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Incentive alignment for blockchain adoption in medicine supply chains

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ABSTRACT

In recent years, blockchain technology has been increasingly adopted in OTC medicine supply chains, enabling customers to track the entire process from raw material purchasing to finished medicine distribution. This improves the brand image and hence expands the market. With the use of blockchain, information transparency can be achieved because data are stored immutably and safely in a distributed database that is accessible by all supply chain members. However, will the incentives for supply chain members to participate in blockchain for larger-scale demand come at the cost of information disclosure? In this paper, to investigate the supply chain members' incentive alignment opportunities towards the adoption of blockchain technology, we consider a two-stage supply chain comprising two medicine manufacturers and a common retailer that has more accurate demand information than the manufacturers have. We find that, interestingly, the retailer has incentives to participate in blockchain when the manufacturers' competition is mild and the demand variance is low. We further investigate the impact of blockchain on total surplus and customer surplus and find that the adoption of blockchain always benefits customers and society; therefore, blockchain can be particularly useful for social goods such as OTC medicine.

1. Introduction

Currently, similar to daily goods, many over-the-counter (OTC) medicines/drugs can be sold without a doctor's prescription. Take the medicine for cold and fever as an example. One can buy medicines, such as *Advil, Vicks DayQuil/NyQuil, Tylenol Extra Strength Caplets, Ganmaoling granules*, and *Ibuprofen,* directly at nearby chain pharmacies. As a result, many pharmaceutical retail giants have emerged that procure a wide variety of medicines from different manufacturers and then resell the medicines to customers. For instance, in China, 360kad (www.360kad.com) is a large online pharmacy that has contracted with more than 2000 medicine manufacturers and sells approximately 4,000 OTC medicines. Almost twenty brands of *Pediatric Paracetamol Artificial Cow-bezoar and Chlorphenamine Maleate Granules*, a common medicine for cold and fever in children, are sold on 360kad online pharmacies, including the famous brands Sunflower and 999. Similar examples can be observed for Walmart, Walgreen pharmacy, CVS Health and UK Meds. Customers may buy *Multi-Symptom Cold & Flu* produced by Advil or Nyquil at Walmart.

Generally, there are different levels of demand variance for different medicines, and the demand for the famous manufacturers' medicines can fluctuate less due to the customers' trust and predictable purchasing behaviors (Zarantonello and Schmitt 2010, Niu

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et al. 2019a). However, in recent years, it has been reported that even famous brands, such as Baxter International Inc. in the US[1] and Fuxing Pharmaceutical Co. Ltd. in China[2], can be accused of quality issues (Chicago Tribune 2016, FDA.com 2012). The reason is that medicine is used for health issues; therefore, customers are always sensitive to medicine quality. To solve this problem, we observe that an increasing number of medicine manufacturers have adopted blockchain technology, based on which all the production information (e.g., raw material supply information, production information, quality control and inspection information, logistics information) is written on blockchain platforms, such as Ethereum[3] (Harvard Business Review 2017). All the supply chain members (even the customers) are allowed to access the information via ERP or APP, and no one can tamper with the records once they are stored in the blockchain network (Choi 2019, Babich and Hilary 2020, Choi et al. 2020a). Clearly, blockchain can be useful for improving the medicine manufacturers' brand image and can hence expand the market because the supply chain members are now capable of tracking all business transactions and ethical and responsible medicine production can be guaranteed (Forbes[4] 2018, Harvard Business Report[5] 2020). Blockchain is also beneficial for pharmaceutical manufacturers, such as AbbVie, Genentech, and Pfizer[6] (Cbinsight 2018), as it has led to an enlarged demand size and has improved customer trust. Under the Pilot Project Program proposed by IBM[7] (IBM 2020), industry leaders Merck (a medicine manufacturer) and Walmart (a pharmaceutical retailer) have even made and announced a collaboration example demonstrating how to verify and track the medicines' quality. Some related practices of using blockchain in medicine supply chains are shown in Table 1.

Having said that, is blockchain always beneficial? Taking a close look at the pharmaceutical retailer's tradeoffs, we find that the answer is: it depends. According to blockchain requirements, the business partners in a supply chain need to share and agree upon key information[8] (EY 2017). According to Deloitte (2017), blockchain offers opportunities to solve the problems of trust and information sharing. Blockchain makes information sharing among stakeholders a reality[9]. In practice, IBM offers a transparent supply chain with a blockchain in which suppliers can improve their forecasting ability with a more accurate demand signal, because the retailer records whether a product has been sold into the blockchain system and suppliers can trace inventory information in near real time (IBM 2020). Then, information from each stage is written in the blockchain, and every supply chain member has a copy. In practice, it is the retailer that has more accurate demand information than the manufacturers (Özer and Wei 2006, Xue et al. 2017); therefore, the pharmaceutical retailer's benefits are established at the cost of demand information sharing[10] (Deloitte 2018).

Therefore, if the pharmaceutical retailer does not have incentives to participate in blockchain, then the blockchain system will become ill-behaved. If the retailer refuses to join the blockchain, there are only pharmaceutical manufacturers on the blockchain. Since blockchain is a distributed ledger that can record information from different sources, the blockchain with the information only from the manufacturers is similar to an offline database. According to the report of the Harvard Business Review (HBR 2017), complexity is a key dimension of blockchain, and a blockchain with only one participant is of little use. In this case, customers cannot obtain the production information of drugs, and manufacturers cannot obtain detailed demand information. In addition, in the adoption of blockchain in Walmart, Brigid McDermott, the Vice President of Blockchain Business Development for IBM, warned that if only a retailer in the ecosystem participates in the blockchain, a safety solution would not work[11] (Digital Initiative 2017). As a result, the blockchain would be ineffective and ill-behaved.

In contrast, blockchain would be more worthwhile when more business partners have signed on it; that is, when the retailer and manufacturer in the supply chain have incentive alignment for blockchain adoption, they are capable of sharing information through blockchain technology. The manufacturers record the product information so that customers can obtain detailed information and have more trust in drugs. On the other hand, the manufacturers can learn more about the demand, and they are better able to schedule production. As a result, the blockchain including the total supply chain is a valid one. Several research questions naturally arise: (1) Under what conditions will all supply chain members achieve incentive alignment towards the adoption of blockchain? (2) Is blockchain beneficial to customers and for the total surplus?

To answer the aforementioned questions, we build a two-stage supply chain model consisting of two medicine manufacturers and a common pharmaceutical retailer. In the pharmaceutical industry, competing with each other, many pharmaceutical manufacturers produce substitutable medicine or healthcare products, while pharmaceutical retailers are often regional monopolies. Take Walmart as an example; in its stores, there are dozens of brands of medicines against cold and cough, including top brands, such as Advil and Vicks. Similar examples can be seen in Walgreens and CVS Health pharmacies. It is a common phenomenon that competition among manufacturers is more intense than that among retailers in the pharmaceutical industry. Therefore, in this paper, to capture the typical industrial practice in the pharmaceutical industry, we assume two competing upstream manufacturers and one monopolistic retailer. The manufacturers' medicines have similar curative effects, so they are substitutable, although their demand variance levels are

[1] https://www.chicagotribune.com (accessed 27 July 2020).
[2] https://www.fda.gov (accessed 27 July 2020).
[3] https://hbr.org/2017/01/the-truth-about-blockchain (accessed 27 July 2020).
[4] https://www.forbes.com (accessed 27 July 2020).
[5] https://hbr.org (accessed 27 July 2020).
[6] https://www.cbinsights.com (accessed 27 July 2020).
[7] https://www.ibm.com (accessed 27 July 2020).
[8] https://www.ey.com (accessed 27 July 2020).
[9] https://www2.deloitte.com (accessed 11 November 2020)
[10] https://www2.deloitte.com (accessed 27 July 2020).
[11] https://digital.hbs.edu (accessed 11 November 2020)

Table 1
Business practice of blockchain adoption.

Companies/ Organizations	The practice of blockchain adoption
MediLedger Project	A project in which pharmaceutical manufacturers, such as GSK, Pfizer, Novartis, and pharmaceutical retailers, such as Walgreens and Walmart, use blockchain to track the medicines.
UKMeds	Blockchain is used for the customers' data management and for medicines' tracing.
JD Health	Blockchain enables supply chain transparency and traceability.

different because of brand image and customer recognition issues. The pharmaceutical retailer is more familiar with the market; therefore, it has accurate demand information, which facilitates its generation of more profits in the medicine reselling business. We consider two scenarios: (1) Scenario NB, in which blockchain is not adopted, and (2) Scenario AB, in which the supply chain members achieve incentive alignment to adopt blockchain. We formulate blockchain's two features: *information transparency* and *quality trust*. The former requires information sharing, especially the retailer's demand information sharing, while the latter helps gain customers' trust and improve the brand image. Our focus is to determine whether incentive alignment opportunities among the competing manufacturers and the pharmaceutical retailer can be identified, without which it is impossible to adopt blockchain. The main findings are summarized as follows.

First, we investigate the wholesale price and quantity decisions in two scenarios. We find that the equilibrium wholesale prices and quantities are both higher in scenario AB than in scenario NB. This is because the adoption of blockchain improves brand image and thereby attracts more customers, which in turn gives manufacturers pricing power to charge a relatively higher wholesale price. We also study the impact of manufacturer competition on wholesale prices and quantities. We find that as the competition intensity increases, the wholesale prices decrease, while the quantities first decrease and then increase. It is straightforward to find decreasing wholesale prices because of the manufacturer's wholesale price war. The sensitivity analysis of the quantities is interesting, and the underlying reasons are subtler. To explain this, we cite Lus and Muriel (2009), who find that the total market potential can be decreasing in competition intensity. This serves as a driving force for the retailer to lower the order quantity. In contrast, tense manufacturer competition results in lower wholesale prices, which leads to a sharp drop in the retailer's procurement cost. This induces the retailer to place a larger order quantity.

Next, among the manufacturers and the retailer, we investigate the incentive alignment opportunities for adopting blockchain. We find that manufacturers always benefit from blockchain adoption, while the retailer's preference depends on the manufacturer's competition intensity and the demand variance level. Only when there is mild manufacturer competition and low demand variance in the market would the retailer be better off in the adoption of blockchain technology. More specifically, the retailer is willing to adopt blockchain only when the benefits from the profit margin increment and the sales quantity increment can offset its loss because of demand information disclosure.

We further examine the impact of blockchain on the total surplus and customer surplus and find that blockchain always results in a larger total surplus and customer surplus. This finding sheds light on the wide use of blockchain for social goods such as OTC medicine.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. We introduce the model settings and describe the assumptions in Section 3. Section 4 presents the corresponding analysis. In Section 5, we extend the basic model by considering the cost of adopting blockchain, the retailer's inaccurate information, the retailer's sales effort, asymmetric substitutability, sequential wholesale pricing, and first-order stochastic dominance. Section 6 concludes this paper and discusses future research directions. All the equilibrium results and proofs are summarized in the Online Appendix.

2. Literature review

This study is related to three streams of literature, namely, blockchain technology, healthcare supply chain product quality, and the impact of competition and cooperation on supply chain performance.

Our study is closely related to the literature on the role of blockchain in supply chain management. As blockchain technology has been adopted in an increasing number of industries, Kumar et al. (2018) point out that the study of blockchain's role can effectively contribute to the literature on operations management (OM) and information system (IS) interfaces. Choi and Luo (2019) investigate how to use blockchain to improve data quality in sustainable fashion supply chains. They find that blockchain may enhance total surplus but may have a negative impact on supply chain profitability. By analyzing several customer utility models, Choi (2019) identifies the value of blockchain in diamond authentication and certification. Choi et al. (2019) then investigated the application of blockchain technology in a mean–variance risk analysis framework. Saberi et al. (2019) point out that blockchain has the potential to solve some global supply chain management problems. Wang et al. (2019) study the benefits and challenges of the adoption of blockchain technology in supply chain management. With the consideration of demand volatility risk, Yoon et al. (2019) examine the effectiveness of blockchain technology in improving the exporting firms' performance in international trades. Hastig and Sodhi (2020) conduct an empirical study by considering the business requirements and critical success factors in the implementation of blockchain. Chod et al. (2020) find that blockchain helps reduce the verification costs for inventory transactions and to secure favorable financing terms at a lower signal cost. Choi et al. (2020a) investigate the impact of blockchain on social media analytics. Choi et al. (2020b) further study the impact of blockchain technology on the on-demand service platform's optimal pricing decisions. Different from these works, our study focuses on the application of blockchain technology in the pharmaceutical industry, in which social goods such as medicines are purchased and resold by retailers. We investigate the incentive alignment opportunities of two manufacturers and their common retailer to adopt blockchain technology when the retailer has more accurate demand information than the manufacturers. We further investigate the supply chain's total surplus, which is an important performance measure of the retailers' social goods selling.

There are arising studies that focus on information sharing based on blockchain technology. Typical examples include Yang (2019), Choi et al. (2019), Dutta et al. (2020), Choi (2020), and Li (2020). Yang (2019) shows that blockchain technology employed in the shipping industry has widely facilitated information sharing among supply chain parties. Choi et al. (2019) point out that blockchain is essential for companies to obtain faithful demand information and avoid the downstream firms' lies. Dutta et al. (2020) point out that information sharing is one of the main characteristics of blockchain. Choi (2020) mentions that companies could track the customers' behaviors. Li (2020) indicates that information sharing could be achieved by using smart technologies such as big data and blockchain. Yu et al. (2020) investigate whether carbon emissions can be reduced if the retailer shares information with the manufacturer through blockchain. Zhang et al. (2020) study the information sharing effect in a luxury supply chain in which the manufacturer can observe the signal of the customers' preferences, while the retailer cannot. Different from the aforementioned literature, our study focuses on OTC medicines and healthcare products that show the characteristics of social goods. Due to the significant social impact of medicines and healthcare products, customers are especially concerned about product authenticity and quality problems. It is difficult for customers to identify whether a drug is real or fake without the adoption of blockchain technology. However, if the pharmaceutical supply chain adopts blockchain technology, customers can verify the authenticity and have more trust in the brand of medicines, resulting thereby in an expansion of market potential. We capture the significant features of blockchain technology in the medicine supply chain. In addition, our study investigates the total surplus, customer surplus, and relative social objectives, which are important for social goods and were not formulated in Shang et al. (2016).

The literature on the healthcare supply chain in the context of product quality is also related. Kornish and Keeney (2008) investigate the optimal commit-or-defer decisions in influenza vaccine production. Deo and Corbett (2009) suggest that yield uncertainty can contribute to a high degree of influenza vaccine supply chain concentration. Shedding light on the Vaccine and Related Biologic Products Advisory Committee's decisions, Cho (2010) finds that a dynamic composition policy can significantly improve the total surplus. Adopting a non-linear programming model, Proano et al. (2012) study the best allocation of combination vaccines and maximize the total social surplus. For perishable medicines, Masoumi et al. (2012) develop a generalized network model in which supply chain members seek profits. Dai et al. (2016) develop a buyback-and-late-rebate (BLR) contract that helps not only to incentivize at-risk early influenza vaccine production but also to eliminate double marginalization. Guo et al. (2019) compare a fee-for-service scheme and a bundled-payment scheme in a three-tier public healthcare system. Chen et al. (2019) use a stochastic dynamic programming model to study a blood center's optimal collection policy and platelet production decisions. Nagurney et al. (2019) investigate the impact of quality differences on supply chain performance. Akbarpour et al. (2020) developed a robust model to improve the efficiency of the medicine relief network. Yoo and Cheong (2018) study the impact of quality improvement mechanisms on supply chain performance. Different from their studies, our study considers the OTC medicine supply chain and the impact of blockchain. Considering medicine manufacturer competition and the retailer's demand information advantage, we focus on how blockchain helps achieve supply chain information transparency.

There is arising literature on the impact of competition and cooperation on supply chain performance. McGuire and Staelin (1983) suggest that tense competition induces supply chain decentralization in a chain-to-chain model. Ganeshan et al. (1999) study a supplier competition model, which, comprising a reliable supplier and an unreliable supplier, helps lower wholesale prices. Later, supplier/manufacturer encroachment arises as a hot topic concerning strategic decisions, such as channel structure, upstream entry and downstream cooperation, and the combination of information flow and/or cash flow. For example, Arya et al. (2007) demonstrate that both the supplier and the retailer may benefit from the supplier's encroachment because the double marginalization effect can be mitigated. Wang et al. (2013) show that the manufacturer's encroachment significantly influences the quantity leadership decisions of a brand owner and its competitive manufacturer. Considering an offshore supplier and a local supplier, Serel (2015) studies a firm's production and price strategy. Lan et al. (2017) consider a retailer offering after-sales services and study its incentives to share private cost information. Li et al. (2018) study upstream competition in a supply chain in which multiple suppliers with different yields and quantity discounts sell products to a single buyer. Niu et al. (2019b) identify the cooperation value via demand information sharing when logistics service providers compete in both price and promised delivery time. Guan et al. (2020) show that a supplier's encroachment may come along with its voluntary information disclosure, which eventually results in improved information transparency and customer quality perceptions. Wang et al. (2020) study the retailers' collection decisions in a reverse supply chain comprised of a dominated retailer and competitive manufacturers. In contrast, we consider a "two-to-one" supply chain structure, which consists of two medicine manufacturers and a retailer. We do not consider manufacturer encroachment but formulate the two manufacturers' free-riding of the retailer's demand information if blockchain is adopted. Although information transparency can also be achieved, the main driving force in our paper is blockchain technology; therefore, we focus on the supply chain members' incentive alignment opportunities towards the adoption of blockchain.

3. Model

We consider a two-stage supply chain consisting of two medicine manufacturers (denoted as M_1 and M_2), who produce and sell substitutable products, and a common pharmaceutical retailer (denoted as R), who buys and resells the two manufacturers' medicines. Since the pharmaceutical retailer is familiar with the market and deals directly with customers, it has accurate demand information. The two manufacturers only know the mean and the demand variance. This assumption is widely used in previous literature, such as Özer and Wei (2006) and Xue et al. (2017). The supply chain structure is illustrated in Fig. 1.

We consider two scenarios.

(1) Scenario NB. The supply chain members do not adopt blockchain technology. Customers cannot obtain information on the whole production process of medicines; therefore, the manufacturers are not well recognized by the customers. The two manufacturers determine the wholesale prices based on the expected demand, while the retailer determines the order quantities and retail prices based on accurate demand information.
(2) Scenario AB. The supply chain members adopt blockchain technology. Customers can access all the key pieces of information on the whole production process of the medicines, from raw material purchasing to finished medicine sales; therefore, they can verify the medicine's quality. As a result, the manufacturers' brand image is improved, resulting in larger market potential. In addition, with the adoption of blockchain, the retailer is required to log the sales information into the blockchain. Therefore, the upstream manufacturers can obtain accurate demand information, based on which they determine their wholesale prices (the case in which the manufacturers cannot obtain accurate information will be discussed in Section 5.2).

The two manufacturers engage in Cournot competition. Their inverse demand functions in scenario NB are as follows:

$$p_1^{NB} = a - q_1^{NB} - bq_2^{NB} + \varepsilon_1$$

$$p_2^{NB} = a - q_2^{NB} - bq_1^{NB} + \epsilon_2$$

The manufacturers' inverse demand functions in scenario AB are as follows:

$$p_1^{AB} = \theta - q_1^{AB} - bq_2^{AB} + \epsilon_1$$

$$p_2^{AB} = \theta - q_2^{AB} - bq_1^{AB} + \epsilon_2$$

For model tractability, the deterministic part of the market potential in scenario NB is normalized to 1 and that in scenario AB is denoted as θ; that is, we have $a = 1$, and $\theta > 1$. This represents that the manufacturers' market is expanded because of the adoption of blockchain technology. We assume θ cannot be too high (i.e., $\theta < \frac{3}{2}$); otherwise, the results will be trivial, as the supply chain members always prefer the adoption of blockchain. $b \in (0, 1)$ represents the product substitutability between the medicines produced by the two manufacturers. ϵ_i ($i \in \{1,2\}$) represents the random part of market potential and captures demand uncertainty. We assume ϵ_i follows a normal distribution with a mean $E[\epsilon_i] = 0$ and a variance $\mathrm{V}[\epsilon_i] = \sigma_i^2$ (a similar setting can be found in previous literature such as Niu et al. 2019a). We assume two manufacturers face different levels of demand uncertainty and $\sigma_1^2 = \lambda\sigma^2, \sigma_2^2 = \sigma^2$, where $\lambda < 1$. That is, without loss of generalization, M_1's medicine has a smaller demand variance than M_2. Since the deterministic part of the market potential in scenario NB is normalized to 1, we require the demand variance to satisfy $\sigma^2 < 1$. We further assume the cost of adopting blockchain technology is zero, where this assumption is relaxed in Section 5.1. We use Table 2 to show the features of blockchain which are helpful in the medicine supply chains and are being modeled.

The event sequence is shown as follows (see Fig. 2 for illustration),

In the first stage, supply chain members decide whether to adopt blockchain technology. If incentive alignment is achieved, then the manufacturers have accurate demand information.

In the second stage, the two manufacturers determine the wholesale price w_i.

In the third stage, the retailer determines the order quantities q_i and, correspondingly, the retail prices p_i.

Finally, the market demand is realized, and revenues are collected accordingly.

The profit functions of the two manufacturers and the retailer are as follows:

$$\pi_{M_1} = w_1 q_1; \pi_{M_2} = w_2 q_2;$$

$$\pi_R = (p_1 - w_1)q_1 + (p_2 - w_2)q_2$$

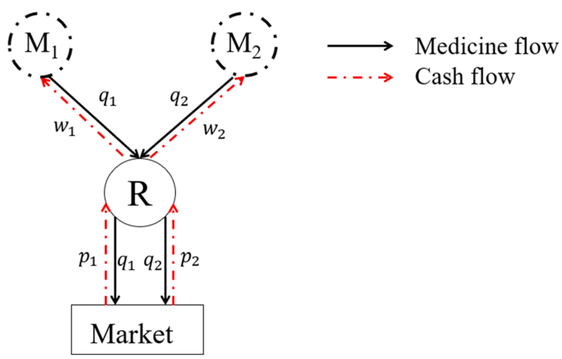


Fig. 1. Supply chain structure.

Table 2
Features of blockchain useful in our work.

