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Research Article

Recycling Mode Choice in a Textile and Apparel Closed-Loop Supply Chain considering Blockchain

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The development of the textile and apparel (T&A) industry has led to an increasing focus on recycling used products. Remanufactured product quality raises consumer concerns, and blockchain can effectively solve this problem. We establish a closed-loop supply chain (CLSC) in which a manufacturer, a retailer, or a third-party recycler collects used T&A products to examine the most efficient recycling mode with and without blockchain and the impact of blockchain on CLSC decisions. The results show that (1) if the manufacturer's recycling cost coefficient is relatively low, used T&A products are collected directly by the manufacturer. Otherwise, the responsibility for recycling used T&A products falls to the retailer or the third-party recycler. It is noteworthy that the manufacturer's choice of recycling mode remains unchanged whether a blockchain is implemented or not. (2) The implementation of blockchain by the manufacturer and the retailer can increase profits and consumers also benefit when the cost of validating blockchain units remains below a certain threshold. (3) When the recycling cost coefficient exceeds a certain threshold, the implementation of blockchain increases prices and recycling rates. These findings offer CLSC members' management insights into how to select the optimal recycling mode and the consequences of implementing blockchain.

1. Introduction

With the dramatic rise in the population globally, environmental issues are becoming increasingly prominent. The textile and apparel (T&A) industry is particularly harmful to the environment [1]. The production and transportation of T&A products consume large amounts of energy and water resources while emitting greenhouse gases and discharging wastewater, causing serious environmental pollution problems [2, 3]. Abbate et al. [4] demonstrated that the apparel industry annually consumes considerable quantities of water resources while emitting large amounts of carbon dioxide gas. Inevitably, continuous environmental pollution arises from the production of T&A products due to the use of dyes and microplastics. The T&A industry has an environmental impact not only in the production process, but also in the disposal of used products which is currently not environment friendly, with most of them disposed of by incineration and landfill. Globally, the majority of used T&A products are disposed of in landfills, despite a significant portion being reused [5]. Thus, T&A enterprises must address the environmental implications. Effective measures are necessary to reduce pollution and promote sustainability.

Currently, numerous companies in China are dedicated in reducing environmental pollution by employing environment friendly materials in the production of T&A products [1]. For example, apparel manufacturers use bio-based materials to reduce dependence on synthetic materials and improve environmental issues [2]. However, it is not enough to consider using environmentally friendly materials. Fast fashion encourages consumers to treat clothes as disposable, thereby reducing their lifespan. Furthermore, consumers lack the concept of sustainability in apparel procurement, maintenance, and disposal. In practice, some companies mitigate environmental pollution by guiding consumers toward sustainable consumption [6, 7]. In recent years, the development of advanced cleaning processes for handling discarded textiles, recycling, and remanufacturing has presented companies with better options to address environmental pollution [8]. The implementation of a CLSC within the T&A industry can effectively alleviate pollution problems. Filho et al. [9] proved that the recycling of T&A products significantly reduces greenhouse gas emissions, chemical pollution, and eutrophication of water bodies. Recycling and remanufacturing are recognized as effective ways to enhance energy and material utilization while mitigating environmental pollution at a relatively low cost [10].

In the process of reverse recycling, various recycling modes exist. The decision on which mode to implement is influenced by different factors, including the cost of implementing the recycling channel. Manufacturers may choose to engage in direct recycling of used and end-of-life products, taking into account a multitude of factors [11]. For example, Teijin Group, a Japanese enterprise engaged in fiber products, fulfils its corporate social responsibility by directly recycling waste fibers and other available resources to remanufacture goods. In general, retail businesses located closest to the consumer market tend to be most effective at recycling [12]. Therefore, retailers often engage in recycling used T&A products. For example, H&M, one of the largest apparel retailers globally, implemented a program for recycling used clothing to reduce its environmental impact and promote sustainable consumption [13]. According to H&M's Annual Sustainability Report published in March 2023, 84% of the company's materials were either recycled or sourced sustainably as of 2022. By 2030, H&M aims to achieve 100% sustainable recycling, with a target of using 30% recycled materials by 2025. Furthermore, third-party recyclers play an important role in collecting used T&A products. For instance, "Flying Ants" is among China's largest third-party recycling platforms for used clothing, with over 50% of the recycled garments being repurposed.

While remanufactured T&A products can effectively alleviate environmental pollution, the quality of these products may raise concerns for some consumers. Traditional supply chain traceability technologies, such as barcodes, QR codes, and RFID, may not provide easily accessible product information for consumers and supply chain stakeholders, resulting in a lack of transparency and trustworthiness [14]. Despite efforts to address consumer concerns regarding the quality of remanufactured T&A products, these concerns cannot be completely eliminated. Blockchain, in contrast to traditional traceability systems, serves as a distributed data ledger that provides supply chain management with traceability, transparency, and reliability [15]. Blockchain can provide consumers with authentic and reliable information about products, thereby enhancing their purchase intention [16]. Blockchain have been implemented into the supply chain management, with Everlane, a U.S. textile enterprise, implementing blockchain across its entire supply chain. Through the official Everlane website, consumers can conveniently access specific information on every product, spanning the complete product cycle from manufacturing to retail. While blockchain enhances product transparency, it also entails costs. Hence, it makes sense to explore the impact of blockchain on the supply chain.

Based on the above description, we have developed three recycling modes. These modes are manufacturer-led and include a retailer and a third-party recycler. Furthermore, we consider the implementation of blockchain by CLSC members within these modes. In this research, we address three questions: (1) which recycling mode does the manufacturer choose when implementing or not implementing blockchain? (2) Under what conditions do the manufacturer and the retailer implement blockchain? (3) What impact does the implementation of blockchain have on the decisions of CLSC members and consumers?

Relevant research covers areas of T&A supply chains, recycling mode choice, and blockchain in supply chain management. To the best of our knowledge, there is little literature that simultaneously addresses recycling modes and blockchain within the context of the T&A CLSC. The main contributions of this paper are summarised below. Firstly, our study offers valuable guidance for a T&A manufacturer in choosing a recycling mode. That is, regardless of whether blockchain is implemented or not, the type of recycling mode a manufacturer chooses depends mainly on the recycling cost coefficient of recyclers. Secondly, this paper provides insights into the collaborative implementation of blockchain by manufacturers and retailers, specifically that blockchain implementation can only improve the profit of the CLSC members when the cost of blockchain is below a threshold, while consumers can also benefit. Thirdly, we offer guidance to CLSC members in the T&A industry on how to make decisions when implementing blockchain.

The structure of this article is as follows: Section 2 is an overview of the two relevant streams of the literature. Section 3 describes the problem and presents assumptions. Section 4 formulates six models and calculates the optimal decision. Section 5 gives a sensitive and comparative analysis of equilibrium results. Section 6 summarises and draws management insights. The appendix contains all proof procedures.

2. Literature Review

There are three relevant literature streams to this paper: T&A supply chains, recycling mode choice in CLSCs, and blockchain in supply chain management.

2.1. T&A Supply Chains. The existing literature has been studied mainly from the perspective of environmental sustainability. Yang et al. [17] conducted an empirical analysis to explore the influence of corporate digitalization on the environmental performance of the T&A industry. Bubicz et al. [18] undertook a qualitative analysis to investigate the management of social sustainability in the apparel supply chains of six global corporations. Majumdar et al. [19] proposed strategies to overcome barriers and analyzed the challenges faced in the T&A supply chains. Similarly, Vishwakarma et al. [20] identified numerous obstacles in achieving sustainability in the management of supply chains for T&A products. They emphasized the crucial role that technology plays in overcoming these challenges. Furthermore, Warasthe et al. [21] conducted a literature review of 127 articles on sustainability in the T&A supply chain. In addition, some scholars have examined decision-making and coordination in T&A supply chains. For instance, Cai et al. [13] conducted an investigation into recycling operations in second-hand apparel supply chains under centralized versus decentralized decision-making. In addition, they examined supply chain coordination through labor cost-sharing contracts. Adhikari et al. [22] investigated the coordination mechanism between members of the textile supply chain under different contracts, taking into account uncertainty on both the supply and demand sides. Adhikari and Bisi [23] proposed a cooperation mechanism for green apparel supply chains based on green cost-sharing and profit-sharing contracts. They evaluated the impact of various parameters on decision variables, profitability, and utility of apparel manufacturers and retailers.

The aforementioned literature primarily explores the sustainability and coordination aspects of T&A supply chains from a theoretical perspective. Differing from previous studies, our research primarily focuses on selecting an appropriate mode for recycling and examines the influence of blockchain on decision-making in CLSCs.

2.2. Recycling Mode Choice in CLSCs. Previous research on CLSC recycling modes has primarily centered on the choice of the recycling agent. Savaskan et al. [12] initially compared the optimal profit of three recycling modes and discovered that the manufacturer and the retailer achieve maximum profits when the recycling agent is the retailer closest to the consumer market. On this basis, Huang et al. [24] investigated the scenario of two recyclers competing to recycle waste products under a dual-channel model. Their findings suggest that the optimal choice of the recycling mode is associated with the intensity of competition between recyclers. Chu et al. [25] proposed a model featuring multiple CLSCs and posited that the preference for recycling modes among manufacturers is influenced by the market size of third-party recyclers. Furthermore, Li Xin [26] demonstrated that the most appropriate recycling mode for electric tram vehicles is based on the third-party recyclers' economies of scale. Yang et al. [27] examined the influence of carbon trading policies on the CLSC recycling model. In addition, Yang et al. [28] noted that irrespective of cost information symmetry, manufacturers receive subsidies from the government and often outsource their recycling activities to third-party recyclers. Scholars have conducted studies on cooperative recycling modes. Zheng et al. [29] conducted a comparison of an independent recycling mode and two cooperative recycling modes. They discovered that cooperative recycling can tremendously enhance the recycling level. Li et al. [30] examined the most suitable joint recycling model for electric vehicle batteries.

In this study, we center our attention on the manufacturer's process of selecting recycling modes. Unlike previous research, we explore the influence of blockchain on this process within a T&A CLSC. We aim to evaluate the impact of blockchain on recycling mode selection by the manufacturer. We provide insights on the potential benefits and drawbacks of implementing blockchain in this context.

