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Research article

Mathematical modeling and numerical analysis of blockchain decision systems by a dynamic game method

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Abstract: In this study, we innovatively applied dynamic game theory to analyze blockchain adoption decisions in competitive environments. By constructing a multi-stage dynamic game model and solving for optimal strategies through backward induction, we overcame the limitations of the traditional static game analysis. Combining the mathematical modeling with numerical simulations, we identified a critical threshold effect of the competition intensity on the blockchain adoption equilibrium. Specifically, when the competition intensity fell below the threshold, blockchain adoptions emerged as the dominant strategy. Beyond this threshold, the equilibrium shifted to a mixed-strategy outcome. Furthermore, we developed a dynamic response mechanism that linked traceability preferences to profit functions. Our model provides a theoretical framework for analyzing blockchain adoptions in competitive settings, while the numerical results offer actionable insights for optimizing the blockchain system design.

Keywords: blockchain; dynamic game; mathematical modeling; numerical analysis

1. Introduction

As an emerging technology, blockchain possesses key features, including security, traceability, and verification. It significantly enhances the supply chain operational efficiency through the improved data management, responsiveness, transparency, and smart contract execution [1,2]. Blockchain technologies are widely adopted across multiple industries such as healthcare, finance, agriculture, e-commerce, and aviation [3]. A prominent example is Nestlé's collaboration with Amazon to develop blockchain solutions for its coffee brand, Chain of Origin, enabling the end-to-end traceability of coffee beans from cultivation through roasting to final brewing [4]. In April 2020, Nestlé further expanded its blockchain integration by joining the IBM Food Trust Program to enhance the supply chain transparency for its premium brand, Zoégas [5]. Similarly, Bumble Bee Foods, one of North America's leading seafood producers, utilizes blockchain to track fishing locations and provide verifiable data on the product authenticity, freshness, safety, and sustainable fishing certifications [6].

Blockchain technologies demonstrate significant potentials in areas such as the product traceability [7,8]. However, its widespread adoption faces practical challenges, primarily due to high implementation costs [9–11]. Adopting blockchain technologies requires substantial investments in the infrastructure development, the equipment maintenance, and the system programming to support the storage, inspection, auditing, and authentication of the product information [12]. The low survival rate of blockchain initiatives indicates the high barriers to adoptions. For instance, only 8% of the 26,000 projects launched in 2016 were operational by 2017 [13]. Notable terminated projects include large-scale implementations, such as the TradeLens platform and the IBM Food Trust. Considering these challenges, we address the following research questions:

1) How does the adoption of blockchain technologies by manufacturers affect the optimal decision-making regarding wholesale and retail prices and traceability levels?

2) What incentives do manufacturers have to implement blockchain technologies under different competitive models, and do manufacturers and retailers have different preferences for blockchain technologies?

3) How do competitions among supply chains and consumer preferences for the product traceability affect each member's optimal decisions and profits?

Regarding the impact of blockchain technologies' adoption on supply chain decisions, researchers have primarily focused on its applications in the supply chain finance [14–16] and the agricultural supply chain [17–19]. Blockchain technology adoptions have a significant impact on the supply chain system performance. Xu et al. [20] explored the impact of blockchain technologies adoptions on the coordination mechanism of green supply chains. Tao et al. [21] investigated the effect of blockchain technologies on the optimal pricing and quality decisions in platform supply chains. Xu and Duan [22] examined the optimal decision-making for the product pricing and the blockchain technology investment under government subsidies. Wu and Yu [23] discussed the impact of blockchain on platform supply chains based on transaction costs and information transparency. Fang et al. [24] studied how commission ratios influence blockchain investment decisions. Shirafkan et al. [25] employed a game-theoretic approach to investigate pricing, advertising, and cybersecurity strategies in blockchain-based supply chains under cryptocurrency volatility. However, these studies do not address the competitive dynamics of supply chains.

This study is closely related to supply chain competitions and dynamic games. Wang et al. [26] pointed out that the vertical integration can be the equilibrium outcome with supply chain competitions. Ha and Tong [27] examined the information sharing and the contract design of supply chain competition systems. Wang et al. [28] compared the conditions for the optimal product pricing under different intensities of supply chain competitions. Ge et al. [29] analyzed Pareto improvement strategies of collaborative innovations using a two-stage game model. Yenipazarli [30] examined the cost-sharing and benefit-sharing contracts using a three-stage game model with the Nash negotiation. Gupta [31] revealed the impact of the choice of sales channels between manufacturers and competitors using a dynamic game model. Li et al. [32] and Li et al. [33] used a dynamic game model to analyze the revenue sharing contract. Yao et al. [34] developed three decision-making models (vertical integration, manufacturer-led Stackelberg, and bargaining) in competitive supply chains to examine member profits. Li et al. [35], developed a pricing and quality decision-making model for competing supply chains under common ownership. Liu et al. [36] constructed a game-theoretic outsourcing model for a dyadic supplier-manufacturer competitive system.

There are few studies on competitive supply chain decision-making models that introduce blockchain technologies. Therefore, in this work, we develop a mathematical model with blockchain technologies for decision making. The major contributions of this work are as follows: First, we combine game theory, decision optimization methods, and numerical simulations to build a mathematical model for a blockchain decision-making system under the supply chain competition environment. Second, we give numerical analyses of the equilibrium results of the mathematical model. Finally, we present significant and insightful implications for the sustainability of blockchain-enabled businesses. The rest of the paper is organized below. We introduce the proposed mathematical model in Section 2. The model solution is presented in Section 3, and the equilibrium is analyzed in Section 4. We conduct numerical analysis in Section 5, and conclude the paper in Section 6.

2. The proposed model

We consider two competing supply chain systems, each consisting of a manufacturer and a retailer. The manufacturer produces the product, which the retailer then sells to the market. As the market leader, the manufacturer decides whether to adopt blockchain technologies to track the production and wholesaling process. Referring to Wu et al. [18], the traceability level x portrays the manufacturer's behavior in adopting blockchain technologies. The higher the manufacturer's investment in blockchain technologies, the stronger the traceability level x of blockchain technologies.

The cost of adopting blockchain technology depends on the level of the traceability. If the level of traceability is increased, the manufacturer must pay a higher investment cost. Referring to Wu et al. [18], the cost of adopting blockchain technologies is expressed by the quadratic function $c = kx^2$, where k is the cost adoption parameter. To facilitate comparisons, we set $k = 1$ in our paper. Note that even if k is not equal to 1, it will not change the major conclusions of this paper; however, it will increase the computational complexity.

When neither manufacturer adopts blockchain technologies, the two supply chains compete only on the price. Thus, the market demand function for the product is shown in Eq (1) when no blockchain technology is adopted.

$$q_i = a - \frac{p_i}{1-b} + \frac{bp_{3-i}}{1-b} \tag{1}$$

where $b \in [0,1]$ denotes the degree of the products substitutability, q_i and p_i are the demand and price of product i, respectively, and a represents the potential market size. When two manufacturers choose to adopt blockchain technologies simultaneously, they compete not only on the price, but also on providing product traceability services. At this point, the market demand function of the product is shown in Eq (2).

$$q_i = a - \frac{p_i}{1-b} + \frac{bp_{3-i}}{1-b} + h(\frac{x_i}{1-b} - \frac{bx_{3-i}}{1-b}) \tag{2}$$

where $h > 0$ represents the consumer preference for the product traceability. Moreover, increasing the consumer preference for the product traceability will increase the demand for products. x_i and x_{3-i} represent the traceability levels of product *i* and product 3-i.