Main features	Use in medicine supply chains	Model formulation
Transparent	Transaction data of medicines recorded in blockchain are visible for all participants.	Retailer's information sharing with blockchain adoption
Immutable	Records of medicines in blockchain are immutable and can be verified by customers, which improves their trust in medicine quality.	Market is expanded when customers can use blockchain for medicine verification
Track and trace	Customers can track the production and logistics information via apps or websites, thus trust the authenticity of medicines.	Market is expanded when customers know how medicines are produced and shipped

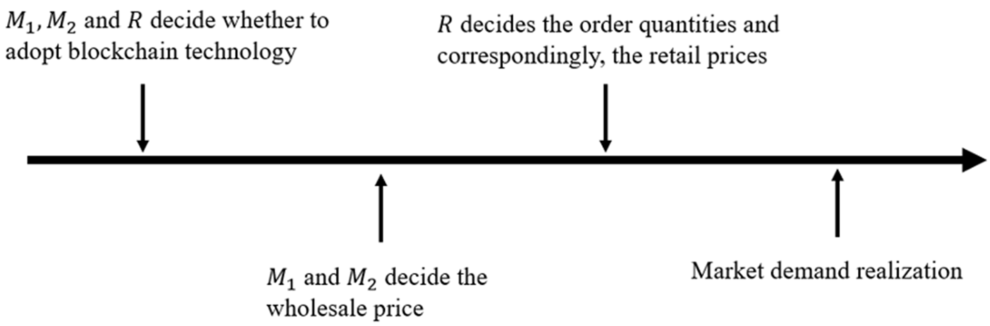


Fig. 2. The event sequence.

4. Analysis

We solve the game by backward induction, and the equilibrium outcomes are summarized in Tables A1 and A2 in Appendix A.

4.1. Analysis of wholesale price

In this subsection, we first compare the equilibrium wholesale prices, and the results are shown in Proposition 1.

Proposition 1.. *Both manufacturers determine higher wholesale prices in scenario AB (i.e.,* $E[w_i^{AB}] > E[w_i^{NB}]$*, and* $i \in \{1, 2\}$*) than in scenario NB.*

The intuition behind Proposition 1 is as follows. As we have mentioned in the Introduction, the adoption of blockchain technology helps achieve supply chain information transparency, improve the quality trust of medicine, and hence expand the market. In scenario AB, anticipating the increased demand, as the two manufacturers' pricing powers are enhanced, they raise the wholesale prices. Although the retailer's purchasing cost becomes higher, the benefit from expanded demand compensates for this cost. Consequently, $E[w_i^{AB}] > E[w_i^{NB}]$ arises as an equilibrium result.

Lemma 1. $\frac{\partial(E[w_i^{AB}])}{\partial b} < \frac{\partial(E[w_i^{NB}])}{\partial b} < 0and\frac{\partial(E[w_i^{AB}]-E[w_i^{NB}])}{\partial b} < 0.$,

Lemma 1 indicates that the wholesale prices in the two scenarios are both decreasing in competition intensity b. As b increases, one manufacturer's product can better substitute for the other's. Therefore, both manufacturers have incentives to lower their wholesale prices to stimulate orders, leading to a fierce "wholesale price war". Lemma 1 also indicates that as the competition intensity b increases, the wholesale price difference between the two scenarios decreases. The reason is that as b increases, the two medicines become more substitutable, and the total market is shrinking (Lus and Muriel 2009; Niu et al. 2020). The manufacturers care more about the market share; therefore, in scenario AB, they both have fewer incentives to raise the wholesale prices.

4.2. Analysis of quantity

We then focus on the retailer's order quantity decisions and have Proposition 2.

Proposition 2.. *The equilibrium order quantities in scenario AB are larger than those in scenario NB (*$E[q_i^{AB}] > E[q_i^{NB}]$*, and* $i \in \{1,2\}$*).*

Table 3
Summary of Parameters

Demand variance for medicine produced byM_2	$\sigma^2 \in (0,1)$, step length 0.1
The ratio of M1′s demand variance to M2′s demand variance	$\lambda \in (0,1)$, step length 0.1

Table 4
Managerial implications

Managerial implications	Rationality
We suggest that manufacturers adopt blockchain, the use of which is consistent with the practice of Pfizer, McKesson and AmerisourceBergen.	Manufacturers have prepared well to adopt blockchain to eliminate the misalignments in the supply chain (Forbes 2019a). They could not only ensure the authenticity of medicines but also gain access to market demand information.
We suggest that retailers adopt blockchain when the manufacturers' competition intensity is mild and the demand variance is low. This is consistent with Walmart's practice.	Since Walmart is one of the largest retailers around the world and has employed a big data program to predict customer demand, it faces low demand variance. Our finding explains why Walmart is willing to adopt blockchain.
Given an intense competition between manufacturers and a high demand variance, adopting blockchain can be harmful for small- and medium-sized pharmaceutical retailers	Demand information is an important resource for retailers, and the loss of an information advantage may hurt the retailers' profit, especially when they find fierce upstream competition and high demand uncertainty.

Table A1
Equilibrium results in scenario NB

$w_1^{NB} = \frac{1-b}{2-b}$	$w_2^{NB} = \frac{1-b}{2-b}$
$q_1^{NB} = \frac{(1-b)(2+b)+\left(2-b^2\right)\varepsilon_1 - b\varepsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$	$q_2^{NB} = \frac{(1-b)(2+b)-b\varepsilon_1+(2-b^2)\varepsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$
$p_1^{NB} = \frac{(2+b)(3-2b)+2\left(3-b^2\right)\varepsilon_1 - b\varepsilon_2}{2(b+2)(2-b)}$	$p_2^{NB} = \frac{(2+b)(3-2b)-b\varepsilon_1+2\left(3-b^2\right)\varepsilon_2}{2(b+2)(2-b)}$
$E[\pi_{M_1}^{NB}] = \frac{1-b}{2(2-b)^2(1+b)}$	$E[\pi_{M_2}^{NB}] = \frac{1-b}{2(2-b)^2(1+b)}$
$E[\pi_R^{NB}] = \frac{2(1-b)+(2-b)^2(1+\lambda)\sigma^2}{4(2-b)^2(1-b^2)}$	

Table A2
Equilibrium results in scenario AB

$w_1^{AB} = \frac{(2+b)(1-b)\theta+2\epsilon_1-b^2\epsilon_1-b\epsilon_2}{(2+b)(2-b)}$	$w_2^{AB} = \frac{(2+b)(1-b)\theta-b\epsilon_1+2\epsilon_2-b^2\epsilon_2}{(2+b)(2-b)}$
$q_1^{AB} = \frac{(1-b)(2+b)\theta+\left(2-b^2\right)\epsilon_1-b\epsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$	$q_2^{AB} = \frac{(1-b)(2+b)\theta-b\epsilon_1+(2-b^2)\epsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$
$p_1^{AB} = \frac{(2+b)(3-2b)\theta+2\left(3-b^2\right)\epsilon_1-b\epsilon_2}{2(b+2)(2-b)}$	$p_2^{AB} = \frac{(2+b)(3-2b)\theta-b\epsilon_1+2\left(3-b^2\right)\epsilon_2}{2(b+2)(2-b)}$
$E[\pi_{M_1}^{AB}] = \frac{(1-b)^2(2+b)^2\theta^2+(2-b^2)^2\lambda\sigma^2+b^2\sigma^2}{2\left(4-b^2\right)^2(1-b^2)}$	$E[\pi_{M_2}^{AB}] = \frac{(1-b)^2(2+b)^2\theta^2+(2-b^2)^2\sigma^2+b^2\lambda\sigma^2}{2\left(4-b^2\right)^2(1-b^2)}$
$E[\pi_{M_1}^{AB}] = \frac{2(1-b)^2(2+b)^2\theta^2+(4-3b^2)(1+\lambda)\sigma^2}{4\left(4-b^2\right)^2(1-b^2)}$	

Recall the result in Proposition 1. With the adoption of blockchain, the two manufacturers may determine higher wholesale prices, which increases the retailer's procurement cost. However, as Proposition 2 indicates, the retailer still has incentives to order more in scenario AB because it can transfer the high procurement cost to customers by determining higher retail prices ($E\left[p_i^{AB}\right] > E[p_i^{NB}]$, and $i \in \{1,2\}$) and can obtain more profits through larger sales quantities. We define the quantity difference between the two scenarios as the index of the *sales increase effect*, which benefits both manufacturers and the retailer. Then, we investigate the impact of competition intensity on the quantities and have Lemma 2.

Lemma 2.. *When*$b < \frac{1}{2}$, *we have* $\frac{\partial E\left[q_i^{AB}\right]}{\partial b} < \frac{\partial E\left[q_i^{NB}\right]}{\partial b} < 0$ *and*$\frac{\partial\left(E\left[q_i^{AB}\right]-E\left[q_i^{NB}\right]\right)}{\partial b} < 0$; *otherwise, we have* $\frac{\partial E\left[q_i^{AB}\right]}{\partial b} > \frac{\partial E\left[q_i^{NB}\right]}{\partial b} > 0$ *and* $\frac{\partial\left(E\left[q_i^{AB}\right]-E\left[q_i^{NB}\right]\right)}{\partial b} > 0$.

Lemma 2 indicates that the retailer's order quantities in the two scenarios are both first decreasing and then increasing in competition intensity$b$. When the competition intensity is low, the retailer's quantity decisions for the two medicines are relatively independent. As b increases, the substitution of two medicines increases, leading to similar customer perceptions and shrunken markets (Lus and Muriel 2009). This serves as a negative force for the retailer to place a large order. However, when b exceeds a threshold (i.e., $b > \frac{1}{2}$), interestingly, we find that the retailer may order more as b increases, despite the shrinking demand. The key reason is that the lowered procurement cost due to the manufacturers' wholesale price war serves as a positive force for the retailer to order more. When b is sufficiently large (i.e., $b > \frac{1}{2}$), the positive force dominates the negative force, and hence, the retailer raises the order quantities as b increases.

Then, we investigate the impact of competition intensity on the quantity difference between the two scenarios. We find that the impact on quantity difference indicates that the *sales increase effect* is first weakened and then enhanced as competition intensity b increases. This finding implies that from the perspective of sales quantity, the manufacturers and the retailer benefit more from blockchain when the competition intensity is either low or high.

4.3. Analysis of the retailer's profit margin

Proposition 3.. *The retailer's expected profit margins in scenario AB are higher than those in scenario NB* ($E[p_i^{AB}] - E[w_i^{AB}] > E[p_i^{NB}] - E[w_i^{NB}]$*, and* $i \in \{1, 2\}$).

Though the retailer has to bear higher procurement costs when adopting blockchain technology (i.e., $E[w_i^{AB}] > E[w_i^{NB}]$, and $i \in \{1, 2\}$) in scenario AB, Proposition 3 shows that the retailer may obtain a higher profit margin. Combining the results we have obtained until now, one can infer that for both the sales quantity and the profit margin, the two manufacturers and the retailer benefit from blockchain.

Lemma 3.. *The impact of competition intensity on the retailer's profit margins shows* $\frac{\partial(E[p_i^{AB}] - E[w_i^{AB}])}{\partial b} > \frac{\partial(E[p_i^{NB}] - E[w_i^{NB}])}{\partial b} > 0$ *and* $\frac{\partial[(E[p_i^{AB}] - E[w_i^{AB}]) - (E[p_i^{NB}] - E[w_i^{NB}])]}{\partial b} > 0$.

The intuition behind Lemma 3 is that as b increases, the manufacturers' competition becomes more intense; therefore, they both lower the wholesale price for a possibly larger market share. The lower wholesale price eventually benefits the retailer. Lemma 3 also indicates that from the perspective of the profit margin, the retailer benefits more from the adoption of blockchain when the competition intensity is high (i.e., $\frac{\partial[(E[p_i^{AB}] - E[w_i^{AB}]) - (E[p_i^{NB}] - E[w_i^{NB}])]}{\partial b} > 0$). In other words, the retailer has more incentives to participate in blockchain when the competing manufacturers' products are highly substitutable.

4.4. Analysis of supply chain members' profits

Next, by comparing their profits in two scenarios, we investigate the supply chain members' incentive alignment opportunities towards the adoption of blockchain. For model simplicity, define $\Phi = (1 + \lambda)\sigma^2$, where Φ is an index of demand uncertainty. A larger Φ represents higher demand uncertainty. Define $b_1 \in (0, 1)$, which uniquely solves $8 - 8\theta^2 + 12\Phi - (6 - 6\theta^2 + 5\Phi){b_1}^2 + 2(\theta^2 - 1){b_1}^3 + \Phi {b_1}^4 = 0$ and $\Phi_1 = \frac{2}{3}(\theta^2 - 1)$. We have Proposition 4.

Proposition 4.. *M_1 and M_2 always benefit from the adoption of blockchain technology, while R benefits when $\Phi < \Phi_1$ and $0 < b < b_1$.*

The reason that M_1 and M_2 are always willing to adopt blockchain technology is as follows. Recall the results in Proposition 1 and 2. The adoption of blockchain not only facilitates the manufacturers to determine higher wholesale prices but also increases the order quantities placed by the retailer, which benefits the manufacturers in terms of both profit margin (i.e., wholesale prices) and sales quantity. In addition, in the blockchain network, manufacturers can access accurate demand information, which enhances their pricing powers. The manufacturers can snatch more profits from the retailer by making better wholesale price decisions based on accurate demand information; this capability removes the retailer's information advantage. These two factors benefit manufacturers and induce them to prefer scenario AB.

Then, we examine the retailer's preference, which depends on the demand variance (indexed by Φ) and the competition intensity b (see Fig. 3 for illustration). Only when the demand variance is low and the manufacturers' competition is mild would the retailer benefit from the adoption of blockchain technology. It is intuitive that the retailer is not willing to adopt blockchain when the demand variance is sufficiently high because much information value would spill over to the manufacturers and this value could not be offset by the benefits from an increased sales quantity and profit margin. In contrast, when the demand variance is low, we find that the retailer prefers blockchain only when the manufacturers' competition is mild. Low competition intensity indicates that the two manufacturers' products are relatively independent and that the total market is large. Intuitively, the retailer has few incentives to share the demand information with the manufacturers through blockchain. Why do the reverse result holds? To better explain the underlying reasons, we divide the retailer's expected profit into two parts: deterministic value and information value. Define $E[\pi_{RD}^{NB}] = \frac{1}{2(2-b)^2(1+b)}$ ($E[\pi_{RD}^{AB}] = \frac{\theta^2}{2(2-b)^2(1+b)}$) and $E[\pi_{RI}^{NB}] = \frac{\Phi}{4(1-b^2)}$ ($E[\pi_{RI}^{AB}] = \frac{(4-3b^2)\Phi}{4(4-b^2)^2(1-b^2)}$) as the deterministic value and information value, respectively. We have the following corollary.

Corollary 1.. $E[\pi_{RD}^{AB}] > E[\pi_{RD}^{NB}]$*, and* $E[\pi_{RI}^{AB}] < E[\pi_{RI}^{NB}]$.

Corollary 1 indicates that with blockchain, the retailer's deterministic value is increased, while the information value is reduced. For the former, we have shown in previous subsections that in scenario AB, the retailer may have profit margins and sales quantities that are higher, resulting in a higher deterministic value. However, the retailer's information value spills over to the manufacturers if it participates in blockchain, and the retailer hence loses the information advantage over the manufacturers. The tradeoff between the gain in deterministic value and the loss in information value plays a critical role in the retailer's preference for blockchain. Fig. 4 illustrates the impact of the manufacturers' competition intensity on this tradeoff. We choose parameter value θ based on JD's report (JD.com Corporate Blog, 2020), which shows that the sales of healthcare products in JD increased by 45% after the adoption of

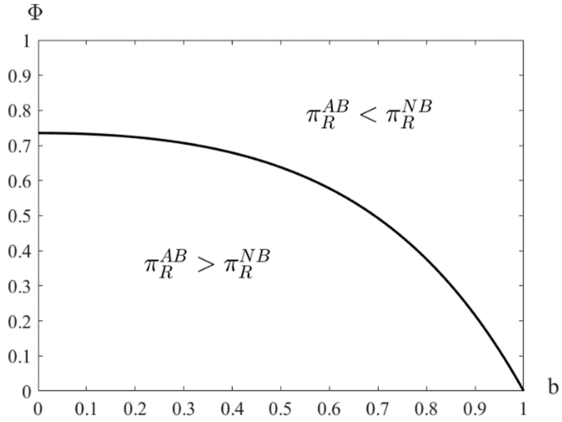


Fig. 3. The retailer's preference in two scenarios ($\theta = 1.45$).

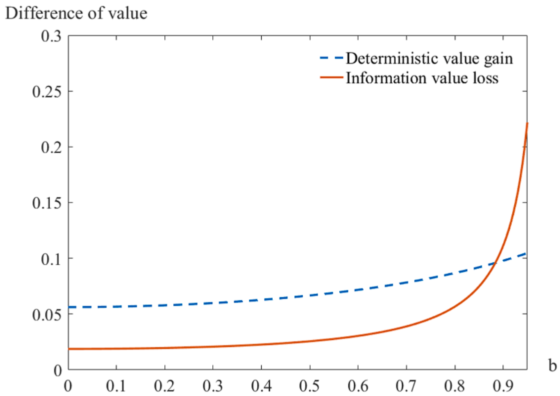


Fig. 4. Impact of manufacturers' competition on the retailer's deterministic value and information value.($\lambda = 0.7, \sigma = 0.4, \theta = 1.45$)

blockchain[12]. We then conduct numerical studies by varying the products' competition intensity, while fixing the demand variance, as listed in Table 3.

We observe that the deterministic value gain is larger under mild competition, while the loss of information value overweighs when the competition intensity exceeds a threshold. Specifically, when the competition intensity b is sufficiently high, the two manufacturers engage in a fierce wholesale price war. Compared to a less competitive situation, the demand information can significantly enhance the manufacturers pricing power, and the need to obtain this information results in more information value spillover, which hurts the retailer. In other words, more intense upstream competition calls for better wholesale price decisions based on accurate demand information. This significantly benefits the manufacturers in the vertical profit allocation because wholesale prices are the profit cutoffs between the manufacturers and the retailer. As a result, when b exceeds a threshold, the retailer's loss in information value dominates the gain in deterministic value, and hence, the retailer is unwilling to adopt blockchain technology.

4.5. Total surplus and customer surplus

Medicine is a typical kind of social good that is directly related to the customers' health and safety; therefore, the firms' social responsibility is very important. How can the firms' profitability and social responsibility be balanced? To answer this question, we examine the total surplus and customer surplus with and without blockchain. Following Singh and Vives (1984), the total surplus includes the two manufacturers' profits, the retailer's profit and the customer surplus and can be formulated as follows:

$$TS_{NB}(q_1, q_2) = q_1^{NB} + q_2^{NB} - \frac{1}{2}(q_1^{NB2} + 2bq_1^{NB}q_2^{NB} + q_2^{NB2})$$

$$TS_{AB}(q_1, q_2) = \theta(q_1^{AB} + q_2^{AB}) - \frac{1}{2}(q_1^{AB2} + 2bq_1^{AB}q_2^{AB} + q_2^{AB2})$$

[12] https://jdcorporateblog.com (accessed 11 November 2020)

$TS_{NB}(q_1, q_2)$ and $TS_{AB}(q_1, q_2)$ are the total surplus functions in scenarios NB and AB, respectively. The corresponding customer surplus can be calculated as follows:

$$CS_{NB} = TS_{NB}(q_1, q_2) - E[\pi_{M_1}^{NB}] - E[\pi_{M_2}^{NB}] - E\left[\pi_R^{NB}\right]$$

$$CS_{AB} = TS_{AB}(q_1, q_2) - E[\pi_{M_1}^{AB}] - E[\pi_{M_2}^{AB}] - E\left[\pi_R^{AB}\right]$$

Substituting the equilibrium outcomes into the above equations, we obtain Lemmas 4 and 5.

Lemma 4.. *In scenario NB, the expected total surplus and customer surplus are as follows:*

$$E[TS_{NB}(q_1, q_2)] = \frac{2(1-b)(7-4b) - (2-b)^2\Phi}{8(2-b)^2(1-b^2)}$$

$$E[CS_{NB}] = \frac{2(1-b) - 3(2-b)^2\Phi}{8(2-b)^2(1-b^2)}$$

Lemma 5.. *In scenario AB, the expected total surplus and customer surplus are as follows:*

$$E[TS_{AB}(q_1, q_2)] = \frac{2(1-b)(2+b)^2(7-4b)\theta^2 + (4-3b^2)\Phi}{8\left(4-b^2\right)^2(1-b^2)}$$

$$E[CS_{AB}] = \frac{2(1-b)(2+b)^2\theta^2 + (28-21b^2+4b^4)\Phi}{8\left(4-b^2\right)^2(1-b^2)}$$

Comparing the outcomes, we have Proposition 5.

Proposition 5.. *The expected total surplus and customer surplus are both higher in scenario AB than in scenario NB (i.e.,* $E[TS_{AB}] > E[TS_{NB}]$, *and* $E[CS_{AB}] > E[CS_{NB}]$).

Proposition 5 indicates that the adoption of blockchain technology can indeed increase the total surplus and customer surplus. There are mainly two benefits. First, blockchain technology enhances the medicines' quality trust, and hence, customers improve their perception and utility levels. Meanwhile, since customers are willing to pay a higher price for medicine of high utility, manufacturers and retailers enjoy benefits from higher profit margins and sales quantities, thereby leading to a higher total surplus. Second, blockchain technology improves supply chain information transparency and facilitates information sharing among supply chain members, both of which are supply chain enhancements that can promote the coordination of the supply chain and enlarge the total supply chain profit pie.

5. Extensions

5.1. Cost of adopting blockchain technology

In practice, the adoption of blockchain can be costly (Choi, 2019). We study two cost structures: unit blockchain cost and fixed blockchain cost[13].

Assume the manufacturers and the retailer pay a unit cost c for blockchain. We denote this scenario as scenario BC. To ensure that all the outcomes are positive, we need $c \le \frac{\theta}{2}$. The three supply chain members' profit functions in scenario BC are as follows, and the outcomes are shown in Table A3 in Appendix A.

$$\pi_{M_1} = (w_1 - c)q_1$$

$$\pi_{M_2} = (w_2 - c)q_2$$

$$\pi_R = (p_1 - w_1 - c)q_1 + (p_2 - w_2 - c)q_2$$

Comparing the equilibrium outcomes with those in scenario NB, we derive Lemma 6.

Lemma 6.. (*(1)*) $E[w^{BC}] > E[w^{NB}]$*;*

(2) When $\frac{1}{2}(\theta - 1) < c < \frac{\theta}{2}$, we have $E\left[q_i^{BC}\right] < E[q_i^{NB}]$, and $i \in \{1, 2\}$.

[13] In scenario FB, a fixed blockchain cost is charged for the use of blockchain technology. Compared with the basic model, the only difference between scenario AB and scenario FB is the fixed cost in the equilibrium profits. Therefore, the fixed cost only weakens the supply chain members' incentives to adopt blockchain and the main insights in basic model are unchanged.