2.3. Blockchain in Supply Chain Management. The transparent and traceable nature of blockchain has facilitated its widespread application in supply chain management across various industries. Paul et al. [31] analyzed the role of blockchain in the financial supply chain and concluded that this technology can enhance investor confidence while reducing market uncertainty. Niu et al. [32] explored the impact of blockchain in the supply chain of over-the-counter medicines and investigated the utilization of blockchain to achieve the traceability of these medicines. Li et al. [33] investigated research in the agricultural supply chain field and stated that the implementation of blockchain may increase supply chain profitability, depending on the cost of implementing the technology. Shen et al. [34] developed a model to study the role of blockchain in the secondary market and provide insights into its implementation in sales platforms. Gong et al. [35] further identified the prerequisites for manufacturers to implement blockchain in a competitive remanufacturing supply chain. Furthermore, numerous academic studies quantitatively analyzed the role of blockchain in supply chains using the lens of game theory. Li et al. [36] posited that blockchain can enhance customers' environmental awareness, which subsequently leads to increased profits for manufacturers and retailers. Similarly, Ma et al. [37] introduced blockchain to enhance the recycling rate and achieve triple sustainability in economic, environmental, and social areas. Likewise, Zhang et al. [16] demonstrated that manufacturers' implementation of this technology could facilitate or hinder the entry of grey marketers. Zhang et al. [38] emphasized the importance of considering blockchain costs, direct marketing costs, and demand volatility when implementing blockchain in a dual-channel supply chain. Conversely, Liu et al. [39] maintained that the implementation of blockchain not only increases consumer confidence in product quality but also raises privacy concerns.

Based on the above literature reviewed, there is limited research on the recycling mode of the T&A CLSC and the implementation of blockchain in supply chain management. To enrich the relevant research, we investigate the selection of recycling modes in the T&A CLSC, taking into account the influence of blockchain on both recycling mode choices and decision-making within the CLSC.

3. Problem Description and Model Assumptions

We establish a T&A CLSC that contains a manufacturer and a retailer. The manufacturer bears responsibility for the sale of new and remanufactured products to consumers through wholesale to the retailer. This paper considers three recycling modes from the perspective of the recycling agent. The manufacturer chooses to recycle used products directly (M recycling mode) or chooses to acquire used products from the retailer (R recycling mode) or the third-party recycler (T recycling mode) by paying transfer prices [27]. Following Liu et al. [39], we posit that the manufacturer and the retailer collaborate to determine the implementation of blockchain and to jointly bear the blockchain verification costs. We formulate six Stackelberg game models to solve the optimal decision. Consistent with Zhang et al. [40], the manufacturer acts as the leader while the retailer and the third-party recycler act as followers. The T&A CLSC structure is shown in Figure 1.

To facilitate calculation handling, the assumptions made in our study are as follows. We consider a single consumer market and assume a consumer market size of 1 to simplify the model calculation [40]. Remanufactured T&A products are visually indistinguishable from new T&A products. Hence, we assume that they are homogeneous [30]. However, the recycling process of used T&A products raises concerns among consumers regarding product quality. The level of concern has a negative impact on consumer demand. The implementation of blockchain has the potential to mitigate these concerns and, consequently, is likely to increase consumer demand by providing greater transparency in product information. We define the positive impact of blockchain on consumer purchase of products as α, $0 < \alpha \leq 1$. The level of consumer concern about products is αs with blockchain [39]. We conclude that the consumer demand function when blockchain is implemented is $q = 1 - p - \alpha s$. When blockchain is not implemented, $\alpha = 1$ holds.

In general, the manufacturer typically allocates more resources to the production of new T&A products than to remanufactured T&A products, since the production expenses for remanufactured T&A products are generally lower than those for new T&A products, i.e., $c_n > c_r > 0$ [41]. Referring to Zhang et al. [40], we assume that the recycling costs for recyclers are $k_i\tau^2/2$, $i \in \{M, R, T\}$. After the retailer or the third-party recycler collects used T&A products at a price A, the manufacturer recycles these at a transfer price B above the recycling price, thus $B > A > 0$ [42]. To make remanufacturing activities meaningful, we can obtain $c_n > B + c_r$ [43]. In this paper, the assumptions regarding blockchain costs were sourced from Liu et al. [39]. Specifically, the manufacturer incurs the blockchain validation expenses in the production chain, while the retailer incurs these expenses in the distribution chain. The unit validation cost of the T&A product amounts to $2b$.

Based on the analysis above, the definitions and notations given in Table 1 are used for the description in this paper.

4. Problem Description and Model Assumptions

In this section, we derive equilibrium results for each of the six models. For equilibrium results to be meaningful, recycling cost coefficients must be satisfied $k_M > (c_n - c_r - A)^2/4 = F_1$, $k_R > (B - A)(c_n - c_r - A)/2 = F_2$, and $k_T > (B - A)(c_n - c_r - B)/2 = F_3$.

4.1. M Recycling Mode. Within the M Recycling mode, the manufacturer determines the wholesale price and recycling rate at the initial stage. Following this, the retailer is responsible for deciding on the retail price. When blockchain is not implemented, the optimization models for the maximization of profits are formulated as follows:

$$\begin{aligned} \max_{w^{NM},\tau^{NM}} \pi_M^{NM} &= \left(w^{NM} - c_n\right)\left(1 - p^{NM} - s\right) \\ &\quad + (c_n - c_r - A)\tau^{NM}\left(1 - p^{NM} - s\right) - \frac{1}{2}k_M\tau^{NM2} \\ s.t. \max_{p^{NM}} \pi_R^{NM} &= \left(p^{NM} - w^{NM}\right)\left(1 - p^{NM} - s\right). \end{aligned} \tag{1}$$

By using reverse induction, we deduce the optimum solution for the model NM, as shown in Theorem 1.

Theorem 1. *The optimal decisions are* $w^{NM*} = (k_M(1 - s + c_n) - 2(1 - s)F_1)/(2(k_M - F_1))$, $p^{NM*} = (k_M(3(1 - s) + c_n) - 4(1 - s)F_1)/(4(k_M - F_1))$, *and* $\tau^{NM*} = (c_n - c_r - A)(1 - s - c_n)/(4(k_M - F_1))$ *in the model NM.*

Thus, the optimal consumer demand and profits are presented as $q^{NM*} = k_M(1 - s - c_n)/(4(k_M - F_1))$, $\pi_M^{NM*} = k_M(1 - s - c_n)^2/(8(k_M - F_1))$, and $\pi_R^{NM*} = k_M^2(1 - s - c_n)^2/(16(k_M - F_1)^2)$.

When there is the implementation of blockchain, the optimization models for the maximization of profits are formulated as follows:

$$\begin{aligned} \max_{w^{YM},\tau^{YM}} \pi_M^{YM} &= \left(w^{YM} - c_n - b\right)\left(1 - p^{YM} - \alpha s\right) \\ &\quad + (c_n - c_r - A)\tau^{YM}\left(1 - p^{YM} - \alpha s\right) - \frac{1}{2}k_M\tau^{YM2} \\ \text{s.t.} \max_{p^{YM}} \pi_R^{YM} &= \left(p^{YM} - w^{YM} - b\right)\left(1 - p^{YM} - \alpha s\right). \end{aligned} \tag{2}$$

Using the calculation method in Theorem 1, the optimal solution for the model YM has been derived, as demonstrated in Theorem 2.

Theorem 2. *The optimal decisions are* $w^{YM*} = (k_M(1 - \alpha s + c_n) - 2(1 - \alpha s - b)F_1)/(2(k_M - F_1))$, $p^{YM*} = (k_M(3(1 - \alpha s) + c_n + 2b) - 4(1 - \alpha s)F_1)/(4(k_M - F_1))$, *and* $\tau^{YM*} = (c_n - c_r - A)(1 - \alpha s - c_n - 2b)/(4(k_M - F_1))$ *in model YM.*

Therefore, the optimal consumer demand and optimal profits are given as $q^{YM*} = k_M(1 - \alpha s - c_n - 2b)/(4(k_M - F_1))$, $\pi_M^{YM*} = k_M(1 - \alpha s - c_n - 2b)^2/(8(k_M - F_1))$, and $\pi_R^{YM*} = k_M^2(1 - \alpha s - c_n - 2b)^2/(16(k_M - F_1)^2)$.

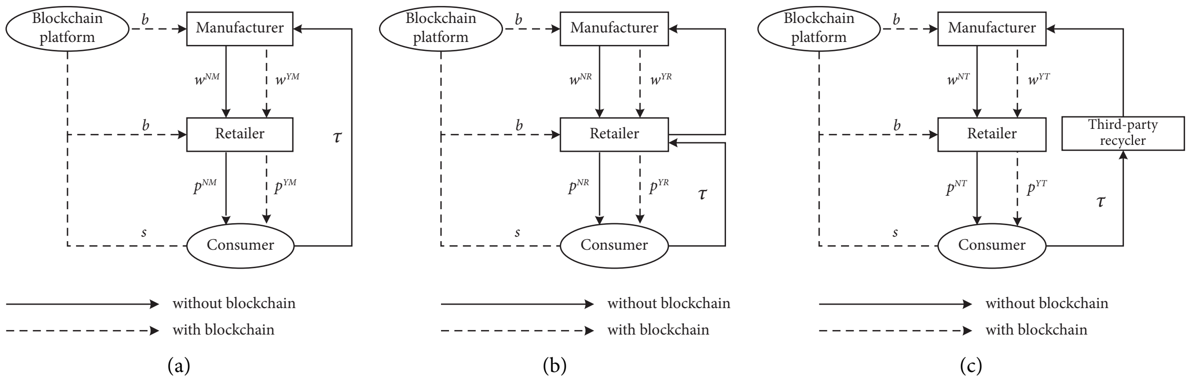

Figure 1: Six models in the T&A CLSC: (a) model NM (YM), (b) model NR (YR), and (c) model NT (YT).

Table 1: Parameters and decision variables.