Based on the manufacturer's choice of blockchain technologies, four competitive models are formed. These models are denoted as *NN*, *NY*, *YN*, and *YY*, where *N* denotes non-adoptions of blockchain technologies and *Y* denotes their adoptions. Due to the symmetry of *NY* and *YN*, we mainly consider *YN*. In the various competitive models, the order of the game between members of the two supply chains is as follows. First, the two manufacturers simultaneously decide whether to adopt blockchain technologies. If they adopt blockchain technologies, they set the optimal wholesale price and traceability level. If they do not adopt blockchain technologies, only the wholesale price is set. Second, the two retailers simultaneously set their retail prices.

The notations used in our paper are shown in Table 1.

Table 1. Notations.

Symbols	Description
i	Subscript, the index of the manufacturer *i* or the product *i*, where $i = \{1, 2\}$
L	Superscript, the blockchain technology choice models, L = {*NN*, *YN*, *NY*, or *YY*}, where *Y* and *N* represent manufacturers that adopt and do not adopt blockchain technologies, respectively
a	The potential market size
b	The degree of the products substitutability, which represents the intensity of supply chain competitions
h	The consumer preference for the product traceability
p_i^L	The retail price of the product *i* for the model *L, L* = *NN*, *NY*, *YN*, or *YY*
q_i^L	The demand of the product *i* for the model *L, L* = *NN*, *NY*, *YN*, or *YY*
w_i^L	The wholesale price of the product *i* for the model *L, L* = *NN*, *NY*, *YN*, or *YY*
x_i^L	The traceability level of the product *i* for the model *L, L* = *NN*, *NY*, *YN*, or *YY*
$\pi_{m_i}^L$	The manufacturer *i*'s profits for the model *L, L* = *NN*, *NY*, *YN*, or *YY*
$\pi_{r_i}^L$	The retailer *i*'s profits for the model *L, L* = *NN*, *NY*, *YN*, or *YY*

3. The model solution

We discuss the optimal decisions and profits of supply chain members under models *NN, YN,* and *YY.* Since models *NY* and *YN* are symmetric, the following analysis considers only model *YN*.

3.1. The NN model

Under the *NN* model, neither supply chains adopt blockchain technologies. The manufacturer and the retailer play a Steinberg game with the following profit functions as shown in Eqs (3) and (4), respectively.

$$\pi_{m_i}^{NN} = w_i(a - \frac{p_i}{1-b} + \frac{bp_{3-i}}{1-b}) \tag{3}$$

$$\pi_{r_i}^{NN} = (p_i - w_i)(a - \frac{p_i}{1-b} + \frac{bp_{3-i}}{1-b}) \tag{4}$$

where $i = 1, 2$.

Using backward induction, we first optimize it by setting the first-order condition with p_i for Eq (4) as shown in Eq (5)

$$\frac{\partial \pi_{r_i}^{NN}}{\partial p_i} = a - \frac{p_i}{1-b} + \frac{bp_{3-i}}{1-b} + \frac{p_i - w_i}{1-b}. \tag{5}$$

Similarly, we get Eq (6),

$$\frac{\partial \pi_{r_i}^{NN}}{\partial p_{3-i}} = a - \frac{p_{3-i}}{1-b} + \frac{bp_i}{1-b} + \frac{p_{3-i} - w_{3-i}}{1-b} \tag{6}$$

Solving Eqs (5) and (6), the reaction function of the retail price can be derived as Eqs (7) and (8).

$$p_i(w_i, w_{3-i}) = \frac{(2+b)(1-b)a + bw_{3-i} + 2w_i}{4-b^2} \tag{7}$$

$$p_{3-i}(w_i, w_{3-i}) = \frac{(2+b)(1-b)a + bw_i + 2w_{3-i}}{4-b^2} \tag{8}$$

The manufacturer *i* uses the reaction function of the retail price as shown in Eqs (7) and (8) in the profit function shown in Eq (3) and takes the first derivatives w.r.t. w_i to get Eq (9).

$$\frac{\partial \pi_{m_i}^{NN}}{\partial w_i} = \frac{a(1-b)(b+2) + 2(b^2-2)w_i + bw_{3-i}}{(1-b)(4-b^2)} = 0 \tag{9}$$

Following the same approach, we can obtain Eq (10).

$$\frac{\partial \pi_{m_{3-i}}^{NN}}{\partial w_{3-i}} = \frac{a(1-b)(b+2) + 2(b^2-2)w_{3-i} + bw_i}{(1-b)(4-b^2)} = 0 \tag{10}$$

Solving Eqs (9) and (10), we can derive the optimal wholesale price w_i^{NN*}. Substituting w_i^{NN*} into Eq (7), the equilibrium retail price p_i^{NN*} is given. Based on the equilibrium decisions above, we can obtain the members' optimal profits for the *NN* model shown in Proposition 1.

Proposition 1. For the *NN* model, there exist unique optimal equilibrium decisions and profits for manufacturers and retailers, such that the following Eqs (11)–(14).

$$p_i^{NN*} = \frac{2(1-b)(3-b^2)a}{(2-b)(4-2b^2-b)}, \tag{11}$$

$$w_i^{NN*} = \frac{(2-b)(1-b)a}{4-2b^2-b}, \tag{12}$$

$$\pi_{m_i}^{NN*} = \frac{(1-b)(4-b^2)(2-b^2)a^2}{(2-b)^2(4-2b^2-b)^2}, \tag{13}$$

$$\pi_{r_i}^{NN*} = \frac{(1-b)(2-b^2)^2a^2}{(2-b)^2(4-2b^2-b)^2}. \tag{14}$$

where $i = 1, 2$.

3.2. The YY model

Under the *YY* model, both manufacturers adopt blockchain technologies. The profit functions of the manufacturer and the retailer can be expressed as Eqs (15) and (16), respectively.

$$\pi_{m_i}^{YY}=w_i[a-\frac{p_i}{1-b}+\frac{bp_{3-i}}{1-b}+h(\frac{x_i}{1-b}-\frac{bx_{3-i}}{1-b})]-x_i^2 \tag{15}$$

$$\pi_{r_i}^{YY}=(p_i-w_i)[a-\frac{p_i}{1-b}+\frac{bp_{3-i}}{1-b}+h(\frac{x_i}{1-b}-\frac{bx_{3-i}}{1-b})] \tag{16}$$

According to the analytical principle of the inverse induction, we first examine the decision-making behavior of retailers. Differentiate Eq (16) partially with respect to p_i to obtain Eq (17).

$$\frac{\partial\pi_{r_i}^{YY}}{\partial p_i}=\left[a+\frac{bp_{3-i}-p_i}{1-b}+h\cdot\frac{x_i-bx_{3-i}}{1-b}\right]-\frac{p_i-w_i}{1-b}=0 \tag{17}$$

The first-order partial derivative with respect to p_{3-i} is derived similarly as shown in Eq (18).

$$\frac{\partial\pi_{r_{3-i}}^{YY}}{\partial p_{3-i}}=\left[a+\frac{bp_i-p_{3-i}}{1-b}+h\cdot\frac{x_{3-i}-bx_i}{1-b}\right]-\frac{p_{3-i}-w_{3-i}}{1-b}=0 \tag{18}$$

The optimal retail price can be obtained by linking Eqs (17) and (18), which are about the wholesale price and the retrospective level. Solving them, we obtain Eqs (19) and (20).

$$p_i(w_i,w_{3-i},x_i,x_{3-i})=\frac{(2+b)(1-b)a+2w_i+(2+b)h(x_i-bx_{3-i})+bw_{3-i}}{4-b^2} \tag{19}$$

$$p_{3-i}(w_i,w_{3-i},x_i,x_{3-i})=\frac{(2+b)(1-b)a+2w_{3-i}+(2+b)h(x_{3-i}-bx_i)+bw_i}{4-b^2} \tag{20}$$

