Timing of Blockchain Adoption in a Supply Chain with Competing Manufacturers

Abstract

Recent improvements in consumers' awareness of product traceability have revealed the disadvantages of traditional supply chain traceability systems. Traditional traceability systems are centralized, and the data that they use are vulnerable to tampering, resulting in a low level of consumer trust. Blockchain technology, as a distributed ledger, can solve these problems. In this study, we examine the blockchain technology introduction decisions of a supply chain involving two competing manufacturers and a single retailer, and their effects on supply chain performance. We find that manufacturers should adopt blockchain technology only when consumer sensitivity to blockchain technology exceeds a certain level and manufacturers who can introduce blockchain technology first are more likely to reap big gains in profits. Regarding the unit verification fee that the retailer pays to the manufacturer when introducing blockchain technology, the manufacturer subsidizes this fee to the retailer in the form of lower wholesale prices. In other words, there is no additional wholesale cost to the retailer for blockchain technology-based products. The results of this study provide guidance for supply chain members' market practices.

Keywords: Supply chain management, Manufacturer competition, Blockchain technology, Consumer traceability awareness.

1. Introduction

In recent years, there have been frequent product quality and safety problems, which have had a negative impact on consumers and enterprises (Manning & Monaghan, 2019). Three Squirrels, a famous snack brand in China, has been the subject of repeated consumer complaints about food safety issues, including but not limited to insect eggs in nuts and moldy canned fruits. In 2018, Changsheng Bio-technology Co. Ltd's fake rabies vaccine incident caused consumer panic and reduced people's trust in the company and even in the Chinese government. People are often unsure of the quality of the products that they buy, and may even inadvertently buy fakes. One study has shown that product defects related to user experience and performance, ease of use, reputation, and versatility can impair consumer perceptions of overall product quality and reduce customer loyalty to product manufacturers (Catenazzo & Paulssen, 2020). Appelhanz, Osburg, Toporowski, and Schumann (2016) found that the information most valued by consumers can be provided by offering products supplied through a traceability system, which can help to overcome the purchase barrier and improve consumers' trust in products and their purchase intentions. Increasingly more consumers are viewing product traceability as a measure of product quality and safety (Aung & Chang, 2014). Therefore, it is very important for manufacturers to establish an efficient and convenient traceability system to protect their interests by preventing and/or dealing with product quality problems, thereby dispelling consumers' doubts.

A traceability system provides accurate and timely information on the flow of materials during production (Appelhanz et al., 2016). Some consumers value traceability systems because they care about the details of the products that they buy (Regattieri, Gamberi, & Manzini, 2007). Traditional supply chain traceability technology such as the Internet-of-things, bar codes, two-dimensional codes and radio frequency identification are centralized systems (George, Harsh, Ray, & Babu, 2019), which lack transparency and trust, and are monopolistic, asymmetric and opaque (Tian, 2016). The data used by these systems can easily be tampered with by stakeholders, and thus consumers have a low level of trust in traditional traceability technology.

As a distributed ledger, blockchain is decentralized and has great application potential in relation to supply chain management (Kouhizadeh, Zhu, & Sarkis, 2020). Blockchain technology refers to a database-based technology that stores and distributes data among all users who are stakeholders in a participating network (Litke, 2019), and has the ability to ensure the reliability, traceability and authenticity of information (Saberi, Kouhizadeh, Sarkis, & Shen, 2019).Traceability systems supported by blockchain technology can solve the problems of information tampering and the consequent reduced credibility of centralized traceability systems.

Napolina, an Italian olive oil brand, and Anchor, a New Zealand milk brand, have both partnered with Provence, a blockchain e-commerce supply chain services platform, to trace their products and materials. In this way, consumers can see the entire life cycle of the products they buy from farm to store shelf, so that they can evaluate the quality of products that they buy. IBM provides Albertsons with its blockchain-based IBM Food Trust network, which allows Albertsons to track lettuce from farm to store shelf to ensure Food safety. Raw Seafoods, a seafood factory, has partnered with IBM to connect outsourcing partners, retailers and restaurant owners around the world to better track seafood products through a blockchain platform, improving seafood traceability, sustainability and preventing fraud. Alibaba teamed up with Australia Post, Blackmores, an Australia nutritional brand, and Pricewaterhouse Coopers to explore how blockchain technology can be used to halt the distribution of counterfeit food (Bindi, 2017). In 2017, Wal-Mart reported the results of a food safety traceability protocol test conducted between the United States and China, reporting that blockchain reduced the time it takes to track food from days to minutes. Since 2018, Carrefour, Europe's largest retailer and Wal-Mart's rival, has been using blockchain ledger technology to track chicken, eggs, and tomatoes from farm to store shelf. Thus, it can be seen that numerous companies have made good progress in relation to quality supervision and traceability of products using blockchain technology.

Blockchain technology is decentralized, open, transparent, encryption-protected and information tamper-proof, and thus can provide better visibility and transparency for supply chains (Kamble, Gunasekaran, & Arha, 2019). In addition, some consumers are sensitive to blockchain technology, that is, they have a high level of requirements regarding the authenticity and traceability of products. When this segment of consumers buys products that do not use blockchain technology, their utility is significantly reduced. Thus, manufacturers need to consider the composition of the market when deciding whether to introduce blockchain technology to enhance product competitiveness.

Retailers purchase products wholesale from manufacturers and then sell them to consumers. Generally, a retailer purchases a range of products from different manufacturers and then sells them simultaneously. For example, Wal-Mart simultaneously sells shampoo and bath lotion purchased from P&G and Unilever, respectively, while Suning simultaneously sells appliances purchased from Gree and Midea. Manufacturers differentiate their products, and this product differentiation may be vertical, horizontal or both (Jin Li, Liang, Shi, & Zhu, 2021). In this study, product differentiation refers to horizontal differentiation such as differences in color, style, brand and taste, while the product quality and function remain constant (Shangguan LL, 2021). Thus, manufacturers need to consider their competitors' reactions when deciding whether to introduce blockchain technology. Two competing manufacturers may have different strategies for introducing blockchain technology. For example, automotive manufacturing brand BMW started using blockchain to empower the automotive parts supply chain in 2018 and successfully conducted a pilot project in 2019. Through blockchain technology BMW improves the visibility of raw materials and components in the global supply chain. In November 2019, Volvo, BMW's rival, started to track cobalt in lithium batteries through a blockchain platform with Oracle to enhance the visibility of raw materials in the supply chain and boost competitiveness. Maersk and IBM designed a blockchain-based supply chain tracking system in 2016 that proved effective in practice in 2017 (Kshetri, 2018). Maersk's rival COSCO Shipping has teamed up with Bank of China and other partners to create a “shipping bill and trade documents blockchain platform” to facilitate cargo tracking. Shipping service providers such as Maersk and COSCO can be seen as product (shipping service) manufacturers. Both provide shipping services with the same function but under different brands, and consigners purchase shipping services from these shipping companies through freight forwarders. Consumers usually have different preferences for products made by different manufacturers. For example, for cars with similar functions and configurations, some consumers prefer BMW and some prefer Volvo, perhaps because they have a particular preference for a certain brand, a certain design or a certain color of the car. Similarly, when shipping goods from one port to another, some consigners prefer Maersk's service, while others prefer COSCO's service. Their preferences for horizontally differentiated products are determined by the company's strategic positioning, long-term reputation and the consumers' own consumption habits, and are difficult to change in the short term. In this study, we consider the case of two competing manufacturers, both of which are able to introduce blockchain technology, and they product horizontally differentiated products with similar functions. One of the manufacturers has more comprehensive strength, is the leader, can first decide whether to introduce blockchain technology. Once the leader introduces blockchain technology, the follower decides whether to do the same, or not, according to his/her own strength and market conditions.

The aim of this study is to investigate the impact of a manufacturer's introduction of blockchain technology on pricing decisions and the profitability of supply chain members. Specifically, we aim to answer the following research questions.

1. What are the equilibrium results under different blockchain technology introduction scenarios?
2. How does the introduction of blockchain technology by manufacturers affect retailers?
3. What are the impacts of different consumer market structures on supply chain members before and after manufacturers introduce blockchain technology?
4. Under what consumer market structure will a manufacturer choose to introduce blockchain technology?

To better understand the issues underlying these questions, we consider a supply chain consisting of two competing manufacturers and a retailer. Then, we obtain the equilibrium results under different blockchain technology introduction modes. Next, we analyze the influence of different market structures on the equilibrium results under different blockchain introduction modes. Furthermore, we compare the equalization results across different blockchain technology introduction modes and explore the impact of the manufacturers' blockchain technology introduction decisions on supply chain performance. Finally, we present our conclusions. From a manufacturer’s perspective, we offer insights into the timing of the introduction of blockchain technology. Before a manufacturer decides to introduce blockchain technology, it is necessary to investigate the impact of blockchain technology on sensitive consumers and the composition of consumers in the market. When the impact of these two factors on profits is higher than the expenditure of introducing blockchain technology, it is beneficial for the manufacturer to introduce blockchain technology.

The rest of this paper is structured as follows. Section 2 presents a review of the relevant literature. Section 3 presents a description of the problem and establishes the model. Section 4 presents an analysis of the equilibrium prices and profits of the supply chain members under different blockchain technology introduction modes. In Section 5, we compare the equilibrium values under different modes. In Section 6, numerical analysis is used to illustrate and verify our conclusions. Section 7 presents conclusions, management implications, limitations of the study, and future research directions.

2. Literature review

Our paper is related to supply chain management with the blockchain technology application, product competition and consumer product traceability awareness.