Notations	Definition
s	Level of consumer quality concerns
α	Influence of blockchain on consumer purchases
c_n/c_r	Unit production cost of new/remanufactured products
b	Unit cost of blockchain validation
A	Unit price of recycling used T&A products
B	Unit price of transferring the used T&A products
k_i	Recycling cost coefficient, $i \in \{M, R, T\}$
w	The unit wholesale price of T&A products
τ	Recycling rate
p	Unit retail price of T&A products
q	Consumer demand for new/remanufactured T&A products
π_M^j/π_R^j	Profit of the manufacturer and retailer in the model j, $j \in \{NM, YM, NR, YR, NT, YT\}$
π_T^{NT}/π_T^{YT}	Profit of the T in models NT and YT
CS^j	Consumer surplus in the model j, $j \in \{NM, YM, NR, YR, NT, YT\}$

4.2. R Recycling Mode. Within the R recycling mode, the manufacturer is responsible for setting the wholesale price, while the retailer subsequently decides on both the retail price and the recycling rate. When blockchain is not implemented, the optimization models for the maximization of profits are formulated as follows:

$$\begin{aligned} &\max_{w^{NR}} \pi_M^{NR} = \left(w^{NR} - c_n\right)\left(1 - p^{NR} - s\right) + \left(c_n - c_r - B\right)\tau^{NR}\left(1 - p^{NR} - s\right) \\ &s.t. \max_{p^{NR},\tau^{NR}} \pi_R^{NR} = \left(p^{NR} - w^{NR}\right)\left(1 - p^{NR} - s\right) + (B - A)\tau^{NR}\left(1 - p^{NR} - s\right) - \frac{1}{2}k_R\tau^{NR2}. \end{aligned} \tag{3}$$

By using reverse induction, we deduce the optimum solution for the model NR, as illustrated in Theorem 3.

Theorem 3. *The optimal decisions are* $w^{NR*} = (2k_R(1 - s + c_n) - 2(1 - s)(F_2 + F_3) - (B - A)^2 c_n)/(4(k_R - F_2))$, $p^{NR*} = (k_R(3(1 - s) + c_n) - 4(1 - s)F_2)/(4(k_R - F_2))$, *and* $\tau^{NR*} = (B - A)(1 - s - c_n)/(4(k_R - F_2))$ *in the model NR.*

Therefore, the optimal consumer demand and optimal profits are given as $q^{NR*} = k_R(1 - s - c_n)/(4(k_R - F_2))$, $\pi_M^{NR*} = k_R(1 - s - c_n)^2/(8(k_R - F_2))$, and $\pi_R^{NR*} = k_R(1 - s - c_n)^2(2k_R - (B - A)^2)/(32(k_R - F_2)^2)$.

When blockchain is implemented in the CLSC, the optimization models for the maximization of profits are formulated as follows:

$$\begin{aligned}&\max_{w^{YR}} \pi_M^{YR} = \left(w^{YR} - c_n - b\right)\left(1 - p^{YR} - \alpha s\right) + (c_n - c_r - B)\tau^{YR}\left(1 - p^{YR} - \alpha s\right)\\&\text{s.t.} \max_{p^{YR},\tau^{YR}} \pi_R^{YR} = \left(p^{YR} - w^{YR} - b\right)\left(1 - p^{YR} - \alpha s\right) + (B - A)\tau^{YR}\left(1 - p^{YR} - \alpha s\right) - \frac{1}{2}k_R\tau^{YR2}.\end{aligned} \tag{4}$$

Using the calculation method in Theorem 3, the optimal solution for the YR model has been derived, as demonstrated in Theorem 4.

Theorem 4. *The optimal decisions are* $w^{YR*} = (2k_R(1-\alpha s + c_n) + 4bF_3 - 2(1-\alpha s)(F_2+F_3) - (B-A)^2 c_n)/(4(k_R - F_2))$, $p^{YR*} = (k_R(3(1-\alpha s) + c_n + 2b) \quad -4(1-\alpha s)F_2)/(4(k_R - F_2))$, *and* $\tau^{YR*} = (B-A)(1-\alpha s - c_n - 2b)/(4(k_R - F_2))$ *in the model* YR.

Therefore, the optimal consumer demand and optimal profits are given as $q^{YR*} = k_R(1-\alpha s - c_n - 2b)/(4(k_R - F_2))$, $\pi_M^{YR*} = k_R(1-\alpha s - c_n - 2b)^2/(8(k_R - F_2))$, and $\pi_R^{YR*} = k_R(1-\alpha s - c_n - 2b)^2(2k_R - (B-A)^2)/(32(k_R - F_2)^2)$.

4.3. T Recycling Mode. Within the T recycling mode, the decision sequence is that the manufacturer determines the wholesale price first, followed by the retailer and the third-party recycler to make the retail price and recycling rate, respectively. When blockchain is not implemented, the optimization models for the maximization of profits are formulated as follows:

$$\begin{aligned}&\max_{w^{NT}} \pi_M^{NT} = \left(w^{NT} - c_n\right)\left(1 - p^{NT} - s\right) + (c_n - c_r - B)\tau^{NT}\left(1 - p^{NT} - s\right)\\&\text{s.t.} \max_{p^{NT}} \pi_R^{NT} = \left(p^{NT} - w^{NT}\right)\left(1 - p^{NT} - s\right)\\&\max_{\tau^{NT}} \pi_T^{NT} = (B - A)\tau^{NT}\left(1 - p^{NT} - s\right) - \frac{1}{2}k_T\tau^{NT2}.\end{aligned} \tag{5}$$

By using reverse induction, we deduce the optimum solution for the model NT, as shown in Theorem 5.

Theorem 5. *The optimal decisions are* $w^{NT*} = (k_T(1-s+c_n) - 2(1-s)F_3)/(2(k_T - F_3))$, $p^{NT*} = (k_T(3(1-s)+c_n) - 4(1-s)F_3)/(4(k_T - F_3))$, *and* $\tau^{NT*} = (B-A)(1-s-c_n)/(4(k_T - F_3))$ *in the model* NT.

Thus, the optimal consumer demand for products and optimal profits are given as $q^{NT*} = k_T(1-s-c_n)/(4(k_T - F_3))$, $\pi_m^{NT*} = k_T(1-s-c_n)^2/(8(k_T - F_3))$, $\pi_R^{NT*} = k_T^2(1-s-c_n)^2/(16(k_T - F_3)^2)$, and $\pi_T^{NT*} = k_T(B-A)^2(1-s-c_n)^2/(32(k_T - F_3)^2)$.

When blockchain is implemented, the optimization models for the maximization of profits are formulated as follows:

$$\begin{aligned}&\max_{w^{YT}} \pi_M^{YT} = \left(w^{YT} - c_n - b\right)\left(1 - p^{YT} - \alpha s\right) + (c_n - c_r - B)\tau^{YT}\left(1 - p^{YT} - \alpha s\right)\\&s.t. \max_{p^{YT}} \pi_R^{YT} = \left(p^{YT} - w^{YT} - b\right)\left(1 - p^{YT} - \alpha s\right)\\&\max_{\tau^{YT}} \pi_T^{YT} = (B - A)\tau^{YT}\left(1 - p^{YT} - \alpha s\right) - \frac{1}{2}k_T\tau^{YT2}.\end{aligned} \tag{6}$$

Using the calculation method in Theorem 5, the optimal solution for the YT model has been derived, as demonstrated in Theorem 6.

Theorem 6. *The optimal decisions are* $w^{YT*} = (k_T(1-\alpha s + c_n) - 2(1-\alpha s - b)F_3)/(2(k_T - F_3))$, $p^{YT*} = (k_T(3(1-\alpha s) + c_n + 2b) - 4(1-\alpha s)F_3)/(4(k_T - F_3))$, *and*

$\tau^{YT*} = (B - A)(1 - \alpha s - c_n - 2b)/(4(k_T - F_3))$ *in the model YT.*

Thus, the optimal consumer demand and optimal profits are given as $q^{YT*} = k_T(1 - \alpha s - c_n - 2b)/(4(k_T - F_3))$, $\pi_M^{YT*} = k_T(1 - \alpha s - c_n - 2b)^2/(8(k_T - F_3))$, $\pi_R^{YT*} = k_T^2(1 - \alpha s - c_n - 2b)^2/(16(k_T - F_3)^2)$, and $\pi_T^{YT*} = k_T(B - A)^2(1 - \alpha s - c_n - 2b)^2/(32(k_T - F_3)^2)$.

5. Sensitive and Comparative Analysis of Equilibrium Results

In this part, the characterization of the equilibrium results is in Subsection 5.1. Then, the optimal decisions of the six models are compared in Subsection 5.2. Moreover, we derive the choice of T&A CLSC member in Subsection 5.3. Finally, we examine the consumer implications of blockchain and recycling modes in Subsection 5.4. By characterizing and comparing the equilibrium results in Theorems 1–6, we can therefore conclude these propositions.

5.1. Sensitivity Analysis of T&A CLSC Members' Optimal Decisions. The implementation of blockchain enhances consumer utility and stimulates consumer demand. However, this also incurs additional costs. We investigate the influence of the relevant blockchain parameters α and b on the optimal decision, as shown in Propositions 7 and 8.

Proposition 7. *Impacts of the parameter α on the optimal decisions are given as follows:*

(1) If $F_1 < k_M < 2F_1$, then $\partial w^{YM*}/\partial\alpha > 0$; if $F_2 < k_R < F_2 + F_3$, then $\partial w^{YR*}/\partial\alpha > 0$; if $F_3 < k_T < 2F_3$, then $\partial w^{YT*}/\partial\alpha > 0$.

(2) If $F_1 < k_M < 4F_1/3$, then $\partial p^{YM*}/\partial\alpha > 0$; if $F_2 < k_R < 4F_2/3$, then $\partial p^{YR*}/\partial\alpha > 0$; if $F_3 < k_T < 4F_3/3$, then $\partial p^{YT*}/\partial\alpha > 0$; $(\partial p^{YR*}/\partial\alpha) > 0$

(3) $\partial\tau^i/\partial\alpha < 0$, $i \in \{YM, YR, YT\}$.

Proposition 7 clarifies that if the recycling cost coefficient of the recycler falls below a threshold, both wholesale and retail prices of T&A products rise, driven by the amplified influence of blockchain on consumer purchases α. The recycling rates always decrease with the amplification of α in the model YM, YR, and YT. Generally, the manufacturer is hesitant to raise wholesale prices to maintain consumer demand. However, when the recycling cost coefficient falls below a threshold, an increase in retail prices does not necessarily lead to a substantial decline in consumer demand. In response to an amplification in α, if consumer demand decreases, the manufacturer may resort to increase wholesale prices as a means to offset losses. Accordingly, the retailer adjusts retail prices upwards in response to the manufacturer's wholesale prices' increase. A larger α decreases in consumer demand. As a result, recyclers choose to reduce the recycling rates of used T&A products.