Next, we analyze the manufacturer's decisions. Bringing Eqs (19) and (20) into Eq (15) of the manufacturers' profit function, we take the first-order partial derivatives with respect to w_i and x_i, respectively, for Eq (15) as shown in Eqs (21) and (22).

$$\frac{\partial\pi_{m_i}^{YY}}{\partial w_i}=\frac{2a(1+b)}{4-b^2}+\frac{2w_i(b^2-2)+bw_{3-i}+h(2-b)(x_i-bx_{3-i})}{(1-b)(4-b^2)}=0 \tag{21}$$

$$\frac{\partial\pi_{m_i}^{YY}}{\partial x_i}=w_ih\left[\frac{-(2+b)-(2+b)b^2+(4-b^2)}{(1-b)(4-b^2)}\right]-2x_i=0 \tag{22}$$

The Hessian matrix is shown in Eqs (23) and (24).

$$H=\begin{bmatrix}\frac{b^2-2}{(1-b)(4-b^2)} & \frac{2-b-3b^2-b^3}{(1-b)(4-b^2)}\\ \frac{2-b-3b^2-b^3}{(1-b)(4-b^2)} & -2\end{bmatrix} \tag{23}$$

$$|H|=\frac{2(2-b^2)-(2-b-3b^2-b^3)^2}{(1-b)(4-b^2)} \tag{24}$$

Thus, the joint concavity of the profit function $\pi_{m_i}^{YY}$ can be ensured. Solving Eqs (21) and (22), we can obtain the following Eqs (25) and (26).

$$w_i(w_{3-i}, x_i, x_{3-i}) = \frac{2a(b^2-1)-bw_{3-i}-h(2-b)(x_i-bx_{3-i})}{2(b^2-2)} \tag{25}$$

$$x_i(w_i) = w_i h\left[\frac{(4-b^2)-(2+b)-(2+b)b^2}{2(1-b)(4-b^2)}\right] \tag{26}$$

Simultaneously solving Eqs (25) and (26), we can derive the optimal wholesale price w_i^{YY*} and x_i^{YY*}. Substituting w_i^{YY*} and x_i^{YY*} into Eq (19), the equilibrium retail price p_i^{YY*}can be derived. From p_i^{YY*}, w_i^{YY*} and x_i^{YY*}, we can obtain optimal profits for the model *YY*, which are shown in Proposition 2.

Proposition 2. For the *YY* model, there exist unique optimal equilibrium decisions and profits for manufacturers and retailers, such that Eqs (27)–(31).

$$w_i^{YY*} = \frac{2(4-b^2)(1-b)\alpha}{(8-4b^2-2b)(2-b)-(2-b^2)h^2} \tag{27}$$

$$x_i^{YY^*} = \frac{h(2-b^2)a}{(8-4b^2-2b)(2-b)-(2-b^2)h^2} \tag{28}$$

$$p_i^{YY*} = \frac{(12-4b^2)(1-b)a}{(8-4b^2-2b)(2-b)-(2-b^2)h^2} \tag{29}$$

$$\pi_{m_i}^{YY*} = \frac{(2-b^2)a^2((16-4b^2)(1-b)-(2-b^2)h^2)}{[(8-4b^2-2b)(2-b)-(2-b^2)h^2]^2} \tag{30}$$

$$\pi_{r_i}^{YY*} = \left[\frac{(4-2b^2)a\sqrt{(1-b)}}{(8-4b^2-2b)(2-b)-(2-b^2)h^2}\right]^2 \tag{31}$$

Corollary 1. When both manufacturers adopt blockchain technologies, there exist $\frac{\partial x_i^{YY^*}}{\partial h} > 0$ and $\frac{\partial \pi_{r_i}^{YY*}}{\partial h} > 0$.

Proof. Given $b < 1$, there exists $(8-4b^2-2b)(2-b)-(2-b^2)h^2 > 0$. From the expression of $x_i^{YY^*}$, it can be derived that $\frac{\partial x_i^{YY^*}}{\partial h} = \frac{2(2-b^2)(8-4b^2-2b)(2-b)ha}{[(8-4b^2-2b)(2-b)-(2-b^2)h^2]^2}$. Therefore, $\frac{\partial x_i^{YY^*}}{\partial \mathrm{h}}$>0. Similarly, it can be proved that $\frac{\partial \pi_{r_i}^{YY*}}{\partial \mathrm{h}} > 0$.

Corollary 1 demonstrates that as consumers' product traceability preference intensifies: (i) The manufacturer's optimal traceability level in Model *YY* increases monotonically, and (ii) correspondingly, the retailer's optimal profit under Model *YY* also exhibits a strictly increasing trend.

3.3. The model YN

In the *YN* model, Manufacturer 1 uses blockchain technologies, while Manufacturer 2 does not. Both manufacturers make decisions simultaneously. Manufacturer 1 determines the product traceability level and the wholesale price. Manufacturer 2 determines only the wholesale price. The two retailers then determine their respective retail prices based on manufacturers' decisions. The profit functions of the supply chain members are shown in the following Eqs (32)–(35).

$$\pi_{m_1}^{YN} = w_1\left(\alpha - \frac{p_1}{1-b} + \frac{bp_2}{1-b} + h\,x_1\right) - x_1{}^2 \tag{32}$$

$$\pi_{m_2}^{YN} = w_2\left(\alpha - \frac{p_2}{1-b} + \frac{bp_1}{1-b}\right) \tag{33}$$

$$\pi_{r_1}^{YN} = (p_1 - w_1)\left(\alpha - \frac{p_1}{1-b} + \frac{bp_2}{1-b} + h\,x_1\right) \tag{34}$$

$$\pi_{r_2}^{YN} = (p_2 - w_2)\left(\alpha - \frac{p_2}{1-b} + \frac{bp_1}{1-b}\right) \tag{35}$$

The problem is solved via the backward induction. In the second stage, the retailer's optimal decision is obtained by letting $\frac{\partial \pi_{r_i}^{YN*}}{\partial p_i} = 0$, which yields Eqs (36) and (37).

$$p_1(w_1, w_2, x_1) = \frac{(2+b)(1-b)\alpha + 2(1-b)h\,x_1 + 2w_1 + bw_2}{4-b^2} \tag{36}$$

$$p_2(w_1, w_2, x_1) = \frac{(2+b)(1-b)\alpha + b(1-b)h\,x_1 + 2w_2 + bw_1}{4-b^2} \tag{37}$$

Since the two manufacturers make decisions based on maximizing their respective profits, substitute Eqs (36) and (37) into Eq (32) and take the first order derivative of w_1 and x_1, which leads to the following Eqs (38) and (39).

$$\frac{\partial \pi_{m_1}^{YN}}{\partial w_i} = \frac{2a - 4w_1 - ab + bw_2 + 2hx_1 - ab^2 + 2b^2w_1 - 2bhx_1}{b^3 - b^2 - 4b + 4} = 0 \tag{38}$$

$$\frac{\partial \pi_{m_1}^{YN}}{\partial x_i} = \frac{2(x_1b^2 - 4x_1 + hw_1)}{4-b^2} = 0 \tag{39}$$

The Hessian matrix is shown in Eqs (40) and (41).

$$H = \begin{vmatrix} \frac{2b^2-4}{b^3-b^2-4b+4} & -\frac{2h}{b^2-4} \\ -\frac{2h}{b^2-4} & -2 \end{vmatrix} \tag{40}$$

$$|H| = \frac{4(b^4 - 6b^2 + bh^2 - h^2 + 8)}{(b^2-4)^2(1-b)} \tag{41}$$

Then, the joint concavity of the profit function $\pi_{m_i}^{YN}$ can be ensured. Solving Eqs (38) and (39), we can obtain $x_1^{YN^*}$, $w_1^{YN^*}$, and $w_2^{YN^*}$. Substituting $x_1^{YN^*}$, $w_1^{YN^*}$, and $w_2^{YN^*}$ into Eq (36), $p_1^{YN^*}$ and $p_2^{YN^*}$ can be derived. Plugging the optimal solutions into the profit function yields $\pi_{m_1}^{YN*}$, $\pi_{m_2}^{YN*}$, $\pi_{r_1}^{YN*}$, and $\pi_{r_2}^{YN*}$.