This paper is related to the application of the blockchain technology in supply chain management. From the perspective of supply chain security and reliability, Chen et al. (2017) discusses how to use blockchain technology to improve supply chain quality management from the perspective of solving the problem caused by lack of trust in supply chain. Azzi, Chamoun, and Sokhn (2019) describes how to integrate blockchain into the supply chain architecture to create a reliable, transparent, trusted and secure system, and they examine the benefits and challenges of introducing blockchain into the supply chain. Schmidt and Wagner (2019) believes that blockchain can limit the impact of opportunistic behaviors, environmental and behavioral uncertainties in the supply chain and reduce transaction costs. Cole, Stevenson, and Aitken (2019) mentioned that for operations and supply chain management, blockchain can improve product safety and security, improve quality management, reduce supply chain transaction costs, etc. Park and Li (2021) show that blockchain technology has the potential to improve the sustainability performance of the supply chain through some case studies. From a supply chain finance and risk management perspective, Lohmer, Bugert, and Lasch (2020) discuss the impact of blockchain technology on supply chain risk management, especially on supply chain resilience. Y. Li, Jiang, Shi, and Wei (2021) investigate the influence of the priority option on supply chain members' blockchain payment service adoption behavior, payment service provider's strategy and its revenue in the context of increasingly popular crypto payment. Wang and Wu (2021) discuss the application of blockchain technology in supply chain finance, they evaluate the supply chain finance risk on blockchain platform and gives the supply chain finance game through relevant experiments. In addition, Kouhizadeh, Saberi, and Sarkis (2021) discuss the obstacles to the application of blockchain technology in sustainable supply chain from a theoretical perspective, providing a foundation for the future application of blockchain technology. Most of the literature mentioned above is theoretical and stereotyped research on the application of blockchain technology in supply chain management. There are also some literatures quantify the application of blockchain in supply chain management from a game theory perspective. Fan, Wu, and Cao (2020) examine whether a supply chain should adopt blockchain technology considering consumers' awareness of traceability and the cost of using blockchain technology, and they also discuss the supply chain coordination when adopting blockchain technology. Choi, Feng, and Li (2020) explore the impact of product information disclosure between the two leasing service platforms on consumer surplus and sellers' interests by establishing a model, and discuss the role of blockchain technology in it. R. Liu, Tan, and Zhao (2021) analyze the pricing and coordination strategy of the vaccine supply chain based on blockchain technology and deeply discuss the value and impact of blockchain technology by establishing a model. Chang, Katehakis, Shi, and Yan (2021) innovatively study what impact the adoption of blockchain technology would have on the classic newsboy model, and analyze the profit optimization of the optimal adoption strategy considering the adoption cost of blockchain technology. In summary, the literatures on the application of blockchain technology in the supply chain mentioned above mostly consider without manufacturer product competition and consumer product traceability awareness..

The second stream of the literature is related with supply chain competition. The existing literature on supply chain competition mainly focuses on the competition between supply chains (Ai, Chen, & Ma, 2012), vertical and horizontal competitions among supply chain members(Jian Li, Wang, & Cheng, 2010; Z. Liu, Anderson, & Cruz, 2012; Wu, Chen, & Hsieh, 2012; Xu, Gurnani, & Desiraju, 2010), and channel competition (G. Li, Huang, Cheng, & Ji, 2015; Y. Liu, Liu, Fan, & Ieee, 2017; Shi, Sun, & Cheng, 2020). Among them, competition among supply chain members is most relevant to our research. Jian Li et al. (2010) investigate the retailer's purchasing strategy in the case of supply interruption in the single-retailer dual-supplier supply chain and the pricing game between two competing suppliers in the case of decentralized decision-making. Xu et al. (2010) examine the channel selection of whether proprietary component manufacturers enter the terminal market to compete with original equipment manufacturers under different product differentiation degrees and production capacity advantages. Z. Liu et al. (2012) look into the effects of competition and consumers' environmental awareness on key supply chain participants. They consider both product competition between manufacturers and competition between retailers. Ai et al. (2012) explore the contract selection problem of two competing supply chains selling alternative products under uncertain demand. Ha, Shang, and Wang (2017) consider the manufacturer's equilibrium rebate decision in a supply chain where two competing manufacturers sell to a common retailer. By establishing a game model, W. Li and Chen (2018) study the influence of pricing timing choice of two competitive manufacturers with differentiated product quality on the profits of retailers, manufacturers and supply chains. The product competition scenario in our paper is similar to Xu et al. (2010). Different manufacturers produce alternative products with the same functions but different brands. Consumers' preference for these two products determined by the company's strategic positioning, long-term reputation and consumers' own consumption habits, and it is difficult to change in a short time. We use a similar approach to Xu et al. (2010) to characterize product competition between the two manufacturers.

The third literature stream related with our paper is consumer traceability awareness. Through the use of ladder technology, van Rijswijk, Frewer, Menozzi, and Faioli (2008) have shown that traceability can help improve consumer confidence in products. And they indicate that consumers often associate traceability with attributes they consider important in product decisions, such as perceptions of product safety, quality and health. These attributes are the key factors that affect consumer purchase in general. Using data from Nanjing, China, C. P. Zhang, Bai, and Wahl (2012) find that consumers in Nanjing are willing to pay a significant positive premium for food traceability, and consumers' awareness of food traceability and food quality and safety certification has a positive impact on consumers' willingness to food traceability. Menozzi, Halawany-Darson, Mora, and Giraud (2015) investigate the attitudes and behaviors of consumers towards traceable foods in Italy and France and they find that consumers have different preferences for traceable foods according to their attitudes and trust in the foods. Rodriguez-Salvador and Calvo Dopico (2020) find that most consumers think traceability of fishery products is necessary. Consumers want traceability to play a necessary role in the fish market and see it as valuable for knowing where the fish came from and verifying the information on the label. Most of these articles study the food supply chain and point out that some consumers in the market attach great importance to product traceability through questionnaires and empirical studies. In this paper, we assume that a certain proportion of consumers in the market cares about product traceability, and we use the degree of discount to the expected reservation price of the product to describe how much these consumers attach importance to product traceability.

According to the literature reviewed above, researches on the application of blockchain technology in supply chain management considering both product competition and consumer traceability awareness are still limited. To fill this gap, we consider the traceability awareness of consumers in the market and establish a supply chain model involving two competitive manufacturers and one retailer to explore the blockchain technology introduction strategies of the two manufacturers in the context of different consumer market structures and consumer traceability awareness. This study contributes to the literature in the following aspects. First, we investigate the application of blockchain technology to supply chain management in the context of product competition. Unlike Fan et al. (2020), who considered the application of blockchain technology in the supply chain under the awareness of consumers' traceability, we also considered the competition of manufacturers' products. Second, from a game theory perspective, we obtain the equilibrium results under different blockchain technology introduction strategies and analyze the factors that affect the equilibrium results through quantitative analysis. The existing literatures are mostly studied from the theoretical and qualitative perspectives. Third, we derive the market conditions for manufacturers to introduce blockchain technology and analyze the impact of product competition on blockchain technology introduction. We find that the introduction of blockchain technology by manufacturers is always beneficial to retailers, and manufacturers tend to introduce blockchain technology only when the introduction cost is low or the proportion of blockchain-sensitive consumers in market is high or the product traceability has a large impact on consumers.

3. Model development

3.1 Problem description and assumptions

We model a supply chain consisting of two manufacturers (M_1 and M_2) and a retailer (R). M_1 wholesales product m_1 to R at wholesale price w_1, and R sets m_1's retail price at p_1 and sells it to consumers. Similarly, M_2 wholesales product m_2 to R at wholesale price w_2, and R sets m_2's retail price at p_2 and sells it to consumers. We assume that there is a segment of consumers in the market who have a high level of requirements regarding product traceability and authenticity. Products using blockchain technology can meet the requirements of these consumers. Therefore, this type of consumer is sensitive to blockchain technology. We focus on the impact of consumers' blockchain technology requirements on manufacturers' blockchain technology introduction strategies. Manufacturers consider when to introduce blockchain technology with a view to maximizing their profits. These two products compete in the final market, in which consumers have different preferences for products made by different manufacturers. The situation of product competition in our study is very similar to the situation of final products manufactured by original equipment manufacturers and proprietary component manufacturers competing in the consumer market in the study of Xu et al. (2010). Therefore, we use a similar model in this study.

We conceptualize the end-product market as a straight line and designate external locations for m_1 and m_2, and the distance between them is f (Pun, 2013; Venkatesh, Chintagunta, & Mahajan, 2006; Xu et al., 2010). Note that f measures the degree of substitution between the products. A smaller value of f implies intensified competition, as shown in Figure 1. Otherwise, the opposite is true. This external distance between the two products may be the result of the strategic positioning of the company and the long-established habits of consumers (Jinfeng, 2021; Xu et al., 2010). Consumers are assumed to be uniformly distributed along the line representing the market and their product preferences differ depending on their position. Consumers will purchase products if they offer positive utility, otherwise they will not purchase them. A consumer's reservation price for an ideally located product is V. Each consumer has linear transportation costs of t per unit of distance, similar to the assumption of Zhou and Che (2021) and Gan, Li, Wang, Zhang, and Huang (2021). A consumer located between two manufacturers at a distance of x from M_1 obtains utility of $U_1 = V - p_1 - tx$ and $U_2 = V - p_2 - t(f - x)$ when purchasing from M_1 and M_2, respectively.

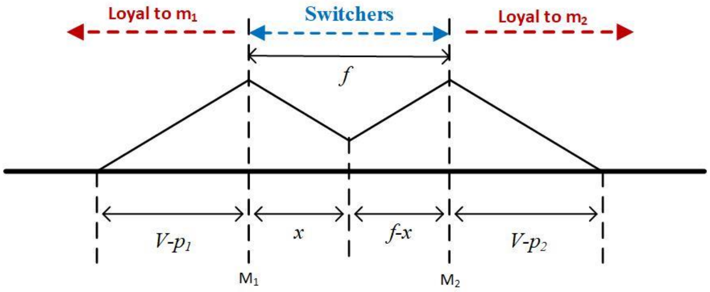


Fig.1. Market characteristics under product competition.

A proportion of consumers, represented by α $(0 < \alpha < 1)$, is blockchain technology-sensitive. These are denoted as type α consumers, and represented by subscript α. This proportion (α) is exogenous and is related to the educational background and consumption habits of consumers. When blockchain technology-sensitive consumers purchase products supplied using blockchain technology, they can easily and reliably trace the life cycle of the products and know that the products they are buying are authentic, so the product is worth V (their reservation price). However, the product is worth $(1 - \theta)V$, if the product does not use blockchain technology, where $1 - \theta$ represents the acceptance of ordinary products by blockchain-sensitive consumers. Because convenient and reliable traceability and product authenticity cannot be guaranteed, blockchain-sensitive consumers will discount the reservation prices of ordinary products and they are more willing to accept products that use blockchain technology than products that do not. Therefore, $0 < \theta < 1$ (P. Zhang, He, & Shi, 2017). The larger θ is, the more sensitive type α consumers are to blockchain technology. Therefore, when characterizing the demand function, we need to consider two types of consumers: α and $1-\alpha$.

We consider three modes of introduction of blockchain technology as follows:

(1) Mode NN: Neither manufacturer introduces blockchain technology, and both of them sell traditional products. In this case, a type α consumer's reservation price for a product (m_1 and m_2) is $(1-\theta)V$, regardless of which manufacturer the product comes from. For ordinary consumers, the reservation price for both products is V.

(2) Mode BN: In this setting, M_1 introduces blockchain technology while M_2 not. Thus, blockchain technology-sensitive consumers discount the reservation price of m_2. M_1 pays a one-off fee (F) to the blockchain technology provider (BTP) for the introduction of blockchain technology. Then, for every m_1 sold, the retailer pays a unit verification fee (s) to M_1 (Jinfeng, 2021). In this case, a type α consumer's reservation price for m_2 is $(1-\theta)V$ and for m_1 is V. For ordinary consumers, the reservation price for both products is V, and the decision on whether to buy m_1 or m_2 is not affected by the introduction of blockchain technology.