Proposition 8. *Impacts of the parameter b on the optimal results are given as $\partial w^j/\partial b > 0$, $\partial p^j/\partial b > 0$, $\partial\tau^j/\partial b < 0$, and $j \in \{YM, YR, YT\}$.*

Proposition 8 describes that in the models YM, YR, and YT, as the unit cost of blockchain validation b increases, both wholesale and retail prices increase, while recycling rates show a declining trend that is contrary to the rise in b. This implies that with a rise in the fees charged to the manufacturer and the retailer on blockchain platforms, they transfer the extra costs to consumers by boosting wholesale and retail prices to maintain their profit margins. Similar results were obtained by Zhang et al. in a dual-channel supply chain study [38]. Moreover, an increase in wholesale prices can result in the retailer's increased retail prices. Consequently, this leads to diminished consumer demand for T&A products with higher prices, causing a decline in recyclers' inclination to recycle used T&A products.

5.2. Comparison of CLSC Members' Equilibrium Decisions. By comparing the wholesale prices, retailer prices, and recycling rates with and without blockchain, we obtain Proposition 9.

Proposition 9. *The optimum results are satisfactory for the following:*

(1) If $k_M > 2(s(1-\alpha) - b)F_1/(s(1-\alpha))$, then $w^{YM*} > w^{NM*}$; if $k_R > (s(1-\alpha)(F_2 + F_3) - 2bF_3)/(s(1-\alpha))$, then $w^{YR*} > w^{NR*}$; if $k_T > 2(s(1-\alpha) - b)F_3/(s(1-\alpha))$, then $w^{YT*} > w^{NT*}$.

(2) If $k_M > 4s(1-\alpha)F_1/(2b + 3s(1-\alpha))$, then $p^{YM*} > p^{NM*}$; if $k_R > 4s(1-\alpha)F_2/(2b + 3s(1-\alpha))$, then $p^{YR*} > p^{NR*}$; if $k_T > 4s(1-\alpha)F_3/\ (2b + 3s(1-\alpha))$, then $p^{YT*} > p^{NT*}$.

(3) If $b < (1-\alpha)s/2$, then $\tau^{YM*} > \tau^{NM*}$, $\tau^{YR*} > \tau^{NR*}$, and $\tau^{YT*} > \tau^{NT*}$.

Proposition 9(1) demonstrates that in three recycling modes, when the recycler's recycling cost coefficient exceeds a threshold, blockchain implementation will result in an increase in wholesale prices. This implies that a higher recycling cost coefficient limits the quantity of used T&A products that a recycler can process. The implementation of blockchain enables consumers to access information, indicating a low percentage of remanufactured products among all T&A products. As consumer concerns regarding product quality decrease and consumer demand rises, the manufacturer responds by increasing wholesale prices. In addition, the manufacturer experiences increased production costs following blockchain implementation and compensates by adjusting wholesale prices.

Proposition 9(2) indicates that when the recycler's recycling cost coefficient exceeds a threshold, retail prices with blockchain exceed the retail prices without blockchain across the three recycling modes. This discrepancy is a result of higher recycling costs, which prompt the upstream manufacturer in the T&A CLSC to raise their prices, thus inflating the purchase costs of the downstream retailer. In addition, the implementation of blockchain imposes supplementary expenses on the retailer. Consequently, to offset the extra costs and maintain profitability, the retailer tends to implement retail prices, effectively transferring the expenses to consumers.

Proposition 9(3) demonstrates that the implementation of blockchain has the potential to increase recycling rates under the same recycling mode, as long as the cost of blockchain unit verification b is below a certain threshold. The function of blockchain to reduce the level of consumer concern about product quality is the main attribute leading to a positive impact on consumer demand. Nevertheless, the implementation of blockchain may increase the cost of producing T&A products. To offset this extra expense, the manufacturer and the retailer each raise their wholesale and retail prices. Higher prices may deter consumer demand. However, when b is lower than a certain threshold, the implementation of blockchain exerts a favorable influence on consumer demand. In this case, the implementation of blockchain will increase consumer demand, which will consequently enhance recycling rates. For instance, H&M has increased consumer trust and engagement by partnering with a blockchain platform, which in turn has increased the recycling rate of T&A products.

By comparing the optimal consumer demand under different models, we obtain Proposition 10.

Proposition 10. *The optimal consumer demands in the six models satisfy the following:*

(1) *If* $b < (1-\alpha)s/2$, *then* $q^{YM*} > q^{NM*}$, $q^{YR*} > q^{NR*}$, *and* $q^{YT*} > q^{NT*}$;

(2) *If* $k_M < k_R F_1/F_2$, *then* $q^{NM*} > q^{NR*}$ *and* $q^{YM*} > q^{YR*}$; *if* $k_R < k_T F_2/F_3$, *then* $q^{NR*} > q^{NT*}$ *and* $q^{YR*} > q^{YT*}$; *if* $k_M < k_T F_1/F_3$, *then* $q^{NM*} > q^{NT*}$ *and* $q^{YM*} > q^{YT*}$.

Proposition 10(1) implies that the implementation of blockchain can increase consumer demand when the blockchain unit verification cost b is lower than a certain amount. That is to say, at b lower than a certain amount, the implementation of blockchain does not cause an excessive increase in cost. In this case, the manufacturer is unlikely to raise wholesale prices significantly, and the reduction in consumer demand due to blockchain costs is likely to be small. Instead, the implementation of blockchain effectively alleviates the degree of consumer concerns about product quality which can increase consumer demand. Therefore, the implementation of blockchain can increase consumer demand when b is relatively small. For example, the implementation of blockchain by H&M to increase data transparency leads to improved consumer trust and heightened consumer demand.

Proposition 10(2) indicates that customers prefer the M recycling mode the most and the T recycling mode the least when the recycler's recycling cost coefficient is relatively low regardless of whether or not the blockchain is implemented. Generally, the manufacturer has the opportunity to recycle directly when the recycling cost coefficient is relatively low. This corresponds to when the manufacturer has the lowest production costs. The wholesale price is determined by the manufacturer's production cost. Therefore, in the M recycling mode, the product's price is the most affordable, which results in increased consumer demand. Similarly, the retailer has the option to lower their prices when it has a lower recycling cost coefficient, leading to higher consumer demand than in the T recycling mode.

5.3. Recycling Mode of CLSC Members

5.3. Recycling Mode of CLSC Members. Comparing the profits of CLSC members in the six models, we obtain Proposition 11.

Proposition 11. *The optimal profits in the six models satisfy the following:*

(1) *If* $b < (1-\alpha)s/2$, *then* $\pi_i^{YM*} > \pi_i^{NM*}$, $\pi_i^{YR*} > \pi_i^{NR*}$, $\pi_i^{YT*} > \pi_i^{NT*}$, $\pi_T^{YT*} > \pi_T^{NT*}$, *and* $i \in \{M, R\}$.

(2) *If* $k_M < k_R F_1/F_2$, *then* $\pi_M^{NM*} > \pi_M^{NR*}$ *and* $\pi_M^{YM*} > \pi_M^{YR*}$; *if* $k_R < k_T F_2/F_3$, *then* $\pi_M^{NR*} > \pi_M^{NT*}$, *and* $\pi_M^{YR*} > \pi_M^{YT*}$; *if* $k_M < k_T F_1/F_3$, *then* $\pi_M^{NM*} > \pi_M^{NT*}$ *and* $\pi_M^{YM*} > \pi_M^{YT*}$.

Proposition 11(1) states that blockchain implementation can lead to increased profits for members of the A&T CLSC when the cost of verifying a unit of blockchain b is below a certain threshold. This is because blockchain can boost consumer demands when b falls below a certain threshold. Regardless of whether the manufacturer and the retailer choose to implement blockchain, they earn the same marginal profit per product. This implies that higher consumer demands lead to higher profits. Increased consumer demand leads to a rise in recycling rates for recyclers. As recycling rates increase, the third-party recycler experiences an increase in profits accordingly. Zhang et al. [41] indicate that the costs of validating blockchain units significantly impact the profits of supply chain participants.

Proposition 11(2) presents that irrespective of the blockchain implementation, when the recycler's recycling cost coefficient is relatively low, the M recycling mode is the most profitable option for the manufacturer, while the T recycling mode is the least profitable. The primary cause is the high consumer demand under the M recycling mode when the recycling cost coefficient is low. Moreover, the profit increases with the rise in consumer demand, given the similar marginal profit of T&A products. Similarly, if the recycler's recycling cost coefficient is low, consumer demand is the lowest under the T recycling mode, resulting in the manufacturer making the least profit under that mode.

To examine the impact of relevant parameters on the decision-making of T&A CLSC members, we refer to Zhang et al. [40] and set $\alpha = 0.5$, $s = 0.3$, $c_n = 0.5$, $c_r = 0.2$, $B = 0.25$, $b = 0.1$, and $k_R = 1$. Since $k_T = 0.5$ is the threshold value for the third-party recycler and unit transfer price B is greater than the recycling price A, we set $k_T = 0.4$, $k_T = 0.6$, and A to vary within the range of $[0, 0.2]$ to study the manufacturer's recycling mode selection, which is shown in Figure 2.