Table A3
Equilibrium results in scenario BC

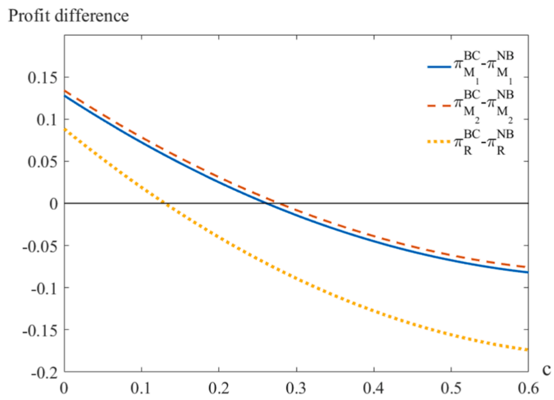
$w_1^{BC} = \frac{(2+b)(bc+(1-b)\theta)+\left(2-b^2\right)\epsilon_1 - b\epsilon_2}{4-b^2}$	$w_2^{BC} = \frac{(2+b)(bc+(1-b)\theta)-b\epsilon_1+(2-b^2)\epsilon_2}{4-b^2}$
$q_1^{BC} = \frac{(2+b)(1-b)(\theta-2c)+\left(2-b^2\right)\epsilon_1 - b\epsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$	$q_2^{BC} = \frac{(2+b)(1-b)(\theta-2c)-b\epsilon_1+(2-b^2)\epsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$
$p_1^{BC} = \frac{(2+b)(2c+a(3-2b)\theta)+2\left(3-b^2\right)\epsilon_1 - b\epsilon_2}{2(4-b^2)}$	$p_2^{BC} = \frac{(2+b)(2c+a(3-2b)\theta)-b\epsilon_1+2(3-b^2)\epsilon_2}{2(4-b^2)}$
$E[\pi_{M_1}^{BC}] = \frac{(2-b-b^2)^2(2c-\theta)^2+b^2\sigma^2+(2-b^2)^2\lambda\sigma^2}{2\left(4-b^2\right)^2(1-b^2)}$	$E[\pi_{M_2}^{BC}] = \frac{(2-b-b^2)^2(2c-\theta)^2+(2-b^2)^2\sigma^2+b^2\lambda\sigma^2}{2\left(4-b^2\right)^2(1-b^2)}$
$E\left[\pi_R^{BC}\right] = \frac{2(1-b)(2+b)^2(2c-\theta)^2+(4-3b^2)(1+\lambda)\sigma^2}{4\left(4-b^2\right)^2(1-b^2)}$	

(3) $E[p_i^{BC}] > E[p_i^{NB}]$, and $i \in \{1,2\}$.

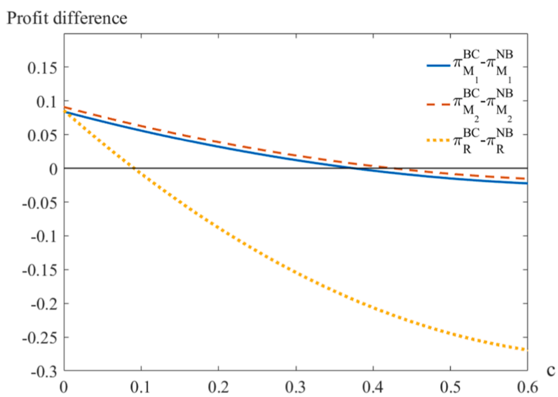
Lemma 6 indicates that the retailer's quantity decision is influenced by the unit blockchain cost and the improvement of market potential. The retailer may order less than scenario NB if the market potential improvement is limited and the unit blockchain cost is high.

Since we cannot obtain analytical solutions for the profit comparison results, we conduct extensive numerical studies to investigate the impact of unit blockchain cost on three supply chain members' profits and their incentives to adopt blockchain technology. Let $\theta = 1.45, \lambda = 0.7, and \sigma = 0.4$; we present two typical curves in Fig. 5.

Fig. 5 shows that the unit blockchain cost c may significantly influence the firms' incentives to adopt blockchain. We first focus on the case in which the competition intensity b is low (see Fig. 5 (a) for illustration). When the unit cost c is low, all the firms benefit from blockchain technology, which verifies the results in the basic model (the special case where $c = 0$). When the unit cost c is in a moderate range, we interestingly observe that there exists an interval in which the retailer and M_1 are not willing to adopt blockchain,



(a) $b = 0.3$



(b) $b = 0.7$

Fig. 5. The impact of c on profit difference.

while M_2 is willing to adopt. This is because M_2 can obtain higher information value than M_1 with blockchain, and hence, M_2 has more incentives to adopt blockchain. In contrast, when the unit cost c is high, both firms have no incentives to adopt blockchain because the benefits cannot offset the cost. Then, we turn to the case in which the competition intensity is high (see Fig. 5(b) for illustration). By comparing Fig. 5 (a) and Fig. 5(b), we observe that the two manufacturers have more incentives to adopt blockchain when the competition intensity is high.

5.2. Inaccurate information

In the basic model, we assume that manufacturers can obtain accurate demand information from the retailer if they all participate in blockchain. However, the shared information can be only an updated signal rather than the truth. Even if the retailer shares accurate demand information, that information can be the last period's information; therefore, the manufacturers' information from the blockchain is slightly inaccurate. Therefore, we investigate the impact of information accuracy on the manufacturers' decisions. We denote the scenario as scenario IB.

When blockchain is adopted, the manufacturers' information on ϵ_i is $\Gamma_i = \epsilon_i + \epsilon$, where ϵ is an updated signal of demand prediction. Following classic literature, such as Ha and Tong (2008), ϵ is independent of demand uncertainty ϵ_i and follows a normal distribution with a mean $E[\epsilon] = 0$ and a variance $V[\epsilon] = \sigma_o^2$. A smaller variance implies a more accurate information forecast. The manufacturers' information forecast is based on the demand information shared in the blockchain. This information potentially enhances demand forecasting.

Therefore, following the results in Vives (1984), Raju and Roy (2000), Ha and Tong (2008), and Niu and Zou (2017), we derive the following:

$$E[\epsilon_1|\Gamma_1] = \frac{\lambda\sigma^2\Gamma_1}{\lambda\sigma^2 + \sigma_o^2} = \frac{\lambda\sigma^2}{\lambda\sigma^2 + \sigma_o^2}(\epsilon_1 + \epsilon)$$

$$E[\epsilon_2|\Gamma_2] = \frac{\sigma^2\Gamma_2}{\sigma^2 + \sigma_o^2} = \frac{\sigma^2}{\sigma^2 + \sigma_o^2}(\epsilon_2 + \epsilon)$$

$$V[\epsilon_1|\Gamma_1] = \frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2 + \sigma_o^2}$$

$$V[\epsilon_2|\Gamma_2] = \frac{\sigma_o^2\sigma^2}{\sigma^2 + \sigma_o^2}$$

According to the above equations, we find that the accuracy of the demand forecast is improved (i.e., $V[\epsilon_i|\Gamma_i] < \sigma_i^2$). The profit functions of the supply chain members are as follows:

$$E[\pi_{M_1}|\Gamma_1] = E[w_1 q_1|\Gamma_1]$$

$$E[\pi_{M_2}|\Gamma_2] = E[w_2 q_2|\Gamma_2]$$

$$E[\pi_R] = (p_1 - w_1)q_1 + (p_2 - w_2)q_2$$

The equilibrium outcomes in scenario IB are summarized in Table A4 in Appendix A. Comparing the equilibria with those in scenario NB, we have Proposition 6:

Proposition 6.. *The retailer always benefits from the adoption of blockchain technology, while M_1 benefits when $\theta > \theta_1$ and M_2 benefits when $\theta > \theta_2$, where*

$$\theta_1 = \sqrt{1 + \frac{4 - 2b^2}{(1-b)^2(b+2)^2}\cdot\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2 + \sigma_o^2} + \frac{3b^2 - b^4}{(1-b)^2(b+2)^2}\cdot\frac{\sigma_o^2\sigma^2}{\sigma^2 + \sigma_o^2}}$$

$$\theta_2 = \sqrt{1 + \frac{3b^2 - b^4}{(1-b)^2(b+2)^2}\cdot\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2 + \sigma_o^2} + \frac{4 - 2b^2}{(1-b)^2(b+2)^2}\cdot\frac{\sigma_o^2\sigma^2}{\sigma^2 + \sigma_o^2}}$$

Proposition 6 shows that both manufacturers benefit from the adoption of blockchain technology when the enlarged market potential is higher than a threshold (i.e.,θ_1 or θ_2), while the retailer always benefits from the adoption of blockchain. The findings are different from those in the basic model. This is mainly because the manufacturer obtains inaccurate demand information such that the retailer's information value loss is lowered. However, the benefit from the enlarged market can cover the information value loss. For manufacturers, inaccurate demand information may have a negative impact on their wholesale price decisions. As a result, they are willing to adopt blockchain technology only when the benefit from an enlarged market is sufficiently large.

Table A4
Equilibrium results in scenario IB

$$w_1^{IB} = \frac{(2+b)(1-b)\theta + (2-b^2)E[\epsilon_1|\Gamma_1] - bE[\epsilon_2|\Gamma_2]}{(2+b)(2-b)}$$

$$w_2^{IB} = \frac{(2+b)(1-b)\theta - bE[\epsilon_1|\Gamma_1] + (2-b^2)E[\epsilon_2|\Gamma_2]}{(2+b)(2-b)}$$

$$q_1^{IB} = \frac{(2+b)(1-b)\theta - 2E[\epsilon_1|\Gamma_1] + b(3-b^2)E[\epsilon_2|\Gamma_2] + (4-b^2)(\epsilon_1 - b\epsilon_2)}{2(2-b)(1-b)(1+b)(2+b)}$$

$$q_2^{IB} = \frac{(2+b)(1-b)\theta + b(3-b^2)E[\epsilon_1|\Gamma_1] - 2E[\epsilon_2|\Gamma_2] + (4-b^2)(\epsilon_2 - b\epsilon_1)}{2(2-b)(1-b)(1+b)(2+b)}$$

$$p_1^{IB} = \frac{\left(6-b-2b^2\right)\theta + \left(2-b^2\right)E[\epsilon_1|\Gamma_1] - bE[\epsilon_2|\Gamma_2] + (2+b)(2-b)\epsilon_1}{2(2+b)(2-b)}$$

$$p_2^{IB} = \frac{\left(6-b-2b^2\right)\theta - bE[\epsilon_1|\Gamma_1] + (2-b^2)E[\epsilon_2|\Gamma_2] + (2+b)(2-b)\epsilon_2}{2(2+b)(2-b)}$$

$$E\left[\pi_{M_1}^{IB}\right] = \frac{(1-b)\theta^2}{2(2-b)^2(1+b)} + \frac{(b^2-2)}{(2+b)^2(2-b)^2(1+b)(1-b)} \cdot \frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2} + \frac{b^2(b^2-3)}{2(2+b)^2(2-b)^2(1+b)(1-b)} \cdot \frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}$$

$$E\left[\pi_{M_2}^{IB}\right] = \frac{(1-b)\theta^2}{2(2-b)^2(1+b)} + \frac{(b^2-2)}{(2+b)^2(2-b)^2(1+b)(1-b)} \cdot \frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2} + \frac{b^2(b^2-3)}{2(2+b)^2(2-b)^2(1+b)(1-b)} \cdot \frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}$$

$$E\left[\pi_R^{IB}\right] = \frac{\theta^2}{2(2-b)^2(1+b)} + \frac{(1+\lambda)\sigma^2}{4(1-b^2)} + \frac{(4+b^2-b^4)}{4(2+b)^2(2-b)^2(1+b)(1-b)} \cdot \frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2} + \frac{(4+b^2-b^4)}{4(2+b)^2(2-b)^2(1+b)(1-b)} \cdot \frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}$$

5.3. Sales efforts

In this subsection, we take the retailer's sales efforts into consideration. We assume that the retailer invests in sales efforts at the cost of $\frac{kx^2}{2}$ and that these efforts contribute to expanding the market potential of the two manufacturers' *products* from a to $a + x$. To guarantee positive outcomes, we assume $k > \frac{1}{(2-b)^2(1+b)}$. We use the superscripts SNB and SAB to represent not adopting blockchain and adopting blockchain scenarios, respectively. We assume that the retailer determines the sales effort level x before the decision of whether to adopt blockchain technology.

The event sequence is shown as follows (see Fig. 6 for illustration):

In the first stage, the retailer determines the sales effort x.

In the second stage, the supply chain members decide whether to adopt blockchain technology. If an incentive alignment is achieved, then the manufacturers have accurate demand information.

In the third stage, the two manufacturers determine the wholesale price w_i.

At the fourth stage, the retailer determines the order quantities q_i and, correspondingly, the retail prices p_i.

Finally, the market demand is realized, and the revenues are collected accordingly.

Then, the inverse demand functions in scenario SNB become the following:

$$p_1^{SNB} = 1 + x - q_1^{SNB} - bq_2^{SNB} + \epsilon_1;$$

$$p_2^{SNB} = 1 + x - q_2^{SNB} - bq_1^{SNB} + \epsilon_2$$

The inverse demand functions in scenario SAB are as follows:

$$p_1^{SAB} = \theta + x - q_1^{SAB} - bq_2^{SAB} + \epsilon_1;$$

$$p_2^{SAB} = \theta + x - q_2^{SAB} - bq_1^{SAB} + \epsilon_2$$

Correspondingly, the profit functions of the two manufacturers and the retailer become the following:

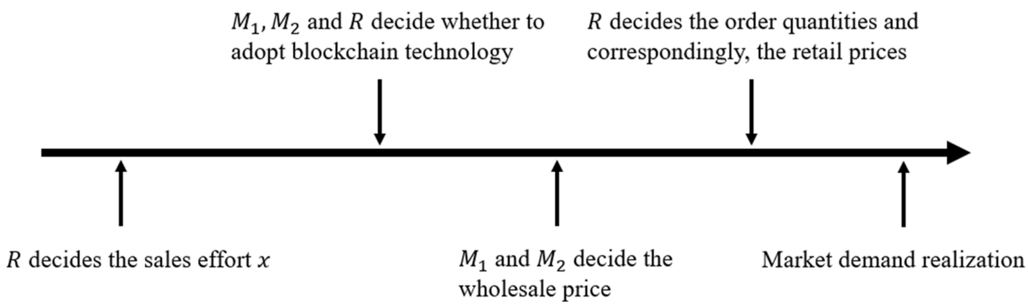


Fig. 6. The event sequence with the sales effort.

$\pi_{M_1} = w_1 q_1; \pi_{M_2} = w_2 q_2;$

$$\pi_R = (p_1 - w_1)q_1 + (p_2 - w_2)q_2 - \frac{kx^2}{2}$$

The equilibrium outcomes in the two scenarios are summarized in Table A5 and Table A6 in Appendix A. Comparing the firms' profits between two scenarios, we have the following proposition.

Proposition 7.. *With the retailer's sale efforts, the manufacturers are willing to adopt blockchain (i.e.,* $E\left[\pi_{M_1}^{SAB}\right] > E[\pi_{M_1}^{SNB}]$*, and* $E\left[\pi_{M_2}^{SAB}\right] > E[\pi_{M_2}^{SNB}]$)

Proposition 7 suggests that considering that the retailer makes sales efforts, the preference of manufacturers is the same as that in the basic model. However, for the retailer, it is more complicated and we cannot obtain a clear analytical solution; therefore, we study the retailer's preference by numerical studies. To verify the results, we develop numerical studies with different values of the main parameters. We find that the retailer adopts blockchain only when the competition is relatively mild, which is a finding similar to that in the basic model.

8.1. Asymmetric substitutability

In this subsection, we investigate the impact of asymmetric substitutable products. We assume that M_1's products are superior to those of M_2. The former can thus be seen as perfect substitutes for the latter, but the reverse is not true. For model tractability, we assume $b_2 = 1$ and that $b_1 = b < 1$(Wang et al. 2013). We use the superscripts ANB and AAB to represent the two scenarios of not adopting blockchain and adopting blockchain, respectively. Further, the inverse demand functions in scenario ANB are as follows:

$p_1^{ANB} = 1 - q_1^{ANB} - bq_2^{ANB} + \epsilon_1;$

$$p_2^{ANB} = 1 - q_2^{ANB} - q_1^{ANB} + \epsilon_2$$

The inverse demand functions in scenario AAB are as follows:

$p_1^{AAB} = \theta - q_1^{AAB} - bq_2^{AAB} + \epsilon_1;$

$$p_2^{AAB} = \theta - q_2^{AAB} - q_1^{AAB} + \epsilon_2$$

The equilibrium outcomes are summarized in Table A7 and Table A8 in Appendix A. Before comparing the supply chain members' profits, we define $b_{A1} \in (0, 1)$, which uniquely satisfies $100 - 100\theta^2 + 173\Phi + (-60 + 60\theta^2 - 36\Phi)b + (-36 + 36\theta^2 - 14\Phi)b^2 + (-4 + 4\theta^2 + 4\Phi)b^3 + \Phi b^4 = 0$.

Proposition 8.. *Given an asymmetric b, the manufacturers are still willing to adopt blockchain (i.e.,* $E\left[\pi_{M_1}^{AAB}\right] > E\left[\pi_{M_1}^{ANB}\right]$, $E\left[\pi_{M_2}^{AAB}\right] > E\left[\pi_{M_2}^{ANB}\right]$*), while the retailer prefers to adopt blockchain when* $\Phi < \frac{100(\theta^2-1)}{173}$ *and* $0 < b < b_{A1}$.

Proposition 8 shows that the main results are robust given asymmetric brand images; that is, two manufacturers are always willing to adopt blockchain, while the preference of the retailer is conditional. Only when the demand variance is low and the competition between manufacturers is mild would the retailer adopt blockchain, which is a result consistent with that in the basic model.

Table A5
Equilibrium results in scenario SNB

$x = \frac{1}{(2-b)^2(1+b)k-1}$	
$w_1^{SNB} = \frac{(2-b)(1-b)(1+b)k}{(2-b)^2(1+b)k-1}$	$w_2^{SNB} = \frac{(2-b)(1-b)(1+b)k}{(2-b)^2(1+b)k-1}$
$q_1^{SNB} = \frac{((2-b)^2(1+b)k-1)(b\epsilon_2-\epsilon_1)-(2-b)(1-b)(1+b)k}{2(1-b^2)(1-4k+3b^2k-b^3k)}$	
$q_2^{SNB} = \frac{b((2-b)^2(1+b)k-1)\epsilon_1+(1-(2-b)^2(1+b)k)\epsilon_2-(2-b)(1-b)(1+b)k}{2(1-b^2)(1-4k+3b^2k-b^3k)}$	
$p_1^{SNB} = \frac{1}{2}(\frac{(2-b)(1+b)(3-2b)k}{(2-b)^2(1+b)k-1}+\epsilon_1)$	$p_2^{SNB} = \frac{1}{2}(\frac{(2-b)(1+b)(3-2b)k}{(2-b)^2(1+b)k-1}+\epsilon_2)$
$E\left[\pi_{M_1}^{SNB}\right] = \frac{(2-b)k((2-b)(1-b)(1+b)k)}{2((2-b)^2(1+b)k-1)^2}$	$E[\pi_{M_2}^{SNB}] = \frac{(2-b)k((2-b)(1-b)(1+b)k)}{2((2-b)^2(1+b)k-1)^2}$
$E[\pi_R^{SNB}] = \frac{2\left(1-b^2\right)k-(1-(2-b)^2(1+b)k)(1+\lambda)\sigma^2}{4(1-b^2)((2-b)^2(1+b)k-1)}$	

Table A6
Equilibrium results in scenario SAB

$x = \frac{2\theta + \epsilon_1 + \epsilon_2}{2(2-b)^2(1+b)k - 2}$
$w_1^{SAB} = \frac{(1+b)(2(b-2)(b-1)(2+b)k\theta + (2(b-2)(b^2-2)k-1)\epsilon_1 + (1-2(2-b)bk)\epsilon_2)}{(2(2+b)(4k-3b^2k+b^3k-1))}$
$w_2^{SAB} = \frac{(1+b)(2(b-2)(b-1)(2+b)k\theta + (1-2(2-b)bk)\epsilon_1 + (-1+2(-2+b)(-2+b^2)k)\epsilon_2)}{(2(2+b)(4k-3b^2k+b^3k-1))}$
$q_1^{SAB} = \frac{8bk\theta - 8k\theta + 2b^2k\theta - 2b^3k\theta + \epsilon_1 - 8k\epsilon_1 + 4bk\epsilon_1 + 4b^2k\epsilon_1 - 2b^3k\epsilon_1 - \epsilon_2 + 4bk\epsilon_2 - 2b^2k\epsilon_2}{4(2-b-b^2)(1-4k+3b^2k-b^3k)}$
$q_2^{SAB} = \frac{8bk\theta - 8k\theta + 2b^2k\theta - 2b^3k\theta - \epsilon_1 + 4bk\epsilon_1 - 2b^2k\epsilon_1 + \epsilon_2 - 8k\epsilon_2 + 4bk\epsilon_2 + 4b^2k\epsilon_2 - 2b^3k\epsilon_2}{4(2-b-b^2)(1-4k+3b^2k-b^3k)}$
$p_1^{SAB} = \frac{(2(2-b)(1+b)(2+b)(3-2b)k\theta - (3+2b-2(2-b)(1+b)k(2(3-b^2)\epsilon_1 - b\epsilon_2)}{(4(2+b)((2-b)^2(1+b)k-1))}$
$p_2^{SAB} = \frac{2(2-b)(1+b)(2+b)(3-2b)k\theta + (3+2b-2(2-b)(1+b)k)(b\epsilon_1 - 2\left(3-b^2\right)k\epsilon_2)}{(4(2+b)((2-b)^2(1+b)k-1))}$
$E[\pi_{M_1}^{SAB}] = \frac{(1+b)(4(2-b)^2(1-b)^2(2+b)^2k^2\theta^2 + (\sigma - 2(2-b)bk\sigma)^2 + \lambda(\sigma - 2(2-b)(2-b^2)k\sigma)^2)}{8(1-b)(2+b)^2(1-(2-b)^2(1+b)k)^2}$
$E[\pi_{M_2}^{SAB}] = \frac{(1+b)(4(2-b)^2(1-b)^2(2+b)^2k^2\theta^2 + \lambda(\sigma - 2(2-b)bk\sigma)^2 + (\sigma - 2(2-b)(2-b^2)k\sigma)^2)}{8(1-b)(2+b)^2(1-(2-b)^2(1+b)k)^2}$
$E\left[\pi_R^{SAB}\right] = \frac{4(b-1)(2+b)^2k\theta^2 + (1-(8-6b^2)k)(1+\lambda)\sigma^2}{8(1-b)(2+b)^2(1-(2-b)^2(1+b)k)^2}$

Table A7
Equilibrium results in scenario ANB

$w_1^{ANB} = \frac{1-b}{3-b}$	$w_2^{ANB} = \frac{1-b}{3-b}$
$q_1^{ANB} = \frac{2(1-b) + 2(3-b)\epsilon_1 - (3-b)(1+b)\epsilon_2}{(3-b)(1-b)(3+b)}$	$q_2^{ANB} = \frac{2(1-b) - (3-b)(1+b)\epsilon_1 + 2(3-b)\epsilon_2}{(3-b)(1-b)(3+b)}$
$p_1^{ANB} = \frac{7-b(2+b) + (3-b)\epsilon_1 + (3-b)\epsilon_2}{9-b^2}$	$p_2^{ANB} = \frac{(5-b^2) - (3-b)\epsilon_1 + (3-b)(2+b)\epsilon_2}{9-b^2}$
$E[\pi_{M_1}^{ANB}] = \frac{2(1-b)}{(3-b)^2(3+b)}$	$E[\pi_{M_2}^{ANB}] = \frac{2(1-b)}{(3-b)^2(3+b)}$
$E\left[\pi_R^{ANB}\right] = \frac{4(1-b) + (3-b)^2\Phi}{(3-b)^2(1-b)(3+b)}$	

Table A8
Equilibrium results in scenario AAB.