(3) Mode BB: In this setting, both of the manufacturers introduce blockchain technology, and consumers can trace both m_1 and m_2. The retailer is required to pay a unit verification fee (s) to the manufacturers for each unit sold, and the consumer's reservation price for both products is V. M_1 and M_2 both pay a one-off fee (F) to the BTP for the introduction of the blockchain technology.

3.2 Notations

For clarity, we give the notations in Table 1.

Table 1

Notations

Notations	Descriptions
Decision variables	
p	The retailer's unit retail price, $p > w > 0$
w	The manufacturers' wholesale price
Parameters	
V	Consumers' reservation price for a product located in their ideal point
f	The competitive intensity between the two products
t	The transportation costs t per unit length
θ	The reservation price discount percentage, $0 < \theta < 1$
F	A fixed fee for manufacturers to introduce blockchain technology
s	The unit verification fee paid by the retailer to the manufacturer
x	The distance between the consumer andM_1, when the consumer is between the two manufacturers
α	Percentage of blockchain-sensitive consumers,$0 < \alpha < 1$
Π	The profit
Superscripts	
α	The blockchain-sensitive consumers
$1 - \alpha$	The ordinary consumers
nn	No blockchain technology (mode NN)
bn	M_1 introduces blockchain technology (mode BN)
bb	Both M_1 and M_2 introduce blockchain technology (mode BB)
Subscripts	
1	The product m_1
2	The product m_2
M_1	The manufacturer M_1
M_2	The manufacturer M_2
R	The retailer

4. Equilibrium

In this section, we investigate the equilibrium decisions of supply chain members under the different blockchain technology introduction modes outlined in the previous section. M_1 ex-ante decides whether to introduce blockchain technology. If M_1 decides to introduce blockchain technology, M_2 then decides whether to introduce it. Then, M_1 and M_2 determine the wholesale prices, w_1 and w_2, respectively, of their products and the retailer determines the retail prices, p_1 and p_2, of m_1 and m_2, respectively. The sequence of events is shown in Fig. 2.

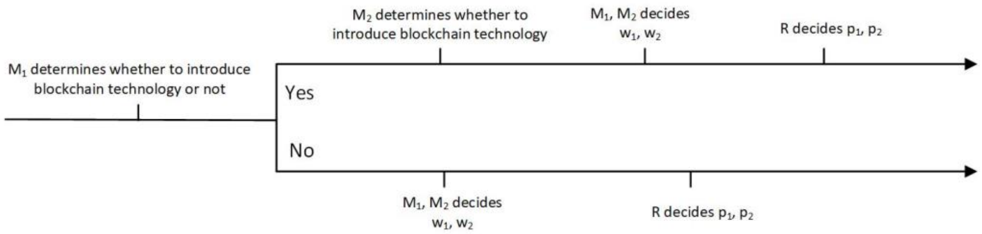
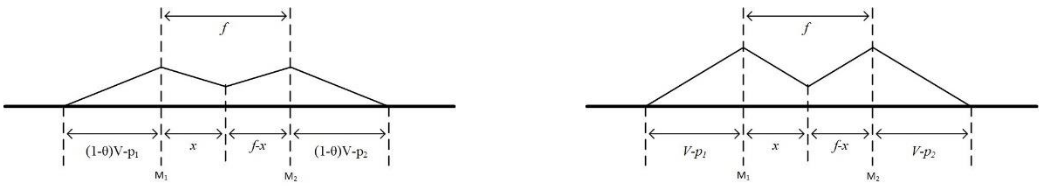


Fig.2. The sequence of events.

4.1 *NN Mode: Neither manufacturer introduces blockchain technology*

In the case of no blockchain technology in the supply chain, a type α consumer located between the two manufacturers at a distance of x from M$_1$ obtains utility of $\mathrm{U}_1^{\alpha}=(1-\theta)V-p_1-tx$ and $\mathrm{U}_2^{\alpha}=(1-\theta)V-p_2-t(f-x)$ when purchasing from M$_1$ and M$_2$, respectively. There is no discount on the reservation price of both products for ordinary consumers. Therefore, a type $1-\alpha$ consumer located between the two manufacturers at a distance of x from M$_1$ obtains utility of $\mathrm{U}_1^{\alpha}=V-p_1-tx$ and $\mathrm{U}_2^{\alpha}=\mathrm{V}-\mathrm{p}_2-t(f-x)$ when purchasing from M$_1$ and M$_2$, respectively. Fig.3 shows the demand in NN mode. That is, we can derive the demand function for different types of consumers regarding products m$_1$ and m$_2$ as follows:



(a) Demand for Type α Consumer (b) Demand for Type $1-\alpha$ Consumer

Fig.3. Demand in NN Mode.

$$\mathrm{D}_1^{\alpha}=\frac{2(1-\theta)V+p_2-3p_1+tf}{2t}$$

$$\mathrm{D}_2^{\alpha}=\frac{2(1-\theta)V-3p_2+p_1+tf}{2t}$$

$$\mathrm{D}_1^{1-\alpha}=\frac{2V+p_2-3p_1+tf}{2t}$$

$$\mathrm{D}_2^{1-\alpha}=\frac{2V-3p_2+p_1+tf}{2t}$$

Hence, we can derive the demand for products m₁ and m₂ as follows:

$$\mathrm{D}_1^{nn}=\alpha D_1^{\alpha}+(1-\alpha)\mathrm{D}_1^{1-\alpha}=\frac{2(1-\alpha\theta)V+p_2-3p_1+tf}{2t}$$

$$\mathrm{D}_2^{nn}=\alpha D_2^{\alpha}+(1-\alpha)\mathrm{D}_2^{1-\alpha}=\frac{2(1-\alpha\theta)V-3p_2+p_1+tf}{2t}.$$

In this case, given the wholesale prices w_1 and w_2, the retailer chooses retail prices p_1 and p_2 to maximize profit Π_R^{nn}, which can be expressed as:

$$\underset{p_1,p_2}{Max}\,\Pi_R^{nn}(p_1,p_2,w_1,w_2)=(p_1-w_1)D_1^{nn}+(p_2-w_2)D_2{}^{nn}\,. \tag{1}$$

Solving the optimization in (1) yields p_1^{nn} and p_2^{nn} as follows:

$$\mathrm{p}_1^{nn}(\mathrm{w}_1,\mathrm{w}_2)=\frac{2V(1-\alpha\theta)+tf+2w_1}{4}$$

$$\mathrm{p}_2^{nn}(\mathrm{w}_1,\mathrm{w}_2)=\frac{2V(1-\alpha\theta)+tf+2w_2}{4}.$$

On the basis of the retailer's optimal response function, the two manufacturers simultaneously determine the wholesale price of the product to maximize their profits as follows:

$$\underset{w_1}{Max}\,\Pi_{M_1}^{nn}(w_1,w_2)=\mathrm{w}_1D_1=w_1\left(\frac{2(1-\alpha\theta)V+\mathrm{p}_2^{nn}(\mathrm{w}_1,\mathrm{w}_2)-3\mathrm{p}_1^{nn}(\mathrm{w}_1,\mathrm{w}_2)+tf}{2t}\right) \tag{2}$$

$$\underset{w_2}{Max}\,\Pi_{M_1}^{nn}(w_1,w_2)=\mathrm{w}_2D_2=w_2\left(\frac{2(1-\alpha\theta)V-3\mathrm{p}_2^{nn}(\mathrm{w}_1,\mathrm{w}_2)+\mathrm{p}_1^{nn}(\mathrm{w}_1,\mathrm{w}_2)+tf}{2t}\right). \tag{3}$$

By solving (2) and (3), we can derive the equilibrium wholesale prices w_1^{nn} and w_2^{nn}. Substituting them back into $p_1^{nn}(w_1,w_2)$ and $p_2^{nn}(w_1,w_2)$ yields the equilibrium outcomes under mode NN.

Lemma 1: *Under mode NN, the equilibrium wholesale prices and retail prices are:*

$$\mathrm{w}_1^{nn} = w_2^{nn} = \frac{2(1-\alpha\theta)V+tf}{5},\ \mathrm{p}_1^{nn} = p_2^{nn} = \frac{7(2(1-\alpha\theta)V+tf)}{20}.$$

The proof of Lemma 1 is presented in the “Appendix”.

On the basis of Lemma 1, we can derive the profits of the two manufacturers and the retailer in mode NN as follows:

$$\Pi_{\mathrm{M}_1}^{nn} = \Pi_{\mathrm{M}_2}^{nn} = \frac{3(2(1-\alpha\theta)V+tf)^2}{100t} \tag{4}$$

$$\Pi_{\mathrm{R}}^{nn} = \frac{9(2(1-\alpha\theta)V+tf)^2}{200t}. \tag{5}$$

Corollary 1 (1) $\frac{\partial \mathrm{w}_1^{nn}}{\partial \alpha} = \frac{\partial \mathrm{w}_2^{nn}}{\partial \alpha} < 0$ and $\frac{\partial \mathrm{p}_1^{nn}}{\partial \alpha} = \frac{\partial \mathrm{p}_2^{nn}}{\partial \alpha} < 0$. (2) $\frac{\partial \Pi_{\mathrm{M}_1}^{nn}}{\partial \alpha} = \frac{\partial \Pi_{\mathrm{M}_2}^{nn}}{\partial \alpha} < 0$ and $\frac{\partial \Pi_{R}^{nn}}{\partial \alpha} < 0$.

Corollary 1 (1) reveals that as the proportion of blockchain technology-sensitive consumers α increases, both the wholesale prices and the retail prices decrease. A large α means a high proportion of blockchain technology-sensitive consumers. It becomes more difficult for the supply chain members to ignore the existence of these consumers. Therefore, the prices need to be lowered to attract more blockchain technology-sensitive consumers. The wholesale price for both manufacturers will also fall, but by less than the retail price, which makes intuitive sense. If one manufacturer keeps the wholesale price unchanged, the retailer will reduce the volume purchased from that manufacturer, which reduces the manufacturer's profits. To reduce the loss of profits both manufacturers' wholesale prices will decrease by the same amount. Losses from the lack of blockchain technology are shared by the manufacturers and the retailer, and thus wholesale prices fall less than retail prices.

Corollary 1 (2) reveals that as the proportion of blockchain technology-sensitive consumers (α) increases, the manufacturers' and retailer's profits decrease. Notably, although the retailer has adopted the strategy of lowering prices to attract consumers, overall market demand is still decreasing with the increase in α, and lowering prices can only offset the declining demand to some degree. As demand and the prices decrease with the increase in α, the profits of both manufacturers and the retailer decrease.