Figure 2 presents the manufacturer's decision regarding the recycling mode. When the manufacturer's recycling cost coefficient k_M is relatively low, the third-party recycling cost coefficient k_T and market recycling price A do not impact the manufacturer's selection of the direct recycling mode. That is to say, the M recycling mode provides the manufacturer with the opportunity to capture additional profit. However, it is worth noting that once k_T rises, the manufacturer tends to avoid

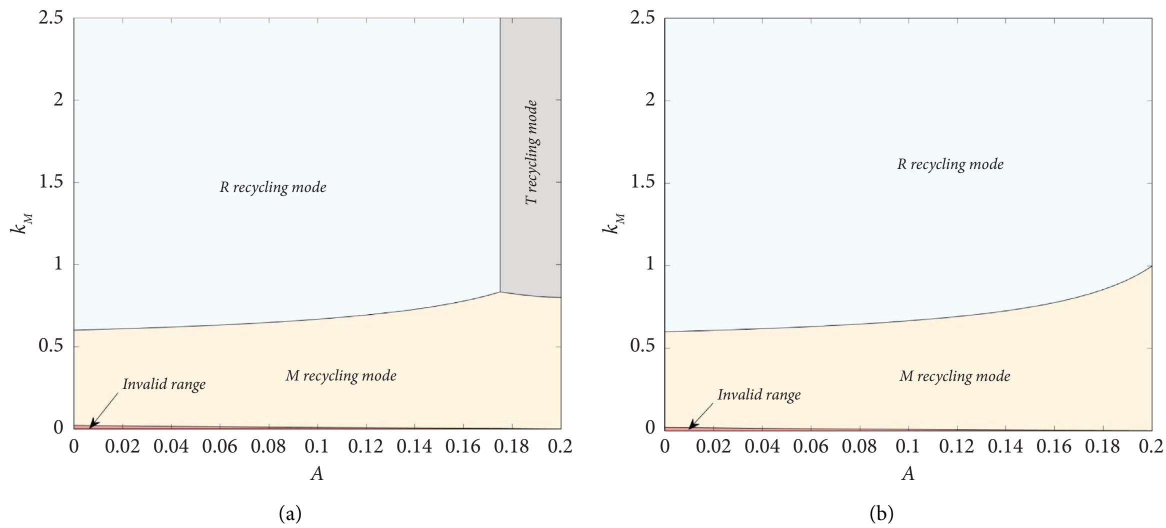

FIGURE 2: Impact of A and k_M on the manufacturer's profits: (a) $k_T = 0.4$ and (b) $k_T = 0.6$.

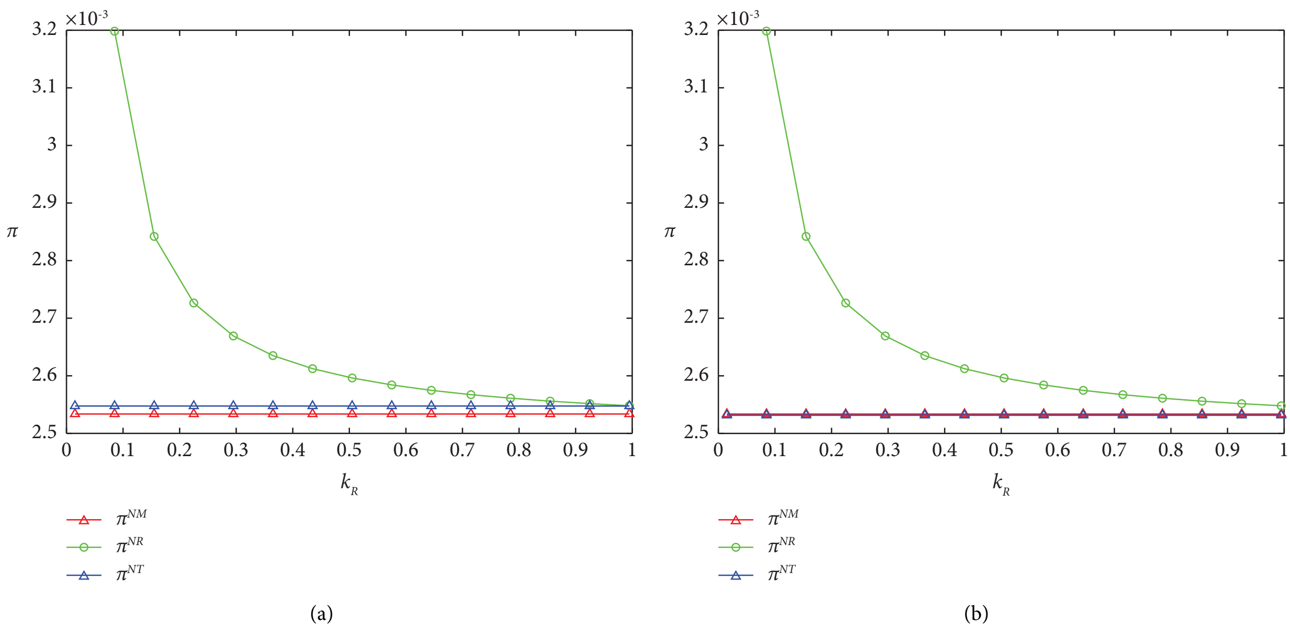

FIGURE 3: Impact of k_R on the retailer's profits: (a) $k_T = 0.4$ and (b) $k_T = 0.6$.

using the third-party recycler. This is because, although the third-party recycler may have efficient recycling channels, its recycling costs may become too high. When k_M is relatively high, the manufacturer's decision on the mode of recycling takes A into account. In particular, when A is relatively high, the manufacturer prefers to choose the T recycling mode, and to select the R recycling mode during periods of lower A. This preference can be attributed to the manufacturer's stronger working relationships with the retailer, which could establish more effective recycling channels or reduce disposal expenses, thus rendering the retailer's recycling more advantageous to the manufacturer when faced with lower A.

To examine the impact of the recycling cost coefficient for the retailer on profits under three distinct recycling modes, we set $A = 0.1$, $k_M = 1.5$, and k_R to vary within the range of $[0.015, 1]$. We examine how retailer's profits are affected by k_R, as shown in Figure 3.

Figure 3 shows that an increase in the recycling cost coefficient k_R results in a decrease in the retailer's profit under the R recycling mode. This is due to that a corresponding increase in recycling expenses causes a decrease in the retailer's profit. Under both the M recycling mode and the T recycling mode, the retailer does not participate in the reverse recycling process. Consequently, k_R does not influence the profit of the retailer. When the third-party recycling coefficient k_T is relatively low, both the manufacturer and the retailer set lower wholesale and retail prices, which increase consumer demand and in turn, the retailer's profits. This trend is relatively evident in the T recycling mode.

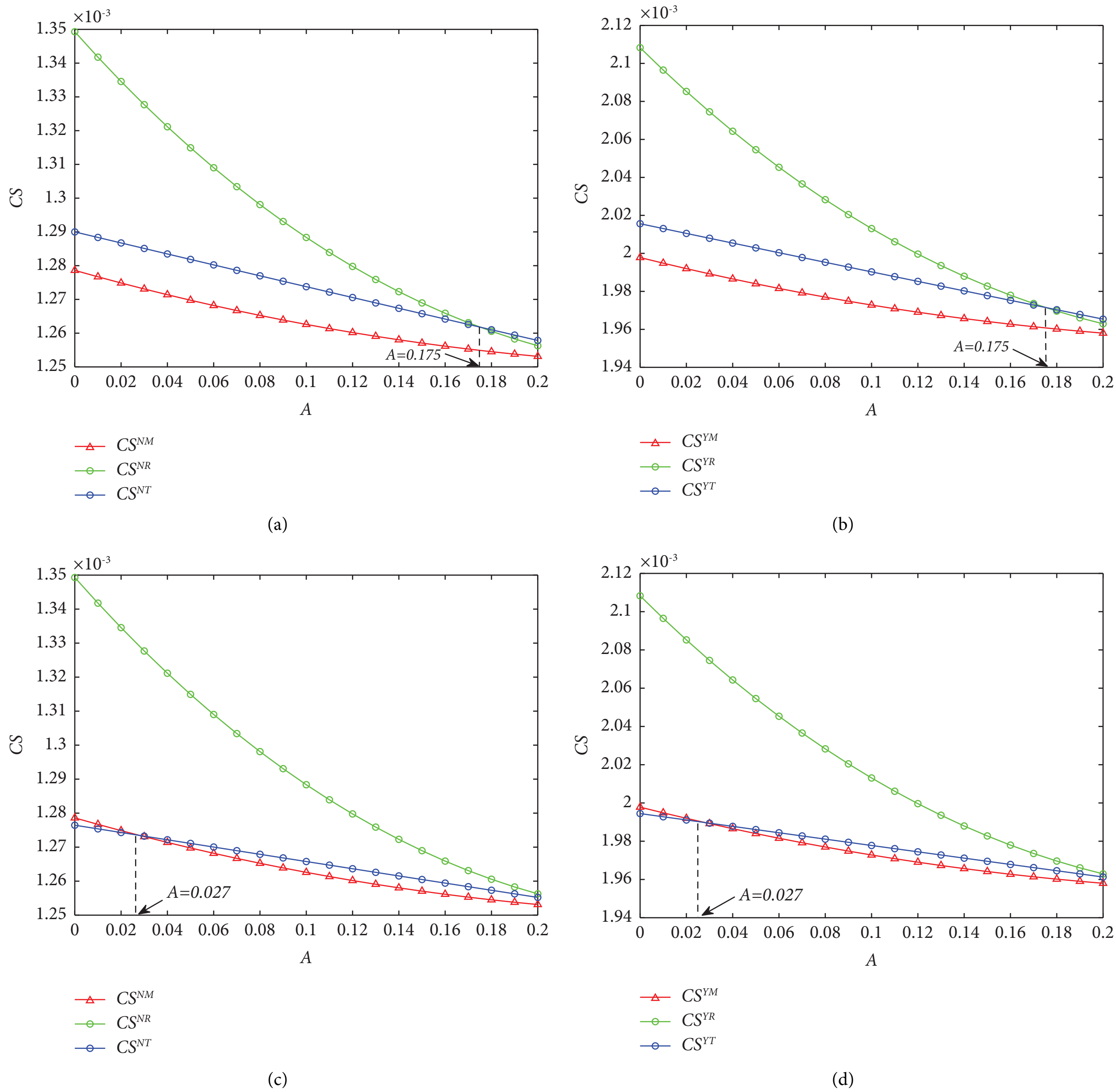

FIGURE 4: Impact of A on the CS: (a) $k_T = 0.4, b = 0.1$, (b) $k_T = 0.4, b = 0.05$, (c) $k_T = 0.6, b = 0.1$, and (d) $k_T = 0.6, b = 0.05$.

