the SPV, and then the SPV decides the expected interest rate r_i. When the ABS financing is ensured, the manufacturer decides the wholesale price w. Finally, the core company decides the retail price p.

The profits of the core company, manufacturer, and SPV in this scenario are given as follows:

$$\pi_c(p, r_s) = D_i(1+e) - wD_c + \beta_n\big(pD_c - D_i(1+r_s)\big) + (1-\beta_n)(-D_i)$$

$$= D_i e - wD_c + \beta_n(pD_c - D_i r_s)$$

$$\pi_m(w) = (w-c)D_c$$

$$\pi_s(r_i) = \beta_n\big(D_i(1+r_s) - D_i(1+r_i)\big) + (1-\beta_n)(D_i - D_i)$$

$$= \beta_n(D_i(1+r_s) - D_i(1+r_i))$$

Acting as an originator in the ABS financing, the core company receives the cash flow in asset pool (i.e., D_i) and obtains an extra yield $D_i e$ by utilizing it. Besides, she offers the fund wD_c to the upstream manufacturer. With probability β_n, the core company's products are sold successfully. Then, she is able to receive the revenue pD_c from the product market and the amount of the accounts payable $D_i(1+r_s)$ will be transferred to the SPV. With probability $1-\beta_n$, the core company fails in the product market, but she still needs to pay the principal D_i to the SPV for investors' rights protection. Note that the manufacturer no longer needs to offer discount to trigger the originator's involvement in this scenario. Moreover, the profit function of the SPV is the same as that in the scenario (N, D).

Lemma 2. *The equilibrium outcomes in the scenario* (N, C) *are given in Table 4.*

Table 4: Equilibrium outcomes in the scenario $(\boldsymbol{N}, \boldsymbol{C})$

Retail price	$p^{NC} = \dfrac{8c - c\,e^2 + 24\beta_n}{32\beta_n}$
Wholesale price	$w^{NC} = \dfrac{c}{2} - \dfrac{4\beta_n}{-8+e^2}$
Service rate	$r_s^{NC} = \dfrac{e}{2\beta_n}$

Interest rate	$r_i^{NC} = \frac{e}{4\beta_n}$
Demand of the product	$D_c^{NC} = \frac{1}{32}(8 + \frac{c(-8+e^2)}{\beta_n})$
Cash flow in the ABS asset pool	$D_i^{NC} = \frac{c^2 e(-8+e^2)}{256\beta_n} + \frac{e\beta_n}{32-e^2}$
Manufacturers' profit	$\pi_m^{NC} = \frac{(c(-8c+e^2)+8\beta_n)^2}{8(8+e^2+8\beta_n)^2}$
Core company's profit	$\pi_c^{NC} = \frac{(c(-8+e^2)+8\beta_n)^2}{1024\beta_n}$
SPV's profit	$\pi_s^{NC} = \frac{e^2\left(c^2(-8+e^2)^2 - 64{\beta_n}^2\right)}{1024(-8+e^2)\beta_n}$

From the equilibrium outcomes in the scenario (N, C), it is observed that the optimal profits of the manufacturer, core company and SPV decrease in the production cost, and increase in the extra yield and the market credibility, respectively. These effects are the same as those in the scenario (N, D).

4.3 Comparison of the scenarios without blockchain technology

Having derived the equilibrium outcomes of the decentralized and centralized scenarios (N, D) and (N, C), we now analyze the optimal strategies for the supply chain members without blockchain.

Proposition 1. *The equilibrium outcomes associated with the decision variables in the scenarios without blockchain technology possess the following properties:* $w^{ND} > w^{NC}$; $p^{ND} < p^{NC}$ *if and only if* $c > \frac{64\beta_n}{-64+e^4+8e^2\beta_n}$; $r_s^{ND} = r_s^{NC}$; *and* $r_i^{ND} = r_i^{NC}$.

Proposition 1 indicates that the wholesale price in the decentralized system is always higher than that in the centralized system. This is because the manufacturer needs to undertake an additional cost of financing discount in the decentralized system, which will weaken the profitability of the manufacturer to a certain extent. Thus, the manufacturer will increase the wholesale price to ensure the profit margin.

The relationship of the retail price depends on the production cost, which represents the financing demand. Specifically, when the production cost is sufficiently high, the retail price in the decentralized system is lower than that in the centralized system. This is because when the production cost is high, the discount of the fund is small. The manufacturer can set a relatively low wholesale price given a small discount of the fund, under which the difference between the wholesale price in the decentralized system and centralized system is small. This is one of the factors that enables the core company to lower her retail price, given a high production cost in the decentralized system. In addition, in the centralized system, the core company has additional profit source from the financing channel, under which she is able to set a relatively high retail price. Therefore, the retail price is higher given a high production cost in the centralized system.

It is interesting to find that both the service rate and interest rate remain unchanged in the decentralized system and centralized system. This is because the two rates are only related to extra yield and the market credibility. The subject who acts as the originator does not affect the above two decisions.

Proposition 2. *The equilibrium outcomes associated with the product demand and cash flow in the ABS asset pool in the scenarios without blockchain technology possess the following properties:* $D_c^{ND} > D_c^{NC}$ *if and only if* $\mathrm{c} > \frac{64\beta_n}{-64+e^4+8e^2\beta_n}$*; and there exist two thresholds* $\widehat{c_1}$ *and* $\widehat{c_2}$ *such that* $D_i^{ND} > D_i^{NC}$ *if* $\mathrm{c} < \widehat{c_1}$ *or* $\mathrm{c} > \widehat{c_2}$.

The first part of Proposition 2 follows Proposition 1 directly. For the cash flow collected in the ABS asset pool, the results depend on the production cost as well. Proposition 2 shows that the cash flow from the ABS in the decentralized system is weaker than that in the centralized system when the production is moderate. As the market credibility β_n and interest rate r_i remains unchanged between the two systems, this result can be explained by discussing the accounts receivable in the financial market wD_c. Note that the wholesale price in the decentralized system is always higher than that in the centralized system, and the demand of the products in the decentralized system is larger than that in the centralized system when the production cost is sufficiently high. Then, if the production cost is very small, the relationship of the wholesale price dominates the relationship of the demand of the products, i.e., $D_i^{ND} > D_i^{NC}$. If the production cost is moderate, the relationship of the demand of the products dominates the relationship of the wholesale price, i.e., $D_i^{ND} < D_i^{NC}$. If the production cost is very high, we obviously have $D_i^{ND} > D_i^{NC}$ because both the wholesale price and the demand of the products in the decentralized system are higher than those in the centralized system.

Proposition 3. *The equilibrium outcomes associated with the profits in the scenarios without blockchain technology possess the following properties:* $\pi_m^{ND} > \pi_m^{NC}$ *if and only if* $c > \widehat{c_3}$*;* $\pi_c^{ND} > \pi_c^{NC}$ *if and only if* $c > \frac{64\beta_n}{-64+e^4+8e^2\beta_n}$*; and there exist two thresholds* $\widehat{c_1}$ *and* $\widehat{c_2}$ *such that* $\pi_s^{ND} > \pi_s^{NC}$ *if* $\mathrm{c} < \widehat{c_1}$ *or* $\mathrm{c} > \widehat{c_2}$*.*

Proposition 3 first indicates the relationship of the manufacturer's profits in the two systems. In Proposition 1, we have shown that the wholesale price in the decentralized system is always larger than that in the centralized system. Then, the relationship of the manufacturer's profits is dominated by the demand of the products, which we have shown in Proposition 2 that when the production cost is sufficiently high, the demand of the products in the decentralized system is larger than that in the centralized system. It implies that the manufacturer's profit in the decentralized system is higher than that in the centralized system if and only if the production cost is sufficiently high.

For the comparison of the core company's profits, we can see that in the decentralized system, her profit is obtained from the product market only, while in the centralized system, she grabs additional profit from the financing market as an originator. Interestingly, when the production cost is sufficiently high, although the core company can obtain the profit from the financing channel, the profit of the core company in the decentralized system is higher than that in the centralized system. This is because when the production cost is sufficiently high, the channel integration will bring about the reduction of the demand of the products and asset-backed security, and their negative effects will harm the core company's profit in the centralized system. Therefore, when the production cost is sufficiently high, it is better for the core company not to carry out the channel integration.

The profit of the SPV is determined by the difference of the service rate and interest rate, and the cash flow in the ABS asset pool. Note that the service rate and interest rate are unchanged in the two systems. Then the relationship of the SPV's profit is only determined by the cash flow in the ABS asset pool. As shown in Proposition 2, when the production cost is sufficiently high or sufficiently low, the cash flow in the ABS asset pool in the decentralized system is larger than that in the centralized system. Thus, the SPV should choose to cooperate with an originator in a decentralized system only if the production cost is sufficiently high or sufficiently low.

Next, we sum up the results for the core company to choose the system without the blockchain technology. When the production cost is small, the core company should choose the centralized system and develop her own originated channel. In other words, the core company should develop her own originated channel when the main business of the core company is to sell low-cost products, such as some functional products, whose production cost is low, demand is large, and market volatility is small. Meanwhile, the risk suffered by the core company who builds her own originated channel is also small. On the other hand, when the production cost is sufficiently large, the core company should choose the decentralized system and find cooperative originator. This strategy is suitable for the company whose main business is to sell high-cost products, such as innovative products, under which production cost is high, the demand is low, the market volatility is large, and the risk of asset securitization is high. And the core company should try to mitigate the risk and cooperate with external originators.

5. With Blockchain Technology

In this section, we consider the case where the originator adopts blockchain technology in systems. In the following, we consider the decentralized and centralized systems, respectively.

5.1 Decentralized system with blockchain technology $(\boldsymbol{B}, \boldsymbol{D})$

In this scenario, the core company does not establish her own originated channel and the originator is responsible to adopt blockchain. The event sequence is the same as that in the scenario (N, D).

The profit functions of the originator and the SPV are given as follows:

$$\pi_o(\theta, r_s) = D_i(1+e) + \beta_b\big(wD_c - D_i(1+r_s)\big) + (1-\beta_b)(-D_i) - (w-\theta)D_c - c_bD_c$$
$$= \beta_b(wD_c - D_ir_s) + D_i\, e - (w - \theta + c_b)D_c$$
$$\pi_s(r_i) = \beta_b\big(D_i(1+r_s) - D_i(1+r_i)\big) + (1-\beta_b)(D_i - D_i)$$
$$= \beta_b\big(D_i(1+r_s) - D_i(1+r_i)\big)$$

There are two differences for the originator and SPV in the presence of blockchain. The first one is that the originator undertakes the additional unit cost c_b for blockchain implementation. Thus, it incurs an additional cost c_bD_c. The second one is that after blockchain adopting, the market credibility of the core company is improved from β_n to β_b.