Proposition 3. For the *YN* model, there exist unique optimal equilibrium decisions and profits for manufacturers and retailers, such that the following Eqs (42)–(50) are derived.

$$w_1^{YN^*} = \frac{(4-b^2)(4-2b^2+b)(2+b)(1-b)a}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2}, \tag{42}$$

$$w_2^{YN^*} = \frac{(4-b^2)(8-3b^2+6b-2b^3-h^2+bh^2)(1-b)a}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2}, \tag{43}$$

$$x_1^{YN^*} = \frac{(4-2b^2+b)(2+b)(1-b)ah}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2}, \tag{44}$$

$$p_1^{YN^*} = \frac{(6-2b^2)(4-2b^2+b)(2+b)(1-b)a}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2}, \tag{45}$$

$$p_2^{YN^*} = \frac{(6-2b^2)(8-3b^2+6b-2b^3-h^2+bh^2)(1-b)a}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2} \tag{46}$$

$$\pi_{m_1}^{YN*} = \frac{(4-2b^2+b)^2(2+b)^2a^2(1-b)\left[(4-b^2)(2-b^2)-(1-b)h^2\right]}{[64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2]^2} \tag{47}$$

$$\pi_{m_2}^{YN*} = \left(\frac{(8-3b^2+6b-2b^3-(1-b)h^2)a}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2}\right)^2(4-b^2)(2-b^2)(1-b) \tag{48}$$

$$\pi_{r_1}^{YN*} = \left(\frac{(2-b^2)(4-2b^2+b)(2+b)a}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2}\right)^2(1-b) \tag{49}$$

$$\pi_{r_2}^{YN*} = \left(\frac{(2-b^2)[8-3b^2+6b-2b^3-(1-b)h^2]a}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2}\right)^2(1-b) \tag{50}$$

Proposition 4. 1) $w_1^{YN^*} > w_2^{YN^*}, p_1^{YN^*} > p_2^{YN^*},\ \pi_{r_1}^{YN^*} > \pi_{r_2}^{YN^*}$.

2) If $h^2 \le \Delta$, then $\pi_{m_1}^{YN^*} \ge \pi_{m_2}^{YN^*}$; if $\Delta < h^2 \le \frac{(4-b^2)[4(2-b^2)^2-b^2]}{(8-3b^2)(1-b)}$, then $\pi_{m_1}^{YN^*} < \pi_{m_2}^{YN^*}$.

Where $\Delta = \frac{(4-2b^2+b)(2+b)(4+2b^3-2b^2-5b)}{(1-b)(2-b)(2-b^2)}$.

Proof. $w_1^{YN^*} - w_2^{YN^*} = \frac{(4-b^2)(1-b)^2h^2a}{64-84b^2+33b^4-4b^6-(8-11b^2+3b^4)h^2}$. Since $(4-b^2)(1-b)^2h^2a > 0$ and $(64-84b^2+33b^4-4b^6) > (8-11b^2+3b^4)h^2$, we have $w_1^{YN^*} > w_2^{YN^*}$. Similarly, we can prove that $p_1^{YN^*} > p_2^{YN^*},\ \pi_{r_1}^{YN^*} > \pi_{r_2}^{YN^*}$.

Because $h^2 \le \frac{(4-b^2)[4(2-b^2)^2-b^2]}{(8-3b^2)(1-b)}$ and $\Delta < \frac{(4-b^2)[4(2-b^2)^2-b^2]}{(8-3b^2)(1-b)}$, therefore, if $h^2 \le \Delta$, then $\pi_{m_1}^{YN^*} \ge \pi_{m_2}^{YN^*}$; if $\Delta < h^2 \le \frac{(4-b^2)[4(2-b^2)^2-b^2]}{(8-3b^2)(1-b)}$, then $\pi_{m_1}^{YN^*} < \pi_{m_2}^{YN^*}$.

The proof of Proposition 4 is completed.

As Proposition 4 shows, when Manufacturer 1 adopts blockchain technologies and Manufacturer 2 does not, Manufacturer 1 gets higher retail prices. It makes Retailer 1 more profitable. However, due to its higher R & D costs, Manufacturer 1 may not achieve the profitability.

Proposition 4 demonstrates that when Manufacturer 1 adopts blockchain technology while Manufacturer 2 does not, retailers face higher wholesale prices, whereas Manufacturer 1 commands higher retail prices. This increases Retailer 1's profits. However, Manufacturer 1 may fail to achieve profitability due to its substantial R & D costs. This finding reveals a competitive dynamic where blockchain adopters gain retail pricing advantages but face profit erosion from technology investments, while non-adopters' competitive disadvantage forces retailers to bear higher wholesale costs, boosting the rival retailer's profits. This reflects the asymmetric distribution of technological innovation benefits across supply chain participants.

4. Equilibrium analysis

In this section, we compare the profits of supply chain members under three competitive models *NN*, *YY*, and *YN*. Since the models *NY* and *YN* are symmetric, the following analysis considers only the *YN* model. In other words, the decision of Manufacturer 1 under the *NY* model is the same as that of Manufacturer 2 under the *YN* model, and the decision of Manufacturer 2 under the *NY* model is the same as that of Manufacturer 1 under the *YN* model.

Proposition 5. 1) $\pi_{m_1}^{YN} \geq \pi_{m_1}^{NN}$.

2) If $h = 1$ and $0 < b \leq 0.76$, then $\pi_{m_1}^{YY} > \pi_{m_1}^{NY}$; if $h = 1$ and $0.76 < b < 1$, then $\pi_{m_1}^{YY} > \pi_{m_1}^{NY}$.

Proof. From the expressions $\pi_{m_1}^{YN}$ and $\pi_{m_1}^{NN}$, if $h^2 \leq \frac{(4-b^2)[4(2-b^2)^2-b^2](16-11b^2+2b^4)}{(1-b)(2-b^2)(8-3b^2)^2}$, then $\pi_{m_1}^{YN} \geq \pi_{m_1}^{NN}$. Since $\frac{(4-b^2)[4(2-b^2)^2-b^2]}{(8-3b^2)(1-b)} \leq \frac{(4-b^2)[4(2-b^2)^2-b^2](16-11b^2+2b^4)}{(1-b)(2-b^2)(8-3b^2)^2}$ and $h^2 \leq \frac{(4-b^2)[4(2-b^2)^2-b^2]}{(8-3b^2)(1-b)}$, it follows that $h^2 \leq \frac{(4-b^2)[4(2-b^2)^2-b^2](16-11b^2+2b^4)}{(1-b)(2-b^2)(8-3b^2)^2}$. Thus, $\pi_{m_1}^{YN} \geq \pi_{m_1}^{NN}$. Because the models NY and YN are symmetric, the profit of Manufacturer 1 under the model NY equals that of Manufacturer 2 under the model YN. Given $h = 1$ and $\pi_{m_1}^{YY} = \pi_{m_1}^{NY}$, there exists $b = 0.76$. Therefore, if $h = 1$ and $0 < b \leq 0.76$, then $\pi_{m_1}^{YY} > \pi_{m_1}^{NY}$; otherwise, $\pi_{m_1}^{YY} > \pi_{m_1}^{NY}$.