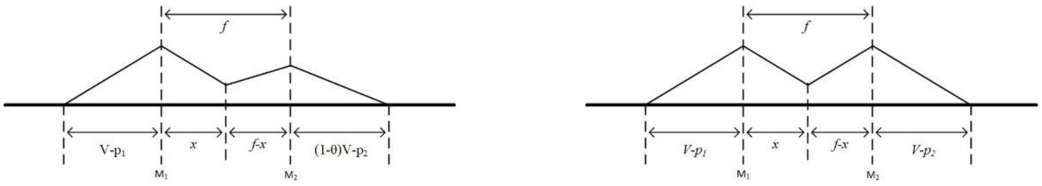
Corollary 2 (1) $\frac{\partial \mathrm{w}_1^{nn}}{\partial \theta} = \frac{\partial \mathrm{w}_2^{nn}}{\partial \theta} < 0$ and $\frac{\partial \mathrm{p}_1^{nn}}{\partial \theta} = \frac{\partial \mathrm{p}_2^{nn}}{\partial \theta} < 0$. (2) $\frac{\partial \Pi_{\mathrm{M}_1}^{nn}}{\partial \theta} = \frac{\partial \Pi_{\mathrm{M}_2}^{nn}}{\partial \theta} < 0$ and $\frac{\partial \Pi_{R}^{nn}}{\partial \theta} < 0$.

Corollary 2 (1) reveals that as type α consumers' reservation price discount (θ) without blockchain technology increases, both wholesale and retail prices decrease. A larger θ means a greater loss of utility for type α consumers buying products without blockchain technology. Further, these consumers are more reluctant to buy traditional products. Thus, the retailer needs to lower prices to increase market demand. Similar to Corollary 1 (1), both the manufacturers will also reduce their wholesale prices.

Corollary 2 (2) reveals that as type α consumers' reservation price discount (θ) increases, the manufacturers' and retailer's profits decrease. Similar to Corollary 1 (2), because both demand and the prices of the products decrease with the increase in θ, and thus the profits of both manufacturers and the retailer decrease.

4.2 Mode BN: Only M$_1$ introduces blockchain technology

In this case, M$_1$ introduces blockchain technology, while M$_2$ does not. There is an additional loss of utility for a type α consumer when purchasing m$_2$, but not when purchasing m₁. A type α consumer located between two manufacturers at a distance of *x* from M₁ obtains utility of $\mathrm{U}_1^{\alpha} = V - p_1 - tx$ and $\mathrm{U}_2^{\alpha} = (1-\theta)\mathrm{V} - \mathrm{p}_2 - t(f-x)$ when purchasing from M₁ and M₂, respectively. Similar to mode NN, a type $1-\alpha$ consumer at the same location obtains utility of $U_1^{\alpha} = V - p_1 - tx$ and $U_2^{\alpha} = V - p_2 - t(f-x)$ when purchasing from M₁ and M₂, respectively. Fig.4 shows the demand in mode BN. That is, we can derive the demand function for different types of consumers regarding m₁ and m₂.



(a) Demand for Type α Consumer (b) Demand for Type $1-\alpha$ Consumer

Fig.4. Demand in Mode BN.

We can derive the demand for products m₁ and m₂ as follows:

$$\mathrm{D}_1^{bn} = \frac{(2+\alpha\theta)V + p_2 - 3p_1 + tf}{2t}$$

$$\mathrm{D}_2^{bn} = \frac{(2-3\alpha\theta)V - 3p_2 + p_1 + tf}{2t}.$$

Given the wholesale prices w_1 and w_2, the retailer chooses retail prices p_1 and p_2 to maximize profit Π_R^{bn}, which can be expressed as:

$$\underset{p_1, p_2}{\mathrm{Max}}\, \Pi_{\mathrm{R}}^{bn}(p_1, p_2, w_1, w_2) = (p_1 - w_1 - s)D_1^{bn} + (p_2 - w_2)D_2{}^{bn}. \tag{6}$$

Solving the optimization in (6) yields p_1^{bn} and p_2^{bn} as follows:

$$\mathrm{p}_1^{bn}(\mathrm{w}_1, \mathrm{w}_2) = \frac{2(V + w_1 + s) + tf}{4}$$

$$\mathrm{p}_2^{bn}(\mathrm{w}_1, \mathrm{w}_2) = \frac{2V(1-\alpha\theta) + 2w_2 + tf}{4}.$$

On the basis of the retailer's optimal response function, the two manufacturers simultaneously determine the wholesale price of the product to maximize their profits as follows:

$$\underset{w_1}{Max}\, \Pi_{M_1}^{bn}(w_1,w_2) = (w_1+s)D_1 - F$$
$$= \frac{(w_1+s)\left((2+\alpha\theta)V + p_2^{bn}(w_1,w_2) - 3p_1^{bn}(w_1,w_2) + tf\right)}{2t} - F \quad (7)$$

$$\underset{w_2}{Max}\, \Pi_{M_1}^{bn}(w_1,w_2) = w_2D_2 = w_2\left(\frac{(2-3\alpha\theta)V - 3\mathrm{p}_2^{bn}(\mathrm{w}_1,\mathrm{w}_2) + \mathrm{p}_1^{bn}(\mathrm{w}_1,\mathrm{w}_2) + tf}{2t}\right). \quad (8)$$

By solving (7) and (8), we can derive the equilibrium wholesale prices w_1^{bn} and w_2^{bn}. Substituting them back into $p_1^{bn}(w_1,w_2)$ and $p_2^{bn}(w_1,w_2)$ yields the equilibrium outcomes under mode BN.

Lemma 2: *Under mode BN, the equilibrium wholesale prices and retail prices are:*

$$\mathrm{w}_1^{bn} = \frac{(14+3\alpha\theta)V+7tf}{35} - s,\ \mathrm{w}_2^{bn} = \frac{(14-17\alpha\theta)V+7tf}{35}.$$
$$\mathrm{p}_1^{bn} = \frac{(98+6\alpha\theta)V+49tf}{140},\ \mathrm{p}_2^{bn} = \frac{(98-104\alpha\theta)V+49tf}{140}.$$

where $0 < \alpha\theta < \frac{7tf+14V}{17V}$.

The proof of Lemma 2 is presented in the "Appendix".

From Lemma 2, it is clear that the unit verification fee (*s*) that the retailer pays to M$_1$ only affects wholesale price w_1. The unit verification fee (*s*) that the retailer pays to M$_1$ is equivalent to a decrease of s in the wholesale price of m$_1$. Therefore, in this mode, we can consider $w_1^{bn} + s$ as the wholesale price of m_1, that is, $w_1^{bn} + s = \frac{(14+3\alpha\theta)V+7tf}{35}$. This means that M$_1$ subsidizes the retailer by *s* in the form of a lower wholesale price. That is, the size of *s* has no effect on M$_1$ and the retailer.

From Lemma 2, we can see that w_2^{bn} can be negative when $\frac{7\mathrm{tf}+14\mathrm{V}}{17\mathrm{V}} < \alpha\theta < 1$. At this point, M$_2$'s profit is negative. When $\frac{7\mathrm{tf}+14\mathrm{V}}{17\mathrm{V}} < \alpha\theta < 1$, M$_1$ introduces blockchain technology to maximize profits, and M_2 follows suit. At this point, the market switches to mode BB. Therefore, mode BN exists only if $0 < \alpha\theta < \frac{7tf+14V}{17V}$, when $\frac{7tf+14V}{17V} < \alpha\theta < 1$, the market is in mode BB, which is analyzed in the next section.

On the basis of Lemma 2, we can derive the profits of the two manufacturers and the retailer under mode BN as follows:

$$\Pi_{M_1}^{bn} = \frac{3\big((14+3\alpha\theta)V+7tf\big)^2}{4900t} - F \tag{9}$$

$$\Pi_{M_2}^{bn} = \frac{3\big((14-17\alpha\theta)V+7tf\big)^2}{4900t} \tag{10}$$

$$\Pi_{R}^{bn} = \frac{9\Big(\big((14-\alpha\theta)V+tf\big)^2 + 2(7\alpha\theta V)^2\Big)}{9800t}. \tag{11}$$

Corollary 3 (1) $\frac{\partial w_1^{bn}}{\partial\alpha} > 0$, $\frac{\partial w_2^{bn}}{\partial\alpha} < 0$ and $\frac{\partial p_1^{bn}}{\partial\alpha} > 0$, $\frac{\partial p_2^{bn}}{\partial\alpha} < 0$ (2) $\frac{\partial \Pi_{M_1}^{bn}}{\partial\alpha} > 0$, $\frac{\partial \Pi_{M_2}^{bn}}{\partial\alpha} < 0$ and $\frac{\partial \Pi_{R}^{bn}}{\partial\alpha} < 0$.

Corollary 3 (1) suggests that as the proportion of blockchain technology-sensitive consumers α increases, the wholesale price and retail price of m_1 increase and m_2's wholesale price and retail price decrease. Because M_1 introduces the blockchain technology while M_2 does not, with the increase in α, the demand for m_1 increases, and thus both M_1 and the retailer can raise their prices for m_1 to maximize their profits. Meanwhile, demand for m_2 decreases, and thus both M_2 and the retailer should lower their prices for m_2 to reduce their loss of profits.

Corollary 3 (2) reveals that as the proportion of blockchain technology-sensitive consumers α increases, M_2's profits and the retailer's profits decrease and M_2's profits increase. Although the price of m_2 has been reduced to attract consumers, m_2's demand is still decreasing with the increase in α, and lowering prices can only offset the declining demand to some extent. As the demand and wholesale price for m_2 decrease with the increase in α, the profits of M_2 decrease. On the contrary, with the increase in α, both the market demand and the wholesale price of m_1 increase, and thus M_1's profit increases. As for the retailer, the profit from selling m_2 decreases and the profit from selling m_1 increases, but the reduced profit from m_2 is greater than the increased profit from m_1. Therefore, the retailer's profit decreases with the increase in α.

Corollary 4 (1) $\frac{\partial w_1^{bn}}{\partial \theta} > 0$, $\frac{\partial w_2^{bn}}{\partial \theta} < 0$ and $\frac{\partial p_1^{bn}}{\partial \theta} > 0$, $\frac{\partial p_2^{bn}}{\partial \theta} < 0$ (2) $\frac{\partial \Pi_{M_1}^{bn}}{\partial \theta} > 0$, $\frac{\partial \Pi_{M_2}^{bn}}{\partial \theta} < 0$ and $\frac{\partial \Pi_R^{bn}}{\partial \theta} < 0$.