$w_1^{AAB} = \frac{(1-b)(5+b)\theta + (7-b(2+b))\epsilon_1 - 2(1+b)\epsilon_2}{(3-b)(5+b)}$	$w_2^{AAB} = \frac{(1-b)(5+b)\theta - 2(1+b)\epsilon_1 + (7-b(2+b))\epsilon_2}{(3-b)(5+b)}$
$q_1^{AAB} = \frac{2((1-b)(5+b)\theta + (7-b(2+b))\epsilon_1 - 2(1+b)\epsilon_2)}{(3-b)(1-b)(3+b)(5+b)}$	$q_2^{AAB} = \frac{2((1-b)(5+b)\theta - 2(1+b)\epsilon_1 + (7-b(2+b))\epsilon_2)}{(3-b)(1-b)(3+b)(5+b)}$
$p_1^{AAB} = \frac{(5+b)(7-b(2+b))\theta + (31-b(-3+b(5+b)))\epsilon_1 + 2(2-b(3+b))\epsilon_2}{(3-b)(3+b)(5+b)}$	$p_2^{AAB} = \frac{\left(5-b^2\right)\theta - 2\epsilon_1 + (7-b^2)\epsilon_2}{9-b^2}$
$E[\pi_{M_1}^{AAB}] = \frac{2((5-4b-b^2)^2\theta^2 + (7-2b-b^2)^2\sigma^2 + 4(1+b)^2\lambda\sigma^2)}{(3-b)^2(1-b)(3+b)(5+b)^2}$	$E[\pi_{M_2}^{AAB}] = \frac{2((5-4b-b^2)^2\theta^2 + 4(1+b)^2\sigma^2 + (7-2b-b^2)^2\lambda\sigma^2)}{(3-b)^2(1-b)(3+b)(5+b)^2}$
$E\left[\pi_R^{AAB}\right] = \frac{4((1-b)(5+b)^2\theta^2 + (13-3b(2+b))\sigma^2 + (13-3b(2+b))\lambda\sigma^2)}{(3-b)^2(1-b)(3+b)(5+b)^2}$	

10.1. First-order stochastic dominance

In the basic model, we assume $E[\epsilon_1] = E[\epsilon_2]$ and $Var[\epsilon 1] > Var[\epsilon_2]$, which is the second-order stochastic dominance. As a complement, we consider a model with first-order stochastic dominance; that is, $E[\epsilon_1] > E[\epsilon_2]$, and $Var[\epsilon_1] = Var[\epsilon_2]$. We assume ϵ_i follows a normal distribution with a mean $E[\epsilon_1] = m$ and $E[\epsilon_2] = 0$, where $m > 0$, and a variance $V[\epsilon_i] = \sigma^2$. We use the superscripts FNB and FAB to represent the two scenarios of not adopting blockchain and adopting blockchain, respectively. The inverse demand functions in scenario FNB are as follows:

$$p_1^{FNB} = 1 - q_1^{FNB} - bq_2^{FNB} + \epsilon_1;$$

$$p_2^{FNB} = 1 - q_2^{FNB} - bq_1^{FNB} + \epsilon_2$$

The inverse demand functions in scenario FAB are as follows:

$p_1^{FAB} = \theta - q_1^{FAB} - bq_2^{FAB} + \epsilon_1;$

$$p_2^{FAB} = \theta - q_2^{FAB} - bq_1^{FAB} + \epsilon_2$$

Correspondingly, the profit functions of manufacturers and retailer become the following:

$\pi_{M_1} = w_1 q_1; \pi_{M_2} = w_2 q_2;$

$$\pi_R = (p_1 - w_1)q_1 + (p_2 - w_2)q_2$$

The equilibrium outcomes in the two scenarios are summarized in Table A9 and Table A10 in Appendix A. We define $b_{F1} \in (0,1)$, which is the unique root of equation $4 + 4m - 4m\theta - 4\theta^2 + 12\sigma^2 + (3m\theta + 3\theta^2 - 3 - 3m - 5\sigma^2)b^2 + (m\theta + \theta^2 - 1 - m)b^3 + \sigma^2 b^4 = 0$. Then, we have the following proposition.

Proposition 9.. *Under the first-order stochastic dominance scenario, two manufacturers always prefer to adopt blockchain (i.e.,* $E\left[\pi_{M_1}^{FAB}\right] > E\left[\pi_{M_1}^{FNB}\right], E\left[\pi_{M_2}^{FAB}\right] > E\left[\pi_{M_2}^{FNB}\right]$*), while the retailer adopts blockchain when* $0 < \sigma < \sqrt{\frac{m\theta + \theta^2 - 1 - m}{3}}$ *and* $0 < b < b_{F1}$.

Proposition 9 shows that the main results are still robust when two manufacturers face a different expectation of demand and the same demand variance. Similarly to the result in the basic model, the retailer adopts blockchain only when the manufacturers' competition is mild and the demand variance is low.

13.1. Sequential wholesale price

In the basic model, we assume the two manufacturers decide wholesale prices simultaneously. In this subsection, we study the impact of the pricing sequence. We consider the event sequence in which M_1 decides its wholesale price first and then M_2 decides the wholesale price. The event sequence is shown as follows (see Fig. 7 for illustration):

In the first stage, the supply chain members decide whether to adopt blockchain technology. If an incentive alignment is achieved, then the manufacturers have accurate demand information Fig. 8..

In the second stage, manufacturer M_1 determines its wholesale price w_1 first.

In the third stage, manufacturer M_2 determines its wholesale price w_2.

At the fourth stage, the retailer determines the order quantities q_i and, correspondingly, the retail prices p_i.

Finally, the market demand is realized, and the revenues are collected accordingly.

We use the superscripts WNB and WAB to represent the two scenarios of not adopting blockchain and adopting blockchain, respectively. The equilibrium outcomes in the two scenarios are summarized in Table A11 and Table A12 in Appendix A.

We define $b_{W1} \in (0, 1)$, which is the second root of equation $32 - 32\theta^2 + 48\sigma^2 + 48\lambda\sigma^2 + (-48 + 48\theta^2 - 44\sigma^2 - 36\lambda\sigma^2)b^2 + (-4 + 4\theta^2)b^3 + (21 - 21\theta^2 + 11\sigma^2)b^4 + (2 - 2\theta^2)b^5 + (-3 + 3\theta^2 + 3\lambda\sigma^2)b^6 = 0$. We have the following proposition.

Proposition 10.. *Under the sequential wholesale pricing scenario, two manufacturers always prefer to adopt blockchain (i.e.,* $E\left[\pi_{M_1}^{WAB}\right] > E\left[\pi_{M_1}^{WNB}\right]$, and $E\left[\pi_{M_2}^{WAB}\right] > E\left[\pi_{M_2}^{WNB}\right]$*), while the retailer adopts blockchain when* $0 < \sigma < \sqrt{\frac{2(\theta^2 - 1)}{3(1+\lambda)}}$ *and* $0 < b < b_{W1}$.

Proposition 10 shows that the main results are still robust when the manufacturer with a famous brand decides wholesale price first and then the other manufacturer sets its wholesale price. Similarly to the basic model, the result here reveals that the retailer adopts blockchain only when the manufacturers' competition is mild and the demand variance is low.

14. Conclusion

OTC medicines are available in every pharmaceutical retailer, regardless of whether the retailer is an online or an offline one. Although OTC medicines are sold similarly to how daily goods are sold, these medicines are used for their effect on the customers' health; therefore, they are typical social goods. In this paper, we focus on the tradeoffs among medicine quality tracking, the pharmaceutical retailer's demand information sharing, and the customers' demand expansion when blockchain is adopted in a two-stage supply chain comprising competing medicine manufacturers and a common pharmaceutical retailer. Since incentive alignment is critical in the adoption of blockchain (otherwise blockchain will be empty and useless), we investigate the preferences of the manufacturers and the retailer for blockchain. We also examine the total surplus and customer surplus to show the OTC medicine's social goods properties.

We first compare the wholesale prices and the quantities with and without blockchain. We find that the adoption of blockchain technology results in higher wholesale prices and quantities, a result that is referred to as the *sales increase effect*. This benefits the manufactures and the retailer. We also find that, interestingly, in both scenarios, the wholesale prices are decreasing in the manufacturers' competition intensity but that the quantities are first decreasing and then increasing in the competition intensity.

We then investigate three supply chain members' preferences for the adoption of blockchain technology. We find that two manufacturers are always better off with blockchain but that for the retailer, the answer depends on the situation. Only when the

Table A9
Equilibrium results in scenario FNB.

$w_1^{FNB} = \frac{(2-b-b^2)+(2-b^2)m}{4-b^2}$	$w_2^{FNB} = \frac{\left(2-b-b^2\right)-bm}{4-b^2}$
$q_1^{FNB} = \frac{\left(2-b-b^2\right)-2m+(4-b^2)(\epsilon_1-b\epsilon_2)}{2(4-5b^2+b^4)}$	$q_2^{FNB} = \frac{(2-b-b^2)+b(3-b^2)m-b(4-b^2)\epsilon_1+(4-b^2)\epsilon_2}{2(4-5b^2+b^4)}$
$p_1^{FNB} = \frac{(6-b-2b^2)+(2-b^2)m+(4-b^2)\epsilon_1}{2(4-b^2)}$	$p_2^{FNB} = \frac{\left(6-b-2b^2\right)-bm+(4-b^2)\epsilon_2}{2(4-b^2)}$
$E[\pi_{M_1}^{FNB}] = \frac{((2-b-b^2)+(2-b^2)m)(\left(2-b-b^2\right)-2m+(4-b^2)m)}{2\left(4-b^2\right)^2(1-b^2)}$	$E[\pi_{M_2}^{FNB}] = \frac{(\left(2-b-b^2\right)-bm)((2-b-b^2)+b(3-b^2)m-b(4-b^2)m)}{2\left(4-b^2\right)^2(1-b^2)}$
$E\left[\pi_R^{FNB}\right] = \frac{2(1-b)(2+b)^2+2(1-b)(2+b)^2m-\left(12-5b^2+b^4\right)m^2+\left(4-b^2\right)^2(2\sigma^2+m^2)}{4\left(4-b^2\right)^2(1-b^2)}$	

Table A10
Equilibrium results in scenario FAB.

$w_1^{FAB} = \frac{\left(2-b-b^2\right)\theta+\left(2-b^2\right)\epsilon_1-b\epsilon_2}{4-b^2}$	$w_2^{FAB} = \frac{\left(2-b-b^2\right)\theta-b\epsilon_1+\left(2-b^2\right)\epsilon_2}{4-b^2}$
$q_1^{FAB} = \frac{\left(2-b-b^2\right)\theta+\left(2-b^2\right)\epsilon_1-b\epsilon_2}{2(4-5b^2+b^4)}$	$q_2^{FAB} = \frac{\left(2-b-b^2\right)\theta+b\epsilon_1+\left(2-b^2\right)\epsilon_2}{2(4-5b^2+b^4)}$
$p_1^{FAB} = \frac{\left(6-b-2b^2\right)\theta+2\left(3-b^2\right)\epsilon_1-b\epsilon_2}{2(4-b^2)}$	$p_2^{FAB} = \frac{\left(6-b-2b^2\right)\theta-b\epsilon_1+2(3-b^2)\epsilon_2}{2(4-b^2)}$
$E[\pi_{M_1}^{FAB}] = \frac{(2-b-b^2)^2\theta^2+2(4-2b-4b^2+b^3+b^4)\theta m+(2-b^2)^2(\sigma^2+m^2)+b^2\sigma^2}{2(4-b^2)^2(1-b^2)}$	$E[\pi_{M_2}^{FAB}] = \frac{(2-b-b^2)^2\theta^2-2b(2-b-b^2)\theta m+b^2(\sigma^2+m^2)+(2-b^2)^2\sigma^2}{2(4-b^2)^2(1-b^2)}$
$E\left[\pi_R^{FAB}\right] = \frac{2(1-b)(2+b)^2\theta(m+a\theta)+(4-3b^2)(2\sigma^2+m^2)}{4\left(4-b^2\right)^2(1-b^2)}$	

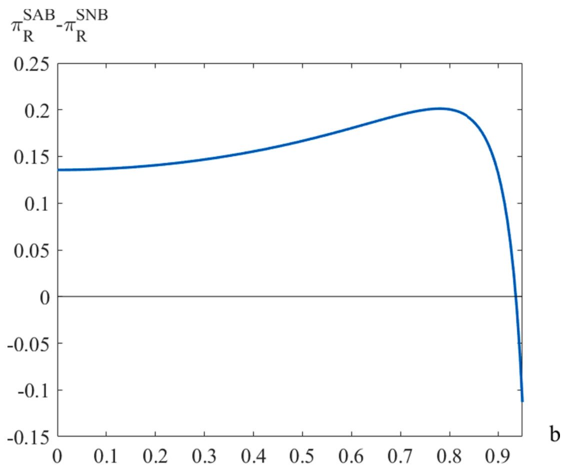


Fig. 7. The retailer's decision with the sales effort.($k = 1, \theta = 1.45, \sigma = 0.4$, and $\lambda = 0.7$)

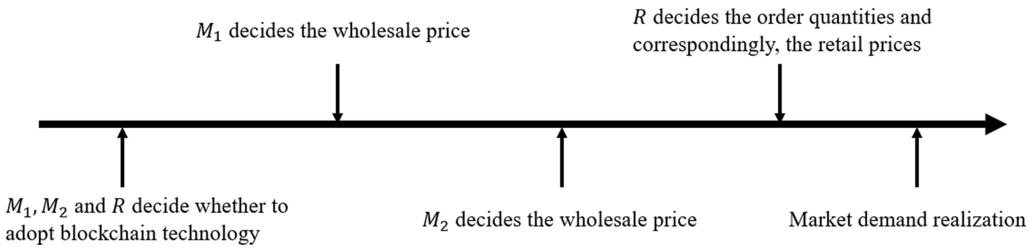


Fig. 8. The event sequence with a sequential wholesale price.

Table A11
Equilibrium results in scenario WNB.

$w_1^{WNB} = \frac{(1-b)(2+b)}{2(2-b^2)}$	$w_2^{WNB} = \frac{4-2b-3b^2+b^3}{4(2-b^2)}$
$q_1^{WNB} = \frac{\left(2-b-b^2\right)+4\epsilon_1-4b\epsilon_2}{8(1-b^2)}$	$q_2^{WNB} = \frac{(1-b)(4+(2-b)b)-4b\left(2-b^2\right)\epsilon_1+4(2-b^2)\epsilon_2}{8(2-3b^2+b^4)}$
$p_1^{WNB} = \frac{6-b-3b^2+4\epsilon_1-2b^2\epsilon_1}{4(2-b^2)}$	$p_2^{WNB} = \frac{12-2b-7b^2+b^3+8\epsilon_2-4b^2\epsilon_2}{8(2-b^2)}$
$E[\pi_{M_1}^{WNB}] = \frac{(2+b)(2-b-b^2)}{16(1+b)(2-b^2)}$	$E[\pi_{M_2}^{WNB}] = \frac{(1-b)(4+(2-b)b)^2}{32(1+b)(2-b^2)^2}$
$E\left[\pi_R^{WNB}\right] = \frac{\left(32-b^2(48+b(4-(3-b)b(7+3b)))\right)+16(2-b^2)^2(1+\lambda)\sigma^2}{64\left(2-b^2\right)^2(1-b^2)}$	

Table A12
Equilibrium results in scenario WNB.

$w_1^{WAB} = \frac{(2-b-b^2)\theta+(2-b^2)\epsilon_1+b\epsilon_1}{2(2-b^2)}$	$w_2^{WAB} = \frac{(1-b)(4+(2-b)b)\theta+b\left(2-b^2\right)\epsilon_1-(4-3b^2)\epsilon_2}{4(2-b^2)}$
$q_1^{WAB} = \frac{\left(2-b-b^2\right)\theta+\left(2-b^2\right)\epsilon_1-b\epsilon_2}{8(1-b^2)}$	$q_2^{WAB} = \frac{(1-b)(4+(2-b)b)\theta+b\left(2-b^2\right)\epsilon_1-(4-3b^2)\epsilon_2}{8(2-3b^2+b^4)}$
$p_1^{WAB} = \frac{\left(6-b-3b^2\right)\theta+3\left(2-b^2\right)\epsilon_1-b\epsilon_2}{4(2-b^2)}$	$p_2^{WAB} = \frac{(12-b(2+(7-b)b))\theta-b(2-b^2)\epsilon_1+(12-7b^2)\epsilon_2}{8(2-b^2)}$
$E[\pi_{M_1}^{WAB}] = \frac{(2-b-b^2)^2\theta^2+(2-b^2)^2\lambda\sigma^2+b^2\sigma^2}{16(1-b^2)(2-b^2)}$	$E[\pi_{M_2}^{WAB}] = \frac{(1-b)^2(4+(2-b)b)^2\theta^2+b^2(2-b^2)^2\lambda\sigma^2+(4-3b^2)^2\sigma^2}{32\left(2-b^2\right)^2(1-b^2)}$
$E\left[\pi_R^{WAB}\right] = \frac{\left(32-b^2(48+b(4+(b-3)b(7+3b)))\right)\theta^2-\left(2-b^2\right)^2\left(4-3b^2\right)\lambda\sigma^2-(16-20b^2+5b^4)\sigma^2}{64\left(2-b^2\right)^2(1-b^2)}$	

manufacturers' competition intensity is mild and the demand variance is low can the retailer's loss of information value because of demand information sharing be limited, inducing it to participate in blockchain. When the demand variance is high or the manufacturers' competition intensity is high, the retailer will suffer from a significant loss of information value; therefore, it has no incentive to participate in blockchain. We further show that if the manufacturers' information obtained in blockchain is not perfectly accurate, then the retailer will always be better off with blockchain, while the manufacturers' profits might be hurt, especially when the market expansion is not significant. Regarding the total surplus and customer surplus, we show that blockchain always benefits the supply chain members; therefore, this finding sheds light on the wide use of blockchain for social goods.

Our findings can be insightful for pharmaceutical retailers and manufacturers, especially when they need to undertake social responsibility. In practice, many famous pharmaceutical manufacturers (e.g., Pfizer, Novartis and GSK) are preparing to adopt blockchain technology (Mediledger 2020). Some pharmacies (e.g., UK Meds) accept using blockchain in situations in which they record the customers' requests and trace and track shipment information. However, it has been reported that some pharmacies are still not ready to use blockchain. For them, we have the following suggestions.

1. We suggest that the manufacturers adopt blockchain. Our finding is consistent with the cases of Pfizer, McKesson and AmerisourceBergen. Manufacturers have prepared well to adopt blockchain to eliminate misalignments in the supply chain[14] (Forbes 2019). By joining a blockchain, they can not only ensure the authenticity of medicines but also have access to market demand information.
2. We suggest that retailers adopt blockchain when the manufacturers' competition intensity is mild and the demand variance is low. This finding is consistent with the case of Walmart, which is mentioned in the Introduction section. Since Walmart is one of the largest retailers around the world and has employed a big data program to predict customer demand, it faces low demand variance. Our finding explains why Walmart is willing to join the blockchain program.
3. Given intense competition between manufacturers and a high demand variance, retailers are suggested to reconsider the decision to adopt blockchain. For common small- and medium-sized pharmaceutical retailers, we also provide the insight that the adoption of blockchain is not necessarily the best choice, especially when facing fierce upstream manufacturer competition and high demand uncertainty.

Compared to the case without blockchain, the adoption of blockchain by supply chain members can result in the improvement of the total surplus and the achievement of a customer surplus. The government is suggested to pay more attention to the application of blockchain in medicine supply chains, as this may not only improve the profit of the supply chain but also be good for customers. This explains why the FDA is running a project titled the FDA Pilot Program that promotes the adoption of blockchain (Mediledger 2020).

[14] https://www.forbes.com (accessed 11 November 2020)

The managerial implications are also presented in Table 4.

We discuss two future research directions to conclude this paper. First, medicine is not always effective. Some medicines are effective because of the manufacturer's production quality control or its purchasing of some specific raw materials. However, the retailer usually cannot inspect the materials purchased and/or determine the level of production quality control. To formulate this as a research issue, production yield uncertainty can be assumed. We predict that the retailer may have more incentives to adopt blockchain technology because it can obtain accurate production information through the blockchain and make better order quantity decisions. Second, we consider a common pharmaceutical retailer selling medicines for two manufacturers. In practice, medicine manufacturers may sell products through multiple retailers, resulting in a cross-selling channel structure. In such a complicated system, the adoption of blockchain can be more difficult because the shared information might spill over to competitors. Consequently, how to balance the increased sales via multiple channels in the context of the information sharing cost can be an interesting problem, but it fundamentally changes our model. We leave it as a future research issue.

CRediT authorship contribution statement

Baozhuang Niu: Conceptualization, Supervision, Project administration, Funding acquisition. **Jian Dong:** Investigation, Writing - review & editing. **Yaoqi Liu:** Writing - original draft, Methodology, Software.