The proof of Proposition 5 is completed.

Proposition 5 reveals that when $h = 1$ and $0 < b \leq 0.76$, the manufacturer's equilibrium structure is *YY*. In other words, when supply chains are not competitive, both supply chains adopting blockchain technologies are the only equilibrium. As the competition intensifies $(0.76 < b < 1)$, the model *YN* or *NY* will turn out to be the final equilibrium, i.e., one chain chooses to adopt blockchain technologies when the other chain inevitably chooses not to absorb blockchain technologies.

Proposition 6. $\pi_{r_1}^{YN} \geq \pi_{r_1}^{NN}$, $\pi_{r_1}^{YY} \geq \pi_{r_1}^{NY}$.

Proof. Under $h = 1$ and $1 > b > 0$, we compare $\pi_{r_1}^{YN*}$ and $\pi_{r_i}^{NN*}$. After substituting $h = 1$ and simplifying both expressions, the inequality reduces to verifying the following inequality (51):

$$\frac{(4-2b^2+b)(2+b)}{56-73b^2+30b^4-4b^6} > \frac{1}{(2-b)(4-2b^2-b)}. \tag{51}$$

Multiplying both sides by the denominators and simplifying yields inequality (52):

$$(4-2b^2+b)(2+b)(2-b)(4-2b^2-b) > 56-73b^2+30b^4-4b^6. \tag{52}$$

Expanding the left-hand side gives $(64-84b^2+33b^4-4b^6)$, leading to inequality (53):

$$64-84b^2+33b^4-4b^6 > 56-73b^2+30b^4-4b^6. \tag{53}$$

Simplifying further, we obtain inequality (54):

$$8-11b^2+3b^4 > 0. \tag{54}$$

For $0 < b < 1$, this quadratic in b^2 is positive, with the positive leading coefficient. Thus, $\pi_{r_1}^{YN*} > \pi_{r_i}^{NN*}$. Similarly, we can prove that $\pi_{r_1}^{YY} \geq \pi_{r_1}^{NY}$.

The proof of Proposition 6 is completed.

From Proposition 6, regardless of whether Manufacturer 2 adopts blockchain technologies, Manufacturer 1's adoption of blockchain technologies can maximize Retailer 1's profit. This implies that, when the competition is high ($0.76 < b < 1$), Manufacturer 1 and Retailer 1 will have different preferences regarding blockchain technologies. If the competitor adopts blockchain technologies, Manufacturer 1 may choose not to adopt them for greater gains. However, at this point, Retailer 1 cannot maximize its gains and prefers that Manufacturer 1 adopts blockchain technologies.

5. Numerical analysis

In this section, we analyze the effects of supply chain competitions and the consumer preference for the product traceability on equilibrium decisions and profits through numerical analyses. In the subsequent analysis, we set $a = 10$ and adopt a four-scenario framework where each figure has four sections, with each section representing one of the following scenarios including extremely low consumer preferences for the product traceability ($h = 0.25$), moderately low consumer preferences for the product traceability ($h = 0.5$), moderately high consumer preferences for the product traceability ($h = 0.75$), and extremely high consumer preferences for the product traceability ($h = 1$). Additionally, models *NY* and *YN* are symmetric, so we express only the *YN* model in the following analysis.

Figure 1 shows the wholesale prices under different models with various levels of consumer preference levels. In the figure, the horizontal axis represents the degree of the products' substitutability, and the vertical axis means wholesale prices. The curves represent wholesale prices in different models *NN*, *NY*, *YN*, and *YY*. From the figure, we notice that for manufacturers, the wholesale price decreases with an increase in the competition. This indicates that the more intense the competition, the more likely the manufacturer is to reduce the wholesale price to increase the demand. Additionally, the wholesale price under the four models satisfies the inequality $YY > YN > NY > NN$, indicating that wholesale prices increase as the number of manufacturers adopting blockchain technology increases.

Figure 2 employs the same horizontal metric of the product substitutability but shifts focus to the retail pricing on the vertical dimension, where the plotted lines demonstrate how selling prices vary under each model (*NN*, *NY*, *YN*, and *YY*). As illustrated in the figure, the retailer's optimal pricing exhibits a downward trend as the competition intensifies. This suggests that the heightened market competition incentivizes the retailer to lower prices in order to stimulate the demand. Furthermore, a comparative analysis of the four pricing models reveals the following price hierarchy: *YY* > *YN* > *NY* > *NN*. This ranking demonstrates that the blockchain adoption leads to the highest retail price, while scenarios without blockchain implementations yield comparatively lower prices.

Both Figures 1 and 2 contain four subplots (a), (b), (c), and (d), representing the progression of consumer preferences for product traceability (h) from weak to strong. It can be observed that from (a) to (d), all three lines except the red line change and shift rightward. This indicates that as consumer preferences for product traceability (h) increase, the gaps between the four lines widen. In other words, the intervals between wholesale prices under the four models (*YY*, *YN*, *NY*, and *NN*) expand with increasing consumer preferences for product traceability, demonstrating that stronger traceability preferences lead to greater wholesale price differentiation. The same trend applies to retail prices.