The profit functions of the manufacturer and core company are as follows:

$$\pi_m(w) = (w - \theta - c)D_c$$
$$\pi_c(p) = \beta_b(p - w)D_c$$

The structures of profit functions in this scenario are similar to those in the scenario (N, D). Note that the only change is the market credibility.

Following the scenario (N, D), we also solve the problem by the backward induction approach. In the first step, we solve the operations problems. That is, given the service and interest rates r_s and r_i, and discount of the fund θ in the financing channel, we first maximize the profit of supply chain members. In the second step, we substitute the best response functions into the originator's and the SPV's profit functions, and solve the financing problem.

Lemma 3. *The equilibrium outcomes in the scenario (B, D) are given in Table 5.*

Table 5: Equilibrium outcomes in the scenario $(\boldsymbol{B}, \boldsymbol{D})$

Retail price	$p^{BD} = \frac{3}{4} + \frac{2(1+c+c_b)}{8+e^2+8\beta_b}$
Wholesale price	$w^{BD} = \frac{1}{2} + \frac{4(1+c+c_b)}{8+e^2+8\beta_b}$
Discount of funding	$\theta^{BD} = -c + \frac{8(1+c+c_b)}{8+e^2+8\beta_b}$
Service rate	$r_s^{BD} = \frac{e}{2\beta_b}$
Interest rate	$r_i^{BD} = \frac{e}{4\beta_b}$

Demand of the product	$D_c^{BD}=\frac{1}{4}-\frac{2(1+c+c_b)}{8+e^2+8\beta_b}$
Cash flow in the ABS asset pool	$D_i^{BD}=\frac{e}{32}-\frac{2(1+c+c_b)^2 e}{(8+e^2+8\beta_b)^2}$
Manufacturers' profit	$\pi_m^{BD}=\frac{(-8c-8c_b+e^2+8\beta_b)^2}{8(8+e^2+8\beta_b)^2}$
Core company's profit	$\pi_c^{BD}=\frac{\beta_b(-8c-8c_b+e^2+8\beta_b)^2}{16(8+e^2+8\beta_b)^2}$
Originator's profit	$\pi_o^{BD}=\frac{(-8c-8c_b+e^2+8\beta_b)^2}{64(8+e^2+8\beta_b)}$
SPV's profit	$\pi_s^{BD}=\frac{e^2(-8c-8c_b+e^2+8\beta_b)(16+8c+8c_b+e^2+8\beta_b)}{128(8+e^2+8\beta_b)^2}$

The equilibrium outcomes in this scenario are similar to those in the scenario (N,D). The manufacturer's and core company's optimal profits decrease in the production cost c, and increase in the extra yield e and the market credibility β_b. Similarly, it is suggested that the manufacturer should make efforts to reduce the production cost, and cooperate with the originator with high benefit of the extra yield due to cash back and the core company with high market credibility. The core company should choose to sell product with less market risk, such as some functional products. Meanwhile, the core company should cooperate with the manufacturer with low production cost and originator with high capital utilization. The originator should strive to improve the extra yield on investment, which will balance the loss caused by financing discount and service rate, and will ultimately increase the profit. Meanwhile, the originator should cooperate with the manufacturer with low production cost and the core company with high market credibility. Finally, the SPV should cooperate with the originator with better extra yield on investment and the core company with high market credibility.

Besides, the impacts of the marginal cost c_b on the equilibrium outcomes are as follows. When c_b increases, the originator should take higher cost for using the blockchain technology, and then it will increase the discount of the fund. Consequently, the manufacturer will increase the wholesale price and the core company will increase the retail price as well. Thus, the demand of the products will be decreased. Therefore, as c_b increases, the price increases while the product demand and cash flow in ABS asset pool decrease. Although all supply chain members set higher unit price, the negative effect of lower demand will eventually reduce the profits of all supply chain members. Therefore, the greater the marginal cost of the blockchain technology, the lower the profits of supply chain members.

5.2 Centralized system with blockchain technology $(\boldsymbol{B}, \boldsymbol{C})$

In this scenario, we consider that the core company establishes her own originated channel and adopts blockchain technology herself. The event sequence is the same as that in the scenario (N, C). We solve the problem from backward.

The profit functions of the core company, manufacturer, and SPV are given as follows:

$$\pi_c(p, \theta, r_s) = D_i(1+e) - wD_c + \beta_b\big(pD_c - D_i(1+r_s)\big) + (1-\beta_b)(-D_i) - c_bD_c$$

$$= D_ie - (w+c_b)D_c + \beta_b(pD_c - D_ir_s)$$

$$\pi_m(w) = (w-c)D_c$$

$$\pi_s(r_i) = \beta_b\big(D_i(1+r_s) - D_i(1+r_i)\big) + (1-\beta_b)(D_i - D_i)$$

$$= \beta_b\big(D_i(1+r_s) - D_i(1+r_i)\big)$$

There are two differences when we compare the above profit functions with those in the scenario (N, C): The first one is that the core company should take the additional cost c_bD_c in this scenario. The second one is that the market credibility is improved from β_n to β_b with blockchain adoption.

Lemma 4. *The equilibrium outcomes in the scenario (B, C) are given in Table 6.*

Table 6: Equilibrium outcomes in the scenario $(\boldsymbol{B}, \boldsymbol{C})$

Retail price	$p^{BC} = \frac{8c + 8c_b - ce^2 + 24\beta_b}{32\beta_b}$
Wholesale price	$w^{BC} = \frac{c}{2} + \frac{4(c_b - \beta_b)}{-8 + e^2}$
Service rate	$r_s^{BC} = \frac{e}{2\beta_b}$
Interest rate	$r_i^{BC} = \frac{e}{4\beta_b}$
Demand of the product	$D_c^{BC} = \frac{1}{32}\left(8 + \frac{c(-8 + e^2) - 8c_b}{\beta_v}\right)$
Cash flow in the ABS asset pool	$D_i^{BC} = \frac{e\big(c(-8 + e^2) + 8(c_b - \beta_b)\big)(-8c_b + c(-8 + e^2) + 8\beta_b)}{256(-8 + e^2)\beta_b}$
Manufacturers' profit	$\pi_m^{BC} = \frac{(-8c_b + c(-8c + e^2) + 8\beta_b)^2}{64(-8+e^2)\beta_b}$

Core company's profit	$\pi_c^{BC} = \frac{(-8c_b + c(-8+e^2) + 8\beta_b)^2}{1024\beta_b}$
SPV's profit	$\pi_s^{BC} = \frac{e^2(c(-8+e^2)^2 + 8(c_b - \beta_b))(-8c_b + c(-8+e^2) + 8\beta_b)}{1024(-8+e^2)\beta_b}$

From the equilibrium outcomes in the scenario (B, C), we can obtain that the optimal profits of the manufacturer, core company, and SPV decrease in the production cost, and increase in the extra yield and the market credibility. These effects are the same as those in the scenario (B, D). Impacts of c_b are quite similar to those in the scenario (B, D). However, one difference is that the wholesale price is unexpectedly decreasing in c_b. The reason is that in the centralized system, the core company is the one who is responsible to adopt blockchain and undertakes the marginal cost. When the marginal cost of blockchain technology is higher, the unit profit margin of the core company is lower, and the manufacturer has to sign a contract with a lower wholesale price.

5.3 Comparison of the scenarios with the blockchain technology

Having derived the equilibrium outcomes in the above scenarios (B, D) and (B, C), we now analyze the optimal strategies for supply chain members in the presence of blockchain implementation.

Proposition 4. *The equilibrium outcomes associated with the decision variables in the scenarios with blockchain technology possess the following properties:* $w^{BD} > w^{BC}$; $p^{BD} > p^{BC}$ *if and only if* $c_b < \frac{8\beta_b}{8+e^2}$ *and* $c < \frac{64c_b + 8c_b e^2 - 64\beta_b}{-64+e^4+8e^2\beta_b}$; $r_s^{BD} = r_s^{BC}$; *and* $r_i^{BD} = r_i^{BC}$.

Proposition 4 first shows the relationship of wholesale price in the two systems with the blockchain technology. It is straightforward to see that the wholesale price set by the manufacturer in the decentralized system is always higher than that in the centralized system. This is because in the decentralized system, the manufacturer needs to take an additional cost associated with the discount of the fund, which will increase the wholesale price to ensure his profitability.

For the relationship of retail price in the two systems, it can be seen that whether the retail price in the decentralized system is higher than that in the centralized system depends on the values of the production cost and marginal cost of blockchain implementation. When the marginal cost of blockchain and production cost are sufficiently low, the retail price in the decentralized system is larger than that in the centralized system. The effect of the production cost on the relationship of the retail price is similar to that in Proposition 1, under which we have explained why a low production cost will increase the retail price in the decentralized system compared to the centralized system. Here, we show that the relationship of the wholesale price is also affected by the marginal cost of the blockchain technology. When the marginal cost of the blockchain technology is sufficiently large, no matter how much the production cost is, the core company is more willing to set a high retail price in the centralized system, because it is difficult for the core company to make profit from the financing channel given a high marginal cost of the blockchain technology. Then, the core company should increase the retail price of product to improve the profit of retail channel to balance the potential loss from financing channel.

For the relationship of the service rate and interest rate, Proposition 4 indicates that both the service rate and interest rate are also unchanged in the two systems. The results and corresponding reasons are the same as those in the scenarios without blockchain technology.

Proposition 5. *The equilibrium outcomes associated with the product demand and cash flow from ABS in the scenarios with blockchain technology possess the following properties:* $D_c^{BD} < D_c^{BC}$ *if and only if* $c_b < \frac{8\beta_b}{8+e^2}$ *and* $c < \frac{64c_b+8c_be^2-64\beta_b}{-64+e^4+8e^2\beta_b}$*; and there exist two thresholds* $\widehat{c_4}$ *and* $\widehat{c_5}$ *such that* $D_i^{BD} > D_i^{BC}$ *if* $c < \widehat{c_4}$ *or* $c > \widehat{c_5}$.

Proposition 5 first shows that the product demand in the decentralized system is smaller than that in the centralized system if and only if both the production cost and marginal cost of the blockchain technology are sufficiently low. This is because, as shown in Proposition 4, given the low production cost and marginal cost of the blockchain technology, the retail price in the decentralized system is higher than that in the centralized system. Besides, Proposition 5 also proposes that the cash flow collected by ABS in the decentralized system is smaller than that in the centralized system when the production is moderate. The results and corresponding reasons are similar to those without the blockchain technology.

Proposition 6. *The equilibrium outcomes associated with the profits in the scenarios with blockchain technology possess the following properties: There exists a threshold* $\widehat{c_6}$ *such that* $\pi_m^{BD} < \pi_m^{BC}$ *if and only if* $c < \widehat{c_6}$*;* $\pi_c^{BD} < \pi_c^{BC}$ *if and only if* $c_b < \frac{8\beta_b}{8+e^2}$ *and* $c < \frac{64c_b+8c_b e^2-64\beta_b}{-64+e^4+8e^2\beta_b}$*; and there exist two thresholds* $\widehat{c_4}$ *and* $\widehat{c_5}$ *such that* $\pi_s^{BD} > \pi_s^{BC}$ *if* $c < \widehat{c_4}$ *or* $c > \widehat{c_5}$.