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Appendix. A: Equilibrium results

Appendix B:. Derivations of equilibrium results

Derivation of Table A1

Given the wholesale prices w_1^{NB} and w_2^{NB}, the retailer solves the following problem to maximize its profit: $\pi_R^{NB} = (1 - q_1^{NB} - bq_2^{NB} + \epsilon_1 - w_1^{NB})q_1^{NB} + (1 - q_2^{NB} - bq_1^{NB} + \epsilon_2 - w_2^{NB})q_2^{NB}$.

This yields $q_1^{NB} = \frac{1-b-w_1^{NB}+bw_2^{NB}+\epsilon_1-b\epsilon_2}{2(1-b^2)}$, $q_2^{NB} = \frac{1-b+bw_1^{NB}-w_2^{NB}-b\epsilon_1+\epsilon_2}{2(1-b^2)}$.

The manufacturers' optimal wholesale prices can be derived by maximizing $E\left[\pi_{M_1}^{NB}\right] = w_1^{NB}E\left[q_1^{NB}\right] = \frac{(1-b-w_1^{NB}+bw_2^{NB})w_1^{NB}}{2(1-b^2)}$; $E\left[\pi_{M_2}^{NB}\right] = w_2^{NB}E\left[q_2^{NB}\right] = \frac{(1-b-w_2^{NB}+bw_1^{NB})w_2^{NB}}{2(1-b^2)}$.

Substituting q_1^{NB} and q_2^{NB} into the manufacturers' profit functions, we have the optimal wholesale prices: $w_1^{NB} = w_2^{NB} = \frac{1-b}{2-b}$, based on which we obtain the other equilibriums as follows

$$q_1^{NB} = \frac{1-b+(b-2)(b\epsilon_2-\epsilon_1)}{2(b-2)(b+1)(b-1)}; q_2^{NB} = \frac{1-b+(b-2)(b\epsilon_2-\epsilon_1)}{2(b-2)(b+1)(b-1)};$$

$$p_1^{NB} = \frac{3-2b+(2-b)\epsilon_1}{2(2-b)}; p_2^{NB} = \frac{3-2b+(2-b)\epsilon_2}{2(2-b)};$$

$E[q_1^{NB}] = E[q_2^{NB}] = \frac{1}{2(2-b)(1+b)}$; $E[p_1^{NB}] = E[p_2^{NB}] = \frac{3-2b}{2(2-b)}$.

Because the manufacturers' profit functions are based on the expectation, we have

$E[\pi_{M_1}^{NB}] = w_1^{NB}E[q_1^{NB}] = \frac{1-b}{2(2-b)^2(1+b)}$; $E\left[\pi_{M_2}^{NB}\right] = w_2^{NB}E\left[q_2^{NB}\right] = \frac{1-b}{2(2-b)^2(1+b)}$.

The retailer's profit is based on accurate demand information, so we substitute the outcomes with accurate demand information and derive its expected profit with information value as $E\left[\pi_R^{NB}\right] = \left(1 - q_1^{NB} - bq_2^{NB} + \epsilon_1 - w_1^{NB}\right)q_1^{NB} + \left(1 - q_2^{NB} - bq_1^{NB} + \epsilon_2 - w_2^{NB}\right)q_2^{NB} = \frac{2(1-b)+(2-b)^2(1+\lambda)\sigma^2}{4(2-b)^2(1-b^2)}$.

Note that the retailer has accurate demand information but the manufacturers do not in scenario NB, so the manufacturers' decisions are based on expected demand and hence, their equilibriums are independent of demand variance σ^2. In contrast, the retailer's decisions are based on accurate demand information so its equilibrium profit includes the item σ^2 that is related to information value (Wang et al. 2014, Wu and Zhang 2014, Niu et al. 2019a). Its equilibrium quantities q_1^{NB}, q_2^{NB} and retail prices p_1^{NB}, p_2^{NB} include the accurate random demand items ϵ_1 and ϵ_2.

Derivation of Table A2

Note that, the manufacturers make decisions based on the expectation when the supply chain does not adopt blockchain while the manufacturers make use of accurate demand information to determine the wholesale prices with the adoption of blockchain.

Given the wholesale price w_1^{AB} and w_2^{AB}, the retailer solves the following problem to maximize its profit: $\pi_R^{AB} = (\theta - q_1^{AB} - bq_2^{AB} + \epsilon_1 - w_1^{AB})q_1^{AB} + (\theta - q_2^{AB} - bq_1^{AB} + \epsilon_2 - w_2^{AB})q_2^{AB}$.

The best order quantities are $q_1^{AB}=\frac{\theta-b\theta-w_1+bw_2+\epsilon_1-b\epsilon_2}{2(1-b^2)}$ and $q_2^{AB}=\frac{\theta-b\theta+bw_1-w_2-b\epsilon_1+\epsilon_2}{2(1-b^2)}$. Anticipating the quantities above, the manufacturers maximize their profit functions by determining wholesale prices as

$$w_1=\frac{(2+b)(1-b)\theta+2\epsilon_1-b^2\epsilon_1-b\epsilon_2}{(2+b)(2-b)}\text{and}w_2=\frac{(2+b)(1-b)\theta-b\epsilon_1+2\epsilon_2-b^2\epsilon_2}{(2+b)(2-b)}.$$

Therefore, the supply chain members' equilibrium outcomes are $w_1^{AB}=\frac{(2+b)(1-b)\theta+2\epsilon_1-b^2\epsilon_1-b\epsilon_2}{(2+b)(2-b)}$, $w_2^{AB}=\frac{(2+b)(1-b)\theta-b\epsilon_1+2\epsilon_2-b^2\epsilon_2}{(2+b)(2-b)}$, $q_1^{AB}=\frac{(2+b)(1-b)\theta+(2-b^2)\epsilon_1-b\epsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$, $q_2^{AB}=\frac{(2+b)(1-b)\theta-b\epsilon_1+(2-b^2)\epsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$.

As a result, their expected profits are $E[\pi_{M_1}^{AB}]=\frac{((2+b)(1-b))^2\theta^2+(2-b^2)^2\lambda\sigma^2+b^2\sigma^2}{2(2+b)^2(2-b)^2(1+b)(1-b)}$, $E[\pi_{M_2}^{AB}]=\frac{((2+b)(1-b))^2\theta^2+(2-b^2)^2\sigma^2+b^2\lambda\sigma^2}{2(2+b)^2(2-b)^2(1+b)(1-b)}$, and$E[\pi_R^{AB}]=\frac{2(1-b)(2+b)^2\theta^2+(4-3b^2)(1+\lambda)\sigma^2}{4(2+b)^2(2-b)^2(1+b)(1-b)}$.

Different from scenario NB, both the manufacturers and the retailer in scenario AB have the accurate demand information and all of their equilibrium profits include the item σ^2 that is related to information value. We also note that the accurate random demand items ϵ_1 and ϵ_2 appear in w_1^{AB}, w_2^{AB}, q_1^{AB}, q_2^{AB}, p_1^{AB} and p_2^{AB}.

Derivation of Table A3

Given the wholesale price w_1^{BC} and w_2^{BC}, the retailer solves the following problem to maximize its profit: $\pi_R^{BC}=(\theta-q_1^{BC}-bq_2^{BC}+\epsilon_1-w_1^{BC}-c)q_1^{BC}+(\theta-q_2^{BC}-bq_1^{BC}+\epsilon_2-w_2^{BC}-c)q_2^{BC}$.

The best order quantities are $q_1^{BC}=\frac{\theta-b\theta-w_1+bw_2+\epsilon_1-b\epsilon_2}{2(1-b^2)}$ and $q_2^{BC}=\frac{\theta-b\theta+bw_1-w_2-b\epsilon_1+\epsilon_2}{2(1-b^2)}$. Anticipating the quantities above, the manufacturers maximize their profit functions by determining wholesale prices as

$w_1^{BC}=\frac{(2+b)(bc+(1-b)\theta)+(2-b^2)\epsilon_1-b\epsilon_2}{4-b^2}$and $w_2^{BC}=\frac{(2+b)(bc+(1-b)\theta)-b\epsilon_1+(2-b^2)\epsilon_2}{4-b^2}$.

Therefore, the supply chain members' equilibrium outcomes are $q_1^{BC}=\frac{(2+b)(1-b)(\theta-2c)+(2-b^2)\epsilon_1-b\epsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$, $q_2^{BC}=\frac{(2+b)(1-b)(\theta-2c)-b\epsilon_1+(2-b^2)\epsilon_2}{2(2-b)(1-b)(1+b)(2+b)}$.

As a result, their expected profits are $E[\pi_{M_1}^{BC}]=\frac{(2-b-b^2)^2(2c-\theta)^2+b^2\sigma^2+(2-b^2)^2\lambda\sigma^2}{2(4-b^2)^2(1-b^2)}$, $E[\pi_{M_2}^{BC}]=\frac{(2-b-b^2)^2(2c-\theta)^2+(2-b^2)^2\sigma^2+b^2\lambda\sigma^2}{2(4-b^2)^2(1-b^2)}$, and $E[\pi_R^{BC}]=\frac{2(1-b)(2+b)^2(2c-\theta)^2+(4-3b^2)(1+\lambda)\sigma^2}{4(4-b^2)^2(1-b^2)}$.

Till now, the outcomes in Table A3 are derived.

Derivation of Table A4

The manufacturers make use of inaccurate demand information to determine the wholesale prices with the adoption of blockchain.

Given the wholesale price w_1^{IB} and w_2^{IB}, the retailer solves the following problem to maximize its profit: $\pi_R^{IB}=(\theta-q_1^{IB}-bq_2^{IB}+\epsilon_1-w_1^{IB})q_1^{IB}+(\theta-q_2^{IB}-bq_1^{IB}+\epsilon_2-w_2^{IB})q_2^{IB}-f$.

The best order quantities are $q_1^{IB}=\frac{\theta-b\theta-w_1+bw_2+\epsilon_1-b\epsilon_2}{2(1-b^2)}$ and $q_2^{IB}=\frac{\theta-b\theta+bw_1-w_2-b\epsilon_1+\epsilon_2}{2(1-b^2)}$. Anticipating the quantities above, the manufacturers maximize their profit functions by determining wholesale prices as

$w_1=\frac{(2+b)(1-b)\theta+(2-b^2)E[\epsilon_1|\Gamma_1]-bE[\epsilon_2|\Gamma_2]}{(2+b)(2-b)}$and $w_2=\frac{(2+b)(1-b)\theta-bE[\epsilon_1|\Gamma_1]+(2-b^2)E[\epsilon_2|\Gamma_2]}{(2+b)(2-b)}$.

Therefore, we have the supply chain members' equilibrium outcomes are

$$w_1^{IB}=\frac{(2+b)(1-b)\theta+(2-b^2)E[\epsilon_1|\Gamma_1]-bE[\epsilon_2|\Gamma_2]}{(2+b)(2-b)},w_2^{IB}=\frac{(2+b)(1-b)\theta-bE[\epsilon_1|\Gamma_1]+(2-b^2)E[\epsilon_2|\Gamma_2]}{(2+b)(2-b)},q_1^{IB}$$
$$=\frac{(2+b)(1-b)\theta-2E[\epsilon_1|\Gamma_1]+b(3-b^2)E[\epsilon_2|\Gamma_2]+(4-b^2)(\epsilon_1-b\epsilon_2)}{2(2-b)(1-b)(1+b)(2+b)},$$

$$q_2^{IB}=\frac{(2+b)(1-b)\theta+b(3-b^2)E[\epsilon_1|\Gamma_1]-2E[\epsilon_2|\Gamma_2]+(4-b^2)(\epsilon_2-b\epsilon_1)}{2(2-b)(1-b)(1+b)(2+b)}$$

Note that, the variance in this subsection becomes conditional variance

$$V[\epsilon_1|\Gamma_1]=\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2},V[\epsilon_2|\Gamma_2]=\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}$$

As a result, their expected profits are $E\left[\pi_{M_1}^{IB}\right]=\frac{(1-b)\theta^2}{2(2-b)^2(1+b)}+\frac{(b^2-2)}{(2+b)^2(2-b)^2(1+b)(1-b)}\cdot\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}+\frac{b^2(b^2-3)}{2(2+b)^2(2-b)^2(1+b)(1-b)}\cdot\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}$, $E\left[\pi_{M_2}^{IB}\right]=\frac{(1-b)\theta^2}{2(2-b)^2(1+b)}+\frac{(b^2-2)}{(2+b)^2(2-b)^2(1+b)(1-b)}\cdot\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}+\frac{b^2(b^2-3)}{2(2+b)^2(2-b)^2(1+b)(1-b)}\cdot\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}$, and $E\left[\pi_R^{IB}\right]=\frac{\theta^2}{2(2-b)^2(1+b)}+\frac{(1+\lambda)\sigma^2}{4(1-b^2)}+\frac{(4+b^2-b^4)}{4(2+b)^2(2-b)^2(1+b)(1-b)}\cdot\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}+\frac{(4+b^2-b^4)}{4(2+b)^2(2-b)^2(1+b)(1-b)}\cdot\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}$.

Derivation of Table A5

Given the sales effort x and wholesale prices w_1^{SNB} and w_2^{SNB}, the retailer solves the following problem to maximize its profit: $\pi_R^{SNB}=q_1^{SNB}(1+x-q_1^{SNB}-bq_2^{SNB}-w_1^{SNB}+\epsilon_1)+q_2^{SNB}(1+x-bq_1^{SNB}-q_2^{SNB}-w_2^{SNB}+\epsilon_2)-\frac{kx^2}{2}$.

This yields $q_1^{SNB}=\frac{(1-b)(1+x)-w_1^{SNB}+bw_2^{SNB}+\epsilon_1-b\epsilon_2}{2(1-b^2)}$, $q_2^{SNB}=\frac{(1-b)(1+x)-w_2^{SNB}+bw_1^{SNB}+\epsilon_2-b\epsilon_1}{2(1-b^2)}$.

The manufacturers' optimal wholesale prices can be derived by maximizing $E\left[\pi_{M_1}^{SNB}\right]=w_1^{SNB}E\left[q_1^{SNB}\right]=\frac{[(1-b)(1+x)-w_1^{SNB}+bw_2^{SNB}]w_1^{SNB}}{2(1-b^2)}$; $E\left[\pi_{M_2}^{SNB}\right]=w_2^{SNB}E\left[q_2^{SNB}\right]=\frac{[(1-b)(1+x)-w_2^{SNB}+bw_1^{SNB}]w_2^{SNB}}{2(1-b^2)}$.

Solving the profit functions of manufacturers, we have the optimal wholesale prices: $w_1^{SNB}=w_2^{SNB}=\frac{(1-b)(1+x)}{2-b}$.

Substituting w_1^{SNB} and w_2^{SNB} into the retailer's profit function, we have the optimal sales effort $x=\frac{1}{(2-b)^2(1+b)k-1}$, based on which we obtain the other equilibriums as follows

$w_1^{SNB}=\frac{(2-b)(1-b)(1+b)k}{(2-b)^2(1+b)k-1}$; $w_2^{SNB}=\frac{(2-b)(1-b)(1+b)k}{(2-b)^2(1+b)k-1}$;

$q_1^{SNB}=\frac{((2-b)^2(1+b)k-1)(b\epsilon_2-\epsilon_1)-(2-b)(1-b)(1+b)k}{2(1-b^2)(1-4k+3b^2k-b^3k)}$;

$q_2^{SNB}=\frac{b((2-b)^2(1+b)k-1)\epsilon_1+(1-(2-b)^2(1+b)k)\epsilon_2-(2-b)(1-b)(1+b)k}{2(1-b^2)(1-4k+3b^2k-b^3k)}$;

$p_1^{SNB}=\frac{1}{2}\left(\frac{(2-b)(1+b)(3-2b)k}{(2-b)^2(1+b)k-1}+\epsilon_1\right)$; $p_2^{SNB}=\frac{1}{2}\left(\frac{(2-b)(1+b)(3-2b)k}{(2-b)^2(1+b)k-1}+\epsilon_2\right)$;

$E[q_1^{SNB}]=\frac{(2-b)(1-b)(1+b)k}{2(1-b^2)(4k-1-3b^2k+b^3k)}$; $E[q_2^{SNB}]=\frac{(2-b)(1-b)(1+b)k}{2(1-b^2)(4k-1-3b^2k+b^3k)}$

$$E[p_1^{SNB}]=E[p_2^{SNB}]=\frac{(2-b)(1+b)(3-2b)k}{2(2-b)^2(1+b)k-2}$$

Because the manufacturers' profit functions are based on expectation, we have

$$E[\pi_{M_1}^{SNB}]=w_1^{SNB}E[q_1^{SNB}]=\frac{(2-b)k((2-b)(1-b)(1+b)k)}{2((2-b)^2(1+b)k-1)^2};\ E\left[\pi_{M_2}^{SNB}\right]=w_2^{SNB}E\left[q_2^{SNB}\right]=\frac{(2-b)k((2-b)(1-b)(1+b)k)}{2((2-b)^2(1+b)k-1)^2}.$$

The retailer's profit is based on accurate demand information, so we substitute the outcomes with accurate demand information and derive its expected profit with information value as $E\left[\pi_R^{SNB}\right]=\left(1+x-q_1^{SNB}-bq_2^{SNB}+\epsilon_1-w_1^{SNB}\right)q_1^{SNB}+\left(1+x-q_2^{SNB}-bq_1^{SNB}+\epsilon_2-w_2^{SNB}\right)q_2^{SNB}=\frac{2(1-b^2)k-(1-(2-b)^2(1+b)k)(1+\lambda)\sigma^2}{4(1-b^2)((2-b)^2(1+b)k-1)}$.

Derivation of Table A6

Given the sales effort x and wholesale prices w_1^{SAB} and w_2^{SAB}, the retailer solves the following problem to maximize its profit: $\pi_R^{SAB}=q_1^{SAB}(\theta+x-q_1^{SAB}-bq_2^{SAB}-w_1^{SAB}+\epsilon_1)+q_2^{SAB}(\theta+x-bq_1^{SAB}-q_2^{SAB}-w_2^{SAB}+\epsilon_2)-\frac{kx^2}{2}$.

The best order quantities are $q_1^{SAB}=\frac{(1-b)(x+\theta)-w_1+bw_2+\epsilon_1-b\epsilon_2}{2(1-b^2)}$ and $q_2^{SAB}=\frac{(1-b)(x+\theta)+bw_1-w_2-b\epsilon_1+\epsilon_2}{2(1-b^2)}$. Anticipating the quantities above, the manufacturers maximize their profit functions by determining wholesale prices as

$w_1^{SAB}=\frac{(2-b-b^2)(x+\theta)+(2-b^2)\epsilon_1+b\epsilon_2}{4-b^2}$ and $w_2^{SAB}=\frac{(2-b-b^2)(x+\theta)+b\epsilon_1+(2-b^2)\epsilon_2}{4-b^2}$.

Substituting w_1^{SAB} and w_2^{SAB} into the retailer's profit function, we have the optimal sales effort $x=\frac{2\theta+\epsilon_1+\epsilon_2}{2(2-b)^2(1+b)k-2}$, based on which we could update the manufacturers' wholesale price decisions and retailer's order quantity decisions.

Therefore, the supply chain members' equilibrium outcomes are

$$w_1^{SAB}=\frac{(1+b)(2(b-2)(b-1)(2+b)k\theta+(2(b-2)(b^2-2)k-1)\epsilon_1+(1-2(2-b)bk)\epsilon_2)}{(2(2+b)(4k-3b^2k+b^3k-1))}$$

$$w_2^{SAB}=\frac{(1+b)(2(b-2)(b-1)(2+b)k\theta+(1-2(2-b)bk)\epsilon_1+(-1+2(-2+b)(-2+b^2)k)\epsilon_2)}{(2(2+b)(4k-3b^2k+b^3k-1))}$$

$$q_1^{SAB}=\frac{8bk\theta-8k\theta+2b^2k\theta-2b^3k\theta+\epsilon_1-8k\epsilon_1+4bk\epsilon_1+4b^2k\epsilon_1-2b^3k\epsilon_1-\epsilon_2+4bk\epsilon_2-2b^2k\epsilon_2}{4(2-b-b^2)(1-4k+3b^2k-b^3k)}$$

$$q_2^{SAB}=\frac{8bk\theta-8k\theta+2b^2k\theta-2b^3k\theta-\epsilon_1+4bk\epsilon_1-2b^2k\epsilon_1+\epsilon_2-8k\epsilon_2+4bk\epsilon_2+4b^2k\epsilon_2-2b^3k\epsilon_2}{4(2-b-b^2)(1-4k+3b^2k-b^3k)}$$

As a result, their expected profits are

$E[\pi_{M_1}^{SAB}]=\frac{(1+b)(4(2-b)^2(1-b)^2(2+b)^2k^2\theta^2+(\sigma-2(2-b)bk\sigma)^2+\lambda(\sigma-2(2-b)(2-b^2)k\sigma)^2)}{8(1-b)(2+b)^2(1-(2-b)^2(1+b)k)^2}$,

$E[\pi_{M_2}^{SAB}]=\frac{(1+b)(4(2-b)^2(1-b)^2(2+b)^2k^2\theta^2+\lambda(\sigma-2(2-b)bk\sigma)^2+(\sigma-2(2-b)(2-b^2)k\sigma)^2)}{8(1-b)(2+b)^2(1-(2-b)^2(1+b)k)^2}$, and $E\left[\pi_R^{SAB}\right]=\frac{4(b-1)(2+b)^2k\theta^2+(1-(8-6b^2)k)(1+\lambda)\sigma^2}{8(1-b)(2+b)^2(1-(2-b)^2(1+b)k)^2}$.

Till now, the outcomes in Table A6 are derived.

Derivation of Table A7

Given the wholesale prices w_1^{ANB} and w_2^{ANB}, the retailer solves the following problem to maximize its profit: $\pi_R^{ANB} = (1 - q_1^{ANB} - bq_2^{ANB} + \epsilon_1 - w_1^{ANB})q_1^{ANB} + (1 - q_2^{ANB} - q_1^{ANB} + \epsilon_2 - w_2^{ANB})q_2^{ANB}$.

This yields $q_1^{ANB} = \frac{(1-b)+2w_1^{ANB}+(1+b)w_2^{ANB}+2\epsilon_1-(1+b)\epsilon_2}{(1-b)(3+b)}$, $q_2^{ANB} = \frac{(1-b)+2w_2^{ANB}+(1+b)w_1^{ANB}+2\epsilon_2-(1+b)\epsilon_1}{(1-b)(3+b)}$.

The manufacturers' optimal wholesale prices can be derived by maximizing $E\left[\pi_{M_1}^{ANB}\right] = w_1^{ANB}E\left[q_1^{ANB}\right] = \frac{[(1-b)+2w_1^{ANB}+(1+b)w_2^{ANB}]w_1^{ANB}}{(1-b)(3+b)}$; $E\left[\pi_{M_2}^{ANB}\right] = w_2^{ANB}E\left[q_2^{ANB}\right] = \frac{[(1-b)+2w_2^{ANB}+(1+b)w_1^{ANB}]w_2^{ANB}}{(1-b)(3+b)}$.