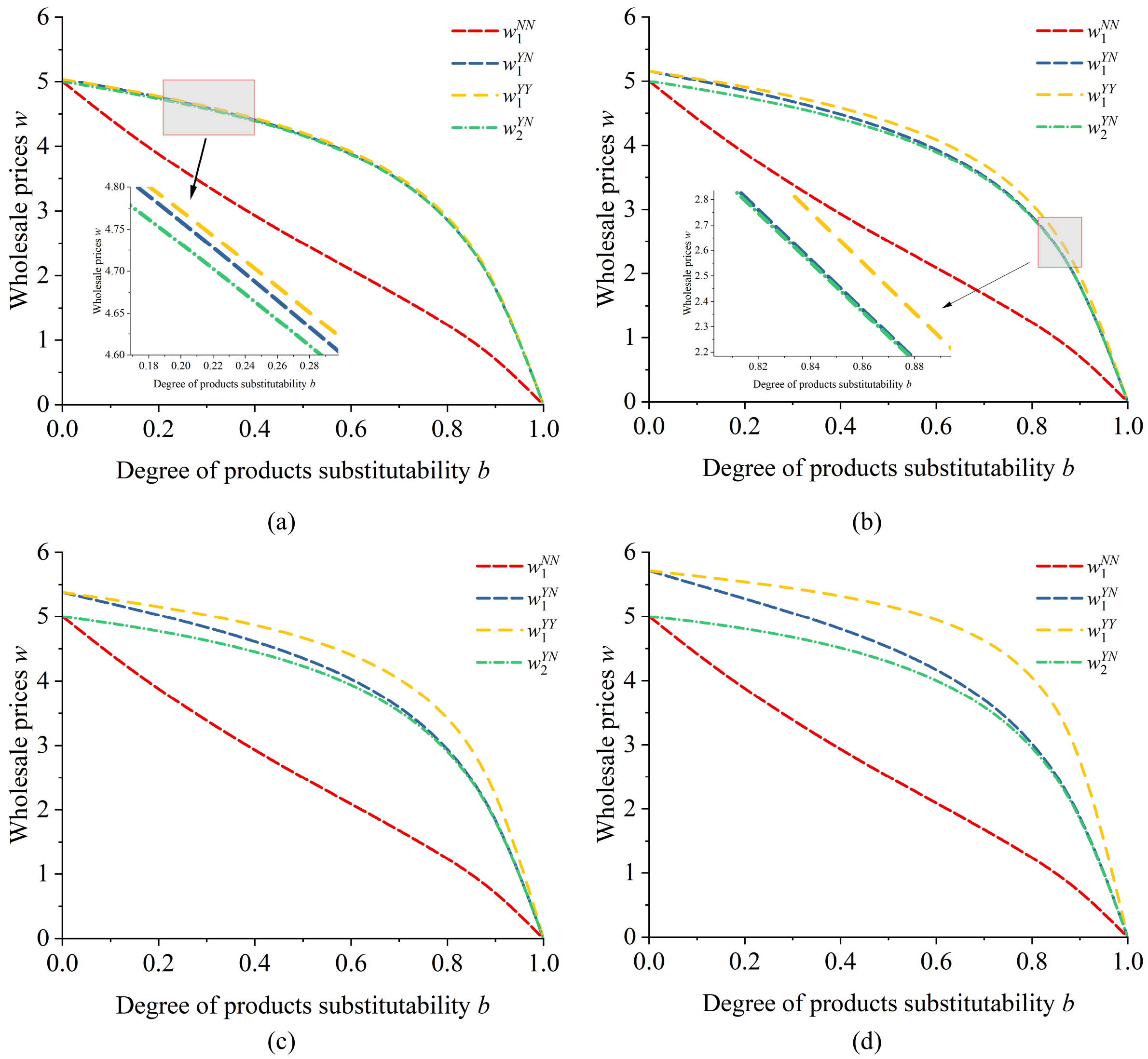

Figure 1. Wholesale prices under different models: (a) $h = 0.25$; (b) $h = 0.5$; (c) $h = 0.75$; (d) $h = 1$.

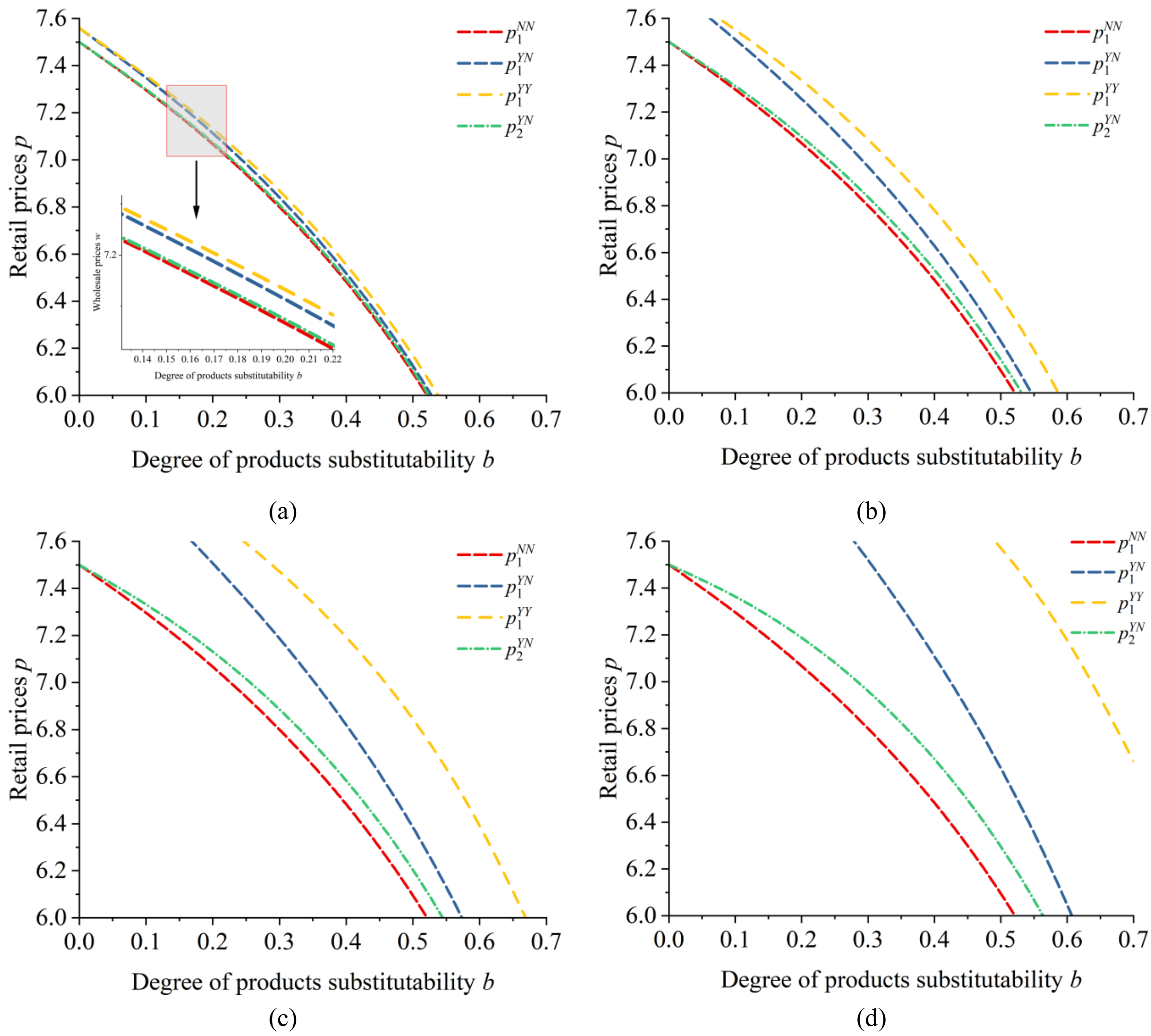

Figure 2. Retail prices under different models: (a) $h = 0.25$; (b) $h = 0.5$; (c) $h = 0.75$; (d) $h = 1$.

Figure 3 shows the traceability levels under four different models. In the figure, the product substitutability degree remains the independent variable, but the dependent variable now tracks traceability levels, with the four characteristic curves revealing how each model (*NN*, *NY*, *YN*, and *YY*) affects product traceability levels at different degrees of the product substitutability. As shown in the figure, the optimal product traceability level under the *YY* model increases with the competition intensity, whereas under the *YN* model, it exhibits a decreasing trend. Under the *YY* model, the optimal traceability level is always higher than that under the *YN* model. Furthermore, the optimal traceability level increases with consumers' preferences for the product traceability.

Figure 4 presents the relationship between the product substitutability (x-axis) and manufacturers' profits (y-axis), with comparative curves distinguishing the four models: *NN*, *NY*, *YN*, and *YY*. The analysis of the chart reveals the following results. For Manufacturer 1, the *YN* model consistently demonstrates the superior performance to the *NN* model across all competition levels, indicating that blockchain adoptions yield greater profits when Manufacturer 2 remains non-adopting. The competitive landscape significantly influences adoption decisions. Under the mild competition, Manufacturer 1 benefits from following Manufacturer 2's adoption strategy, whereas beyond a threshold, the non-adoption becomes preferable. Notably, in highly competitive scenarios, the mutual adoption proves less profitable than the joint non-adoption for both supply chains. Furthermore, manufacturers' profits exhibit an inverted U-shaped relationship with the competition intensity. In other words, for manufacturers, when $0 < b \leq 0.76$ and $h = 1$, the YY model (dual-blockchain adoption) emerges as the dominant strategy. However, when $0.76 < b < 1$ and $h = 1$, NY and YN (one manufacturer adopts blockchain technologies while the other does not) become equilibrium strategies.