Proposition 6 first indicates that the manufacturer's profit in the decentralized system is lower than that in the centralized system if and only if the production cost is sufficiently low. This result is similar to the scenario without the blockchain technology. This is also mainly because of the joint interaction of the wholesale price and the product demand. Similar to the scenario without the blockchain technology, the profit of the core company in the decentralized system can also be higher than that in the centralized system under certain conditions. When the production cost and marginal cost of the blockchain technology are sufficiently low, the channel integration will bring about the increase of the demand of the products and asset-backed security, and the positive effects will benefit the core company's profit in the centralized system. Therefore, when the production cost and marginal cost are sufficiently low, the core company is suggested to carry out the channel integration. Moreover, the relationship of the SPV's profit is also similar to the scenario without the blockchain technology. The service rate and interest rate are unchanged in the two systems, and then the relationship of the SPV's profit follows the relationship of the cash flow in the ABS asset pool. Thus, the SPV should choose to cooperate with an originator in a decentralized system when the production cost is sufficiently high or sufficiently low.

To summarize, for the optimal channel strategy with blockchain technology, it is suggested that the core company should choose the centralized system and develop her own originated channel if and only if the production cost and the marginal cost of the blockchain technology are small.

6. Impacts of the Blockchain Technology

In this section, we investigate whether the blockchain technology should be adopted in the decentralized system and centralized system, respectively.

Proposition 7. *(1) In the decentralized system:* $w^{ND} > w^{BD}$ *if and only if* $c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8 + e^2 + 8\beta_n}$*;* $p^{ND} > p^{BD}$ *if and only if* $c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8 + e^2 + 8\beta_n}$*;* $\theta^{ND} > \theta^{BD}$ *if and only if* $c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8 + e^2 + 8\beta_n}$*;* $r_s^{ND} > r_s^{BD}$ *and* $r_i^{ND} > r_i^{BD}$*. (2) In the centralized system:* $w^{NC} < w^{BC}$ *if and only if* $c_b < \beta_b - \beta_n$*;* $p^{NC} > p^{BC}$ *if and only if* $c_b < \frac{-8c\beta_n + 8c\beta_b + ce^2\beta_n - ce^2\beta_b}{8\beta_n}$*;* $r_s^{NC} > r_s^{BC}$ *and* $r_i^{NC} > r_i^{BC}$*.*

The first part of Proposition 7 shows the results associated with the wholesale price, retail price, discount of the fund, service rate, and interest rate in the decentralized system. It indicates that the wholesale price, retail price, and discount of fund in the decentralized system without blockchain technology are higher than those with blockchain technology, if the marginal cost of the blockchain technology is relatively low. The reason is as follows: When the marginal cost of the blockchain technology taken by the originator is sufficiently low, the low marginal cost can be exchanged for a high market credibility that can reduce the risk of financing failure of the originator. Then, the originator is willing to reduce the discount of fund signed with the manufacturer to attract more financing opportunities. Consequently, the manufacturer will reduce the wholesale price and then the core company will drop the retail price as a result. Besides, Proposition 7 proposes that the service rate and interest rate are blunted in the decentralized system with blockchain. This is because when the blockchain technology is introduced, the market becomes more creditable, and then the originator will take the initiative to reduce the service rate provided to the downstream SPV. Consequently, the SPV will reduce the interest rate provided to the investors.

The second part of Proposition 7 shows the results associated with the wholesale price, retail price, service rate, and interest rate in the centralized system. In the centralized system the marginal cost of the blockchain technology is paid by the core company. Then a lower marginal cost enables the core company to reduce the retail price in exchange for more demand of the products. Interestingly, differing from the decentralized system where the manufacturer will reduce the wholesale price in the presence of blockchain with a low marginal cost, the wholesale price will be increased for blockchain adoption with a low marginal cost in the centralized system. This is because in the centralized system, when the marginal cost is low, the core company is able to earn a relatively high profit margin from the financing. Then, she has a strong incentive to induce the investors' involvement and raise the cash flow in the asset pool, which depends on the product demand and wholesale price. Therefore, acting as the retailer at the same time, the core company is willing to drop the retail price for the increment of demand and sign a contract with the manufacturer at a high wholesale price. Note that the relationship of the service rate and interest rate in the centralized system are the same as those in the decentralized system.

Proposition 8. *(1) In the decentralized system:* $D_c^{ND} < D_c^{BD}$ *if and only if* $c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8 + e^2 + 8\beta_n}$*;* $D_i^{ND} < D_i^{BD}$ *if and only if* $c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8 + e^2 + 8\beta_n}$*. (2) In the centralized system:* $D_c^{NC} < D_c^{BC}$ *if and only if* $c_b < \frac{-8c\beta_n + 8c\beta_b + ce^2\beta_n - ce^2\beta_b}{8\beta_n}$*;* $D_i^{NC} < D_i^{BC}$ *if and only if* $c_b < \beta_b - \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n - \beta_b) + 64\beta_n^3\beta_b}}{8\beta_n}$.

Proposition 8 shows the results associated with the product demand and the cash flow in the ABS asset pool. It indicates that in both systems, both indexes are increased when the blockchain technology is introduced with a low marginal cost. For the change of the product demand, the increase is due to the drop of the retail price after adopting blockchain with a low marginal cost as shown in Proposition 7. Recall that the cash flow is determined by the market credibility, interest rate, wholesale price, and the product demand. After introducing the blockchain technology with a low marginal cost, the market credibility and product demand will be increased. Although the blockchain adoption will drop the interest rate and has complex impacts on the wholesale price, the increment of demand spurred by blockchain dominates all the negative effects. Thus, given the low marginal cost of the blockchain technology, the collected cash flow from ABS is increased in the decentralized and centralized systems with the blockchain technology.

Proposition 9. *(1) In the decentralized system:* $\pi_m^{ND} < \pi_m^{BD}$ *if and only if* $c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8 + e^2 + 8\beta_n}$; $\pi_c^{ND} < \pi_c^{BD}$ *if and only if* $c_b < \widehat{c_{b1}}$; $\pi_o^{ND} < \pi_o^{BD}$ *if and only if* $c_b < \widehat{c_{b2}}$; *and* $\pi_s^{ND} < \pi_s^{BD}$ *if and only if* $c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8 + e^2 + 8\beta_n}$. *(2) In the centralized system:* $\pi_m^{NC} < \pi_m^{BC}$ *if and only if* $c_b < \widehat{c_{b3}}$, $\pi_c^{NC} < \pi_c^{BC}$ *if and only if* $c_b < \widehat{c_{b3}}$; *and* $\pi_s^{NC} < \pi_s^{BC}$ *if and only if* $c_b < \beta_b - \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n - \beta_b) + 64\beta_n{}^3\beta_b}}{8\beta_n}$.

Proposition 9 shows the supply chain members' incentives of adopting blockchain in the decentralized and centralized systems. In the decentralized system, the originator decides whether to adopt blockchain. When the marginal cost of blockchain technology is sufficiently high, the originator prefers not to introduce the blockchain technology even if it can improve the market creditability. Similarly, for other supply chain members, only when the marginal cost of the blockchain technology is sufficiently low, their profits with blockchain are higher than those in the absence of blockchain. Therefore, regardless of whether the supply chain members have the decision-making right to introduce the blockchain technology, their preferences are the same. That is, when the marginal cost of the blockchain technology is small, introducing the blockchain technology is beneficial to all supply chain members. In the centralized system, the core company decides whether to introduce the blockchain technology. When the marginal cost of blockchain technology is sufficiently low, the core company will introduce the blockchain technology. An all-win situation is also achieved when the blockchain technology is introduced with a low marginal cost.

7. Conclusion

In this paper we study the operations strategy issues of SCF with consideration of fintech, i.e., ABS. We first study that whether the core company should establish her own originated channel with and without blockchain implementation, respectively. In order to answer this research question, we examine four scenarios in the paper, that is, the decentralized system without blockchain technology, the centralized system without blockchain technology, the decentralized system with blockchain technology, and the centralized system with blockchain technology. Then we further study the impacts of the blockchain technology on the SCF systems by comparing scenarios with and without blockchain technology. We summarize the major findings and managerial implications as follows:

Without the blockchain technology, when the core company establishes her own originated channel, the manufacturer should decrease his wholesale price. The core company should increase her retail price if the production cost is sufficiently high. Interestingly, both the service rate and interest rate remain unchanged when the core company establishes her own originated channel. It implies that no matter which one is the originator, the investment return rate of the investors will not be affected. It suggests that the investors do not need to take the supply chain structure into consideration when choosing ABS products. Regarding the effects of the centralization on the profits, we find that the core company's profit in the centralized system is higher than that in the decentralized system when the production cost is low. It suggests that the core company should develop her own originated channel when her main business concentrates on low-cost products, such as functional products. On the other hand, the core company should cooperate with an external originator in the decentralized system when her main business is to sell high-cost products, such as innovative products. Other supply chain members' profits will also be affected by the core company's centralization strategy. Specifically, whether the centralization is beneficial to them depends on the value of production cost. Under certain conditions, the supply chain members can achieve an all-win situation, especially for the supply chain that produces and sells high-cost products. The effects of the centralization on the decision variables and profits are similar in cases with and without blockchain implementation. The only difference is about the additional condition associated with the marginal cost of blockchain adoption. Compared to the decentralized system, the core company increases the retail price in the centralized system when the marginal cost of the blockchain technology is sufficiently high, meanwhile, the core company should cooperate with an external originator, which is undertaken by the core company in the centralized system.

The impacts of the blockchain technology on the wholesale price, retail price, and discount of the fund depend on the marginal cost of introducing the blockchain technology. In the decentralized system, the originator is responsible for the blockchain implementation, if any. When the marginal cost of the blockchain technology is sufficiently low, the originator should decrease the discount of funds after introducing this technology, such that the manufacturer and the core company will reduce the wholesale price and retail price, respectively. In the centralization system, the core company is in charge of the blockchain adoption. Interestingly, the sufficiently low marginal cost of the blockchain technology leads the core company to decrease the retail price; on the contrary, it leads the manufacturer to increase the wholesale price. Moreover, in both systems, the service rate and interest rate always drop in the presence of blockchain, because the market becomes more creditable. Regarding the effect of the blockchain technology on the profits in the decentralized and centralized systems, we find that all supply chain members' profits are improved, if the marginal cost of the blockchain technology is sufficiently low. Regardless of the supply chain structure, all supply chain members should take a positive attitude towards the introduction of the blockchain technology.