Corollary 4 (1) reveals that as type α consumers' reservation price discount (θ) increases, both the wholesale price and retail price of m_1 increase and both the wholesale price and retail price of m_2 decrease. A larger θ means a greater loss of utility for type α consumers purchasing products without blockchain technology, so they are more reluctant to buy traditional products. Therefore, demand for m_2 decreases but demand for m_1 increases. Thus, M_1 and the retailer can raise their prices for m_1 to increase their profits. Meanwhile, M_2 and the retailer should lower their prices for m_2 to offset their loss of profits.

Corollary 4 (2) reveals that as type α consumers' reservation price discount (θ) increases, M_2's and the retailer's profit decreases and M_1's profit increases. Because both the demand and wholesale price for m_2 decrease with the increase in θ, M_2's profit decreases. In contrast, since both the demand and wholesale price for m_1 increase with the increase in θ, M_1's profit increases. The retailer's profit from selling m_2 decreases, while its profit from selling m_1

increases, but the reduced profit from selling m₂ is more than the increased profit from selling m₁, and thus retailer's profit decreases with the increase in θ.

4.3 Mode BB: Both manufacturers introduce blockchain technology

In mode BB, both manufacturers introduce the blockchain technology, and thus there is no loss of utility for a type α consumer when purchasing products, that is, they obtain the same utility as a type $1-\alpha$ consumer. Thus, in this mode, there is no need to distinguish between the two types of consumers. A consumer located between two manufacturers at a distance of x from M₁ obtains utility of $\mathrm{U}_1 = V - p_1 - tx$ and $U_2 = \mathrm{V} - \mathrm{p}_2 - t(f-x)$ when purchasing from M₁ and M₂, respectively.

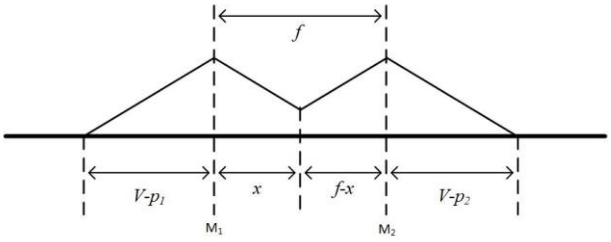


Fig.5. Demand in BB mode.

We can derive the demand for product m_1 and m₂ as follows:

$$\mathrm{D}_1^{bb} = \frac{2V + p_2 - 3p_1 + tf}{2t}$$

$$\mathrm{D}_2^{bb} = \frac{2V - 3p_2 + p_1 + tf}{2t}$$

Given the wholesale prices w_1 and w_2, the retailer chooses retail prices p_1 and p_2 to maximize profit Π_{R}^{bb}, which can be expressed as:

$$\underset{p_1,p_2}{\mathrm{Max}}\, \Pi_{\mathrm{R}}^{bb}(p_1, p_2, w_1, w_2) = (p_1 - w_1 - s)D_1^{bb} + (p_2 - w_2 - s){D_2}^{bb}. \tag{12}$$

Solving the optimization in (12) yields p_1^{bb} and p_2^{bb} as follows:

$$p_1^{bb}(w_1, w_2) = \frac{2(V + w_1 + s) + tf}{4}$$

$$p_2^{bb}(w_1, w_2) = \frac{2(V+w_2+s)+tf}{4}.$$

On the basis of the retailer's optimal response function, the two manufacturers simultaneously determine the wholesale price of the product to maximize their profits as follows:

$$\underset{w_1}{Max}\, \Pi_{M_1}^{bb}(w_1, w_2) = (w_1 + s)D_1 - F$$
$$= \frac{(w_1 + s)\left(2V + p_2^{bb}(w_1, w_2) - 3p_1^{bb}(w_1, w_2) + tf\right)}{2t} - F \tag{13}$$

$$\underset{w_2}{Max}\, \Pi_{M_2}^{bb}(w_1, w_2) = (w_2 + s)D_2 - F$$
$$= \frac{(w_2 + s)\left(2V - 3p_2^{bb}(w_1, w_2) + p_1^{bb}(w_1, w_2) + tf\right)}{2t} - F. \tag{14}$$

By solving (13) and (14), we can derive the equilibrium wholesale prices w_1^{bb} and w_2^{bb}. Substituting them back into $p_1^{bb}(w_1, w_2)$ and $p_2^{bb}(w_1, w_2)$ yields the equilibrium outcomes under mode BB.

Lemma 3: *Under mode BB, the equilibrium wholesale prices and retail prices are:*

$$w_1^{bb} = w_2^{bb} = \frac{2V+tf}{5} - s,\ p_1^{bb} = p_2^{bb} = \frac{7(2V+tf)}{20}.$$

The proof of Lemma 3 is presented in the "Appendix".

From Lemma 3, it is clear that the unit verification fee (s) that the retailer pays to the manufacturers affects the wholesale prices, while the retail prices p_1 and p_2 are independent of s. Similar to Lemma 2, we can consider $w_1^{bb} + s$ as the wholesale price of m1 and $w_2^{bb} + s$ as the wholesale price of m2, that is, $w_1^{bb} + s = w_2^{bb} + s = \frac{2V+tf}{5}$. This means that the manufacturers subsidize the retailer by *s* in the form of a lower wholesale price.

On the basis of Lemma 3, we can derive the profits of the two manufacturers and the retailer under mode BB as follows:

$$\Pi_{\mathrm{M}_1}^{bb} = \Pi_{M_2}^{bb} = \frac{3(2V + tf)^2}{100t} - F \tag{15}$$

$$\Pi_{\mathrm{R}}^{bb} = \frac{9(2V + tf)^2}{200t}. \tag{16}$$

Corollary 5 (1) $\frac{\partial \mathrm{w}_1^{bb}}{\partial \alpha} = \frac{\partial \mathrm{w}_2^{bb}}{\partial \alpha} = 0$ and $\frac{\partial \mathrm{p}_1^{bb}}{\partial \alpha} = \frac{\partial \mathrm{p}_2^{bb}}{\partial \alpha} = 0$. (2) $\frac{\partial \Pi_{\mathrm{M}_1}^{bb}}{\partial \alpha} = \frac{\partial \Pi_{\mathrm{M}_2}^{bb}}{\partial \alpha} = 0$ and $\frac{\partial \Pi_{R}^{bb}}{\partial \alpha} = 0$. (3) $\frac{\partial \mathrm{w}_1^{bb}}{\partial \theta} = \frac{\partial \mathrm{w}_2^{bb}}{\partial \theta} = 0$ and $\frac{\partial \mathrm{p}_1^{bb}}{\partial \theta} = \frac{\partial \mathrm{p}_2^{bb}}{\partial \theta} = 0$. (2) $\frac{\partial \Pi_{\mathrm{M}_1}^{bb}}{\partial \theta} = \frac{\partial \Pi_{\mathrm{M}_2}^{bb}}{\partial \theta} = 0$ and $\frac{\partial \Pi_{R}^{bb}}{\partial \theta} = 0$.

From Corollary 5, it can be seen that the wholesale prices, retail prices, manufacturers' profits and the retailer's profit in mode BB are unaffected by the proportion of type α consumers and the reservation price discount percentage θ. Because both manufacturers introduced blockchain technology, it makes no difference to the manufacturers and the retailer whether consumers are blockchain-sensitive or not. Both types of consumers in the same exogenous position obtain the same utility when they buy the same products . Therefore, the proportion of blockchain technology-sensitive consumers (α) and the size of the reservation price discount (θ) are unrelated to the optimal prices and profits of supply chain members in mode BB.

5. Analysis and discussion

In the previous sections, we obtained the supply chain members' optimal pricing strategies and optimal profits under different blockchain introduction modes. In this section, we compare the optimal pricing strategies under the different modes, and then analyze the impact of the introduction of blockchain technology on the supply chain members' pricing strategies and profits.

First, we obtain the following propositions by comparing the optimal prices of the supply chain members under the three modes.

Proposition 1 *For the three modes of blockchain technology introduction, the retailer's optimal pricing is as follows:*

(i) *If* $0 < \alpha\theta \leq e$, *then* $p_1^{bn} > p_1^{bb} > p_1^{nn}$, $p_2^{bb} > p_2^{nn} > p_2^{bn}$;

(ii) *If* $\mathrm{e} \leq \alpha\theta < 1$, *then* $p_1^{bb} > p_1^{nn}$, $p_2^{bb} > p_2^{nn}$.

where $\mathrm{e} = \frac{7(\mathrm{tf}+2\mathrm{V})}{17\mathrm{V}}$.

The proof of Proposition 1 is presented in the "Appendix".

From proposition 1, It can be seen that the introduction of blockchain technology will definitely lead to the improvement of the product's price, which is similar to the study of Fan et al. (2020). Fan et al. (2020) find that introducing blockchain technology led suppliers to raise wholesale prices when consumer traceability awareness is high and introducing blockchain technology would definitely lead retailers to raise retail prices. Proposition 1 (i) shows that when the condition for the existence of mode BN is established, the retail price of m_1 is highest in mode BN and lowest in mode NN, while the retail price of m_2 is highest in mode BB and lowest in mode BN. In mode BN, only M_1 adopts blockchain technology, and thus all other things being equal, all blockchain-sensitive consumers tend to buy product m_1. The retailer will increase profits by raising m_1's price. In this case, m_1 is more competitive than m_2 and the retail price of m_1 is highest in this mode. In the case where both manufacturers introduce blockchain technology, the competitiveness of the two products is similar. Compared with mode BN, the price of m_1 needs to be lowered to attract consumers. Since the introduction of blockchain technology will increase the products' prices, m_2's retail price is highest in mode BB. In addition, in mode BN, type α consumers are more reluctant to purchase product m_2 because of the lack of blockchain technology, and thus m_2's price is lowest in mode BN.

Proposition 1 (ii) shows that when there is no mode BN, the prices for both products are always higher in mode BB than in mode NN. In mode BB, both manufacturers introduce blockchain technology and incur additional fixed costs, and thus the price of both products will increase in an attempt to pass on some of the additional costs to consumers.

Proposition 2 *For the three modes of blockchain technology introduction, the wholesale price charged to retailer exhibits the follows:*

(i) *If* $0 < \alpha\theta \leq s_1$, *then* $w_1^{nn} \geq w_1^{bn} > w_1^{bb}$, $w_2^{nn} > w_2^{bn} \geq w_2^{bb}$;

(ii) *If* $s_1 < \alpha\theta < s_2$, *then* $w_1^{bn} > w_1^{nn} > w_1^{bb}$, $w_2^{nn} > w_2^{bb} > w_2^{bn}$;

(iii) *If* $s_2 \leq \alpha\theta < e$, *then* $w_1^{bn} > w_1^{bb} \geq w_1^{nn}$, $w_2^{bb} \geq w_2^{nn} > w_2^{bn}$.