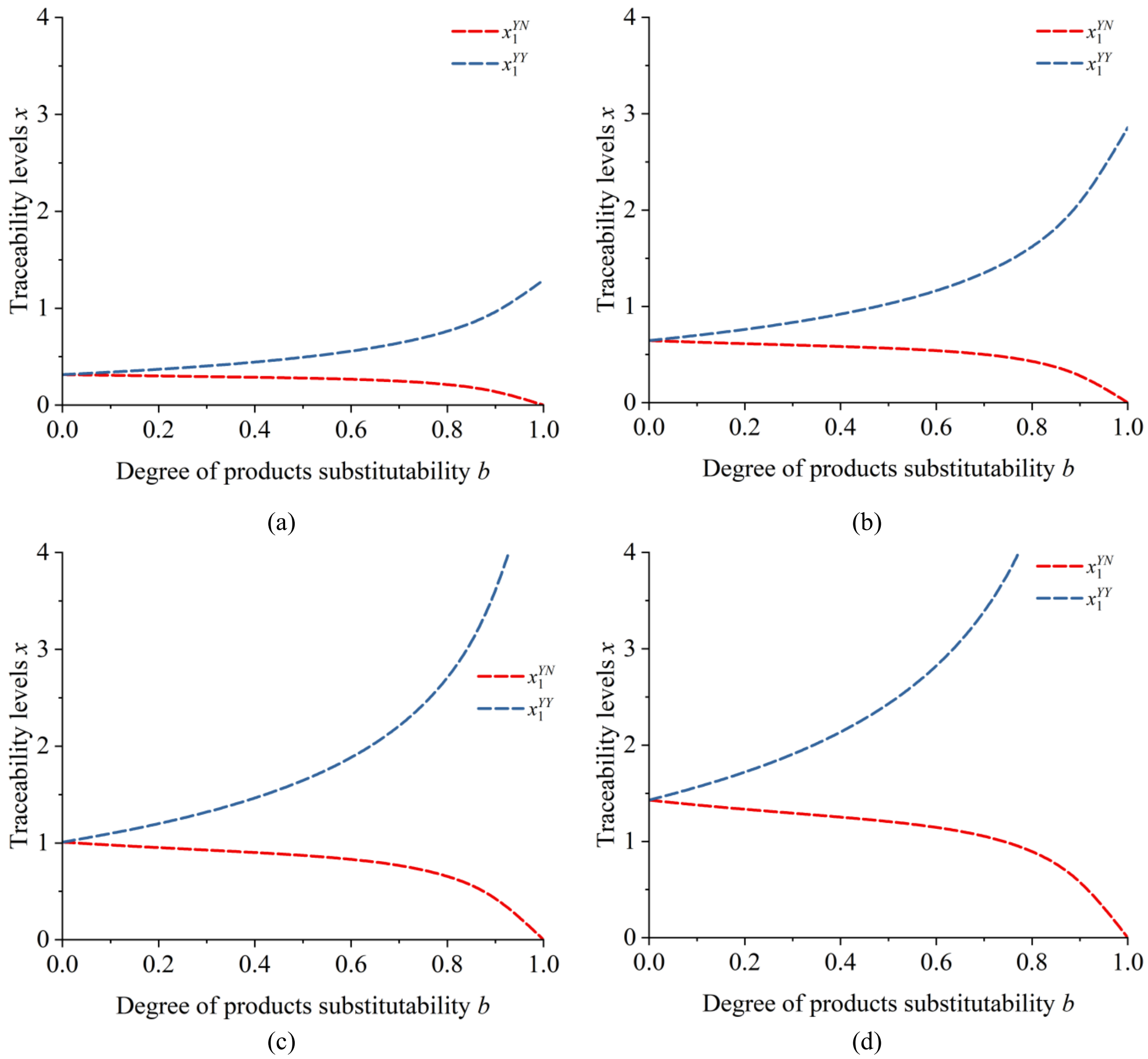

Figure 3. Traceability levels under different models: (a) $h = 0.25$; (b) $h = 0.5$; (c) $h = 0.75$; (d) $h = 1$.

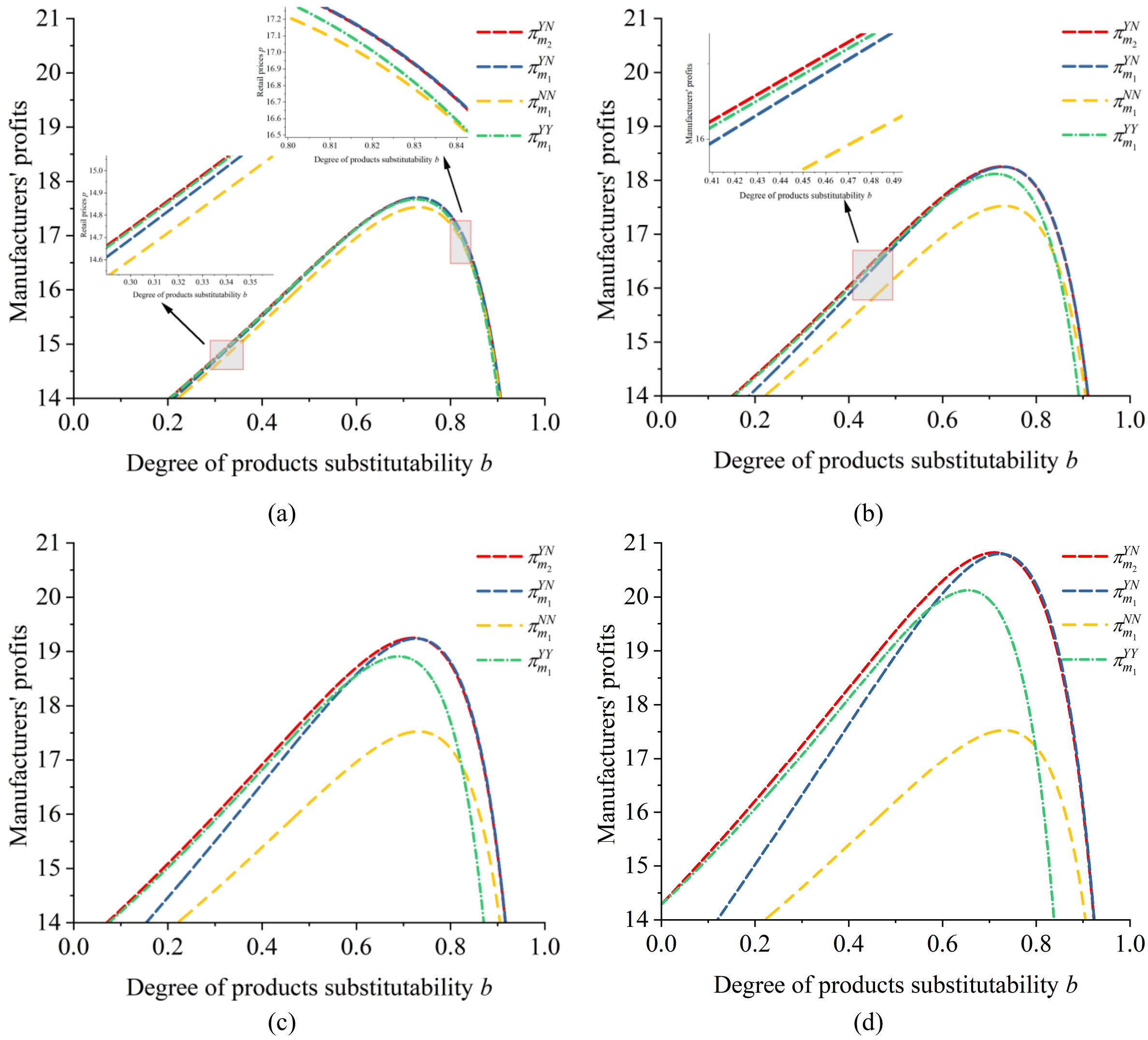

Figure 4. Manufacturers' profits under different models: (a) $h = 0.25$; (b) $h = 0.5$; (c) $h = 0.75$; (d) $h = 1$.