5.4. Impact of Blockchain and Recycling Mode on Consumers. When there is an implementation blockchain, the consumer surplus (CS) calculation formula is $CS = \int_{1-\alpha s-q}^{1-\alpha s} (1 - p - \alpha s) dp$. When blockchain is not implemented, the CS calculation formula is $CS = \int_{1-s-q}^{1-s} (1 - p - s)dp$. To gain a deeper understanding of the impact of blockchain on consumers, we conduct a comparison of CS with blockchain and without blockchain in different recycling modes and obtain Proposition 12.

Proposition 12. *The CS in the six models satisfy when* $b < (1 - \alpha)s/2$, *then* $CS^{YM*} > CS^{NM*}$, $CS^{YR*} > CS^{NR*}$, $CS^{YT*} > CS^{NT*}$.

Proposition 12 highlights the correlation between the unit verification cost of blockchain b and its impact on consumers. The implementation of blockchain yields positive consequences for consumers by enhancing the transparency of product information and boosting consumers' willingness to purchase. However, if b exceed a certain value, both the manufacturer and the retailer choose to raise prices to maintain profit margins, in which the positive impact of blockchain on consumers is offset by its negative impact, resulting in a decrease in consumer surplus.

To investigate the role of recycling mode on CS, we compare CS across the three recycling modes, presented in Figure 4.

Figure 4 shows that consumers in the R recycling mode typically derive greater benefits compared to the M recycling mode or the T recycling mode. As the retailer engages in direct communication with consumers and serves as their closest point of contact, consumers exhibit higher levels of trust in the retailer compared to other members of the T&A CLSC. This enables consumers to reap greater benefits within the R recycling mode. However, it should be noted that higher recycling price A has an inverse effect on consumer benefits. As recyclers retrieve used products from consumers at higher A, the cost of remanufacturing increases. This can result in both the manufacturer and the retailer passing on the additional cost to consumers through higher prices, thereby compromising CS. Notably, under the R recycling mode, the impact of A on the level of CS is particularly significant.

6. Conclusions

Based on a CLSC in the T&A industry, we construct three recycling modes and consider the implementation of blockchain, developing six Stackelberg game models. For different models, we deduce optimal solutions. We present an in-depth analysis of manufacturer's decisions regarding recycling models in consideration of blockchain implementation. Through a comparative examination of the optimal decision-making and profit of CLSC members under different models, our study explores the specific conditions that influence the manufacturer's and the retailer's decision to implement blockchain. In addition, we compare the impact of blockchain on the decision-making of CLSC members and consumers. The results show that (1) if the manufacturer's recycling cost coefficient is relatively low, used T&A products are collected directly by the manufacturer. Otherwise, the responsibility for recycling used T&A products falls to the retailer or the third-party recycler. German clothing brand Puma decided to hire third-party recyclers to handle their used products, as creating a new recycling business themselves would have been more expensive. It is noteworthy that the manufacturer's choice of recycling mode remains unchanged whether or not blockchain is implemented. (2) Blockchain can lead to increased profits and benefits consumers when the cost of validating blockchain units remains below a certain threshold. Therefore, CLSC members should implement blockchain when the cost of blockchain is relatively low. (3) When the recycling cost coefficient exceeds a threshold, the implementation of blockchain results in a price increase. Meanwhile, it consistently enhances the recycling rate of T&A products. Nike and Adidas have successfully implemented blockchain into their supply chains, thereby enhancing transparency and trustworthiness. This implementation has effectively mitigated consumer concerns about product quality, subsequently boosting consumer demand and driving higher profits.

Combined with the above analysis, this paper presents some management implications for the T&A CLSC. Firstly, when selecting a recycling mode for used products, manufacturers should prioritize the cost of establishing recycling channels as the key consideration. The implementation of blockchain does not influence the choice of recycling model. Secondly, manufacturers and retailers primarily prioritize the cost per unit of validation when implementing blockchain, as high costs can negatively impact the profits of supply chain members. Finally, when implementing blockchain, companies should only consider implementing a high-price strategy if they face relatively high recycling expenses. Besides, with the implementation of blockchain, companies typically can enhance their recycling rates.

This paper has certain limitations due to incomplete consideration of the problem. Firstly, blockchain expenses incurred during production and distribution processes are shared between the manufacturer and retailer. However, dominant and follower entities bear different proportions of blockchain validation costs. Secondly, this paper exclusively examines the positive impact of blockchain on consumer demand. The implementation of blockchain may potentially decrease consumer demand due to concerns over consumer privacy. In addition, this paper discusses the use of a single recycling entity in the recycling model, whereas manufacturers can directly recycle products while authorizing third-party recyclers to collect used T&A products.

Appendix

A. Proof of Theorem 1

Proof of Theorem 1. Since $\partial^2\pi_R^{NM}/\partial p^{NM2} = -2 < 0$, π_R^{NM} is concave on p^{NM}. It can be obtained from $\partial\pi_R^{NM}/\partial p^{NM} = 0$ that $p^{NM} = (1 - s + w^{NM})/2$.

By substituting p^{NM} into π_M^{NM}, the Hessian matrix of π_M^{NM} in terms of w^{NM} and τ^{NM} is $H^{NM} = \begin{pmatrix} -1 & -(c_n - c_r - A)/2 \\ -(c_n - c_r - A)/2 & -k_M \end{pmatrix}$. It can be verified that $|H_1^{NM}| = -1 < 0$. If $|H_2^{NM}| > 0$, then we have $k_M > (c_n - c_r - A)^2/4$. The assumption is needed in the full study. Under this assumption, π_M^{NM} is strictly concave with respect to w^{NM} and τ^{NM}. It can obtain from $\partial\pi_M^{NM}/\partial w^{NM} = 0$ and $\partial\pi_M^{NM}/\partial\tau^{NM} = 0$ that $w^{NM*} = (2k_M(1 - s + c_n) - (1 - s)(c_n - c_r - A)^2)/(4k_M - (c_n - c_r - A)^2)$ and $\tau^{NM*} = (c_n - c_r - A)(1 - s - c_n)/(4k_M - (c_n - c_r - A)^2)$.

Substituting w^{NM*} and τ^{NM*} into p^{NM}, we have $p^{NM*} = (k_M(3(1 - s) + c_n) - (1 - s) \quad (c_n - c_r - A)^2)/(4k_M - (c_n - c_r - A)^2)$. In order to make the results meaningful, it is necessary to ensure that the recycling rate τ^{NM*} is positive, then we have $s + c_n < 1$. □

B. Proof of Theorem 2

Proof of Theorem 2. Since $\partial^2\pi_r^{YM}/\partial p^{YM2} = -2 < 0$, π_R^{YM} is concave on p^{YM}. It can be obtained from $\partial\pi_R^{YM}/\partial p^{YM} = 0$ that, $p^{YM} = (1 - \alpha s + w^{YM} + b)/2$.

By substituting p^{YM} into π_M^{YM}, the Hessian matrix of π_M^{YM} in terms of w^{YM} and τ^{YM} is $H^{YM} = \begin{pmatrix} -1 & -(c_n - c_r - A)/2 \\ -(c_n - c_r - A)/2 & -k_M \end{pmatrix}$. We can find that $|H_1^{YM}| = -1 < 0$. From the assumption $k_M > (c_n - c_r - A)^2/4$, it can be shown that $|H_2^{YM}| = k_M - (c_n - c_r - A)^2/4 > 0$. Thus, H^{YM} is negative definite. π_M^{YM} is strictly concave with respect to w^{YM} and τ^{YM}. It can be obtained from $\partial\pi_M^{YM}/\partial w^{YM} = 0$ and $\partial\pi_M^{YM}/\partial\tau^{YM} = 0$ that $w^{YM*} = (2k_M(1-\alpha s + c_n) - (1-\alpha s - b)(c_n - c_r - A)^2)/(4k_M - (c_n - c_r - A)^2)$ and $\tau^{YM*} = (c_n - c_r - A)\quad(1-\alpha s - c_n - 2b)/(4k_M - (c_n - c_r - A)^2)$.

Substituting w^{YM*} and τ^{YM*} into p^{YM}, we have $p^{YM*} = (k_M(3(1-\alpha s) + c_n + 2b) - (1-\alpha s)\ (c_n - c_r - A)^2)/(4k_M - (c_n - c_r - A)^2)$. In order to make the results meaningful, it is necessary to ensure that the recycling rate τ^{YM*} is positive, and then we have $s + c_n + 2b < 1$. □

C. Proof of Theorem 3

Proof of Theorem 3. The Hessian matrix of π_R^{NR} in terms of p^{NR} and τ^{NR} is $H^{NR} = \begin{pmatrix} -2 & -(B-A) \\ -(B-A) & -k_R \end{pmatrix}$. We can verify that $|H_1^{NR}| = -2 < 0$. If $|H_2^{NR}| = 2k_R - (B-A)^2 > 0$, then we have $k_R > (B-A)^2/2$. Under this assumption, π_R^{NR} is strictly concave with respect to p^{NR} and τ^{NR}. It can be obtained from $\partial\pi_R^{NR}/\partial p^{NR} = 0$ and $\partial\pi_R^{NR}/\partial\tau^{NR} = 0$ that, $p^{NR} = (k_R(1-s-w) - (a-s)(B-A)^2)/(2k_R - (B-A)^2)$ and $\tau^{NR} = (B-A)(1-s-w^{NR})/(2k_R - (B-A)^2)$.

By substituting p^{NR} and τ^{NR} into π_M^{NR}, the second derivative of π_M^{NR} to w^{NR} is $\partial^2\pi_M^{NR}/\partial w^{NR2} = -2k_R(2k_r - (B-A)\ (c_n - c_r - A))/(2k_R - (B-A)^2)^2$. If $\partial^2\pi_M^{NR}/\partial w^{NR2} < 0$, then we have $k_R > (B-A)(c_n - c_r - A)/2$. Under this assumption, π_M^{NR} is concave on w^{NR}. From $\partial\pi_M^{NR}/\partial w^{NR} = 0$, we have $w^{NR*} = (2k_R(1-s+c_n) - (1-s)(B-A)\ (2c_n - 2c_r - B - A) - (B-A)^2 c_n)/(2(2k_R - (B-A)\ (c_n - c_r - A)))$.