(iv) *If* $\mathrm{e} \leq \alpha\theta < 1$, *then* $w_1^{bb} > w_1^{nn}$, $w_2^{bb} > w_2^{nn}$.

where: $s_1 = \frac{35s}{17V}$, $s_2 = \frac{5s}{2V}$, $\mathrm{e} = \frac{7(\mathrm{tf}+2\mathrm{V})}{17\mathrm{V}}$ and $0 < s_1 < s_2 < e < 1$.

The proof of Proposition 2 is presented in the "Appendix".

Proposition 2 shows that the proportion of type α consumers and the reservation price discount percentage θ influence the manufacturers' wholesale prices to the retailer. A larger $\alpha\theta$ means that consumers in the market are more sensitive to blockchain technology and blockchain technology has a greater impact on demand. Specifically, Proposition 2 (i) shows that when $\alpha\theta$ is less than a certain value (s_1), both m_1 and m_2 have the highest wholesale prices in mode NN and lowest in mode BB. In mode BB, both manufacturers introduce blockchain technology, resulting in a decrease in the relative power of M_1 compared with mode BN. As a result, the wholesale price of m_1 in mode BB is always lower than that in mode BN.

In mode BN, M$_1$ needs to subsidize the unit verification cost (s) to the retailer in the form of a reduced wholesale price, which leads to $w_1^{nn} \geq w_1^{bn}$. Therefore, $w_1^{nn} \geq w_1^{bn} > w_1^{bb}$. In mode BN, only M$_1$ introduces blockchain technology, resulting in a decrease in the relative power of M$_2$ compared with mode NN. Therefore, the wholesale price of m$_2$ in mode BN is always lower than that in mode NN. Compared with the price reduction as a result of the lack of blockchain technology in mode BN, the subsidy to the retailer in the form of a wholesale price reduction in mode BB is higher, which results in $w_2^{bn} \geq w_2^{bb}$. Therefore, $w_2^{nn} > w_2^{bn} \geq w_2^{bb}$.

Proposition 2 (ii) shows that with the increase in $\alpha\theta$, when $\alpha\theta$ is in a certain region ($s_1 < \alpha\theta \leq s_2$), the wholesale price of m$_1$ is highest in mode BN and lowest in mode BB, and the wholesale price of m$_2$ is highest in mode NN and lowest in mode BN. In mode BN, only M$_1$ introduces blockchain technology. Compared with the scenario in proposition 2 (i), it becomes more important for manufacturers to introduce blockchain technology, M$_1$ can further increase the wholesale price, while M$_2$ can only further reduce the wholesale price in an effort to increase demand despite the lack of blockchain technology.

Proposition 2 (iii) shows that with the increase in $\alpha\theta$, when $\alpha\theta$ is in a certain region ($s_2 \leq \alpha\theta < e$), the wholesale price of m$_1$ is highest in mode BN and lowest in mode NN, and the wholesale price of m$_2$ is highest in mode BB and lowest in mode BN. In this case, the decision regarding the introduction of blockchain technology has a great impact on demand. In mode NN, both manufacturers will reduce their wholesale price by more than the unit verification cost (s) paid to the retailer as a subsidy in the form of a wholesale price reduction in mode BB. That is, the wholesale prices of both m$_1$ and m$_2$ in mode BB are higher than those in mode NN. Additionally, in mode BN, m$_1$'s wholesale price is highest and m$_2$'s wholesale price is lowest.

Proposition 2 (iv) shows that with the increase in $\alpha\theta$, when $\alpha\theta$ is higher than a certain value (e), mode BN will not exist, and the wholesale price in mode BB will always be higher than that in mode NN for both manufacturers. At this point, blockchain technology has a huge impact on demand. Both manufacturers choose to introduce blockchain technology, and the wholesale price of products is higher than before.

Next, we analyze the impact of competition intensity between the manufacturers and the introduction of blockchain technology on supply chain members' profits. By comparing the profits of supply chain members in different modes, the following propositions can be obtained.

Proposition 3 *For the three modes of blockchain technology introduction, the supply chain members' profits vary with competition intensity f as follows:*

(i) $\frac{d\Pi_{M1}^{bn}}{df} > \frac{d\Pi_{M1}^{bb}}{df} > \frac{d\Pi_{M1}^{nn}}{df} > 0.$

(ii) $\frac{d\Pi_{M2}^{bb}}{df} > \frac{d\Pi_{M2}^{nn}}{df} > \frac{d\Pi_{M2}^{bn}}{df} > 0.$

(iii) $\frac{d\Pi_{R}^{bb}}{df} > \frac{d\Pi_{R}^{bn}}{df} > \frac{d\Pi_{R}^{nn}}{df} > 0.$

The proof of Proposition 3 is presented in the "Appendix".

Proposition 3 shows that the profits of supply chain members increase with the increase in f, that is, the profits of supply chain members increase with a decrease in the competitive intensity between the two manufacturers. Notably, under different blockchain technology introduction strategies, the profits of supply chain members are affected differently by the intensity of competition. Specifically, Proposition 3 (i) shows that M$_1$'s profit is most affected by competitive intensity in mode BN and least affected in mode NN. In mode BN, M_1 attracts the majority of blockchain technology-sensitive consumers. Here, the weakened competition between the two manufacturers can significantly increase M_1's profit. In mode NN, the lack of blockchain technology leads to a limited increase in profit when the competition between the two manufacturers is weakened. Proposition 3 (ii) shows that M_2's profit is most affected by competitive intensity in mode BB and least affected in mode BN. Because in mode BN, M_2 can't attract the blockchain technology-sensitive consumers and the weakened competition between the two manufacturers can only improve M_2's profit slightly. Proposition 3 (iii) shows that the retailer's profit is most affected by competitive intensity in mode BB and least affected in mode NN. From Proposition 3, we can see that the adoption of blockchain technology leads to a more significant impact of competitive intensity among manufacturers on the profits of supply chain members. In the study of Z.-P. Li, Ceong, and Lee (2021), from a different research perspective from this paper, they find that blockchain technology enables companies to maintain a sustainable competitive advantage in an uncertain environment.

It can be seen from Proposition 3 that after the introduction of blockchain technology, manufacturers should consider how to reduce the competition among manufacturers to enhance their profits, such as adopting vertical product differentiation strategy, creating featured products to improve product advantages, etc.

Proposition 4 *For the three modes of blockchain technology introduction, the following statements about* M_1*'s profits hold true*:

(i) *If* $0 < \alpha\theta \leq e_1$, *then* $\Pi_{M1}^{nn} \geq \Pi_{M1}^{bn} > \Pi_{M1}^{bb}$.

(ii) *If* $\mathrm{e}_1 < \alpha\theta \leq e_2$, *then* $\Pi_{M1}^{bn} > \Pi_{M1}^{nn} \geq \mathit{\Pi}_{M1}^{bb}$.

(iii) *If* $\mathrm{e}_2 < \alpha\theta < e$, *then* $\Pi_{M1}^{bn} > \Pi_{M1}^{bb} > \mathit{\Pi}_{M1}^{nn}$.

(iv) *If* $\mathrm{e} \leq \alpha\theta < 1$, *then* $\Pi_{M1}^{bb} > \mathit{\Pi}_{M1}^{nn}$.

where $e_1 = \frac{7(51ftV+102V^2-\sqrt{51}t\sqrt{\frac{V^2(-1100Ft+51(ft+2V)^2)}{t^2}})}{561V^2}$, $e_2 = \frac{3ftV+6V^2-\sqrt{3}t\sqrt{\frac{V^2(-100Ft+3(ft+2V)^2)}{t^2}}}{6V^2}$ and $\mathrm{e} = \frac{7(tf+2V)}{17V}$. $\mathrm{e}_1 < e_2 < e$.

The proof of Proposition 4 is presented in the “Appendix”.

Proposition 4 shows the influence of the introduction of blockchain technology on M₁’s profit under different $\alpha\theta$ value. Specifically, Proposition 4 (i) shows that when $\alpha\theta$ is less than a certain value (e_1), M₁’s profit is highest in mode NN and lowest in mode BB. Similar to Chang et al. (2021)’s statement, the introduction of blockchain technology increases demand. At this point, the introduction of blockchain technology only produces a small increase in demand, such that the benefits of introducing blockchain technology are less than the costs of introducing it. In mode BB, both M₁ and M₂ introduce blockchain technology, and M₁ not only has to meet the costs of introducing blockchain technology, but also loses the technological advantage it enjoyed in mode BN. Therefore, M₁’s profits are lowest in mode BB. In this scenario, considering the cost of introduction, the manufacturers’ profits are greatest without blockchain technology. Therefore, M₁ chooses not to introduce blockchain technology.

Proposition 4 (ii) shows that with the increase in $\alpha\theta$, when $\alpha\theta$ is in a certain region ($e_1 < \alpha\theta \leq e_2$), M₁’s profit is highest in mode BN and lowest in mode BB. In this case, for M₁, the introduction of blockchain technology is effective in attracting consumers. If only M₁ introduces blockchain technology, that is, mode BN applies, the increased profits as a result of the introduction of blockchain technology can cover the introduction costs. Therefore, M₁'s profit increases and is greater in mode in BN than that in mode NN. However, if M_2 also chooses to introduce blockchain technology, the relative power of M_1 declines, and the introduction of blockchain technology does more harm than good. Therefore, M_1's profit decreases in mode BB compared with mode NN. In this case, M_1 needs to consider M_2's reaction before deciding whether to introduce blockchain technology.

Proposition 4 (iii) shows that when $\alpha\theta$ is in a certain region ($e_2 < \alpha\theta < e$), M_1's profit is highest in mode BN and lowest in mode NN. Here, demand is significantly affected by the introduction of blockchain technology. Even if both manufacturers introduce blockchain technology, M_1's increased profit as a result of the introduction of blockchain technology still covers the cost of introduction, and if M_2 does not introduce blockchain technology, M_1 obtains even more profits. Therefore, in this case, M_1's profit is highest in mode BN and lowest in mode NN. In this scenario, M_1 will choose to introduce blockchain technology to maximize its own profit.

Proposition 4 (iv) shows that when $\alpha\theta$ is higher than a certain value (e), mode BN does not exist and M_1's profit in mode BB is higher than that in mode NN.

The determination of which mode applies requires the joint decision of M_1 and M_2. Next, we analyze M_2's profit and obtain the following proposition.

Proposition 5 *For the three modes of blockchain technology introduction, the following statements regarding* M_2*'s profit hold true*:

(i) *If* $0 < \alpha\theta \leq e_3$, *then* $\Pi_{M2}^{nn} > \Pi_{M2}^{bn} \geq \Pi_{M2}^{bb}$.

(ii) *If* $e_3 < \alpha\theta \leq e_2$, *then* $\Pi_{M2}^{nn} \geq \Pi_{M2}^{bb} > \Pi_{M2}^{bn}$.