There are some limitations in this paper, which provide some interesting future research directions. First, in this paper we consider that the core company will pay all the accounts receivable to the originator with a certain probability. It will be interesting to consider the possibility of a partial repayment made by the core company in the future research. Second, for the advantage of blockchain implementation, we only consider that it can improve the market credibility in this paper. In the future research, we may consider other applications or features of blockchain technologies, such as smart contract. The impacts of those applications and features of the SFC with ABS are worthy to be further investigated. Finally, it will be interesting to extend our research to consider supply chains with competition.

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Appendix

Proof of Lemma 1. In the scenario (N, C), it is easy to show that the profit functions of the core company, manufacturer and SPV are concave in p, w and r_i, respectively. Then, the optimal solutions $p = \frac{1+w}{2}$, $w = \frac{1+c+\theta}{2}$ and $r_i = \frac{r_s}{2}$ can be obtained by the first-order condition, i.e., $\frac{\partial \pi_c}{\partial p} = 0$, $\frac{\partial \pi_m}{\partial w} = 0$ and $\frac{\partial \pi_s}{\partial r_i} = 0$. Substituting them into the originator's profit, we get $\frac{\partial^2 \pi_o}{\partial r_s^2} = \frac{1}{8}\beta_n^2(-1 + c + \theta)(1 + c + \theta) < 0$. Thus, the objective function is concave in r_s and we have $r_s^{ND} = \frac{e}{2\beta_n}$. Meanwhile, $\frac{\partial^2 \pi_o}{\partial \theta^2} = \frac{1}{32}(-e^2 - 8(1 + \beta_n)) < 0$, so we can get the optimal solution by the first-order condition $\theta^{ND} = -c + \frac{8(1+c)}{8+e^2+8\beta_n}$. After substituting r_s^{ND} and θ^{ND} into the functions of corresponding terms, we can easily obtain the outcomes w^{ND}, p^{ND}, r_i^{ND}, D_c^{ND}, D_i^{ND}, π_m^{ND}, π_c^{ND}, $\pi_o^{ND}$and π_s^{ND}. ■

Proof of Lemma 2. In the scenario (N, C), it is easy to show that the profit function of SPV is concave in r_i, so the optimal response can be obtained by the first-order condition, i.e., $r_i = \frac{r_s}{2}$. Substituting it into the core company's profit, we can obtain that the objective function is jointly concave in p and r_s. By the first-order conditions, we can obtain the optimal solutions as follows $r_i^{NC} = \frac{e}{2\beta_n}$ and $p = \frac{8w-e^2w+8\beta_n}{16\beta_n}$. Substituting them into the manufacturer's profit function, we can get that $\frac{\partial^2 \pi_m}{\partial w^2} = \frac{-8+e^2}{8\beta_n}$<0. By the first-order condition, we have $w^{NC} = \frac{c}{2} - \frac{4\beta_n}{-8+e^2}$. After substituting r_i^{ND} and w^{NC} into the functions of corresponding terms, we can easily obtain the outcomes p^{NC}, r_i^{NC}, D_c^{NC}, D_i^{NC}, π_m^{NC}, π_c^{NC} and π_s^{NC}. ■

Proof of Lemma 3. The proof of the optimal solutions in the scenario (B, D) are similar to those in the scenario (N, D). ■

Proof of Lemma 4. The proof of the optimal solutions in the scenario (B, C) are similar to those in the scenario (N, C). ■

Proof of Proposition 1.

a. Define $\Delta p^{NDNC} = p^{ND} - p^{NC}$. Then, we have

$$\Delta p^{NDNC} = \frac{c(-8+e^2)}{32\beta_n} + \frac{2(1+c)}{8+e^2+8\beta_n}.$$

Taking the first derivative of Δp^{NDNC} with respect to c, we have $\frac{\partial \Delta p^{NDNC}}{\partial c} = \frac{-8+e^2}{32\beta_n} + \frac{2}{8+e^2+8\beta_n} < 0$, implying that Δp^{NDNC} decreases in c. Then let $\Delta p^{NDNC}(c) = 0$, we can obtain the solution $c = -\frac{64\beta_n}{-64+e^4+8e^2\beta_n}$, which is in the boundaries of c. Thus $p^{ND} > p^{NC}$ if and only if $0 < c < -\frac{64\beta_n}{-64+e^4+8e^2\beta_n}$.

b. Define $\Delta w^{NDNC} = w^{ND} - w^{NC}$. Then, we have

$$\Delta w^{NDNC} = \frac{1}{2} - \frac{c}{2} + \frac{4\beta_n}{-8+e^2} + \frac{4(1+c)}{8+e^2+8\beta_n}.$$

Taking the first derivative of Δw^{NDNC} with respect to c, we have $\frac{\partial \Delta w^{NDNC}}{\partial c} = -\frac{1}{2} + \frac{4}{8+e^2+8\beta_n} < 0$, implying that Δw^{NDNC} decreases in c. Then let $\Delta w^{NDNC}(c) = 0$, we can obtain the solution $c = \frac{e^4+8e^2(1+2\beta_n)+64(-2+\beta_n^2)}{(-8+e^2)(e^2+8\beta_n)}$, which, however, is out of the boundaries of c. Thus, we have $w^{ND} > w^{NC}$.

c. It is clear that ${r_s}^{ND} = {r_s}^{NC}$.

d. It is clear that ${r_i}^{ND} = {r_i}^{NC}$. ■

Proof of Proposition 2.

a. Define $\Delta {D_c}^{NDNC} = {D_c}^{ND} - {D_c}^{NC}$. Then, we have

$$\Delta {D_c}^{NDNC} = -\frac{c(-8+e^2)}{32\beta_n} - \frac{2(1+c)}{8+e^2+8\beta_n}.$$

Taking the first derivative of $\Delta {D_c}^{NDNC}$ with respect to c, we have $\frac{\partial \Delta {D_c}^{NDNC}}{\partial c} = \frac{-8+e^2}{32\beta_n} - \frac{2}{8+e^2+8\beta_n} < 0$, implying that $\Delta {D_c}^{NDNC}$ decreases in c. Then let $\Delta {D_c}^{NDNC}(c) = 0$, we can obtain the solution $c = -\frac{64\beta_n}{-64+e^4+8e^2\beta_n}$, which is the boundaries of c. Thus, ${D_c}^{ND} > {D_c}^{NC}$ if and only if $c > -\frac{64\beta_n}{-64+e^4+8e^2\beta_n}$.

b. Define $\Delta {D_i}^{NDNC} = {D_i}^{ND} - {D_i}^{NC}$. Then, we have

$$\Delta {D_i}^{NDNC} = \frac{1}{256} e \left(8 - \frac{c^2(-8+e^2)}{\beta_n} + \frac{64\beta_n}{-8+e^2} - \frac{512(1+c)^2}{(8+e^2+8\beta_n)^2}\right).$$

Taking the second derivative of $\Delta D_i{}^{NDNC}$ with respect to c, we have $\frac{\partial^2 \Delta D_c{}^{NDNC}}{\partial c^2} = \frac{1}{256} e\left(\frac{-8+e^2}{\beta_n} - \frac{512}{(8+e^2+8\beta_n)^2}\right) > 0$, implying that $\Delta D_i{}^{NDNC}$ is convex in c. Then let $\Delta D_i{}^{NDNC}(c) = 0$, we obtain two solutions $\widehat{c_1} = \frac{-512(-8+e^2)\beta_n}{(-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_n+64(-8+e^2)^2{\beta_n}^2} - \frac{2\sqrt{2}\sqrt{\left((-8+e^2)\beta_n(8+e^2+8\beta_n)^2\left(e^8+24e^6\beta_n-4096{\beta_n}^3+64e^4(-3+\beta_n(-1+3\beta_n))+512e^2(2+\beta_n(-2+(-2+\beta_n)\beta_n))\right)\right)}}{(-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_n+64(-8+e^2)^2{\beta_n}^2}$ and $\widehat{c_2} = \frac{-512(-8+e^2)\beta_n}{(-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_n+64(-8+e^2)^2{\beta_n}^2} + \frac{2\sqrt{2}\sqrt{\left((-8+e^2)\beta_n(8+e^2+8\beta_n)^2\left(e^8+24e^6\beta_n-4096{\beta_n}^3+64e^4(-3+\beta_n(-1+3\beta_n))+512e^2(2+\beta_n(-2+(-2+\beta_n)\beta_n))\right)\right)}}{(-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_n+64(-8+e^2)^2{\beta_n}^2}$. It can be show that $\widehat{c_2}$ is in the boundaries of c and larger than $\widehat{c_1}$. Meanwhile, we have $\Delta D_i{}^{NDNC}\big|_{c=0} = \frac{e^2}{128}(1+\frac{8\beta_n}{-8+e^2} - \frac{64}{(8+e^2+8\beta_n)^2})$, which may be negative or positive; and $\Delta D_i{}^{NDNC}\big|_{c=\frac{8\beta_n}{8-e^2}} = \frac{e^2(8-\frac{512(1-\frac{8\beta_n}{8-e^2})^2}{(8+e^2+8\beta_n)^2}}{1024} > 0$. Thus, there exist two thresholds $\widehat{c_1}$ and $\widehat{c_2}$ such that $D_i^{ND} > D_i^{NC}$ *if* $c < \widehat{c_1}$ *or* $c > \widehat{c_2}$. ■

Proof of Proposition 3.

a. Define $\Delta\pi_m{}^{NDNC} = \pi_m{}^{ND} - \pi_m{}^{NC}$. Then, we have

$$\Delta\pi_m{}^{NDNC} = \frac{1}{64}\left(\frac{8\left(-8c+e^2+8\beta_n\right)^2}{(8+e^2+8\beta_n)^2} + \frac{\left(c\left(-8+e^2\right)+8\beta_n\right)^2}{(-8+e^2)\beta_n}\right).$$

Taking the second derivative of $\Delta\pi_m{}^{NDNC}$ with respect to c, we have $\frac{\partial^2 \Delta\pi_m{}^{NDNC}}{\partial c^2} = \frac{1}{64}(\frac{-8+e^2}{\beta_n} + \frac{512}{(8+e^2+8\beta_n)^2}) < 0$, implying that $\Delta\pi_m{}^{NDNC}$ is concave in c. Then let $\Delta\pi_m{}^{NDNC}(c) = 0$, we obtain two solutions. The first one is $\widehat{c_3} = -\frac{2\beta_n\left(8+e^2+8\beta_n\right)^2(-4+\sqrt{2}\sqrt{-\frac{e^4\left(-8+e^2+8\beta_n\right)^2}{(-8+e^2)\beta_n\left(8+e^2+8\beta_n\right)^2} - \frac{256}{\left(8+e^2+8\beta_n\right)^2} + \frac{32}{8+e^2+8\beta_n}})}{e^6+8e^4(1+2\beta_n)+64e^2\left(-1+\beta_n^2\right)-512(1+\beta_n+\beta_n^2)}$, which is in the boundaries of c. The second one is $-\frac{2\beta_n\left(8+e^2+8\beta_n\right)^2(-4-\sqrt{2}\sqrt{-\frac{e^4\left(-8+e^2+8\beta_n\right)^2}{(-8+e^2)\beta_n\left(8+e^2+8\beta_n\right)^2} - \frac{256}{\left(8+e^2+8\beta_n\right)^2} + \frac{32}{8+e^2+8\beta_n}})}{e^6+8e^4(1+2\beta_n)+64e^2\left(-1+\beta_n^2\right)-512(1+\beta_n+\beta_n^2)}$, which is out of the boundaries of c. Thus, there exists a threshold $\widehat{c_3}$ such that $\pi_m^{ND} > \pi_m^{NC}$ if and only if $c > \widehat{c_3}$.