By substituting w^{NR*} into p^{NR} and τ^{NR}, we have $p^{NR*} = (k_R\ (3(1-s) + c_n) - 2(1-s)(B-A)(c_n - c_r - A))/(2\ (2k_R - (B-A)(c_n - c_r - A)))$ and $\tau^{NR*} = (B-A)(1 - s - c_n)/(2(2k_R - (B-A)(c_n - c_r - A)))$. □

D. Proof of Theorem 4

Proof of Theorem 4. The Hessian matrix of π_R^{YR} in terms of p^{YR} and τ^{YR} is $H^{YR} = \begin{pmatrix} -2 & -(B-A) \\ -(B-A) & -k_R \end{pmatrix}$. We can verify that $|H_1^{YR}| = -2 < 0$. From the assumption $k_R > (B-A)(c_n - c_r - A)/2$, we have $|H_2^{YR}| = 2k_R - (B-A)^2 > 0$. Thus, π_R^{YR} is strictly concave with respect to p^{YR} and τ^{YR}. It can be obtained from $\partial\pi_R^{YR}/\partial p^{YR} = 0$ and $\partial\pi_R^{YR}/\partial\tau^{YR} = 0$ that $p^{YR} = (k_R(1-\alpha s + w^{YR} + b) - (1-\alpha s)(B-A)^2)/(2k_R - (B-A)^2)$ and $\tau^{YR} = (B-A)(1-\alpha s - w^{YR} - b)/(2k_R - (B-A)^2)$.

By substituting p^{YR} and τ^{YR} into π_M^{YR}, the second derivative of π_M^{YR} to w^{YR} is $\partial^2\pi_M^{YR}/\partial w^{YR2} = -2k_R(2k_R - (B-A)(c_n - c_r - A))/(2k_R - (B-A)^2)^2$. From the assumption $k_R > (B-A)(c_n - c_r - A)/2$, we have $\partial^2\pi_M^{YR}/\partial w^{YR2} < 0$. Therefore, π_M^{NR} is concave on w^{NR}. From $\partial\pi_M^{NR}/\partial w^{NR} = 0$, we have $w^{YR*} = (2k_R(1-\alpha s + c_n) + 2b\ (B-A)(c_n - c_r - B) - (1-s)(B-A)\ (2c_n - 2c_r - B - A) - (B-A)^2 c_n)/(2(2k_R - (B-A)(c_n - c_r - A)))$.

By substituting w^{YR*} into p^{YR} and τ^{YR}, we have $p^{YR*} = (k_R(3(1-\alpha s) + c_n + 2b) - 2(1-\alpha s)(B-A)\ (c_n - c_r - A))/(2(2k_R - (B-A)(c_n - c_r - A)))$ and $\tau^{YR*} = (B-A)\ (1-\alpha s - c_n - 2b)/\ (2(2k_R - (B-A)(c_n - c_r - A)))$. □

E. Proof of Theorem 5

Proof of Theorem 5. Since $\partial^2\pi_R^{NT}/\partial p^{NT2} = -2 < 0$ and $\partial^2\pi_T^{NT}/\partial\tau^{NT2} = -k_T < 0$, π_R^{NT} is concave on p^{NT} and π_T^{NT} is concave on τ^{NT}. It can be received from $\partial\pi_R^{NT}/\partial p^{NT} = 0$ and $\partial\pi_T^{NT}/\partial\tau^{NT} = 0$ that $p^{NT} = (1 - s + w^{NT})/2$ and $\tau^{NT} = (B-A)(1-s-w^{NT})/2k_T$.

Substituting p^{NT} and τ^{NT} into π_M^{NT} and finding the second derivative of w^{NT} for π_M^{NT}, we have $\partial^2\pi_M^{NT}/\partial w^{NT2} = -(2k_T - (B-A)(c_n - c_r - B))/2k_T$. If $\partial^2\pi_M^{NT}/\partial w^{NT2} < 0$, then we have $k_T > (B-A)(c_n - c_r - B)/2$. Under this assumption, π_M^{NT} is concave on w^{NT}. Thus, we can obtain $w^{NT*} = (k_T(1-s+c_n) - (1-s)(B-A)\quad(c_n - c_r - B))/(2k_T - (B-A)(c_n - c_r - B))$ from $\partial\pi_M^{NT}/\partial w^{NT} = 0$.

By substituting w^{NT*} into p^{NT} and τ^{NT}, we have $p^{NT*} = (k_T(3(1-s) + c_n) - 2(1-s)(B-A)\ (c_n - c_r - B))/(2(2k_T - (B-A)(c_n - c_r - A)))$ and $\tau^{NT*} = (B-A)(1-s-c_n)/(2(2k_T - (B-A)(c_n - c_r - B)))$. □

F. Proof of Theorem 6

Proof of Theorem 6. Since $\partial^2\pi_R^{YT}/\partial p^{YT2} = -2 < 0$ and $\partial^2\pi_T^{YT}/\partial\tau^{YT2} = -k_T < 0$, π_R^{YT} is concave on p^{YT} and π_T^{YT} is concave on τ^{YT}. It can be received from $\partial\pi_R^{YT}/\partial p^{YT} = 0$ and $\partial\pi_T^{YT}/\partial\tau^{YT} = 0$ that $p^{YT} = (1-\alpha s + w^{YT} + b)/2$ and $\tau^{YT} = (B-A)(1-\alpha s - w^{YT} - b)/2k_T$.

By substituting p^{YT} and τ^{YT} into π_M^{YT} and finding the second derivative of w^{YT} for π_M^{YT}, we have $\partial^2\pi_M^{YT}/\partial w^{YT2} = -(2k_T - (B-A)(c_n - c_r - B))/2k_T$. From the assumption $k_T > (B-A)(c_n - c_r - B)/2$, we have $\partial^2\pi_M^{YT}/\partial w^{YT2} < 0$. Thus, π_M^{YT} is concave on w^{YT}. We can obtain $w^{YT*} = (k_T(1-\alpha s + c_n) - (1-\alpha s - b)(B-A)\ (c_n - c_r - B))/(2k_T - (B-A)(c_n - c_r - B))$ from $\partial\pi_M^{YT}/\partial w^{YT} = 0$.

By substituting w^{YT*} into p^{YT} and τ^{YT}, we have $p^{YT*} = (k_T(3(1-\alpha s) + c_n + 2b) - 2(1-\alpha s)(B-A)\ (c_n - c_r - B))/(2\ (2k_T - (B-A)(c_n - c_r - A)))$ and $\tau^{YT*} = (B-A)\ (1-\alpha s - c_n - 2b)/\ (2(2k_T - (B-A)(c_n - c_r - B)))$. □

G. Proof of Proposition 7

Proof of Proposition 7. From the assumption $k_M > (c_n - c_r - A)^2/4$, $k_R > (B-A)(c_n - c_r - A)/2$, and $k_T > (B-A)(c_n - c_r - B)/2$ and by examining the impacts of α on the optimal decisions in the models YM, YR, and YT, it is easily verified that $\partial\tau^{YR*}/\partial\alpha = -s(B-A)/(2k_R - (B-A)(c_n - c_r - A)) < 0$ and $\partial\tau^{YT*}/\partial\alpha = -s(B-A)/(2k_T - \theta(B-A)(c_n - c_r - B)) < 0$. If $(c_n - c_r - A)^2/4 < k_M < (c_n - c_r - A)^2/2$, then $\partial w^{YM*}/\partial\alpha = -s\quad(2k_M - (c_n - c_r - A)^2)/(4k_M - (c_n - c_r - A)^2) > 0$, if $(B-A)(c_n - c_r - A)/2 < k_R < (B-A)(2c_n - 2c_r - B - A)/2$, then $\partial w^{YR*}/\partial\alpha = -s(2k_R - (B-A)\ (2c_n - 2c_r - B - A))/(2(2k_R - (B-A)\quad(c_n - c_r - A))) > 0$, if $(B-A)(c_n - c_r -$

$B)/2 < k_T < (B-A)\ (c_n - c_r - B)$, then $\partial w^{YT*}/\partial\alpha = -s(k_T - (B-A)\ (c_n - c_r - B))/\ (2k_T - (B-A)(c_n - c_r - B)) > 0$, if $(c_n - c_r - A)^2/\ 4 < k_M < (c_n - c_r - A)^2/3$, then $\partial p^{YM*}/\partial\alpha = -s(3k_M - \ (c_n - c_r - A)^2)/\ (4k_M - (c_n - c_r - A)^2) > 0$, if $(B-A)(c_n - c_r - A)/2 < k_R < 2(B-A)(c_n - c_r - A)/3$, then $\partial p^{YR*}/\partial\alpha = -s(3k_R - 2(B-A)(c_n - c_r - A))/(2(2k_R - (B-A)(c_n - c_r - A))) > 0$, if $(B-A)(c_n - c_r - B)/2 < k_T < 2(B-A)\ (c_n - c_r - B)/3$, then $\partial p^{YT*}/\partial\alpha = -s(3k_T - 2(B-A)(c_n - c_r - B))/(2k_T - (B-A)(c_n - c_r - B)) > 0$. □

H. Proof of Proposition 8

Proof of Proposition 8. From the assumption $k_M > (c_n - c_r - A)^2/4$, $k_R > (B-A)(c_n - c_r - A)/2$, $k_T > (B-A)(c_n - c_r - B)/2$ and by examining the impacts of b on the optimal decisions in the models YM, YR, and YT, it is easily verified that $\partial w^{YM*}/\partial b = (c_n - c_r - A)^2/(4k_M - (c_n - c_r - A)^2) > 0$, $\partial w^{YR*}/\partial b = (B-A)(c_n - c_r - B)/(2k_R - (B-A)\ (c_n - c_r - A)) > 0$, $\partial w^{YT*}/\partial b = (B-A)(c_n - c_r - B)/\ (2k_T - (B-A)(c_n - c_r - B)) > 0$, $\partial p^{YM*}/\partial b = 2k_M/(4k_M - (c_n - c_r - A)^2) > 0$, $\partial p^{YR*}/\partial b = k_R/(2k_R - (B-A)(c_n - c_r - A)) > 0$, and $\partial p^{YT*}/\partial b = k_T/(2k_T - (B-A)(c_n - c_r - B)) > 0$ $\partial\tau^{YM*}/\partial b = -2(c_n - c_r - A)/(4k_M - (c_n - c_r - A)^2) < 0$, $\partial\tau^{YR*}/\partial b = -(B-A)/(2k_R - (B-A)(c_n - c_r - A)) < 0$, and $\partial\tau^{YT*}/\partial b = -(B-A)/(2k_T - (B-A)(c_n - c_r - B)) < 0$ □