(iii) If $\mathrm{e}_2 < \alpha\theta < e$*, then* $\Pi_{M2}^{bb} > \Pi_{M2}^{nn} > \mathit{\Pi}_{M2}^{bn}$.

(iv) If $\mathrm{e} \le \alpha\theta < 1$*, then* $\Pi_{M2}^{bb} > \Pi_{M2}^{nn}$

where $e_3 = \frac{7(3ftV+6V^2-\sqrt{3}t\sqrt{\frac{V^2(-100Ft+3(ft+2V)^2)}{t^2}})}{51\mathrm{V}^2}$, $e_2 = \frac{3ftv+6v^2-\sqrt{3}t\sqrt{\frac{v^2(-100Ct+3(ft+2v)^2)}{t^2}}}{6v^2}$ and $\mathrm{e} = \frac{7(tf+2V)}{17V}$. $0 < e_3 < e_2 < e < 1$.

The proof of Proposition 5 is presented in the "Appendix".

Proposition 5 shows the influence of the introduction of blockchain technology on M_2's profit under different αθ value. Specifically, Proposition 5 (i) shows that when $\alpha\theta$ is less than a certain value (e_3), M_2's profit is highest in mode NN and lowest in mode BB. Similar to Proposition 4, here, the introduction of blockchain technology has a small impact on the increase in demand, and considering the cost of introduction, for manufacturers, the profit is greatest without the introduction of blockchain technology. In mode BB, M_1's introduction of blockchain technology leads to a decrease in M_2's profits. Therefore, M_2's profit is lowest in mode BB.

Proposition 5 (ii) shows that when $\alpha\theta$ is in a certain region ($e_3 < \alpha\theta \le e_2$), M_2's profit is highest in mode NN and lowest in mode BN. In this case, the introduction of blockchain technology is effective in attracting consumers. However, the cost for M_2 is higher than the additional profits earned through the introduction of blockchain technology. Therefore, M_2's profit is highest when neither manufacturer introduces blockchain technology. Compared with mode NN, M_2's profit decreases in both mode BB and mode BN, decreasing more in mode BN. In this mode, M_2 expects M_1 not to introduce blockchain technology. If M_1 introduces blockchain technology, M_2 should also introduce blockchain technology to compete with M_1 for market share.

Proposition 5 (iii) shows that when $\alpha\theta$ is in a certain region ($e_2 < \alpha\theta < e$), M_2's profit is highest in mode BB and lowest in mode BN. Here, demand is significantly affected by the introduction of blockchain technology. If M_2 does not introduce blockchain technology after M_1 does so, m_2 will be less competitive. The majority of consumers will choose m_1. Thus, M_2's profit will be lower than that in mode NN. If M_2 chooses to introduce blockchain technology, the cost is lower relative to the additional profits gained through the introduction of blockchain technology. Therefore, M_2's profit is higher in mode BB than in mode NN.

Proposition 5 (iv) shows that when $\alpha\theta$ is higher than a certain value (e), mode BN does not exist, and M_2's profit is higher in mode BB than in mode NN.

Next, we analyze retailer's profit and obtain the following proposition.

Proposition 6 *For the three modes of blockchain technology introduction, the retailer's profits are as follows:*

$$\Pi_R^{bb} > \Pi_R^{bn} > \mathit{\Pi}_R^{nn}$$

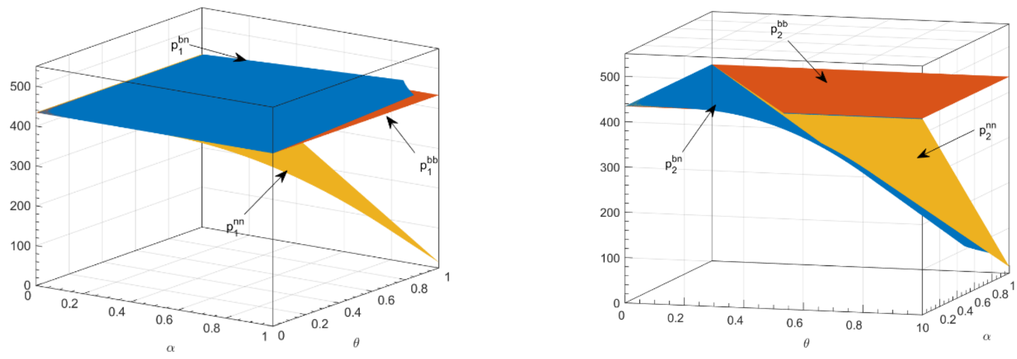
The proof of Proposition 6 is presented in the "Appendix".

Proposition 6 shows that retailer's profit is highest in mode BB and lowest in mode NN, which means that the introduction of blockchain technology by manufacturers always benefits the retailer. When a product is supplied using blockchain technology, the retailer pays a unit verification fee to the manufacturer and there is no fixed expense for the retailer. Notably, manufacturers subsidize the unit verification fee (s) to the retailer in the form of a wholesale price reduction. Thus, for retailers, the introduction of blockchain technology does not introduce additional costs, but enables them to increase their sales volume and the prices of the products they sell. Therefore, retailers obtain the highest profits in mode BB and the lowest in mode NN.

6. Numerical studies

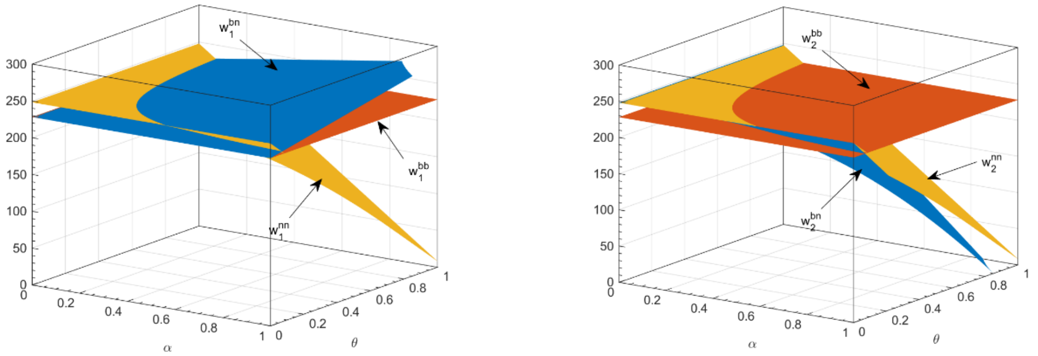
In this section, we conduct numerical analyses to verify the changes in prices and profits of supply chain members under different blockchain introduction modes and the blockchain introduction strategy choices under different market environments. Without loss of generality, we use the following settings: $f = 20,\ t = 2,\ s = 20,\ V = 600$, and $F = 2500$. In the following, we illustrate the impact of the proportion of type α consumers and the reservation price discount percentage θ on the supply chain members' pricing strategies and profits.

Fig. 6 shows the impact of the proportion of type α consumers and the reservation price discount percentage θ on the retailer's pricing strategy. From Fig. 6 (a), it can be seen that when αθ is less than a certain value ($0 < \alpha\theta < \frac{497}{510}$), $p_1^{bn} > p_1^{bb} > p_1^{nn}$ always holds, and when the condition for the existence of mode BN is not valid, that is, when αθ is greater than a certain value ($\frac{497}{510} \leq \alpha\theta < 1$), $p_1^{bb} > p_1^{nn}$ always holds. Fig. 6 (b) shows the optimal pricing of m_2 under the different modes. When mode BN exists, m_2 is at its lowest price, and when the condition for the existence of mode BN is not valid, the price of m_2 is higher when both parties introduce blockchain technology than when neither party introduces it. These findings are consistent with Proposition 1.



(a) m_1's pricing (b) m_2's pricing

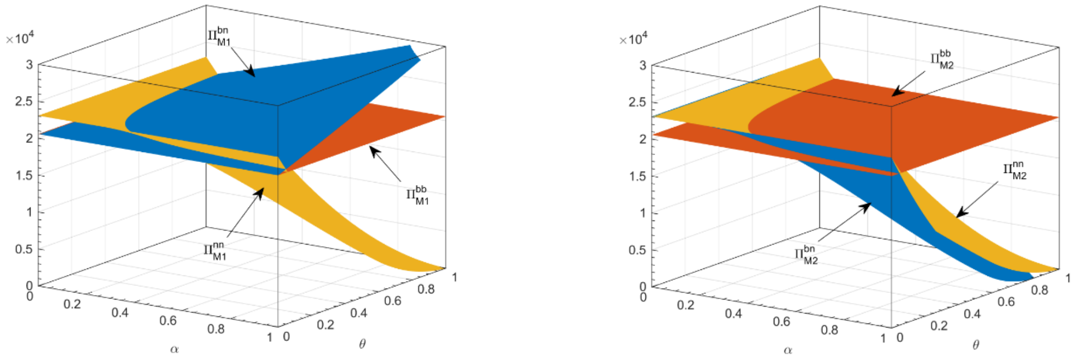
Fig.6. Retailer's pricing strategy regarding m_1 and m_2.



(a) M_1's wholesale pricing strategy (b) M_2's wholesale pricing strategy

Fig.7. Manufacturers' wholesale pricing strategies

Fig. 7 shows the impact of the proportion of type α consumers and the reservation price discount percentage θ on the two manufacturers' wholesale pricing strategies. When $\alpha\theta$ is lower than a certain value ($0 < \alpha\theta \leq \frac{7}{102}$), the optimal pricing strategies of M_1 and M_2 are similar; they both charge the highest wholesale price in mode NN and the lowest wholesale price in mode BB. With the increase in $\alpha\theta$, the wholesale price of m_1 increases and the wholesale price of m_2 decreases. When $\frac{7}{102} < \alpha\theta < \frac{1}{12}$, M_1 has the highest wholesale price in mode BN, while M_2 has the lowest wholesale price in mode BN. This is because as the impact of blockchain technology on the market increases, M_1 with blockchain can increase the wholesale price, while M_2 without blockchain technology can only reduce the wholesale price. When $\frac{1}{12} \leq \alpha\theta < \frac{497}{510}$, the introduction of blockchain technology has a significant positive impact on demand, and M_2 has the highest wholesale price in mode BB and the lowest wholesale price in mode BN, while M_1 has the highest wholesale price in mode BN and the lowest wholesale price in mode NN. When $\frac{491}{510} \leq \alpha\theta < 1$, mode BN does not exist, and both manufacturers have the highest wholesale price in mode BB and the lowest wholesale price in mode NN. These findings are consistent with Proposition 2.



(a) M_1's profit (b) M_2's profit

Fig.8. The optimal profit of manufacturers under different modes.