b. Define $\Delta\pi_c{}^{NDNC} = \pi_c{}^{ND} - \pi_c{}^{NC}$. Then, we have

$$\Delta\pi_c{}^{NDNC} = \frac{\beta_n(-8c+e^2+8\beta_n)^2}{16(8+e^2+8\beta_n)^2} - \frac{(c(-8+e^2)+8\beta_n)^2}{1024\beta_n}.$$

Taking the second derivative of $\Delta\pi_c{}^{NDNC}$ with respect to c, we have $\frac{\partial^2\Delta\pi_c{}^{NDNC}}{\partial c^2} = -\frac{(-8+e^2)^2}{512\beta_n} + \frac{8\beta_n}{(8+e^2+8\beta_n)^2}) < 0$, implying that $\Delta\pi_c{}^{NDNC}$ is concave in c. Then let $\Delta\pi_c{}^{NDNC}(c) = 0$, we can obtain that there are two solutions: $-\frac{64\beta_n}{-64+e^4+8e^2\beta_n}$ and $-\frac{16\beta_n(4+e^2+8\beta_n)}{-64+e^4+8(-16+e^2)\beta_n}$. However, only $-\frac{64\beta_n}{-64+e^4+8e^2\beta_n}$ is in the boundaries of c. Thus, $\pi_c{}^{ND} > \pi_c{}^{NC}$ if and only if $c > -\frac{64\beta_n}{-64+e^4+8e^2\beta_n}$.

c. Define $\Delta\pi_s{}^{NDNC} = \pi_s{}^{ND} - \pi_s{}^{NC}$. Then, we have

$$\Delta\pi_s{}^{NDNC} = \frac{e^2(8-\frac{c^2(-8+e^2)}{\beta_n}+\frac{64\beta_n}{-8+e^2}-\frac{512(1+c)^2}{(8+e^2+8\beta_n)^2})}{1024}.$$

Taking the second derivative of $\Delta\pi_s{}^{NDNC}$ with respect to c, we have $\frac{\partial^2\Delta\pi_s{}^{NDNC}}{\partial c^2} = \frac{e^2(\frac{-8+e^2}{\beta_n}-\frac{512}{(8+e^2+8\beta_n)^2})}{1024} > 0$, implying that $\Delta\pi_s{}^{NDNC}$ is convex in c. Then let $\Delta\pi_s{}^{NDNC}(c) = 0$, we can obtain two solutions $\widehat{c_1}$and $\widehat{c_2}$. It can be show that $\widehat{c_2}$ is in the boundaries of c and larger than $\widehat{c_1}$. Meanwhile, we have $\Delta\pi_s{}^{NDNC}|_{c=0} = \frac{e^2}{128}(1 + \frac{8\beta_n}{-8+e^2} - \frac{64}{(8+e^2+8\beta_n)^2})$, which may be negative or positive; $\Delta\pi_s{}^{NDNC}|_{c=\frac{8\beta_n}{8-e^2}} = \frac{e^2(8-\frac{512(1-\frac{8\beta_n}{8-e^2})^2}{(8+e^2+8\beta_n)^2}}{1024} > 0$. Thus, there exist two thresholds $\widehat{c_1}$ and $\widehat{c_2}$ such that $\pi_s^{ND} > \pi_s^{NC}$ $if\ c < \widehat{c_1}\ or\ c > \widehat{c_2}$.■

Proof of Proposition 4.

a. Define $\Delta p^{BDBC} = p^{BD} - p^{BC}$. Then, we have

$$\Delta p^{BDBC} = \frac{-8(c+c_b)+ce^2}{32\beta_b} + \frac{2(1+c+c_b)}{8+e^2+8\beta_n}.$$

Taking the first derivative of Δp^{BDBC} with respect to c, we have $\frac{\partial\Delta p^{BDBC}}{\partial c} = \frac{-8+e^2}{32\beta_b} + \frac{2}{8+e^2+8\beta_b} < 0$, implying that Δp^{BDBC} decreases in c. Then let $\Delta p^{BDBC}(c) = 0$, we obtain the solution $c = \frac{64c_b+8c_be^2-64\beta_b}{-64+e^4+8e^2\beta_b}$, which is in the boundaries of c when $0 < c_b < \frac{8\beta_b}{8+e^2}$.

Given the condition $c_b > \frac{8\beta_b}{8+e^2}$, Δp^{BDBC} is always negative. Thus, we have $p^{BD} > p^{BC}$ if and only if $0 < c < \frac{64c_b+8c_b e^2-64\beta_b}{-64+e^4+8e^2\beta_b}$ and $0 < c_b < \frac{8\beta_b}{8+e^2}$.

b. Define $\Delta w^{BDBC} = w^{BD} - w^{BC}$. Then, we have

$$\Delta w^{BDBC} = \frac{1}{2} - \frac{c}{2} - \frac{4(c_b-\beta_b)}{-8+e^2} + \frac{4(1+c+c_b)}{8+e^2+8\beta_b}.$$

Taking the first derivative of Δw^{BDBC} with respect to c, we have $\frac{\partial \Delta w^{BDBC}}{\partial c} = -\frac{1}{2} + \frac{4}{8+e^2+8\beta_b} < 0$, implying that Δw^{BDBC} decreases in c. Then let $\Delta w^{BDBC}(c) = 0$, we obtain the solution $c = \frac{e^4-64c_b(2+\beta_b)+8e^2(1+2\beta_b)+64(-2+\beta_b^2)}{(-8+e^2)(e^2+8\beta_b)}$, which, however, is out of the boundaries of c. Thus, $w^{BD} > w^{BC}$.

c. It is clear that ${r_s}^{BD} = {r_s}^{BC}$.

d. It is clear that ${r_i}^{BD} = {r_i}^{BC}$. ■

Proof of Proposition 5.

a. Define ${\Delta D_c}^{BDBC} = {D_c}^{BD} - {D_c}^{BC}$. Then, we have

$${\Delta D_c}^{BDBC} = -\frac{8(c+c_b)-ce^2}{32\beta_b} - \frac{2(1+c+c_b)}{8+e^2+8\beta_b}.$$

Taking the first derivative of ${\Delta D_c}^{BDBC}$ with respect to c, we have $\frac{\partial {\Delta D_c}^{BDBC}}{\partial c} = \frac{-8-e^2}{32\beta_b} - \frac{2}{8+e^2+8\beta_b} < 0$, implying that ${\Delta D_c}^{BDBC}$ decreases in c. Then let ${\Delta D_c}^{BDBC}(c) = 0$, we obtain the solution $c = \frac{64c_b+8c_b e^2-64\beta_b}{-64+e^4+8e^2\beta_b}$, which is in the boundaries of c when $0 < c_b < \frac{8\beta_b}{8+e^2}$. Given the condition $c_b > \frac{8\beta_b}{8+e^2}$, ${\Delta D_c}^{BDBC}$ is always negative. Thus, ${D_c}^{ND} > {D_c}^{NC}$ if and only if $0 < c < \frac{64c_b+8c_b e^2-64\beta_b}{-64+e^4+8e^2\beta_b}$ and $0 < c_b < \frac{8\beta_b}{8+e^2}$.

b. Define ${\Delta D_i}^{BDBC} = {D_i}^{BD} - {D_i}^{BC}$. Then, we have

$${\Delta D_i}^{BDBC} = \frac{1}{256} e \left(8 - \frac{512(1+c+c_b)^2}{(8+e^2+8\beta_b)^2} - \frac{(c(-8+e^2)+8(c_b-\beta_b))(-8c_b+c(-8+e^2)+8\beta_b}{(-8+e^2)\beta_b}\right).$$

Taking the second derivative of ${\Delta D_i}^{BDBC}$ with respect to c, we have $\frac{\partial^2 {\Delta D_c}^{BDBC}}{\partial c^2} = \frac{1}{256} e \left(\frac{-8+e^2}{\beta_b} - \frac{512}{(8+e^2+8\beta_b)^2}\right) > 0$, implying that ${\Delta D_i}^{BDBC}$ is convex in c. Then let ${\Delta D_i}^{BDBC}(c) = 0$, we obtain two solutions $\widehat{c_4} =$

$$\frac{-512(1+c_b)(-8+e^2)\beta_b}{((-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_b+64(-8+e^2)^2{\beta_b}^2)}-$$

$$\frac{2\sqrt{2}\sqrt{(-8+e^2)(8+e^2+8\beta_b)^2\left(-16c_b\beta_b\left(e^6+16e^4(1+\beta_b)-512\beta_b(1+\beta_b)+64e^2\left(-3+{\beta_b}^2\right)\right)\right)}}{((-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_b+64(-8+e^2)^2{\beta_b}^2)}-$$

$$\frac{2\sqrt{2}\sqrt{(-8+e^2)(8+e^2+8\beta_b)^2\left(8{c_b}^2\left(e^6+8e^4(1+\beta_b)-512(1+\beta_b)^2+64e^2\left(-1+\beta_b(2+\beta_b)\right)\right)\right)}}{((-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_b+64(-8+e^2)^2{\beta_b}^2)}-$$

$$\frac{2\sqrt{2}\sqrt{(-8+e^2)(8+e^2+8\beta_b)^2\left(\beta_b\left(e^8+24e^6\beta_b-4096{\beta_b}^3+64e^4\left(-3+\beta_b(-1+3\beta_b)\right)+512e^2\left(2+\beta_b(-2+(-2+\beta_b)\beta_b)\right)\right)\right)}}{((-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_b+64(-8+e^2)^2{\beta_b}^2)}$$

and $\widehat{c_5}=\frac{-512(1+c_b)(-8+e^2)\beta_b}{((-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_b+64(-8+e^2)^2{\beta_b}^2)}+$

$$\frac{2\sqrt{2}\sqrt{(-8+e^2)(8+e^2+8\beta_b)^2\left(-16c_b\beta_b\left(e^6+16e^4(1+\beta_b)-512\beta_b(1+\beta_b)+64e^2\left(-3+{\beta_b}^2\right)\right)\right)}}{((-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_b+64(-8+e^2)^2{\beta_b}^2)}+$$

$$\frac{2\sqrt{2}\sqrt{(-8+e^2)(8+e^2+8\beta_b)^2\left(8{c_b}^2\left(e^6+8e^4(1+\beta_b)-512(1+\beta_b)^2+64e^2\left(-1+\beta_b(2+\beta_b)\right)\right)\right)}}{((-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_b+64(-8+e^2)^2{\beta_b}^2)}+$$

$$\frac{2\sqrt{2}\sqrt{(-8+e^2)(8+e^2+8\beta_b)^2\left(\beta_b\left(e^8+24e^6\beta_b-4096{\beta_b}^3+64e^4\left(-3+\beta_b(-1+3\beta_b)\right)+512e^2\left(2+\beta_b(-2+(-2+\beta_b)\beta_b)\right)\right)\right)}}{((-64+e^4)^2+16(-8+e^2)(-32+e^4)\beta_b+64(-8+e^2)^2{\beta_b}^2)}$$