Substituting q_1^{ANB} and q_2^{ANB} into the manufacturers' profit functions, we have the optimal wholesale prices: $w_1^{ANB} = w_2^{ANB} = 1 - \frac{2}{3-b}$, based on which we obtain the other equilibriums as follows

$$q_1^{ANB} = \frac{2(1-b)+2(3-b)\epsilon_1-(3-b)(1+b)\epsilon_2}{(3-b)(1-b)(3+b)}; q_2^{ANB} = \frac{2(1-b)-(3-b)(1+b)\epsilon_1+2(3-b)\epsilon_2}{(3-b)(1-b)(3+b)};$$

$$p_1^{ANB} = \frac{7-b(2+b)+(3-b)\epsilon_1+(3-b)\epsilon_2}{9-b^2}; p_2^{ANB} = \frac{(5-b^2)-(3-b)\epsilon_1+(3-b)(2+b)\epsilon_2}{9-b^2};$$

$E[q_1^{ANB}] = E[q_2^{ANB}] = \frac{2(1-b)}{(3-b)(1-b)(3+b)}$;

$$E[p_1^{ANB}] = \frac{7-b(2+b)}{9-b^2}; E[p_2^{ANB}] = \frac{(5-b^2)}{9-b^2}.$$

Because the manufacturers' profit functions are based on expectation, we have

$E[\pi_{M_1}^{ANB}] = w_1^{ANB}E[q_1^{ANB}] = \frac{2(1-b)}{(3-b)^2(3+b)}$;

$$E\left[\pi_{M_2}^{ANB}\right] = w_2^{ANB}E\left[q_2^{ANB}\right] = \frac{2(1-b)}{(3-b)^2(3+b)}$$

The retailer's profit is based on accurate demand information, so we substitute the outcomes with accurate demand information and derive its expected profit with information value as $E\left[\pi_R^{ANB}\right] = (1 - q_1^{ANB} - bq_2^{ANB} + \epsilon_1 - w_1^{ANB})q_1^{ANB} + (1 - q_2^{ANB} - q_1^{ANB} + \epsilon_2 - w_2^{ANB})q_2^{ANB} = \frac{4(1-b)+(3-b)^2(1+\lambda)\sigma^2}{(3-b)^2(1-b)(3+b)}$.

Derivation of Table A8

Given the wholesale price w_1^{AAB} and w_2^{AAB}, the retailer solves the following problem to maximize its profit: $\pi_R^{AAB} = (\theta - q_1^{AAB} - bq_2^{AAB} + \epsilon_1 - w_1^{AAB})q_1^{AAB} + (\theta - q_2^{AAB} - q_1^{AAB} + \epsilon_2 - w_2^{AAB})q_2^{AAB}$.

The best order quantities are $q_1^{AAB} = \frac{(1-b)\theta-2w_1+(1+b)w_2+2\epsilon_1-(1+b)\epsilon_2}{(1-b)(3+b)}$ and $q_2^{AAB} = \frac{(1-b)\theta-2w_2+(1+b)w_1+2\epsilon_2-(1+b)\epsilon_1}{(1-b)(3+b)}$. Anticipating the quantities above, the manufacturers maximize their profit functions by determining wholesale prices as

$w_1^{AAB} = \frac{(1-b)(5+b)\theta+(7-b(2+b))\epsilon_1-2(1+b)\epsilon_2}{(3-b)(5+b)}$ and $w_2^{AAB} = \frac{(1-b)(5+b)\theta-2(1+b)\epsilon_1+(7-b(2+b))\epsilon_2}{(3-b)(5+b)}$.

Therefore, the supply chain members' equilibrium outcomes are

$w_1^{AAB} = \frac{(1-b)(5+b)\theta+(7-b(2+b))\epsilon_1-2(1+b)\epsilon_2}{(3-b)(5+b)}$, $w_2^{AAB} = \frac{(1-b)(5+b)\theta-2(1+b)\epsilon_1+(7-b(2+b))\epsilon_2}{(3-b)(5+b)}$, $q_1^{AAB} = \frac{2((1-b)(5+b)\theta+(7-b(2+b))\epsilon_1-2(1+b)\epsilon_2)}{(3-b)(1-b)(3+b)(5+b)}$ and

$$q_2^{AAB} = \frac{2((1-b)(5+b)\theta-2(1+b)\epsilon_1+(7-b(2+b))\epsilon_2)}{(3-b)(1-b)(3+b)(5+b)}$$

As a result, their expected profits are

$$E[\pi_{M_1}^{AAB}] = \frac{2((5-4b-b^2)^2\theta^2+(7-2b-b^2)^2\sigma^2+4(1+b)^2\lambda\sigma^2)}{(3-b)^2(1-b)(3+b)(5+b)^2}$$

$E[\pi_{M_2}^{AAB}] = \frac{2((5-4b-b^2)^2\theta^2+4(1+b)^2\sigma^2+(7-2b-b^2)^2\lambda\sigma^2)}{(3-b)^2(1-b)(3+b)(5+b)^2}$, and

$$E\left[\pi_R^{AAB}\right] = \frac{4((1-b)(5+b)^2\theta^2+(13-3b(2+b))\sigma^2+(13-3b(2+b))\lambda\sigma^2)}{(3-b)^2(1-b)(3+b)(5+b)^2}$$

Till now, the outcomes in Table A8 are derived.

Derivation of Table A9

Given the wholesale prices w_1^{FNB} and w_2^{FNB}, the retailer solves the following problem to maximize its profit: $\pi_R^{FNB} = (1 - q_1^{FNB} - bq_2^{FNB} + \epsilon_1 - w_1^{FNB})q_1^{FNB} + (1 - q_2^{FNB} - q_1^{FNB} + \epsilon_2 - w_2^{FNB})q_2^{FNB}$.

This yields $q_1^{FNB} = \frac{1-b-w_1^{FNB}+bw_2^{FNB}+\epsilon_1-b\epsilon_2}{2-2b^2}$, $q_2^{FNB} = \frac{1-b-w_2^{FNB}+bw_1^{FNB}+\epsilon_2-b\epsilon_1}{2-2b^2}$.

The manufacturers' optimal wholesale prices can be derived by maximizing $E\left[\pi_{M_1}^{FNB}\right] = w_1^{FNB}E\left[q_1^{FNB}\right] = \frac{(1-b+m-w_1^{FNB}+bw_2^{FNB})w_1^{FNB}}{2-2b^2}$; $E\left[\pi_{M_2}^{FNB}\right] = w_2^{FNB}E\left[q_2^{FNB}\right] = \frac{(1-b-w_2^{FNB}+bw_1^{FNB}-bm)w_2^{FNB}}{2-2b^2}$.

Substituting q_1^{FNB} and q_2^{FNB} into the manufacturers' profit functions, we have the optimal wholesale prices: $w_1^{FNB} = \frac{2-b-b^2+(2-b^2)m}{4-b^2}$ and $w_2^{FNB} = \frac{2-b-b^2-bm}{4-b^2}$, based on which we obtain the other equilibriums as follows

$q_1^{FNB} = \frac{2(1-b)+2(3-b)\epsilon_1-(3-b)(1+b)\epsilon_2}{(3-b)(1-b)(3+b)}$; $q_2^{FNB} = \frac{2(1-b)-(3-b)(1+b)\epsilon_1+2(3-b)\epsilon_2}{(3-b)(1-b)(3+b)}$;

$p_1^{FNB} = \frac{7-b(2+b)+(3-b)\epsilon_1+(3-b)\epsilon_2}{9-b^2}$; $p_2^{FNB} = \frac{(5-b^2)-(3-b)\epsilon_1+(3-b)(2+b)\epsilon_2}{9-b^2}$;

$E[q_1^{FNB}] = \frac{2-b-b^2-2m+(4-b^2)(\epsilon_1+b\epsilon_2)}{2(4-5b^2+b^4)}$;

$$E[q_2^{FNB}] = \frac{(2-b-b^2)+b(3-b^2)m-b(4-b^2)\epsilon_1+(4-b^2)\epsilon_2}{2(4-5b^2+b^4)}$$

$E[p_1^{FNB}] = \frac{(6-b-2b^2)+(2-b^2)m+(4-b^2)\epsilon_1}{2(4-b^2)}$; $E[p_2^{FNB}] = \frac{\left(6-b-2b^2\right)-bm+(4-b^2)\epsilon_2}{2(4-b^2)}$.

Because the manufacturers' profit functions are based on expectation, we have

$E[\pi_{M_1}^{FNB}] = w_1^{FNB}E[q_1^{FNB}] = \frac{((2-b-b^2)+(2-b^2)m)(\left(2-b-b^2\right)-2m+(4-b^2)m)}{2\left(4-b^2\right)^2(1-b^2)}$; $E\left[\pi_{M_2}^{FNB}\right] = w_2^{FNB}E\left[q_2^{FNB}\right] = \frac{(\left(2-b-b^2\right)-bm)((2-b-b^2)+b(3-b^2)m-b(4-b^2)m)}{2\left(4-b^2\right)^2(1-b^2)}$.

The retailer's profit is based on accurate demand information, so we substitute the outcomes with accurate demand information and derive its expected profit with information value as $E\left[\pi_R^{FNB}\right] = (1 - q_1^{FNB} - bq_2^{FNB} + \epsilon_1 - w_1^{FNB})q_1^{FNB} + (1 - q_2^{FNB} - q_1^{FNB} + \epsilon_2 - w_2^{FNB})q_2^{FNB} = \frac{2(1-b)(2+b)^2+2(1-b)(2+b)^2m-\left(12-5b^2+b^4\right)m^2+\left(4-b^2\right)^2(2\sigma^2+m^2)}{4\left(4-b^2\right)^2(1-b^2)}$.

Derivation of Table A10

Given the wholesale price w_1^{FAB} and w_2^{FAB}, the retailer solves the following problem to maximize its profit: $\pi_R^{FAB} = (\theta - q_1^{FAB} - bq_2^{FAB} + \epsilon_1 - w_1^{FAB})q_1^{FAB} + (\theta - q_2^{FAB} - bq_1^{FAB} + \epsilon_2 - w_2^{FAB})q_2^{FAB}$.

The best order quantities are $q_1^{FAB} = \frac{(1-b)\theta-w_1^{FAB}+bw_2^{FAB}+\epsilon_1-b\epsilon_2}{2(1-b^2)}$ and $q_2^{FAB} = \frac{(1-b)\theta-w_2^{FAB}+bw_1^{FAB}+\epsilon_2-b\epsilon_1}{2(1-b^2)}$. Anticipating the quantities above, the manufacturers maximize their profit functions by determining wholesale prices as

$w_1^{FAB} = \frac{\left(2-b-b^2\right)\theta+\left(2-b^2\right)\epsilon_1-b\epsilon_2}{4-b^2}$ and $w_2^{FAB} = \frac{\left(2-b-b^2\right)\theta-b\epsilon_1+\left(2-b^2\right)\epsilon_2}{4-b^2}$.

Therefore, the supply chain members' equilibrium outcomes are $w_1^{FAB} = \frac{\left(2-b-b^2\right)\theta+\left(2-b^2\right)\epsilon_1-b\epsilon_2}{4-b^2}$, $w_2^{FAB} = \frac{\left(2-b-b^2\right)\theta-b\epsilon_1+\left(2-b^2\right)\epsilon_2}{4-b^2}$, $q_1^{FAB} = \frac{\left(2-b-b^2\right)\theta+\left(2-b^2\right)\epsilon_1-b\epsilon_2}{2(4-5b^2+b^4)}$, $q_2^{FAB} = \frac{\left(2-b-b^2\right)\theta+b\epsilon_1+\left(2-b^2\right)\epsilon_2}{2(4-5b^2+b^4)}$.

As a result, their expected profits are

$$E[\pi_{M_1}^{FAB}] = \frac{(2-b-b^2)^2\theta^2+2(4-2b-4b^2+b^3+b^4)\theta m+(2-b^2)^2(\sigma^2+m^2)+b^2\sigma^2}{2(4-b^2)^2(1-b^2)}$$

$E[\pi_{M_2}^{FAB}] = \frac{(2-b-b^2)^2\theta^2-2b(2-b-b^2)\theta m+b^2(\sigma^2+m^2)+(2-b^2)^2\sigma^2}{2(4-b^2)^2(1-b^2)}$, and $E\left[\pi_R^{FAB}\right] = \frac{2(1-b)(2+b)^2\theta(m+a\theta)+(4-3b^2)(2\sigma^2+m^2)}{4\left(4-b^2\right)^2(1-b^2)}$.

Till now, the outcomes in Table A10 are derived.

Derivation of Table A11

Given the wholesale prices w_1^{WNB} and w_2^{WNB}, the retailer solves the following problem to maximize its profit: $\pi_R^{WNB} = (1 - q_1^{WNB} - bq_2^{WNB} + \epsilon_1 - w_1^{WNB})q_1^{WNB} + (1 - q_2^{WNB} - bq_1^{WNB} + \epsilon_2 - w_2^{WNB})q_2^{WNB}$.

This yields $q_1^{WNB}=\frac{1-b-w_1^{WNB}+bw_2^{WNB}+\epsilon_1-b\epsilon_2}{2(1-b^2)}$, $q_2^{WNB}=\frac{1-b+bw_1^{WNB}-w_2^{WNB}-b\epsilon_1+\epsilon_2}{2(1-b^2)}$.

The manufacturers' optimal wholesale prices can be derived by maximizing $E\left[\pi_{M_1}^{WNB}\right]=w_1^{WNB}E\left[q_1^{WNB}\right]=\frac{(1-b-w_1^{WNB}+bw_2^{WNB})w_1^{NB}}{2(1-b^2)}$; $E\left[\pi_{M_2}^{WNB}\right]=w_2^{WNB}E\left[q_2^{WNB}\right]=\frac{(1-b-w_2^{WNB}+bw_1^{WNB})w_2^{WNB}}{2(1-b^2)}$.

Substituting q_1^{WNB} and q_2^{WNB} into the manufacturers' profit functions, we solve the optimal wholesale price: $w_2^{WNB}=\frac{1}{2}(1-b+bw_1^{WNB})$ first. Then, we solve the $w_1^{WNB}=\frac{(1-b)(2+b)}{2(2-b^2)}$ based on w_2^{WNB}. Therefore, we could obtain the updated w_2^{WNB} and other equilibriums as follows

$w_2^{WNB}=\frac{4-2b-3b^2+b^3}{4(2-b^2)}$;

$q_1^{WNB}=\frac{(2-b-b^2)+4\epsilon_1-4b\epsilon_2}{8(1-b^2)}$; $q_2^{WNB}=\frac{(1-b)(4+(2-b)b)-4b(2-b^2)\epsilon_1+4(2-b^2)\epsilon_2}{8(2-3b^2+b^4)}$;
$p_1^{WNB}=\frac{6-b-3b^2+4\epsilon_1-2b^2\epsilon_1}{4(2-b^2)}$; $p_2^{WNB}=\frac{12-2b-7b^2+b^3+8\epsilon_2-4b^2\epsilon_2}{8(2-b^2)}$;
$E[q_1^{WNB}]=\frac{(2-b-b^2)}{8(1-b^2)}$; $E[q_2^{WNB}]=\frac{(1-b)(4+(2-b)b)}{8(2-3b^2+b^4)}$;
$E[p_1^{WNB}]=\frac{6-b-3b^2}{4(2-b^2)}$; $E[p_2^{WNB}]=\frac{12-2b-7b^2+b^3}{8(2-b^2)}$.

Because the manufacturers' profit functions are based on expectation, we have

$$E[\pi_{M_1}^{WNB}]=w_1^{WNB}E[q_1^{WNB}]=\frac{(2+b)(2-b-b^2)}{16(1+b)(2-b^2)};\ E\left[\pi_{M_2}^{WNB}\right]=w_2^{WNB}E\left[q_2^{WNB}\right]=\frac{(1-b)(4+(2-b)b)^2}{32(1+b)(2-b^2)^2}.$$

The retailer's profit is based on accurate demand information, so we substitute the outcomes with accurate demand information and derive its expected profit with information value as $\pi_R^{WNB}=(1-q_1^{WNB}-bq_2^{WNB}+\epsilon_1-w_1^{WNB})q_1^{WNB}+(1-q_2^{WNB}-bq_1^{WNB}+\epsilon_2-w_2^{WNB})q_2^{WNB}=\frac{32-b^2(48+b(4-(3-b)b(7+3b)))+16(2-b^2)^2(1+\lambda)\sigma^2}{64(2-b^2)^2(1-b^2)}$.

Derivation of Table A12

Given the wholesale price w_1^{WAB} and w_2^{WAB}, the retailer solves the following problem to maximize its profit: $\pi_R^{WAB}=(\theta-q_1^{WAB}-bq_2^{WAB}+\epsilon_1-w_1^{WAB})q_1^{WAB}+(\theta-q_2^{WAB}-bq_1^{WAB}+\epsilon_2-w_2^{WAB})q_2^{WAB}$.

The best order quantities are $q_1^{WAB}=\frac{\theta-b\theta-w_1^{WAB}+bw_2^{WAB}+\epsilon_1-b\epsilon_2}{2(1-b^2)}$ and $q_2^{WAB}=\frac{\theta-b\theta+bw_1^{WAB}-w_2^{WAB}-b\epsilon_1+\epsilon_2}{2(1-b^2)}$. Anticipating the quantities above, the manufacturers maximize their profit functions by determining wholesale prices sequentially.

First, we maximize the profit function of M_2 and we have $w_2^{WAB}=\frac{1}{2}(\theta-b\theta+bw_1-b\epsilon_1+\epsilon_2)$. Then, substituting w_2^{WNB} into profit function, we could obtain $w_1^{WAB}=\frac{(2-b-b^2)\theta+(2-b^2)\epsilon_1+b\epsilon_1}{2(2-b^2)}$. And we are able to obtain the updated w_2^{WNB} based on w_1^{WAB}. Therefore, we have

$w_1^{WAB}=\frac{(2-b-b^2)\theta+(2-b^2)\epsilon_1+b\epsilon_1}{2(2-b^2)}$ and

$$w_2^{WAB}=\frac{(1-b)(4+(2-b)b)\theta+b(2-b^2)\epsilon_1-(4-3b^2)\epsilon_2}{4(2-b^2)}$$

Correspondingly, the supply chain members' equilibrium outcomes are $q_1^{WAB}=\frac{(2-b-b^2)\theta+(2-b^2)\epsilon_1-b\epsilon_2}{8(1-b^2)}$, $q_2^{WAB}=\frac{(1-b)(4+(2-b)b)\theta+b(2-b^2)\epsilon_1-(4-3b^2)\epsilon_2}{8(2-3b^2+b^4)}$.

As a result, their expected profits are $E[\pi_{M_1}^{WAB}]=\frac{(2-b-b^2)^2\theta^2+(2-b^2)^2\lambda\sigma^2+b^2\sigma^2}{16(1-b^2)(2-b^2)}$, $E[\pi_{M_2}^{WAB}]=\frac{(1-b)^2(4+(2-b)b)^2\theta^2+b^2(2-b^2)^2\lambda\sigma^2+(4-3b^2)^2\sigma^2}{32(2-b^2)^2(1-b^2)}$, and $E[\pi_R^{WAB}]=\frac{(32-b^2(48+b(4+(b-3)b(7+3b))))\theta^2-(2-b^2)^2(4-3b^2)\lambda\sigma^2-(16-20b^2+5b^4)\sigma^2}{64(2-b^2)^2(1-b^2)}$.

Appendix C:. Proofs

Proof of Proposition 1

Based on Table A1 and Table A2, the difference of the expected wholesale prices with and without blockchain is

$$E\left[w_1^{AB}\right]-E\left[w_1^{NB}\right]=\frac{(1-b)\theta}{2-b}-\frac{1-b}{2-b}=\frac{(1-b)(\theta-1)}{2-b}$$

Because the market potential with blockchain θ is larger than 1, and the manufacturers' competition intensity b is between 0 and 1, we know the items $2-b$, $1-b$ and $\theta-1$ are all positive. Therefore, $E[w_1^{AB}]-E[w_1^{NB}]>0$ always holds. Similarly, we can prove $E[w_2^{AB}]-E[w_2^{NB}]>0$.

Proof of Lemma 1

Based on Table A1 and Table A2, taking the first-order conditions with respect to b, we have $\frac{\partial(E[w_i^{AB}])}{\partial b}=-\frac{\theta}{(b-2)^2}<0$, $\frac{\partial(E[w_i^{NB}])}{\partial b}=-\frac{1}{(b-2)^2}<0$, and $\frac{\partial(E[w_i^{AB}])}{\partial b}-\frac{\partial(E[w_i^{NB}])}{\partial b}=-\frac{(\theta-1)}{(b-2)^2}<0$.
Therefore, it can be shown that $\frac{\partial(E[w_i^{AB}])}{\partial b}<\frac{\partial(E[w_i^{NB}])}{\partial b}<0$, and $\frac{\partial(E[w_i^{AB}]-E[w_i^{NB}])}{\partial b}=\frac{(1-\theta)}{(b-2)^2}<0$.

Proof of Proposition 2

The difference of the expected order quantities with and without blockchain is

$$E[q_i^{AB}]-E[q_i^{NB}]=\frac{\theta}{2(2-b)(1+b)}-\frac{1}{2(2-b)(1+b)}=\frac{(\theta-1)}{2(2-b)(1+b)}$$

Similarly, we find that the items $(\theta-1)$, $(2-b)$ and $(1+b)$ are all positive, so $E[q_i^{AB}]-E[q_i^{NB}]>0$ always holds.

Proof of Lemma 2

Taking the first-order conditions with respect to b, we have $\frac{\partial E[q_i^{AB}]}{\partial b}=\frac{(2b-1)\theta}{2(2-b)^2(1+b)^2}$, $\frac{\partial E[q_i^{NB}]}{\partial b}=\frac{2b-1}{2(2-b)^2(1+b)^2}$, and $\frac{\partial E[q_i^{AB}]}{\partial b}-\frac{\partial E[q_i^{NB}]}{\partial b}=\frac{(\theta-1)(2b-1)}{2(2-b)^2(1+b)^2}$.
Because the items $2(2-b)^2(1+b)^2$ and $(\theta-1)$ are positive, it is easy to show that $\frac{\partial E[q_i^{AB}]}{\partial b}<0$, $\frac{\partial E[q_i^{NB}]}{\partial b}<0$ and $\frac{\partial E[q_i^{AB}]}{\partial b}<\frac{\partial E[q_i^{NB}]}{\partial b}$ hold when $b<\frac{1}{2}$. We further conduct a sensitive analysis of $E[q_i^{AB}]-E[q_i^{NB}]$ with respect to b, and have $\frac{\partial(E[q_i^{AB}]-E[q_i^{NB}])}{\partial b}=\frac{(2b-1)(\theta-1)}{2(2-b)^2(1+b)^2}$. Thus, when $b<\frac{1}{2}$, we have $\frac{\partial(E[q_i^{AB}]-E[q_i^{NB}])}{\partial b}<0$; Otherwise, we have $\frac{\partial(E[q_i^{AB}]-E[q_i^{NB}])}{\partial b}>0$.