Fig. 8 shows the impact of the proportion of type α consumers and the reservation price discount percentage θ on the profits of the two manufacturers. Fig. 8 (a) indicates that when $\alpha\theta$ is less than a certain value ($0 < \alpha\theta \leq \frac{7(3162-\sqrt{9296994})}{16830}$), M_1's profit is highest in mode NN and lowest in mode BB. With the increase in $\alpha\theta$, the introduction of blockchain technology is increasingly important for the supply chain, and M_1's profit in mode BN surpasses that in mode NN. That is, when $\frac{7(3162-\sqrt{9296994})}{16830} < \alpha\theta \leq \frac{186-\sqrt{30846}}{180}$, M_1's profit is highest in mode BN and lowest in mode BB. when $\frac{186-\sqrt{30846}}{180} < \alpha\theta < \frac{497}{510}$, the importance of blockchain technology is further highlighted, and M_1's profit is lowest in mode NN and highest in mode BN. In this scenario, since M_1'profit is lowest in mode NN, M_1 will introduce blockchain technology regardless of whether M_2 follows. When $\frac{491}{510} \le \alpha\theta < 1$, mode BN does not exist. Then, M_1's profit is highest in mode BB and lowest in mode NN. In this scenario, M1 will also chose to introduce blockchain technology. These findings are consistent with Proposition 3.

Fig. 8 (b) shows the impact of α and θ on M_2's profits under the different modes. When $\alpha\theta$ is less than a certain value ($0 < \alpha\theta \le \frac{7(186-\sqrt{30846})}{1530}$), M_2's profit is highest in mode NN and lowest in mode BB. In this case, the impact of blockchain technology on demand is minimal, and thus the cost of introducing blockchain technology results in lower profits. When $\frac{7(186-\sqrt{30846})}{1530} < \alpha\theta \le \frac{186-\sqrt{30846}}{180}$, M_2's profit is lowest in mode BN and highest in mode NN. In this case, M_2 expects M_1 not to introduce blockchain technology, but when M_1 introduces it, M_2 follows. When $\frac{186-\sqrt{30846}}{180} < \alpha\theta < \frac{497}{510}$, M_2's profit is highest in mode BB and lowest in mode BN. In this case, M_1 obtains excess market share in mode BN. Therefore, M_2's profit is lowest in mode BN. In fact, mode BN doesn't appear in this situation. Because once M_1 introduces blockchain technology, M_2 will follow. When $\frac{491}{510} \le \alpha\theta < 1$, because M_2's wholesale price is negative, mode BN does not exist. In this case, M_2's profit is highest in mode BB and lowest in mode NN. These findings are consistent with Proposition 4. Fig.8 also shows that when αθ is larger than a certain value, the introduction of blockchain technology is beneficial to manufacturers' profits.

Next, we undertake an empirical analysis of the retailers' profits under the different modes.

Fig. 9 shows the impact of the proportion of type α consumers and the reservation price discount percentage θ on the retailer's profits under the different modes. From Fig. 9, it can be seen that regardless of the value of α and θ, the manufacturers' introduction of blockchain technology is always beneficial to the retailer. The more products retailers sell that adopt blockchain technology, the better off they are and the higher the value of $\alpha\theta$, the more the retailer's profit increases in mode BB compared with mode NN. Thus, it can be seen that the retailer's profit in mode BB is always higher than that in mode BN and the retailer's profit under mode BN is always higher than that in mode NN. This finding is consistent with Proposition 5. The introduction of blockchain technology can attract blockchain technology-sensitive consumers to buy products, which can lead to higher profits for retailers. Therefore, retailers want their upstream manufacturers to sell products that incorporate blockchain technology, so that they can reach a wider consumer market and make higher profits.

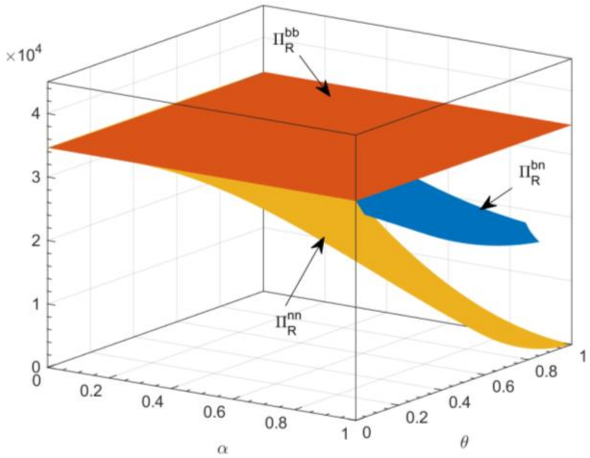
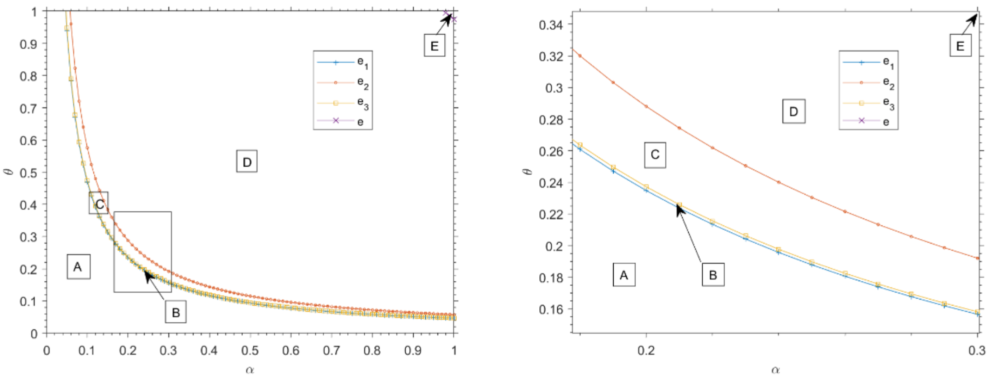


Fig.9. Retailer’s optimal profit under different modes.

We can obtain the final blockchain introduction strategy for the supply chain based on M_1 and M_2’s profits in the different modes. Owing to the complexity of the calculations, we used numerical calculations to obtain an intuitive explanation. Fig. 10 shows the intuitive optimal strategies under different decision-making modes. Because the values of e_1 and e_3 are similar, it is difficult to distinguish them in Fig.10 (a). Fig.10 (b) shows an enlargement of the rectangular area highlighted in the lower left corner in Fig.10 (a).



(a) Optimal mode selection (b) Enlarged version inside rectangle

Fig.10. Optimal mode selection.

Fig. 10 shows that when α and θ are in region A ($0 < \alpha\theta \le e_1$), both M_1 and M_2 enjoy their highest profits in mode NN and neither choose to introduce blockchain technology. Thus, in this case, the supply chain's blockchain technology introduction mode is mode NN.

When α and θ are in region B ($e_1 < \alpha\theta \le e_3$), M_1's profit is highest in mode BN. M_2's profit is highest in mode NN and lowest in mode BB. In this case, M_1 chooses to introduce blockchain technology. Since M_2's profit in mode BN is higher than that in mode BB, M_2 will not introduce blockchain technology. Therefore, when α and θ are in region B, the supply chain's introduction mode is mode BN.

When α and θ are in region C ($e_3 < \alpha\theta \le e_2$), M_1's profit is highest in mode BN and lowest in mode BB. In this case, M_2's profit in mode BB is higher than that in mode BN, if M_1 introduces blockchain technology, M_2 will also introduce blockchain technology. As a rational participant, M_1 can predict M_2's response. Therefore, to avoid becoming BB mode, M_1 chose not to introduce blockchain technology. Then, the final equilibrium in this scenario is mode NN.

When α and θ are in region D ($e_2 < \alpha\theta \leq e$), M_1's profits are highest in mode BN and M_2's profits are highest in mode BB. Because M_2's profits are higher in mode BB than in mode BN, if M_1 introduces blockchain technology, M_2 will also introduce blockchain technology. Based on that M_1's profits are higher in mode BB than in mode NN, M_1 chooses to introduce blockchain technology. Then, the supply chain's blockchain technology introduction mode is mode BB.

When α and θ are in region E, mode BN does not exist. Both M_1 and M_2's profits are highest in mode BB, and thus both choose to introduce blockchain technology. In this case, the supply chain's blockchain technology introduction mode is mode BB.

On the basis of the above analysis, when α and θ are in region A or C, the supply chain's blockchain technology introduction mode is mode NN. When α and θ are in region B, the supply chain's blockchain technology introduction mode is mode BN. When α and θ are in regions D or E, the supply chain's blockchain technology introduction mode is mode BB. When a manufacturer considers whether to introduce blockchain technology, it not only needs to examine the market consumer structure and investigate consumer sensitivities, but also needs to consider how competitors might react. In certain market environments (Region B), it is more profitable to be the first to introduce blockchain technology.

7. Conclusions

Given that the introduction of blockchain technology can satisfy some consumers' preferences for product authenticity and product traceability, in this study, we consider a supply chain in which two manufacturers sell competing products through the same retailer and analyze the impact of different blockchain technology introduction modes on supply chain performance. We further explore the timing of manufactures introducing blockchain technology.

7.1 *Managerial insights*

We provide some managerial insights for practice. First, for manufacturers, when deciding whether to introduce blockchain technology, they should consider not only their own profits, but also the impact of their competitors' optimal response and their blockchain technology introduction strategy. Second, from Lemma 2 and Lemma 3, we can see that the size of the unit verification fee does not matter to either the manufacturer or the retailer. Thus, there is no need for manufacturers and retailers to spend much time negotiating the size of the unit verification fee. Third, Proposition 1, Proposition 2, Proposition 4 and Proposition 5 show that the introduction of blockchain technology in different market environments has different impacts on the price changes of supply chain members and manufacturers' profits. Therefore, supply chain members need to pay attention to the types of consumers in the market and understand consumer psychology and additional requests for products through market research. Only in this way can they recognize the right time to introduce blockchain technology and price their products accordingly to obtain higher profits. In addition, manufacturers who can introduce blockchain technology first are more likely to reap big gains in profits, it is important for manufacturers to strengthen themselves to become leaders in the industry.

7.2 Limitations and future research

There are some limitations in this study, which provides ideas for future research. First, it only considers two manufacturers and one retailer, whereas in reality there are more members in the supply chain, such as suppliers and third-party logistics providers, which should be considered in future research. Second, we assume that there is full understanding by all parties of consumer behavior. Information asymmetry can be considered in future research. What's more, we can investigate whether the retailer should conduct market research into consumer behavior and, if so, how they should share the information they obtain with manufacturers. Thus, supply chain coordination can be added into future research. Third, demand in our model is deterministic, and thus in future research we should consider the inherent uncertainty of market demand. In this paper, we consider both the blockchain technology-sensitive consumers and ordinary consumers. In future studies, we can focus on the blockchain technology-sensitive consumers to get more profound and interesting conclusions.

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