. It can be shown that $\widehat{c_5}$ within the boundaries of c and larger than $\widehat{c_4}$. Meanwhile, we have $\Delta {D_i}^{BDBC}\big|_{c=0}=\frac{e^2\left(8+\frac{64(c_b-\beta_b)^2}{(-8+e^2)\beta_b}-\frac{512(1+c_b)^2}{(8+e^2+8\beta_b)^2}\right)}{1024}$, which may be negative or positive; $\Delta {D_i}^{BDBC}\big|_{c=\frac{8(\beta_b-c)}{8-e^2}}=\frac{e^2\left(8-\frac{512\left(1+c_b+\frac{8(c_b-\beta_b)}{(-8+e^2)}\right)^2}{(8+e^2+8\beta_b)^2}\right)}{1024}>0$. Thus, we there exist two thresholds $\widehat{c_4}$ and $\widehat{c_5}$ such that $D_i^{BD}>D_i^{BC}$ if $c<\widehat{c_5}$ or $c>\widehat{c_4}$. ■

Proof of Proposition 6.

a. Define $\Delta {\pi_m}^{BDBC}={\pi_m}^{BD}-{\pi_m}^{BC}$. Then, we have

$$\Delta {\pi_m}^{BDBC}=\frac{1}{64}\left(\frac{8\left(-8c-8c_b+e^2+8\beta_b\right)^2}{(8+e^2+8\beta_b)^2}+\frac{\left(-8c_b+c(-8+e^2)+8\beta_b\right)^2}{(-8+e^2)\beta_b}\right).$$

Taking the second derivative of $\Delta {\pi_m}^{BDBC}$ with respect to c, we have $\frac{\partial^2\Delta {\pi_m}^{BDBC}}{\partial c^2}=\frac{1}{64}\left(\frac{-8+e^2}{\beta_b}+\frac{512}{(8+e^2+8\beta_b)^2}\right)<0$, implying that $\Delta {\pi_m}^{BDBC}$ is concave in c. Then let $\Delta {\pi_m}^{BDBC}(c)=0$, we can obtain two solutions. The first one is $\widehat{c_6}=$

$$\frac{-512\beta_b+8c_b\left(e^4+16e^2(1+\beta_b)+64\left(1+\beta_b+{\beta_b}^2\right)\right)}{\left(e^6+8e^4(1+2\beta_b)+64e^2\left(-1+{\beta_b}^2\right)-512\left(1+\beta_b+{\beta_b}^2\right)\right)}-$$

$$\frac{2\beta_b(8+e^2+8\beta_b)\left(8\sqrt{2}\sqrt{-\frac{e^4(-8-8c_b+e^2+8\beta_b)^2}{(-8+e^2)\beta_b(8+e^2+8\beta_b)^2}}e^2\left(-4+\sqrt{2}\sqrt{-\frac{e^4(-8-8c_b+e^2+8\beta_b)^2}{(-8+e^2)\beta_b(8+e^2+8\beta_b)^2}}\right)+8\beta_b\left(-4+\sqrt{2}\sqrt{-\frac{e^4(-8-8c_b+e^2+8\beta_b)^2}{(-8+e^2)\beta_b(8+e^2+8\beta_b)^2}}\right)\right)}{\left(e^6+8e^4(1+2\beta_b)+64e^2\left(-1+{\beta_b}^2\right)-512\left(1+\beta_b+{\beta_b}^2\right)\right)}$$

, which is in the boundaries of c. The second one is $\frac{-512\beta_b+8c_b\left(e^4+16e^2(1+\beta_b)+64\left(1+\beta_b+{\beta_b}^2\right)\right)}{\left(e^6+8e^4(1+2\beta_b)+64e^2\left(-1+{\beta_b}^2\right)-512\left(1+\beta_b+{\beta_b}^2\right)\right)}+$

$$\frac{2\beta_b(8+e^2+8\beta_b)\left(8\sqrt{2}\sqrt{-\frac{e^4(-8-8c_b+e^2+8\beta_b)^2}{(-8+e^2)\beta_b(8+e^2+8\beta_b)^2}}e^2\left(-4+\sqrt{2}\sqrt{-\frac{e^4(-8-8c_b+e^2+8\beta_b)^2}{(-8+e^2)\beta_b(8+e^2+8\beta_b)^2}}\right)+8\beta_b\left(-4+\sqrt{2}\sqrt{-\frac{e^4(-8-8c_b+e^2+8\beta_b)^2}{(-8+e^2)\beta_b(8+e^2+8\beta_b)^2}}\right)\right)}{\left(e^6+8e^4(1+2\beta_b)+64e^2\left(-1+{\beta_b}^2\right)-512\left(1+\beta_b+{\beta_b}^2\right)\right)}$$

, which, however, is out of the boundaries of c. Thus, $\pi_m^{BD} > \pi_m^{BC}$ if and only if $c > \widehat{c_6}$.

b. Define $\Delta{\pi_c}^{BDBC} = {\pi_c}^{BD} - {\pi_c}^{BC}$. Then, we have

$$\Delta{\pi_c}^{BDBC} = \frac{\beta_b(-8c-8c_b+e^2+8\beta_b)^2}{16(8+e^2+8\beta_b)^2} - \frac{\left(-8c_b+c(-8+e^2)+8\beta_b\right)^2}{1024\beta_b}.$$

Taking the second derivative of $\Delta{\pi_c}^{BDBC}$ with respect to c, we have $\frac{\partial^2\Delta{\pi_c}^{BDBC}}{\partial c^2} = -\frac{(-8+e^2)^2}{512\beta_b} + \frac{8\beta_b}{(8+e^2+8\beta_b)^2} < 0$, implying that $\Delta{\pi_c}^{BDBC}$ is concave in c. Then let $\Delta{\pi_c}^{BDBC}(c) = 0$, we obtain two solutions $\frac{64c_b+8c_be^2-64\beta_b}{-64+e^4+8e^2\beta_b}$ and $-\frac{8(-2\beta_b(4+e^2+8\beta_b)+c_b(8+e^2+16\beta_b))}{-64+e^4+8(-16+e^2)\beta_b}$. However, only $\frac{64c_b+8c_be^2-64\beta_b}{-64+e^4+8e^2\beta_b}$ is in the boundaries of c. Thus, ${\pi_c}^{BD} > {\pi_c}^{BC}$ if and only if $c > \frac{64c_b+8c_be^2-64\beta_b}{-64+e^4+8e^2\beta_b}$.

c. Define $\Delta{\pi_s}^{BDBC} = {\pi_s}^{BD} - {\pi_s}^{BC}$. Then, we have

$$\Delta{\pi_s}^{BDBC} = \frac{e^2\left(8-\frac{512(1+c+c_b)^2}{(8+e^2+8\beta_b)^2}-\frac{(c(-8+e^2)+8(c_b-\beta_b))(-8c_b+c(-8+e^2)+8\beta_b}{(-8+e^2)\beta_b}\right)}{1024}.$$

Taking the second derivative of $\Delta{\pi_s}^{BDBC}$ with respect to c, we have $\frac{\partial^2\Delta{\pi_s}^{BDBC}}{\partial c^2} = \frac{e^2\left(\frac{8-e^2}{\beta_b}-\frac{512}{(8+e^2+8\beta_b)^2}\right)}{1024} > 0$, implying that $\Delta{\pi_s}^{BDBC}$ is convex in c. Then let $\Delta{\pi_s}^{BDBC}(c) = 0$, we obtain two solutions $\widehat{c_4}$ and $\widehat{c_5}$. It can be shown that $\widehat{c_5}$ is in the boundaries of c and larger than $\widehat{c_4}$. Meanwhile, we have $\Delta{\pi_s}^{BDBC}|_{c=0} = \frac{e^2\left(8+\frac{64(c_b-\beta_b)^2}{(-8+e^2)\beta_b}-\frac{512(1+c_b)^2}{(8+e^2+8\beta_b)^2}\right)}{1024}$, which may be negative or positive; $\Delta{\pi_s}^{BDBC}|_{c=\frac{8(\beta_b-c)}{8-e^2}} = \frac{e^2(8-\frac{512\left(1+c_b+\frac{8(c_b-\beta_b)}{(-8+e^2)}\right)^2}{(8+e^2+8\beta_b)^2}}{1024} > 0$. Thus, there exist two thresholds $\widehat{c_4}$ and $\widehat{c_5}$ such that $\pi_s^{BD} > \pi_s^{BC}$ if $c < \widehat{c_4}$ or $c > \widehat{c_5}$. ■

Proof of Proposition 7.