Proof of Proposition 3

Note that $E[p_i^{AB}]-E[w_i^{AB}]=\frac{\theta}{4-2b}$, and $E[p_i^{NB}]-E[w_i^{NB}]=\frac{1}{4-2b}$.
Because $\theta>1$, it can be shown that $E[p_i^{AB}]-E[w_i^{AB}]>E[p_i^{NB}]-E[w_i^{NB}]$ holds.

Proof of Lemma 3

Taking the first-order conditions of $(E[p_i^{AB}]-E[w_i^{AB}])$ and $(E[p_i^{NB}]-E[w_i^{NB}])$ with respect to b, we have

$\frac{\partial(E[p_i^{AB}]-E[w_i^{AB}])}{\partial b}=\frac{2\theta}{(4-2b)^2}>0$;

$\frac{\partial(E[p_i^{NB}]-E[w_i^{NB}])}{\partial b}=\frac{2}{(4-2b)^2}>0$;

$$\frac{\partial(E[p_i^{AB}]-E[w_i^{AB}])}{\partial b}-\frac{\partial(E[p_i^{NB}]-E[w_i^{NB}])}{\partial b}=\frac{2(\theta-1)}{(4-2b)^2}>0$$

Proof of Proposition 4

The difference between M_1's expected profits with and without blockchain is

$$E\left[\pi_{M_1}^{AB}\right]-E\left[\pi_{M_1}^{NB}\right]=\frac{(1-b)^2(2+b)^2\theta^2+\left(2-b^2\right)^2\lambda\sigma^2+b^2\sigma^2}{2(\mathrm{b}+2)^2(2-b)^2(1-\mathrm{b})(1+\mathrm{b})}-\frac{1-b}{2(2-b)^2(1+b)}=\frac{(1-b)^2(2+b)^2(\theta^2-1)+\left(b^2+\left(2-b^2\right)^2\lambda\right)\sigma^2}{2(b+2)^2(2-b)^2(1-b)(1+b)}$$

Since $\theta>1$, $b\in(0,1)$, $\lambda>0$ and $\sigma^2>0$, the items $(1-b)^2(2+b)^2(\theta^2-1)$, $\left(b^2+\left(2-b^2\right)^2\lambda\right)\sigma^2$ and $2(b+2)^2(2-b)^2(1-b)(1+b)$ are all positive, so $E\left[\pi_{M_1}^{AB}\right]-E\left[\pi_{M_1}^{NB}\right]>0$ always holds.

The difference between M_2's expected profits with and without blockchain is

$$E\left[\pi_{M_2}^{AB}\right]-E\left[\pi_{M_2}^{NB}\right]=\frac{(1-b)^2(2+b)^2\theta^2+\left(b^2-2\right)^2\sigma^2+b^2\lambda\sigma^2}{2(\mathrm{b}+2)^2(2-b)^2(1-\mathrm{b})(1+\mathrm{b})}-\frac{1-b}{2(2-b)^2(1+b)}$$
$$=\frac{(1-b)^2(2+b)^2(\theta-1)(\theta+1)+\left(4+b^4+b^2(\lambda-4)\right)\sigma^2}{2(\mathrm{b}+2)^2(2-b)^2(1-b)(1+\mathrm{b})}$$

Similarly, the items $(1-b)^2(2+b)^2(\theta-1)(\theta+1)$, $\left(4+b^4+b^2(\lambda-4)\right)\sigma^2$ and $2(\mathrm{b}+2)^2(2-b)^2(1-b)(1+\mathrm{b})$ are all positive, so $E\left[\pi_{M_2}^{AB}\right]-E\left[\pi_{M_2}^{NB}\right]>0$ always holds.

The difference between R's expected profits with and without blockchain is

$$E\left[\pi_R^{AB}\right]-E\left[\pi_R^{NB}\right]=\frac{2(1-b)^2(2+b)^2\theta^2+(4-3b^2)(1+\lambda)\sigma^2}{4\left(4-b^2\right)^2(1-b^2)}-\frac{2(1-b)+(2-b)^2(1+\lambda)\sigma^2}{4(2-b)^2(1-b^2)}$$

$$=\frac{2(1-b)(2+b)^2(\theta-1)(\theta+1)-(12-5b^2+b^4)(1+\lambda)\sigma^2}{4\left(4-b^2\right)^2(1-b^2)}$$

The item $4\left(4-b^2\right)^2(1-b^2)$ is positive. Let $\Phi=(1+\lambda)\sigma^2$. We find that $2(1-b)(2+b)^2(\theta-1)(\theta+1)-(12-5b^2+b^4)(1+\lambda)\sigma^2$ can be rewritten as $2(1-b)(2+b)^2(\theta-1)(\theta+1)-(12-5b^2+b^4)\Phi$.

It is easy to show that $2(1-b)(2+b)^2>0$ and $\left(12-5b^2+b^4\right)>0$. Let $2(1-b)(2+b)^2(\theta^2-1)-\left(12-5b^2+b^4\right)\Phi=0$ and it can be rewritten as $\frac{12-5b^2+b^4}{2(1-b)(2+b)^2}=\frac{(\theta^2-1)}{\Phi}$.

Define $f(b)=\frac{12-5b^2+b^4}{2(1-b)(2+b)^2}$, which is continuous when $b\in(0,1)$. Then, we have $\frac{\partial f(b)}{\partial b}=\frac{(2-b)b(8+9b+6b^2+b^3)}{2(1-b)^2(2+b)^3}>0$, which indicates that $f(b)$ is increasing in b. Therefore, $f(b)_{min}=f(0)=\frac{3}{2}$.

When $\frac{(\theta^2-1)}{\Phi}\leq\frac{3}{2}$, we find $\frac{12-5b^2+b^4}{2(1-b)(2+b)^2}>\frac{(\theta^2-1)}{\Phi}$ always holds. When $\frac{(\theta^2-1)}{\Phi}>\frac{3}{2}$, there exists a unique b_1 satisfying $\frac{12-5b_1^2+b_1^4}{2(1-b_1)(2+b_1)^2}=\frac{(\theta^2-1)}{\Phi}$. When $b<b_1$, we find $\frac{12-5b^2+b^4}{2(1-b)(2+b)^2}<\frac{(\theta^2-1)}{\Phi}$ holds. Therefore, when $\Phi<\Phi_1=\frac{2}{3}(\theta^2-1)$ and $\mathrm{b}<b_1$, we have $E\left[\pi_R^{AB}\right]-E\left[\pi_R^{NB}\right]>0$; Otherwise, we have $E\left[\pi_R^{AB}\right]-E\left[\pi_R^{NB}\right]<0$.

Proof of Corollary 1

The difference of R's deterministic value part in two scenarios is

$$E\left[\pi_{RD}^{AB}\right]-E\left[\pi_{RD}^{NB}\right]=\frac{\theta^2}{2(2-b)^2(1+b)}-\frac{1}{2(2-b)^2(1+b)}=\frac{\theta^2-1}{2(2-b)^2(1+b)};$$

Since $\theta>1$ and $b\in(0,1)$, the items θ^2-1 and $2(2-b)^2(1+b)$ are both positive, so $E\left[\pi_{RD}^{AB}\right]-E\left[\pi_{RD}^{NB}\right]>0$ always holds.

The difference between R's information value part in two scenarios is

$$E\left[\pi_{RI}^{AB}\right]-E\left[\pi_{RI}^{NB}\right]=\frac{\left(4-3b^2\right)\Phi}{4(\mathrm{b}+2)^2(2-\mathrm{b})^2(1-\mathrm{b})(1+\mathrm{b})}-\frac{\Phi}{4(1-\mathrm{b})(1+\mathrm{b})}=\frac{\left(5b^2-b^4-12\right)\Phi}{4(b+2)^2(2-b)^2(1-b)(1+b)}<0$$

Similarly, the item $(5b^2-b^4-12)\Phi$ is negative while item $4(b+2)^2(2-\mathrm{b})^2(1-b)(1+b)$ is positive, so $E\left[\pi_{RI}^{AB}\right]-E\left[\pi_{RI}^{NB}\right]<0$ always holds.

Proof of Lemma 4

Substituting the equilibrium outcomes in NB scenario into $TS_{NB}(q_1,q_2)=q_1^{NB}+q_2^{NB}-\frac{1}{2}\left(q_1^{NB^2}+2bq_1^{NB}q_2^{NB}+q_2^{NB^2}\right)$, we derive the expected total surplus as:

$$E[TS_{NB}(q_1,q_2)]=\frac{2(1-b)(7-4b)-(2-b)^2\Phi}{8(2-b)^2(1-\mathrm{b})(1+\mathrm{b})}$$

Correspondingly, the expected customer surplus in NB scenario is

$$CS_{NB}=U_{NB}(q_1,q_2)-E\left[\pi_{M_1}^{NB}\right]-E\left[\pi_{M_2}^{NB}\right]-E\left[\pi_R^{NB}\right]=\frac{2(1-b)-3(2-b)^2\Phi}{8(2-b)^2(1-\mathrm{b})(1+\mathrm{b})}$$

Proof of Lemma 5

Substituting the equilibrium outcomes in AB scenario into $TS_{AB}(q_1,q_2) = \theta(q_1^{AB}+q_2^{AB}) - \frac{1}{2}({q_1^{AB}}^2 + 2bq_1^{AB}q_2^{AB} + {q_2^{AB}}^2)$, we derive the expected total surplus as:

$$E[TS_{AB}(q_1,q_2)] = \frac{2(1-b)(2+b)^2(7-4b)\theta^2 + (4-3b^2)\Phi}{8(\mathrm{b}+2)^2(\mathrm{b}-2)^2(1-\mathrm{b})(1+\mathrm{b})}$$

Correspondingly, the expected customer surplus in AB scenario is

$$CS_{NB} = U_{NB}(q_1,q_2) - E[\pi_{M_1}^{NB}] - E[\pi_{M_2}^{NB}] - E[\pi_R^{NB}] = \frac{2(1-b)(2+b)^2\theta^2 + (28-21b^2+4b^4)\Phi}{8(\mathrm{b}+2)^2(\mathrm{b}-2)^2(1-\mathrm{b})(1+\mathrm{b})}$$

Proof of Proposition 5

The difference between the expected total surplus in two scenarios is

$$E[TS_{AB}] - E[TS_{NB}] = \frac{2(1-b)(2+b)^2(7-4b)(\theta-1)(1+\theta) + (20-11b^2+b^4)\Phi}{8(\mathrm{b}+2)^2(2-\mathrm{b})^2(1-\mathrm{b})(1+\mathrm{b})}$$

Since $\theta > 1$, $b \in (0,1)$ and $\Phi > 0$, the items $2(1-b)(2+b)^2(7-4b)(\theta-1)(1+\theta)$, $(20-11b^2+b^4)\Phi$ and $8(\mathrm{b}+2)^2(2-\mathrm{b})^2(1-\mathrm{b})(1+\mathrm{b})$ are all positive, so $E[TS_{AB}] - E[TS_{NB}] > 0$ always holds.

The difference in the expected customer surplus in two scenarios is

$$E[CS_{AB}] - E[CS_{NB}] = \frac{2(1-b)(2+b)^2(\theta-1)(1+\theta) + \left(20-b^4-3b^2\right)\Phi}{8(b+2)^2(b-2)^2(1-b)(1+b)}$$

Similarly, items $2(1-b)(2+b)^2(\theta-1)(1+\theta)$, $\left(20-b^4-3b^2\right)\Phi$ and $8(b+2)^2(b-2)^2(1-b)(1+b)$ are all positive, so $E[CS_{AB}] - E[CS_{NB}] > 0$ always holds.

Taking the first-order conditions of $(E[CS_{AB}] - E[CS_{NB}])$ with respect to b, we have

$$\frac{\partial(E[CS_{AB}] - E[CS_{NB}])}{\partial b} = \frac{3(1-\mathrm{b})^2(1+\mathrm{b})^2 b(2+b)^3(\theta-1)(1+\theta) + b\left(108-71b^2+10b^4+b^6\right)\Phi}{4\left(4-b^2\right)^3\left(1-b^2\right)^2}$$

The items $3(1-\mathrm{b})^2(1+\mathrm{b})^2 b(2+b)^3(\theta-1)(1+\theta)$, $b\left(108-71b^2+10b^4+b^6\right)\Phi$ and $4\left(4-b^2\right)^3\left(1-b^2\right)^2$ are all positive, so $\frac{\partial(E[CS_{AB}]-E[CS_{NB}])}{\partial b} > 0$ always holds.

Proof of Lemma 6

Comparing the equilibrium outcomes in BC scenario with those in NB scenario, we have

$E\left[w^{BC}\right] - E\left[w^{NB}\right] = \frac{b(1+c-\theta)+\theta-1}{2-b} = \frac{(1-b)(\theta-1)+bc}{2-b} > 0$;

$E[q_1^{BC}] - E[q_1^{NB}] = E[q_2^{BC}] - E[q_2^{NB}] = \frac{\theta-1-2c}{2(2-b)(1+b)}$. Therefore, when $c < \frac{1}{2}(\theta-1)$, we have $\frac{\theta-1-2c}{2(2-b)(1+b)} > 0$; Otherwise, we have $\frac{\theta-1-2c}{2(2-b)(1+b)} < 0$.

$$E\left[p_1^{BC}\right] - E\left[p_1^{NB}\right] = E\left[p_2^{BC}\right] - E\left[p_2^{NB}\right] = \frac{3-2c+2b(\theta-1)-3\theta}{2(b-2)} = \frac{(3-2b)(\theta-1)+2c}{2(2-b)} > 0$$

Proof of Proposition 6

Comparing M_1's expected profits in IB scenario and that in NB scenario, we have

$$E\left[\pi_{M_1}^{IB}\right] - E\left[\pi_{M_1}^{NB}\right] = \frac{1}{2}\left(\frac{b-1}{(2-b)^2(1+b)} + \frac{(1-b)\theta^2}{(1+b)(2-b)^2} + \frac{2\left(b^2-2\right)}{\left(1-b^2\right)\left(4-b^2\right)^2}\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2} + \frac{b^2(b^2-3)}{(1-b^2)(4-b^2)^2}\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}\right)$$

Since $\frac{\partial\left(E\left[\pi_{M_1}^{IB}\right] - E\left[\pi_{M_1}^{NB}\right]\right)}{\partial\theta} = \frac{(1-b)\theta}{(1+b)(2-b)^2} > 0$, we find $E\left[\pi_{M_1}^{IB}\right] - E\left[\pi_{M_1}^{NB}\right]$ is increasing in θ. When $\theta > \theta_1 =$

$\sqrt{1+\frac{4-2b^2}{(b-1)^2(b+2)^2}\bullet\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}+\frac{3b^2-b^4}{(b-1)^2(b+2)^2}\bullet\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}}$, it can be shown that $E\left[\pi_{M_1}^{IB}\right]-E\left[\pi_{M_1}^{NB}\right]>0$; Otherwise, we have $E\left[\pi_{M_1}^{IB}\right]-E\left[\pi_{M_1}^{NB}\right]<0$.

Similarly, comparing M_2's expected profits in IB scenario and that in NB scenario, we have

$$E\left[\pi_{M_2}^{IB}\right]-E\left[\pi_{M_2}^{NB}\right]=\frac{1}{2}\left(\frac{b-1}{(2-b)^2(1+b)}+\frac{(1-b)\theta^2}{(1+b)(2-b)^2}+\frac{2\left(b^2-2\right)}{\left(1-b^2\right)\left(4-b^2\right)^2}\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}+\frac{b^2\left(b^2-3\right)}{(1-b^2)(4-b^2)^2}\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}\right)$$

Similarly, since $\frac{\partial\left(E\left[\pi_{M_1}^{IB}\right]-E\left[\pi_{M_1}^{NB}\right]\right)}{\partial\theta}=\frac{(1-b)\theta}{(1+b)(2-b)^2}>0$, it can be shown that $E\left[\pi_{M_2}^{IB}\right]-E\left[\pi_{M_2}^{NB}\right]$ is increasing in θ. When $\theta>\theta_2=\sqrt{1+\frac{3b^2-b^4}{(b-1)^2(b+2)^2}\bullet\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}+\frac{4-2b^2}{(b-1)^2(b+2)^2}\bullet\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}}$, we have $\left[\pi_{M_2}^{IB}\right]-E\left[\pi_{M_2}^{NB}\right]>0$; Otherwise, we have $E\left[\pi_{M_2}^{IB}\right]-E\left[\pi_{M_2}^{NB}\right]<0$.

Similarly, comparing R's expected profits in IB scenario and that in NB scenario, we have

$$E\left[\pi_R^{IB}\right]-E\left[\pi_R^{NB}\right]=\frac{\left(8-2b^3-b^2\right)\left(\theta^2-1\right)}{4\left(4-b^2\right)^2\left(1-b^2\right)}+\frac{4-b^4+b^2}{4\left(4-b^2\right)^2\left(1-b^2\right)}\left(\frac{\lambda\sigma_o^2\sigma^2}{\lambda\sigma^2+\sigma_o^2}+\frac{\sigma_o^2\sigma^2}{\sigma^2+\sigma_o^2}\right)>0$$

Proof of Proposition 7

With the retailer's sales effort, the difference between the profit of M_1 in two scenarios is

$$E\left[\pi_{M_1}^{SAB}\right]-E\left[\pi_{M_1}^{SNB}\right]=\frac{(1+b)(4(2-b)^2(1-b)^2(2+b)^2k^2(1-\theta^2)-\sigma^2+(4(2-b)bk(1-(2-b)bk)+(1-2(2-b)(2-b^2)k)^2\lambda)\sigma^2)}{8(1-b)(2+b)^2(4k+b^3k-1-3b^2k)^2}$$

We have $8(1-b)(2+b)^2\left(4k+b^3k-1-3b^2k\right)^2>0$ and the signs of $E\left[\pi_{M_1}^{SAB}\right]-E\left[\pi_{M_1}^{SNB}\right]$ depends on $(1+b)(4(2-b)^2(1-b)^2(2+b)^2k^2(1-\theta^2)-\sigma^2+(4(2-b)bk(1-(2-b)bk)+(1-2(2-b)(2-b^2)k)^2\lambda)\sigma^2)$.

We define $f(\lambda)=(1+b)\left(1-2(2-b)\left(2-b^2\right)k\right)^2\lambda\sigma^2+(1+b)\left(4(2-b)^2(1-b)^2(2+b)^2k^2\left(\theta^2-1\right)+\sigma^2+4(2-b)bk(1-(2-b)bk)\sigma^2\right)$ which is a liner function of λ. Because $\frac{\partial f(\lambda)}{\partial\lambda}=-(1+b)\left(1-2(2-b)\left(2-b^2\right)k\right)^2\sigma^2<0$, we have $f(\lambda)$ decreases in λ and $f(\lambda)>\lim_{\lambda\to1}f(\lambda)$ holds for $0<\lambda<1$.

Since $(1+b)\left(\sigma-2(-2+b)\left(-2+b^2\right)k\sigma\right)^2>0$ and $4(2-b)^2(1-b)^2(2+b)^2k^2\left(\theta^2-1\right)+(\sigma-2(2-b)bk\sigma)^2>0$, We have $\lim_{\lambda\to1}f(\lambda)=(1+b)\left(\sigma-2(-2+b)\left(-2+b^2\right)k\sigma\right)^2+(1+b)\left(4(2-b)^2(1-b)^2(2+b)^2k^2\left(\theta^2-1\right)+(\sigma-2(2-b)bk\sigma)^2\right)>0$. As a result, $f(\lambda)>\lim_{\lambda\to1}f(\lambda)>0$ which means that $(1+b)\left(4(2-b)^2(1-b)^2(2+b)^2k^2\left(1-\theta^2\right)-\sigma^2+\left(4(2-b)bk(1-(2-b)bk)+\left(1-2(2-b)\left(2-b^2\right)k\right)^2\lambda\right)\sigma^2\right)>0$.

Therefore, we have $E\left[\pi_{M_1}^{SAB}\right]-E\left[\pi_{M_1}^{SNB}\right]>0$.

With the retailer's sales effort, the difference between the profit of M_2 in two scenarios is

$$E\left[\pi_{M_2}^{SAB}\right]-E\left[\pi_{M_2}^{SNB}\right]=\frac{(1+b)((1+\lambda)\sigma^2-4(2-b)k(2-b^2+b\lambda)\sigma^2+4(2-b)^2k^2((2-b-b^2)^2(\theta^2-1)+(4+b^4-b^2(4-\lambda))\sigma^2))}{8(1-b)(2+b)^2(4k-1-3b^2k+b^3k)^2}$$

The signs of $E\left[\pi_{M_2}^{SAB}\right]-E\left[\pi_{M_2}^{SNB}\right]$ depend on $(1+b)((1+\lambda)\sigma^2-4(2-b)k(2-b^2+b\lambda)\sigma^2+4(2-b)^2k^2((2-b-b^2)^2(\theta^2-1)+(4+b^4-b^2(4-\lambda))\sigma^2))$ for $8(1-b)(2+b)^2\left(4k-1-3b^2k+b^3k\right)^2>0$. Rewrite the expression of $(1+b)((1+\lambda)\sigma^2-4(2-b)k(2-b^2+b\lambda)\sigma^2+4(2-b)^2k^2((2-b-b^2)^2(\theta^2-1)+(4+b^4-b^2(4-\lambda))\sigma^2))$ and we define $g(\lambda)=4(2-b)^2((2-b-b^2)^2k^2(\theta^2-1)+\sigma^2-8(2-b)k\sigma^2+4(2-b)b^2k\sigma^2+16(2-b)^2k^2\sigma^2-16(2-b)^2b^2k^2\sigma^2+4(2-b)^2b^4k^2\sigma^2+\lambda(\sigma^2-4(2-b)bk\sigma^2+4(2-b)^2b^2k^2\sigma^2)$.

Taking the first order condition with respect to λ, we have $\frac{\partial g(\lambda)}{\partial\lambda}=(\sigma^2+4(-2+b)bk\sigma^2+4(-2+b)^2b^2k^2\sigma^2)$.