Figure 5 shows the retail profit under four different models. In the figure, the horizontal axis represents the degree of the product substitutability, and the vertical axis means wholesale prices. The curves represent retailers' profits in different models, *NN*, *NY*, *YN*, and *YY*. The figure demonstrates some interesting findings regarding retailer profits under different models. For Retailer 1, the *YN* model consistently outperforms the *NN* model, indicating that the blockchain adoption by Manufacturer 1 generates higher profits when Manufacturer 2 remains non-adopting. Furthermore, the *YY* model demonstrates the superior performance to *NY*, suggesting that Retailer 1 benefits more when both supply chains adopt blockchain technologies rather than the unilateral adoption. Importantly, *YY* consistently yields the highest profits for Retailer 1 across all competition levels, outperforming *NN* in all scenarios. The analysis also reveals an inverted U-shaped relationship between the competition intensity and retailer profits. Retailers' profits initially increase as the competition intensifies due to the expanded demand from lower retail prices but eventually decline when the excessive competition makes price reductions unsustainable. Notably, when $0 < b \leq 0.76$ and $h = 1$, manufacturers' adoption decisions enable retailers to maximize profits, while $0.76 < b < 1$, Retailers and manufacturers have different opinions on whether to adopt blockchain technologies. In addition, as consumer preferences for the product traceability increase, the retailers' profits of the two competing supply chains increase.

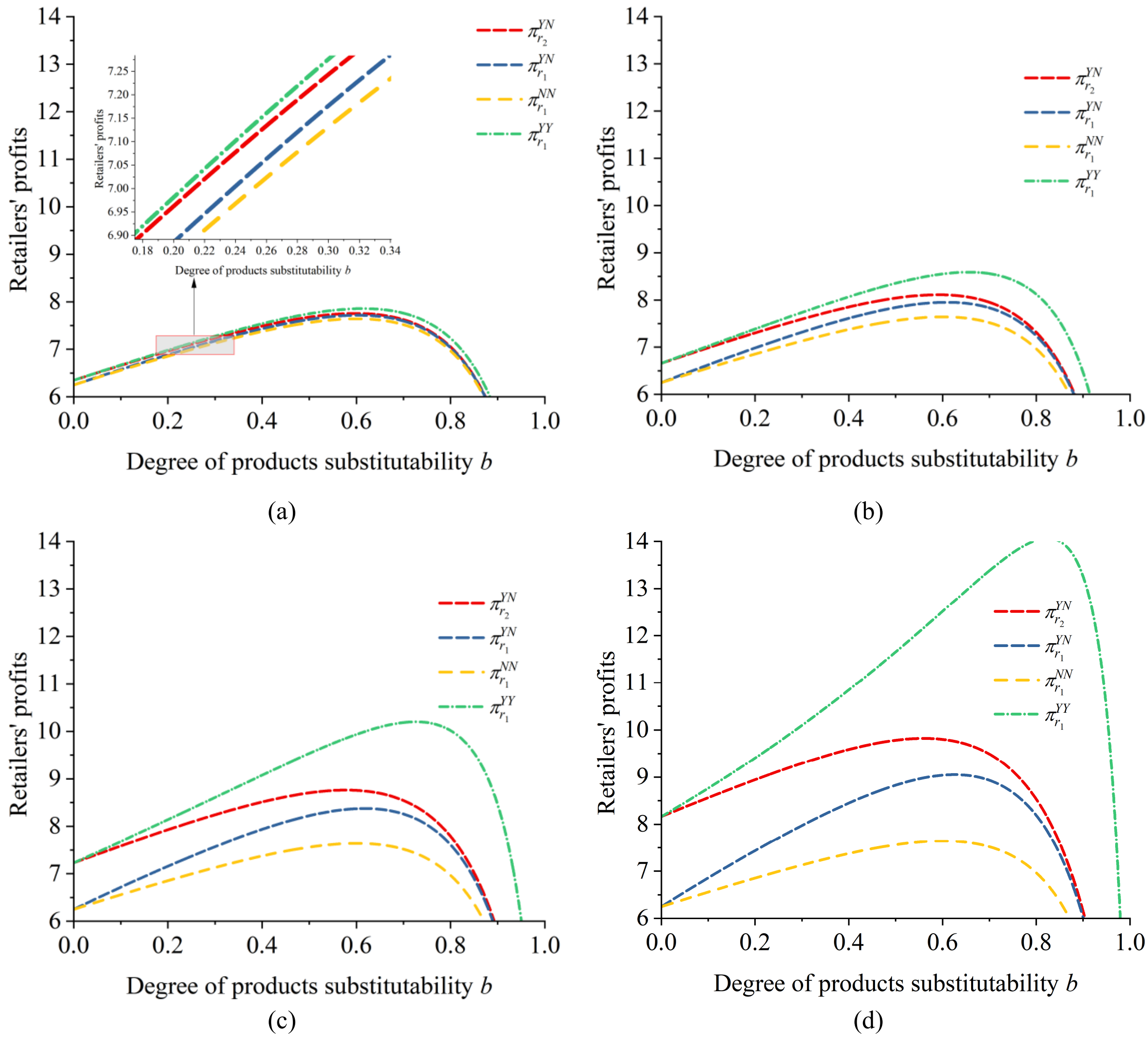

Figure 5. Retails' profits under different models: (a) $h = 0.25$; (b) $h = 0.5$; (c) $h = 0.75$; (d) $h = 1$.

6. Conclusions

Here, we study a competing system comprising two manufacturers and two retailers. Each entity may or may not choose to adopt blockchain technologies to provide consumers with the product traceability information. Consumers in the market have preferences regarding the product traceability. First, three dynamic game mathematical models are constructed and analyzed to find the optimal solutions under various competition models. Second, the equilibrium strategies of supply chain members are revealed through mathematical models and the numerical analysis. We have the following findings: (i) When the competition in the supply chain is not intense, adopting blockchain technologies is the preferred strategy for manufacturers. As the competition intensifies, both adopting and not adopting blockchain technologies coexist as equilibrium strategies. (ii) The change in consumers' preferences for the product traceability is the most important factor. Changes in consumer preferences for the product traceability do not significantly affect manufacturers' equilibrium strategies.

Consumers' preferences for the product traceability change only equilibrium strategies when the competition reaches a critical level. (iii) As consumer preferences for the product traceability increase, the traceability levels and retailers' profits of the two competing supply chains increase. However, the profits of manufacturers who adopt blockchain technologies decline when the competition becomes very intense.

The managerial implications derived from the research findings are as follows: First, manufacturers should evaluate market competition intensity before adopting blockchain technology. In low-competition environments, such as emerging markets or differentiated niche segments, manufacturers should prioritize blockchain strategy by collaborating with retailers to enhance product traceability, which can yield premium benefits. In highly competitive markets, such as mature industries with frequent price wars, manufacturers should make balanced blockchain adoption decisions based on competitors' strategies to avoid profit erosion from excessive competition. Second, manufacturers must closely monitor consumer preferences for product traceability. When significant increases are detected, they should increase R & D investments while optimizing cost structures to offset marginal revenue declines caused by intensified competition. Last, retailers should reassess the value of exclusive cooperation clauses because selectively opening supply chain collaborations during blockchain adoption may maximize returns more effectively than strict exclusivity.

Our results provide a basis for further theoretical research and practice. However, there are some shortcomings. For example, the uncertainty of demand is not considered. Moreover, we set that the competitive supply chain is a symmetric system. The equilibrium solution is not considered when there are differences in the market size and blockchain research and development costs, etc.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare there is no conflict of interest.

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