(1) In the decentralized system

a. Define $\Delta p^{NDBD} = p^{ND} - p^{BD}$. Then, we have

$$\Delta p^{NDBD} = \frac{2(1+c)}{8+e^2+8\beta_n} - \frac{2(1+c+c_b)}{8+e^2+8\beta_b}.$$

Taking the first derivative of Δp^{NDBD} with respect to c_b, we have $\frac{\partial \Delta p^{NDBD}}{\partial c_b} = -\frac{2}{8+e^2+8\beta_b} < 0$, implying that Δp^{NDBD} decreases in c_b. Then we let $\Delta p^{NDBD}(c_b) = 0$, we can obtain the solution $c_b = \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$, which is in the boundaries of c_b. Thus, $p^{ND} > p^{BD}$ if and only if $0 < c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$.

b. Define $\Delta w^{NDBD} = w^{ND} - w^{BD}$. Then, we have

$$\Delta w^{NDBD} = \frac{4(1+c)}{8+e^2+8\beta_n} - \frac{4(1+c+c_b)}{8+e^2+8\beta_b}.$$

Taking the first derivative of Δw^{NDBD} with respect to c_b, we have $\frac{\partial \Delta w^{NDBD}}{\partial c_b} = -\frac{4}{8+e^2+8\beta_b} < 0$, implying that Δw^{NDBD} decreases in c_b. Then let $\Delta w^{NDBD}(c_b) = 0$, we obtain the solution $c_b = \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$, which is in the boundaries of c_b. Thus, $w^{ND} > w^{BD}$ if and only if $0 < c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$.

c. Define $\Delta\theta^{NDBD} = \theta^{ND} - \theta^{BD}$. Then, we have

$$\Delta\theta^{NDBD} = \frac{4(1+c)}{8+e^2+8\beta_n} - \frac{4(1+c+c_b)}{8+e^2+8\beta_b}.$$

Taking the first derivative of $\Delta\theta^{NDBD}$ with respect to c_b, we have $\frac{\partial \Delta\theta^{NDBD}}{\partial c_b} = -\frac{4}{8+e^2+8\beta_b} < 0$, implying that $\Delta\theta^{NDBD}$ decreases in c_b. Then let $\Delta\theta^{NDBD}(c_b) = 0$, we obtain the solution $c_b = \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$, which is in the boundaries of c_b. Thus, we have $\theta^{ND} > \theta^{BD}$ if and only if $0 < c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$.

d. Define $\Delta {r_s}^{NDBD} = {r_s}^{ND} - {r_s}^{BD}$. Then, we have $\Delta {r_s}^{NDBD} = \frac{e(-\beta_n+\beta_b)}{2\beta_n\beta_b}$. It is clear that ${r_s}^{ND} > {r_s}^{BD}$ due to $\beta_n < \beta_b$.

e. Define $\Delta {r_i}^{NDBD} = {r_i}^{ND} - {r_i}^{NC}$. Then, we have $\Delta {r_i}^{NDBD} = \frac{e(-\beta_n+\beta_b)}{4\beta_n\beta_b}$. It is clear that

$r_i^{ND} > r_i^{BD}$ due to $\beta_n < \beta_b$.

(2) In the centralized system

a. Define $\Delta p^{NCBC} = p^{NC} - p^{BC}$. Then, we have

$$\Delta p^{NCBC} = \frac{-8c_b\beta_n + c(-8+e^2)(\beta_n - \beta_b)}{32\beta_n\beta_b}.$$

Taking the first derivative of Δp^{NCBC} with respect to c_b, we have $\frac{\partial \Delta p^{NCBC}}{\partial c_b} = -\frac{1}{4\beta_b} < 0$, implying that Δp^{NCBC} decreases in c_b. Then let $\Delta p^{NCBC}(c_b) = 0$, we obtain the solution $c_b = \frac{-8c\beta_n + ce^2\beta_n + 8c\beta_b - ce^2\beta_b}{8\beta_n}$, which is in the boundaries of c_b. Thus, we have $p^{NC} > p^{BC}$ if and only if $0 < c_b < \frac{-8c\beta_n + ce^2\beta_n + 8c\beta_b - ce^2\beta_b}{8\beta_n}$.

b. Define $\Delta w^{NCBC} = w^{NC} - w^{BC}$. Then, we have

$$\Delta w^{NCBC} = -\frac{4(c_b + \beta_n - \beta_b)}{-8+e^2}.$$

Taking the first derivative of Δw^{NCBC} with respect to c_b, we have $\frac{\partial \Delta w^{NCBC}}{\partial c_b} = -\frac{4}{8+e^2} < 0$, implying that Δw^{NCBC} decreases in c_b. Then let $\Delta w^{NCBC}(c_b) = 0$, we obtain the solution $c_b = -\beta_n + \beta_b$, which is in the boundaries of c_b. Thus, we have $w^{NC} > w^{BC}$ if and only if $0 < c_b < -\beta_n + \beta_b$.

c. Define $\Delta r_s^{NCBC} = r_s^{NC} - r_s^{BC}$. Then, we have $\Delta r_s^{NCBC} = \frac{e(-\beta_n + \beta_b)}{2\beta_n\beta_b}$. It is clear that $r_s^{NC} > r_s^{BC}$ due to $\beta_n < \beta_b$.

d. Define $\Delta r_i^{NCBC} = r_i^{ND} - r_i^{NC}$. Then, we have $\Delta r_i^{NCBC} = \frac{e(-\beta_n + \beta_b)}{4\beta_n\beta_b}$. It is clear that $r_i^{NC} > r_i^{BC}$ due to $\beta_n < \beta_b$. ■

Proof of Proposition 8.

(1) In the decentralized system

a. Define $\Delta D_c^{NDBD} = D_c^{ND} - D_c^{BD}$. Then, we have

$$\Delta D_c^{NDBD} = -\frac{2(1+c)}{8+e^2+8\beta_n} + \frac{2(1+c+c_b)}{8+e^2+8\beta_b}.$$

Taking the first derivative of ΔD_c^{NDBD} with respect to c_b, we have $\frac{\partial \Delta D_c^{NDBD}}{\partial c_b} = \frac{2}{8+e^2+8\beta_b} > 0$, implying that ΔD_c^{NDBD} increases in c. Then let $\Delta D_c^{NDBD}(c_b) = 0$, we obtain the solution $c_b = \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$, which is in the boundaries of c_b. Thus, ${D_c}^{ND} > {D_c}^{BD}$ if and only if $0 < c_b < \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$.

b. Define $\Delta {D_i}^{NDBD} = {D_i}^{ND} - {D_i}^{BD}$. Then, we have

$$\Delta {D_i}^{NDBD} = -\frac{2(1+c)^2 e}{(8+e^2+8\beta_n)^2} + \frac{2(1+c+c_b)^2 e}{(8+e^2+8\beta_b)^2}.$$

Taking the second derivative with respect to $\Delta {D_i}^{NDBD}$, we have $\frac{\partial^2 \Delta {D_i}^{NDBD}}{\partial {c_b}^2} = \frac{4e}{(8+e^2+8\beta_b)^2} > 0$, implying that $\Delta {D_i}^{NDBD}$ is convex in c_b. Then let $\Delta {D_i}^{NDBD}(c_b) = 0$, we obtain two solutions. The first one is $-\frac{2(1+c)\left(e^2+4(2+\beta_n+\beta_b)\right)}{8+e^2+8\beta_n}$, which, however, is negative and certainly out of the boundaries of c_b. The second one is $\frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$, which is in the boundaries of c_b. Thus, ${D_i}^{ND} > {D_i}^{BD}$ if and only if $c_b > \frac{-8\beta_n - 8c\beta_n + 8\beta_b + 8c\beta_b}{8+e^2+8\beta_n}$.

(2) In the decentralized system

a. Define $\Delta {D_c}^{NCBC} = {D_c}^{NC} - {D_c}^{BC}$. Then, we have

$$\Delta {D_c}^{NCBC} = \frac{8c_b\beta_n - c(-8+e^2)(\beta_n - \beta_b)}{32\beta_n\beta_b}.$$

Taking the first derivative of $\Delta {D_c}^{NCBC}$ with respect to c_b, we have $\frac{\partial \Delta {D_c}^{NCBC}}{\partial c_b} = \frac{1}{4\beta_b} > 0$, implying that $\Delta {D_c}^{NCBC}$ increases in c. Then let $\Delta {D_c}^{NCBC}(c_b) = 0$, we obtain the solution $c_b = \frac{-8c\beta_n + ce^2\beta_n + 8c\beta_b - ce^2\beta_b}{8\beta_n}$, which is in the boundaries of c_b. Thus, ${D_c}^{NC} > {D_c}^{BC}$ needs to be met $0 < c_b < \frac{-8c\beta_n + ce^2\beta_n + 8c\beta_b - ce^2\beta_b}{8\beta_n}$.

b. Define $\Delta {D_i}^{NCBC} = {D_i}^{NC} - {D_i}^{BC}$. Then, we have

$$\Delta {D_i}^{NCBC} = \frac{e\left(-c^2(-8+e^2)^2(\beta_n-\beta_b) + 64\beta_n\left({c_b}^2 - (2c_b+\beta_n)\beta_b + {\beta_b}^2\right)\right)}{256(-8+e^2)\beta_n\beta_b}.$$

Taking the second derivative of $\Delta {D_i}^{NCBC}$ with respect to c_b, we have $\frac{\partial^2 \Delta {D_i}^{NCBC}}{\partial {c_b}^2} = \frac{e}{4(-8+e^2)\beta_b} < 0$, implying that $\Delta {D_i}^{NCBC}$ is concave in c_b. Then let $\Delta {D_i}^{NCBC}(c_b) = 0$, we obtain two solutions. The first one is $\beta_b + \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n-\beta_b) + 64\beta_n^3\beta_b}}{8\beta_n}$, which is larger than out of the boundaries of c_b. The second one is $\beta_b - \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n-\beta_b) + 64\beta_n^3\beta_b}}{8\beta_n}$, which is in the boundaries of c_b. Thus, $D_i^{NC} > D_i^{BC}$ if and only if $c_b > \beta_b - \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n-\beta_b)+64\beta_n^3\beta_b}}{8\beta_n}$. ■

Proof of Proposition 9.

(1) In the decentralized system

a. Define $\Delta\pi_m{}^{NDBD} = \pi_m{}^{ND} - \pi_m{}^{BD}$. Then, we have

$$\Delta\pi_m{}^{NDBD} = \frac{1}{8}\left(\frac{8\left(-8c+e^2+8\beta_n\right)^2}{(8+e^2+8\beta_n)^2} - \frac{\left(-8c-8c_b+e^2+8\beta_b\right)^2}{(8+e^2+8\beta_b)^2}\right).$$

Taking the second derivative of $\Delta\pi_m{}^{NDBD}$ with respect to c_b, we have $\frac{\partial^2\Delta\pi_m{}^{NDBD}}{\partial c_b{}^2} = -\frac{16}{(8+e^2+8\beta_b)^2} < 0$, implying that $\Delta\pi_m{}^{NDBD}$ is concave in c_b. Then let $\Delta\pi_m{}^{NDBD}(c_b) = 0$, we obtain two solutions: $\frac{-8\beta_n-8c\beta_n+8\beta_b+8c\beta_b}{8+e^2+8\beta_n}$ and $-\frac{e^4+8e^2(1+\beta_n+\beta_b)+32(\beta_n+\beta_b+2\beta_n\beta_b)-8c\left(e^2+4(2+\beta_n+\beta_b)\right)}{4(8+e^2+8\beta_n)}$. However, only $\frac{-8\beta_n-8c\beta_n+8\beta_b+8c\beta_b}{8+e^2+8\beta_n}$ is in the boundaries of c_b. Thus, $\pi_m{}^{ND} > \pi_m{}^{BD}$ if and only if $c_b > \frac{-8\beta_n-8c\beta_n+8\beta_b+8c\beta_b}{8+e^2+8\beta_n}$.