Define $y(k)=\sigma^2+k(4b^2\sigma^2-8b\sigma^2)+k^2(16b^2\sigma^2-16b^3\sigma^2+4b^4\sigma^2)$ which is a quadratic function of k. We have $\frac{\partial y(k)}{\partial k}=(4b^2\sigma^2-8b\sigma^2)+2k(16b^2\sigma^2-16b^3\sigma^2+4b^4\sigma^2)$ and $\frac{\partial^2y(k)}{\partial k^2}=2(16b^2\sigma^2-16b^3\sigma^2+4b^4\sigma^2)$. Because $\frac{\partial^2y(k)}{\partial k^2}>0$, $\frac{\partial y(k)}{\partial k}$ increases in k and $\frac{\partial y(k)}{\partial k}>\lim_{k\to0}\frac{\partial y(k)}{\partial k}$ holds.

We have $\lim_{k\to0}\frac{\partial y(k)}{\partial k}=(4b^2\sigma^2-8b\sigma^2)$ and $\frac{\partial y(k)}{\partial k}>0$ only when $k>\frac{1}{2b-b^2}$. That is, $y(k)$ has the minimum value $y(k)=\sigma^2$for $k=\frac{1}{2b-b^2}$. Then, we have $y(k)>0$.

As a result, $\frac{\partial g(\lambda)}{\partial\lambda}>0$ always hold and we have $g(\lambda)>\lim_{\lambda\to0}g(0)$.

Because $\lim_{\lambda\to 0} g(0) = 4(2-b)^2(1-b)^2(2+b)^2k^2(\theta^2-1) + \left(\sigma - 2(2-b)\left(2-b^2\right)k\sigma\right)^2 > 0$, we have $g(\lambda) > 0$ for $\lambda \in (0,1)$ Therefore, $(1+b)\left((1+\lambda)\sigma^2 - 4(2-b)k\left(2-b^2+b\lambda\right)\sigma^2 + 4(2-b)^2k^2\left(\left(2-b-b^2\right)^2(\theta^2-1) + \left(4+b^4-b^2(4-\lambda)\right)\sigma^2\right)\right) > 0$ holds and $E\left[\pi_{M_2}^{SAB}\right] - E\left[\pi_{M_2}^{SNB}\right] > 0$ can be proven.

Proof of Proposition 8

Given asymmetric b, the difference between M_1's profit in two scenarios is

$$E\left[\pi_{M_1}^{AAB}\right] - E\left[\pi_{M_1}^{ANB}\right] = \frac{2(1-b)^2(5+b)^2(\theta^2-1) + 2(4(1+b)^2 + (7-b(2+b))^2\lambda)\sigma^2}{(3-b)^2(1-b)(3+b)(5+b)^2}$$

Because $(3-b)^2(1-b)(3+b)(5+b)^2 > 0$ and $2(1-b)^2(5+b)^2(\theta^2-1) + 2\left(4(1+b)^2 + (7-b(2+b))^2\lambda\right)\sigma^2 > 0$, we have $E\left[\pi_{M_1}^{AAB}\right] - E\left[\pi_{M_1}^{ANB}\right] > 0$.

The difference between M_2's profit in two scenarios is

$$E\left[\pi_{M_2}^{AAB}\right] - E\left[\pi_{M_2}^{ANB}\right] = \frac{4(1-b)(5+b)^2(\theta^2-1) + (173-36b-14b^2+4b^3+b^4)(1+\lambda)\sigma^2}{(3-b)^2(1-b)(3+b)(5+b)^2}$$

Because $173-36b-14b^2+4b^3+b^4 > 173-36b-14b^2 > 120$, $(3-b)^2(1-b)(3+b)(5+b)^2 > 0$ and $4(1-b)(5+b)^2(\theta^2-1) > 0$, we have $E\left[\pi_{M_2}^{AAB}\right] - E\left[\pi_{M_2}^{ANB}\right] > 0$.

The difference between the retailer's profit in two scenarios is

$$E\left[\pi_R^{AAB}\right] - E\left[\pi_R^{ANB}\right] = \frac{4(1-b)(5+b)^2(\theta^2-1) - (173+b(2+b)(b(2+b)-18))\Phi}{(3-b)^2(1-b)(3+b)(5+b)^2}$$

Because $(3-b)^2(1-b)(3+b)(5+b)^2 > 0$, the signs of $E\left[\pi_R^{AAB}\right] - E\left[\pi_R^{ANB}\right]$ depend on $4(1-b)(5+b)^2(\theta^2-1) - (173+b(2+b)(b(2+b)-18))\Phi$, which can be rewritten as $-100(-1+\theta^2) + b(60(-1+\theta^2) - 36\Phi) + b^2(36(-1+\theta^2) - 14\Phi) + 173\Phi + b^3(4(-1+\theta^2) + 4\Phi) + b^4\Phi$.

It is easy to show that $4(1-b)(5+b)^2 > 0$ and $(173+b(2+b)(b(2+b)-18)) > 0$. Let $4(1-b)(5+b)^2(\theta^2-1) - (173+b(2+b)(b(2+b)-18))\Phi = 0$ and it can be rewritten as $\frac{(173+b(2+b)(b(2+b)-18))}{4(1-b)(5+b)^2} = \frac{(\theta^2-1)}{\Phi}$.

Define $t(b) = \frac{(173+b(2+b)(b(2+b)-18))}{4(1-b)(5+b)^2}$, which is continuous when $b \in (0,1)$. Then, we have $\frac{\partial t(b)}{\partial b} = \frac{339+415b+58b^2-30b^3-13b^4-b^5}{4(1-b)^2(5+b)^3} > 0$, which indicates that $t(b)$ is increasing in b. Therefore, $t(b)_{min} = t(0) = \frac{173}{100}$.

When $\frac{(\theta^2-1)}{\Phi} \le \frac{173}{100}$, we find $\frac{(173+b(2+b)(b(2+b)-18))}{4(1-b)(5+b)^2} > \frac{(\theta^2-1)}{\Phi}$ always holds. When $\frac{(\theta^2-1)}{\Phi} > \frac{173}{100}$, there exists a unique b_{A1} satisfying $\frac{(173+b(2+b)(b(2+b)-18))}{4(1-b)(5+b)^2} = \frac{(\theta^2-1)}{\Phi}$. When $b < b_{A1}$, we find $\frac{(173+b(2+b)(b(2+b)-18))}{4(1-b)(5+b)^2} < \frac{(\theta^2-1)}{\Phi}$ holds. Therefore, when $\Phi < \Phi_{A1} = \frac{100}{173}(\theta^2-1)$, and $b < b_{A1}$, we have $E\left[\pi_R^{AAB}\right] - E\left[\pi_R^{ANB}\right] > 0$.

Proof of Proposition 9

Given M_1's the expectation of demand m, the difference between M_1's profit in two scenarios is

$$E\left[\pi_{M_1}^{FAB}\right] - E\left[\pi_{M_1}^{FNB}\right] = \frac{(2-b-b^2)(\theta-1)(2(1+2m+\theta) + b(1+\theta+b(1+2m+\theta))) + (4-3b^2+b^4)\sigma^2}{2\left(4-b^2\right)^2(1-b^2)}$$

Because $2\left(4-b^2\right)^2(1-b^2) > 0$, the signs of $E\left[\pi_{M_1}^{AAB}\right] - E\left[\pi_{M_1}^{ANB}\right]$ depend on $(2-b-b^2)(\theta-1)(2(1+2m+\theta) + b(1+\theta+b(1+2m+\theta))) + (4-3b^2+b^4)\sigma^2$. We have $(2-b-b^2) > 2(1-b) > 0$and $(4-3b^2+b^4)\sigma^2 > (4-3b+b)\sigma^2 > 2\sigma^2 > 0$, therefore $(2-b-b^2)(\theta-1)(2(1+2m+\theta) + b(1+\theta+b(1+2m+\theta))) + (4-3b^2+b^4)\sigma^2 > 0$ holds. As a result, $E\left[\pi_{M_1}^{FAB}\right] - E\left[\pi_{M_1}^{FNB}\right] > 0$ can be proven.

The difference between M_2's profit in two scenarios is

$$E\left[\pi_{M_2}^{FAB}\right] - E\left[\pi_{M_2}^{FNB}\right] = \frac{(2b^3-4b)(1+m+m\theta+\theta^2) + (4+b^4)(1+\theta^2+\sigma^2) + b^2(2m^2+2m(1+\theta) - 3(1+\theta^2+\sigma^2))}{2\left(4-b^2\right)^2(1-b^2)}$$

Because $2\left(4-b^2\right)^2(1-b^2) > 0$, the signs of $E\left[\pi_{M_2}^{FAB}\right] - E\left[\pi_{M_2}^{FNB}\right]$ depend on $(2b^3-4b)(1+m+m\theta+\theta^2) + 4(1+\theta^2+\sigma^2) + b^4(1+\theta^2+\sigma^2) + b^2(2m^2+2m(1+\theta) - 3(1+\theta^2+\sigma^2))$, which can be rewritten as a quadratic function of θ.

We define $L(\theta) = 4(1+\sigma^2) - 4b(1+m) + b^2\left(2b(1+m) + 2m(1+m) - 3(1+\sigma^2) + b^2(1+\sigma^2)\right) - (4bm - 2b^2m - 2b^3m)\theta + (4 - 4b - 3b^2 + 2b^3 + b^4)\theta^2$. It is easy to show that $L(\theta)$ increases in θ when $\theta > \frac{bm}{2-b-b^2}$. Therefore, we have $L(\theta) > Min\{\lim_{\theta\to 1} L(\theta), L\left(\frac{bm}{2-b-b^2}\right)\}$ for any $\theta > 1$.

We have $L(1) = 2(b(1+b+m)-2)^2 + \left(4 - 3b^2 + b^4\right)\sigma^2 > 0$ and $L\left(\frac{bm}{2-b-b^2}\right) = (b(1+b+m)-2)^2 + \left(4 - 3b^2 + b^4\right)\sigma^2 > 0$. Therefore, $L(\theta) > 0$ holds and $E\left[\pi_{M_2}^{FAB}\right] - E\left[\pi_{M_2}^{FNB}\right] > 0$ can be proven.

The difference between R's profit in two scenarios is

$$E\left[\pi_R^{FAB}\right] - E\left[\pi_R^{FNB}\right] = \frac{(1-b)(2+b)^2(\theta-1)(1+m+\theta) - (12 - 5b^2 + b^4)\sigma^2}{2\left(4-b^2\right)^2(1-b^2)}$$

Because $2\left(4-b^2\right)^2(1-b^2) > 0$, the signs of $E\left[\pi_R^{FAB}\right] - E\left[\pi_R^{FNB}\right]$ depend on $(1-b)(2+b)^2(\theta-1)(1+m+\theta) - (12 - 5b^2 + b^4)\sigma^2$. It is easy to show that $(1-b)(2+b)^2 > 0$ and $(12 - 5b^2 + b^4) > 0$. Let $(1-b)(2+b)^2(\theta-1)(1+m+\theta) - (12 - 5b^2 + b^4)\sigma^2 = 0$ and it can be rewritten as $\frac{12-5b^2+b^4}{(1-b)(2+b)^2} = \frac{(\theta-1)(1+m+\theta)}{\sigma^2}$.

Define $K(b) = \frac{12-5b^2+b^4}{(1-b)(2+b)^2}$, which is continuous when $b \in (0,1)$. Then, we have $\frac{\partial K(b)}{\partial b} = \frac{(2-b)b(8+b(3+b)^2)}{(1-b)^2(2+b)^3} > 0$, which indicates that $K(b)$ is increasing in b. Therefore, $K(b)_{min} = K(0) = 3$.

When $\frac{(\theta-1)(1+m+\theta)}{\sigma^2} \leq 3$, we find $\frac{12-5b^2+b^4}{(1-b)(2+b)^2} > \frac{(\theta-1)(1+m+\theta)}{\sigma^2}$ always holds. When $\frac{(\theta-1)(1+m+\theta)}{\sigma^2} > 3$, there exists a unique b_{F1} satisfying $\frac{12-5b^2+b^4}{(1-b)(2+b)^2} = \frac{(\theta-1)(1+m+\theta)}{\sigma^2}$. When $b < b_{F1}$, we find $\frac{12-5b^2+b^4}{(1-b)(2+b)^2} < \frac{(\theta-1)(1+m+\theta)}{\sigma^2}$ holds. Therefore, when $\sigma < \sqrt{\frac{m\theta+\theta^2-1-m}{3}}$, and b $< b_{F1}$, we have $E\left[\pi_R^{FAB}\right] - E\left[\pi_R^{FNB}\right] > 0$.

Proof of Proposition 10

Facing a sequential wholesale price, the difference between M_1's profit in two scenarios is

$$E\left[\pi_{M_1}^{WAB}\right] - E\left[\pi_{M_1}^{WNB}\right] = \frac{(2-b-b^2)^2(\theta^2-1) + (b^2 + (2-b^2)^2\lambda)\sigma^2}{16(2-b^2)(1-b^2)}$$

Because $(2-b-b^2)^2(\theta^2-1) + \left(b^2 + (2-b^2)^2\lambda\right)\sigma^2 > 0$ and $16(2-b^2)(1-b^2) > 0$, we have $E\left[\pi_{M_1}^{WAB}\right] - E\left[\pi_{M_1}^{WNB}\right] > 0$.

The difference between M_2's profit in two scenarios is

$$E\left[\pi_{M_2}^{WAB}\right] - E\left[\pi_{M_2}^{WNB}\right] = \frac{(1-b)^2(4+(2-b)b)^2(\theta^2-1) + ((4-3b^2)^2 + b^2(2-b^2)^2\lambda)\sigma^2}{32(2-b^2)^2(1-b^2)}$$

Because $(1-b)^2(4+(2-b)b)^2(\theta^2-1) + \left((4-3b^2)^2 + b^2(2-b^2)^2\lambda\right)\sigma^2 > 0$ and $32(2-b^2)^2(1-b^2) > 0$, we have $E\left[\pi_{M_2}^{WAB}\right] - E\left[\pi_2^{WNB}\right] > 0$.

The difference between R's profit in two scenarios is

$$E\left[\pi_R^{WAB}\right] - E\left[\pi_R^{WNB}\right] = \frac{\left(32 - b^2\left(48 + 4b - 21b^2 - 2b^3 + 3b^4\right)\right)(\theta^2-1) - (11b^4 + 3b^6\lambda + 48(1+\lambda) - 4b^2(11+9\lambda))\sigma^2}{64\left(2-b^2\right)^2(1-b^2)}$$

Because $64\left(2-b^2\right)^2(1-b^2) > 0$, the signs of $E\left[\pi_R^{WAB}\right] - E\left[\pi_R^{WNB}\right]$ depend on $\left(32 - b^2\left(48 + 4b - 21b^2 - 2b^3 + 3b^4\right)\right)(\theta^2-1) - (11b^4 + 3b^6\lambda + 48(1+\lambda) - 4b^2(11+9\lambda))\sigma^2$. It is easy to show that $32 - b^2\left(48 + 4b - 21b^2 - 2b^3 + 3b^4\right) > 0$ and $11b^4 + 3b^6\lambda + 48(1+\lambda) - 4b^2(11+9\lambda) > 0$. Let $\left(32 - b^2\left(48 + 4b - 21b^2 - 2b^3 + 3b^4\right)\right)(\theta^2-1) - (11b^4 + 3b^6\lambda + 48(1+\lambda) - 4b^2(11+9\lambda))\sigma^2 = 0$ and it can be rewritten as $\frac{11b^4+3b^6\lambda+48(1+\lambda)-4b^2(11+9\lambda)}{32-b^2\left(48+4b-21b^2-2b^3+3b^4\right)} = \frac{\left(\theta^2-1\right)}{\sigma^2}$.

Define $G(b) = \frac{11b^4+3b^6\lambda+48(1+\lambda)-4b^2(11+9\lambda)}{32-b^2\left(48+4b-21b^2-2b^3+3b^4\right)}$, which is continuous when $b \in (0, 1)$. Then, we have $\frac{\partial G(b)}{\partial b} = \frac{1792b+576b^2-2624b^3-656b^4+1656b^5+220b^6-528b^7-22b^8+66b^9}{(b^2(48+b(4-(3-b)b(7+3b)))-32)^2} + \frac{(2304b+576b^2-4032b^3-624b^4+2952b^5+216b^6-1008b^7-36b^8+126b^9+6b^{10})\lambda}{(b^2(48+b(4-(3-b)b(7+3b)))-32)^2}$. We define $M(b) = 2304 + 576\text{b} - 4032b^2 - 624b^3 + 1952b^4$. Taking the first order condition with respect to b, we have $\frac{\partial M(b)}{\partial b} = 576 - 8064\text{b} - 1872b^2 + 7808b^3$. Taking the second order condition with respect to b, we have $\frac{\partial^2 M(b)}{\partial b^2} = -4032 - 3544b + 23424b^2$. Similarly, we can obtain $\frac{\partial^3 M(b)}{\partial b^3} = -3544 + 46848\text{b}$, $\frac{\partial^4 M(b)}{\partial b^4} = -46848$. It is easy to show that $\frac{\partial^3 M(b)}{\partial b^3}$ decreases in b and $\frac{\partial^3 M(b)}{\partial b^3} = 0$ when $b = \frac{3544}{46848}$. Then, $\frac{\partial^2 M(b)}{\partial b^2}$ has the minimum value $\frac{\partial^2 M(b)}{\partial b^2} < 0$ when $b = \frac{3544}{46848}$, $\lim_{b\to 0}\frac{\partial^2 M(b)}{\partial b^2} < 0$ and $\lim_{b\to 0}\frac{\partial^2 M(b)}{\partial b^2} > 1$. Therefore, $\frac{\partial M(b)}{\partial b}$ decreases in b first and then increases in b. Because of $\frac{\partial M(b)}{\partial b} < 0$ when $= \frac{1}{2}$,$\lim_{b\to 0}\frac{\partial M(b)}{\partial b} > 0$ and $\lim_{b\to 1}\frac{\partial M(b)}{\partial b} < 0$, we know that $M(b)$ increases in b first and then decreases in b. As a result, we have $M(b) > \min\{\lim_{b\to0}M(b), \lim_{b\to1}M(b)\}$. Because $\lim_{b\to0}M(b) = 2304 > 0$ and $\lim_{b\to1}M(b) = 176 > 0$, $M(b) > 0$ holds for any $b \in (0,1)$.

Then we have $\frac{(2304b+576b^2-4032b^3-624b^4+2952b^5+216b^6-1008b^7-36b^8+126b^9+6b^{10})\lambda}{(b^2(48+b(4-(3-b)b(7+3b)))-32)^2} > 0$ since $(b^2(48+b(4-(3-b)b(7+3b)))-32)^2 > 0$, $M(b) > 0$ and $1000b^5 + 216b^6 - 1008b^7 - 36b^8 + 126b^9 + 6b^{10} > 0$. Similarly, we obtain that $\frac{1792b+576b^2-2624b^3-656b^4+1656b^5+220b^6-528b^7-22b^8+66b^9}{(b^2(48+b(4-(3-b)b(7+3b)))-32)^2} > 0$ holds for any $b \in (0,1)$.

As a result, we have $\frac{\partial G(b)}{\partial b} > 0$ which indicates that $G(b)$ is increasing in b. Therefore, $G(b)_{min} = G(0) = \frac{3(1+\lambda)}{2}$. When $\frac{(\theta^2-1)}{\sigma^2} \le \frac{3(1+\lambda)}{2}$, we find $\frac{11b^4+3b^6\lambda+48(1+\lambda)-4b^2(11+9\lambda)}{32-b^2(48+4b-21b^2-2b^3+3b^4)} > \frac{(\theta^2-1)}{\sigma^2}$ always holds. When $\frac{(\theta^2-1)}{\sigma^2} > \frac{3(1+\lambda)}{2}$, there exists a unique b_{W1} satisfying $\frac{11b^4+3b^6\lambda+48(1+\lambda)-4b^2(11+9\lambda)}{32-b^2(48+4b-21b^2-2b^3+3b^4)} = \frac{(\theta^2-1)}{\sigma^2}$. When $b < b_{W1}$, we find $\frac{11b^4+3b^6\lambda+48(1+\lambda)-4b^2(11+9\lambda)}{32-b^2(48+4b-21b^2-2b^3+3b^4)} < \frac{(\theta^2-1)}{\sigma^2}$ holds. Therefore, when $\sigma < \sqrt{\frac{2(\theta^2-1)}{3(1+\lambda)}}$, and $b < b_{W1}$, we have $E[\pi_R^{WAB}] - E[\pi_R^{WNB}] > 0$.

Appendix D:. Single supply chain structure

In the basic model, we assume two manufacturers compete in the upstream and sell medicine through a common retailer. In this subsection, we consider the scenario where there is only one manufacturer and one retailer. We use the superscript ONB and OAB to represent the two scenarios of not adopting blockchain and adopting blockchain, respectively. The inverse demand function in scenario ONB is

$$p_1^{ONB} = 1 - q_1^{ONB} + \epsilon_1;$$

The inverse demand function in scenario OAB is

$$p_1^{OAB} = \theta - q_1^{OAB} + \epsilon_1;$$

In scenario ONB, the equilibrium wholesale price, quantity, retail price, and the supply chain members' profits are

(1) $w_1^{ONB} = \frac{1}{2}$;
(2) $q_1^{ONB} = \frac{1}{4}(1 + 2\epsilon_1)$;
(3) $p_1^{ONB} = \frac{1}{4}(3 + 2\epsilon_1)$;
(4) $E[\pi_{M_1}^{ONB}] = \frac{1}{8}$, $E[\pi_R^{ONB}] = \frac{1}{16} + \frac{\sigma^2}{4}$.

In scenario AAB, the equilibrium wholesale price, quantity, retail price, and the supply chain members' profits are

(1) $w_1^{OAB} = \frac{1}{2}(\theta + \epsilon_1)$;
(2) $q_1^{OAB} = \frac{1}{4}(\theta + \epsilon_1)$;
(3) $p_1^{OAB} = \frac{3}{4}(\theta + \epsilon_1)$;
(4) $E[\pi_{M_1}^{OAB}] = \frac{\theta^2+\sigma^2}{8}$, $E[\pi_R^{OAB}] = \frac{\theta^2+\sigma^2}{16}$.

We can observe that the manufacturer always benefits from adopting blockchain technology while the retailer benefits from it only when $\sigma^2 < \frac{\theta^2-1}{3}$. The result is similar to the scenario where there are two manufacturers and one common retailer, the latter is more complicated with the competition effect.

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