b. Define $\Delta\pi_c{}^{NDBD} = \pi_c{}^{ND} - \pi_c{}^{BD}$. Then, we have

$$\Delta\pi_c{}^{NDBD} = \frac{1}{16}\left(\frac{\beta_n\left(-8c+e^2+8\beta_n\right)^2}{(8+e^2+8\beta_n)^2} - \frac{\beta_b\left(-8c-8c_b+e^2+8\beta_b\right)^2}{(8+e^2+8\beta_b)^2}\right).$$

Taking the second derivative of $\Delta\pi_c{}^{NDBD}$ with respect to c_b, we have $\frac{\partial^2\Delta\pi_c{}^{NDBD}}{\partial c_b{}^2} = -\frac{4\beta_b}{(8+e^2+8\beta_b)^2} < 0$, implying that $\Delta\pi_c{}^{NDBD}$ is concave in c_b. Then let $\Delta\pi_c{}^{NDBD}(c_b) = 0$, we obtain two solutions: $\widehat{c_{b1}} = -\frac{8c\beta_b+64\sqrt{\frac{\beta_n\left(-8c+e^2+8\beta_n\right)^2\beta_b}{\left(8+e^2+8\beta_n\right)^2\left(8+e^2+8\beta_b\right)^2}}+\left(e^2+8\beta_b\right)\left(\left(16+e^2\right)\sqrt{\frac{\beta_n\left(-8c+e^2+8\beta_n\right)^2\beta_b}{\left(8+e^2+8\beta_n\right)^2\left(8+e^2+8\beta_b\right)^2}}+\beta_b\left(-1+8\sqrt{\frac{\beta_n\left(-8c+e^2+8\beta_n\right)^2\beta_b}{\left(8+e^2+8\beta_n\right)^2\left(8+e^2+8\beta_b\right)^2}}\right)\right)}{8\beta_b}$

and

$-\frac{8c\beta_b-64\sqrt{\frac{\beta_n\left(-8c+e^2+8\beta_n\right)^2\beta_b}{\left(8+e^2+8\beta_n\right)^2\left(8+e^2+8\beta_b\right)^2}}+\left(e^2+8\beta_b\right)\left(\left(16+e^2\right)\sqrt{\frac{\beta_n\left(-8c+e^2+8\beta_n\right)^2\beta_b}{\left(8+e^2+8\beta_n\right)^2\left(8+e^2+8\beta_b\right)^2}}+\beta_b\left(-1+8\sqrt{\frac{\beta_n\left(-8c+e^2+8\beta_n\right)^2\beta_b}{\left(8+e^2+8\beta_n\right)^2\left(8+e^2+8\beta_b\right)^2}}\right)\right)}{8\beta_b}$

. However,

only $\widehat{c_{b1}}$ is in the boundaries of c_b. Thus, $\pi_c{}^{ND} > \pi_c{}^{BD}$ if and only if $c > \widehat{c_{b1}}$.

c. Define $\Delta\pi_s{}^{NDBD} = \pi_s{}^{ND} - \pi_s{}^{BD}$. Then, we have:

$$\Delta\pi_s^{NDBD} = \frac{1}{2}e^2\left(-\frac{(1+c)^2}{(8+e^2+8\beta_n)^2} + \frac{(1+c+c_b)^2}{(8+e^2+8\beta_b)^2}\right).$$

Taking the second derivative of $\Delta\pi_s^{NDBD}$ with respect to c_b, we have $\frac{\partial^2\Delta\pi_s^{NDBD}}{\partial {c_b}^2} = \frac{e^2}{(8+e^2+8\beta_b)^2} > 0$, implying that $\Delta\pi_s^{NDBD}$ is convex in c_b. Then let $\Delta\pi_s^{NDBD}(c_b) = 0$, we obtain two solutions: $\frac{-8\beta_n-8c\beta_n+8\beta_b+8c\beta_b}{8+e^2+8\beta_n}$ and $-\frac{2(1+c)\left(e^2+4(2+\beta_n+\beta_b)\right)}{8+e^2+8\beta_n}$. However, only $\frac{-8\beta_n-8c\beta_n+8\beta_b+8c\beta_b}{8+e^2+8\beta_n}$ is in the boundaries of c_b. Thus, $\pi_s^{ND} > \pi_s^{BD}$ if and only if $c_b > \frac{-8\beta_n-8c\beta_n+8\beta_b+8c\beta_b}{8+e^2+8\beta_n}$.

d. Define $\Delta\pi_o^{NDBD} = \pi_o^{ND} - \pi_o^{BD}$. Then, we have

$$\Delta\pi_o^{NDBD} = \frac{1}{64}\left(-\frac{\left(-8c+e^2+8\beta_n\right)^2}{8+e^2+8\beta_n} - \frac{\left(-8c-8c_b+e^2+8\beta_b\right)^2}{8+e^2+8\beta_b}\right).$$

Taking the second derivative of $\Delta\pi_o^{NDBD}$ with respect to c_b, we have $\frac{\partial^2\Delta\pi_o^{NDBD}}{\partial {c_b}^2} = -\frac{2}{8+e^2+8\beta_b} < 0$, implying that $\Delta\pi_o^{NDBD}$ is concave in c_b. Then let $\Delta\pi_o^{NDBD}(c_b) = 0$, we obtain two solutions $\widehat{c_{b2}} = -c + \beta_b - \sqrt{\frac{(-8c+e^2+8\beta_n)^2}{(8+e^2+8\beta_n)(8+e^2+8\beta_b)}} - \beta_b\sqrt{\frac{(-8c+e^2+8\beta_n)^2}{(8+e^2+8\beta_n)(8+e^2+8\beta_b)}} - \frac{1}{8}e^2(-1 + \sqrt{\frac{(-8c+e^2+8\beta_n)^2}{(8+e^2+8\beta_n)(8+e^2+8\beta_b)}})$ and $-c + \beta_b - \sqrt{\frac{(-8c+e^2+8\beta_n)^2}{(8+e^2+8\beta_n)(8+e^2+8\beta_b)}} + \beta_b\sqrt{\frac{(-8c+e^2+8\beta_n)^2}{(8+e^2+8\beta_n)(8+e^2+8\beta_b)}} - \frac{1}{8}e^2(-1 + \sqrt{\frac{(-8c+e^2+8\beta_n)^2}{(8+e^2+8\beta_n)(8+e^2+8\beta_b)}})$. However, only $\widehat{c_{b2}}$ is in the boundaries of c_b. Thus, $\pi_o^{ND} < \pi_o^{BD}$ if and only if $0 < c_b < \widehat{c_{b2}}$.

(2) In the centralized system

a. Define $\Delta\pi_m^{NCBC} = \pi_m^{NC} - \pi_m^{BC}$. Then, we have

$$\Delta\pi_m^{NCBC} = \frac{-\frac{\left(c(-8+e^2)+8\beta_n\right)^2}{\beta_n} + \frac{\left(-8c_b+c(-8+e^2)+8\beta_b\right)^2}{\beta_b}}{64(-8+e^2)}.$$

Taking the second derivative of $\Delta\pi_m^{NCBC}$ with respect to c_b, we have $\frac{\partial^2\Delta\pi_m^{NCBC}}{\partial {c_b}^2} = -\frac{1}{(-8+e^2)\beta_b} < 0$, implying that $\Delta\pi_m^{NCBC}$ is concave in c_b. Then let $\Delta\pi_m^{NCBC}(c_b) = 0$, we have two solutions: $\widehat{c_{b3}} = \frac{1}{8}c(-8+e^2) + \beta_b - \frac{\sqrt{\beta_n(c(-8+e^2)+8\beta_n)^2\beta_b}}{8\beta_n}$ and $\frac{1}{8}c(-8+e^2) + \beta_b + \frac{\sqrt{\beta_n(c(-8+e^2)+8\beta_n)^2\beta_b}}{8\beta_n}$. However, only $\widehat{c_{b3}}$ is in the boundaries of c_b. Thus, $\pi_m^{NC} > \pi_m^{BC}$ if and only if $c_b > \widehat{c_{b3}}$.

b. Define $\Delta\pi_c{}^{NCBC} = \pi_c{}^{NC} - \pi_c{}^{BC}$. Then, we have

$$\Delta\pi_c{}^{NCBC} = \frac{-\frac{\left(c(-8+e^2)+8\beta_n\right)^2}{\beta_n} - \frac{\left(-8c_b+c(-8+e^2)+8\beta_b\right)^2}{\beta_b}}{1024}.$$

Taking the second derivative of $\Delta\pi_c{}^{NCBC}$ with respect to c_b, we have $\frac{\partial^2\Delta\pi_c{}^{NCBC}}{\partial c_b{}^2} = -\frac{1}{16\beta_b} < 0$, implying that $\Delta\pi_c{}^{NCBC}$ is concave in c_b. Let $\Delta\pi_c{}^{NCBC}(c_b) = 0$, we obtain two solutions: $\widehat{c_{b3}} = \frac{1}{8}c(-8+e^2) + \beta_b - \frac{\sqrt{\beta_n(c(-8+e^2)+8\beta_n)^2\beta_b}}{8\beta_n}$ and $\frac{1}{8}c(-8+e^2) + \beta_b + \frac{\sqrt{\beta_n(c(-8+e^2)+8\beta_n)^2\beta_b}}{8\beta_n}$. However, only $\widehat{c_{b3}}$ is in the boundaries of c_b. Thus, $\pi_c{}^{NC} > \pi_c{}^{BC}$ if and only if $c_b > \widehat{c_{b3}}$.

c. Define $\Delta\pi_s{}^{NCBC} = \pi_s{}^{NC} - \pi_s{}^{BC}$. Then, we have

$$\Delta\pi_s{}^{NCBC} = \frac{e^2\left(-c^2(-8+e^2)^2(\beta_n-\beta_b)+64\beta_n\left(c_b{}^2-(2c_b+\beta_n)\beta_b+\beta_b{}^2\right)\right)}{1024(-8+e^2)\beta_n\beta_b}.$$

Taking the second derivative of $\Delta\pi_s{}^{NCBC}$ with respect to c_b, we have $\frac{\partial^2\Delta\pi_s{}^{NCBC}}{\partial c_b{}^2} = \frac{e^2}{16(-8+e^2)\beta_b} < 0$, implying that $\Delta\pi_s{}^{NCBC}$ is concave in c_b. Then let $\Delta\pi_s{}^{NCBC}(c_b) = 0$, we obtain two solutions: $\beta_b - \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n-\beta_b)+64\beta_n^3\beta_b}}{8\beta_n}$ and $\beta_b + \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n-\beta_b)+64\beta_n^3\beta_b}}{8\beta_n}$. However, only $\beta_b - \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n-\beta_b)+64\beta_n^3\beta_b}}{8\beta_n}$ is in the boundaries of c_b. Thus, $\pi_s{}^{NC} > \pi_s{}^{BC}$ if and only if $c_b > \beta_b - \frac{\sqrt{c^2(-8+e^2)^2\beta_n(\beta_n-\beta_b)+64\beta_n^3\beta_b}}{8\beta_n}$. ■