I. Proof of Proposition 9

Proof of Proposition 9. Comparing the optimal decisions, we have

(1) $w^{NM*} - w^{YM*} = ((s(1-\alpha) - b)\ (c_n - c_r - A)^2 - 2s(1-\alpha)k_M)/(4k_M - (c_n - c_r - A)^2)$, if $k_M > (s(1-\alpha) - b)(c_n - c_r - A)^2/(2s(1-\alpha))$, then $w^{YM*} > w^{NM*}$,

If $k_R > (B-A)(s(1-\alpha)\ (2c_n - 2c_r - B - A) - 2b(c_n - c_r - B))/2s(1-\alpha)$, then $w^{NR*} - w^{YR*} = ((B-A)(s(1-\alpha)(2c_n - 2c_r - B - A) - 2b\ (c_n - c_r - B)) - 2s(1-\alpha)\ k_R)/(2(2k_R - (B-A)(c_n - c_r - A))) < 0$,

If $k_T > (B-A)(c_n - c_r - B)(s(1-\alpha) - b)/(s(1-\alpha))$, then $w^{NT*} - w^{YT*} = ((B-A)(c_n - c_r - B)\ (s(1-\alpha) - b) - s(1-\alpha)k_T)/2k_T - (B-A)(c_n - c_r - B) < 0$;

(2) $p^{NM*} - p^{YM*} = (s(1-\alpha)(c_n - c_r - A)^2) - \ (2b + 3s(1-\alpha))k_M)/(4k_M - (c_n - c_r - A)^2)$, if $k_M > s(1-\alpha)(c_n - c_r - A)^2/(2b + 3s(1-\alpha))$, then $p^{YM*} > p^{NM*}$,

If $k_R > 2s(1-\alpha)(B-A)\ (c_n - c_r - A)/(2b + 3s(1-\alpha))$, then $p^{NR*} - p^{YR*} = (2s(1-\alpha)(B-A)(c_n - c_r - A)) - (2b + 3s(1-\alpha))k_R)/(2(2k_R - (B-A)(c_n - c_r - A))) < 0$,

If $k_T > 2s(1-\alpha)(B-A)(c_n - c_r - B)/(2b + 3s(1-\alpha))$, then $p^{NT*} - p^{YT*} = (2s(1-\alpha)(B-A)(c_n - c_r - B)) - (2b + 3s(1-\alpha))k_T)/(2(2k_T - (B-A)(c_n - c_r - B))) < 0$;

(3) $\tau^{NM*} - \tau^{YM*} = (c_n - c_r - A)\ (2b - s + \alpha s)/(4k_M - (c_n - c_r - A)^2)$, $\tau^{NR*} - \tau^{YR*} = (B-A)(2b + \alpha s - s)/(2(2k_R - (B-A)(c_n - c_r - A)))$, $\tau^{NT*} - \tau^{YT*} = (B-A)(2b + \alpha s - s)/(2(2k_T - (B-A)(c_n - c_r - B)))$, if $b < (1-\alpha)s/2$, then $\tau^{YM*} > \tau^{NM*}$, $\tau^{YR*} > \tau^{NR*}$, and $\tau^{YT*} > \tau^{NT*}$. □

J. Proof of Proposition 10

Proof of Proposition 10. Comparing the optimal consumer demands, we have

(1) $q^{NM*} - q^{YM*} = k_M(2b + \alpha s - s)/(4k_M - (c_n - c_r - A)^2)$, $q^{NR*} - q^{YR*} = k_R(2b + \alpha s - s)/(2(2k_R - (B-A)\ (c_n - c_r - A)))$, $q^{NT*} - q^{YT*} = k_T(2b + \alpha s - s)/(2(2k_T - (B-A)(c_n - c_r - B)))$, if $b < (1-\alpha)s/2$, then $p^{YM*} > p^{NM*}$, $p^{YR*} > p^{NR*}$, and $p^{YT*} > p^{NT*}$;

(2) If $k_M < (c_n - c_r - A)k_R/\ (2(B-A))$, then $q^{NM*} - q^{NR*} = (1 - s - c_n)\ (c_n - c_r - A)(k_R(c_n - c_r - A) - 2k_M\ (B-A))/(2(4k_M - (c_n - c_r - A)^2)(2k_R - (B-A)(c_n - c_r - A))) > 0$ and $q^{YM*} - q^{YR*} = (1 - \alpha s - c_n - 2b)\ (c_n - c_r - A)\ (k_R(c_n - c_r - A) - 2k_M(B-A))/\ (2(4k_M - (c_n - c_r - A)^2)(2k_R - (B-A)(c_n - c_r - A))) > 0$.

If $k_R < (c_n - c_r - A)k_T/(c_n - c_r - B)$, then $q^{NR*} - q^{NT*} = (1 - s - c_n)\ (B-A)\ (k_T(c_n - c_r - A) - k_R(c_n - c_r - B))/(2(2\ k_T - (B-A)(c_n - c_r - B))(2k_R - (B-A)(c_n - c_r - A))) > 0$ and $q^{YR*} - q^{YT*} = (1 - \alpha s - c_n - 2b)(B-A)(k_T(c_n - c_r - A) - k_R(c_n - c_r - B))/(2(2k_T - (B-A)\ (c_n - c_r - B))(2k_R - (B-A)(c_n - c_r - A))) > 0$

If $k_R < (c_n - c_r - A)/c_n - c_r - Bk_T$, then $q^{NM*} - q^{NT*} = (1 - s - c_n)\ (k_T(c_n - c_r - A)^2 - 2k_M(B-A)\ (c_n - c_r - B))/(2\ \ (2k_T - (B-A)(c_n - c_r - B))(4k_M - (c_n - c_r - A)^2) > 0$ and $q^{YM*} - q^{YT*} = (1 - \alpha s - c_n - 2b)(k_T(c_n - c_r - A)^2 - 2k_M(B-A)\ (c_n - c_r - B)/(2(2k_T - (B-A)\ (c_n - c_r - B))(4k_M - (c_n - c_r - A)^2) > 0$. □

K. Proof of Proposition 11

Proof of Proposition 11. Comparing the optimal profits of three CLSC members in the six models, we have

(1) $\pi_M^{NM*} - \pi_M^{YM*} = k_M(2b + \alpha s - s)\ (2 - \alpha s - s - 2c_n - 2b)/(2(4k_M - (c_n - c_r - A)^2))$,

$\pi_M^{NR*} - \pi_M^{YR*} = k_R(2b + \alpha s - s)(2 - \alpha s - s - 2c_n - 2b)/(4(2k_R - (B-A)(c_n - c_r - A)))$

$\pi_M^{NT*} - \pi_M^{YT*} = k_T(2b + \alpha s - s)(2 - \alpha s - s - 2c_n - 2b)/(4(2k_T - (B-A)(c_n - c_r - B)))$

$\pi_R^{NM*} - \pi_R^{YM*} = k_M^2(2b + \alpha s - s)\ (2 - \alpha s - s - 2c_n - 2b)/\ ((4k_M - (c_n - c_r - A)^2)^2)$

$\pi_R^{NR*} - \pi_R^{YR*} = k_R(2k_R - (B-A))^2(2b + \alpha s - s)\ (2 - \alpha s - s - 2c_n - 2b)/(8(2k_R - (B-A)\ (c_n - c_r - A))^2)$

$\pi_R^{NT*} - \pi_R^{YT*} = k_T^2(2b + \alpha s - s)\ (2 - \alpha s - s - 2c_n - 2b)/(4(2k_T - (B-A)(c_n - c_r - B))^2)$

$\pi_T^{NT*} - \pi_T^{YT*} = k_T(B-A)^2(2b + \alpha s - s)\ (2 - \alpha s - s - 2c_n - 2b)/(8(2k_T - (B-A)(c_n - c_r - B))^2)$, if $b < (1-\alpha)s/2$, then $\pi_M^{YM*} > \pi_M^{NM*}$, $\pi_M^{YR*} > \pi_M^{NR*}$,

$\pi_M^{YT*} > \pi_M^{NT*}$, $\pi_R^{YM*} > \pi_R^{NM*}$, $\pi_R^{YR*} > \pi_R^{NR*}$, $\pi_R^{YT*} > \pi_R^{NT*}$, and $\pi_T^{YT*} > \pi_T^{NT*}$.

(2) If $k_M < (c_n - c_r - A)k_R/(2(B-A))$, then $\pi_M^{NM*} - \pi_M^{NR*} = (1-s-c_n)^2 (c_n - c_r - A)(k_R(c_n - c_r - A) - 2k_M(B-A))/(4(4k_M - (c_n - c_r - A)^2)\ (2k_R - (B-A)\ (c_n - c_r - A))) > 0$ and $\pi_M^{YM*} - \pi_M^{YR*} = (1 - \alpha s - c_n - 2b)^2 (c_n - c_r - A)\quad (k_R(c_n - c_r - A) - 2k_M(B-A))/(4(4k_M - (c_n - c_r - A)^2)\quad (2k_R - (B-A)(c_n - c_r - A))) > 0$,

If $k_R < (c_n - c_r - A)k_T/(c_n - c_r - B)$, then $\pi_M^{NR*} - \pi_M^{NT*} = (1-s-c_n)^2 (B-A)\ \ (k_T(c_n - c_r - A) - k_R(c_n - c_r - B))/(4(2k_T - (B-A)(c_n - c_r - B))\ (2k_R - (B-A)\ (c_n - c_r - A))) > 0$ and $\pi_M^{YR*} - \pi_M^{YT*} = (1 - \alpha s - c_n - 2b)^2 (B-A)(k_T(c_n - c_r - A) - k_R(c_n - c_r - B))/(4(2k_T - (B-A)(c_n - c_r - B))(2k_R - (B-A)(c_n - c_r - A))) > 0$,

If $k_M < (c_n - c_r - A)^2 k_T/(2(B-A)(c_n - c_r - B))$, then $\pi_M^{NM*} - \pi_M^{NT*} = (1-s-c_n)^2\quad (k_T(c_n - c_r - A)^2 - 2k_M(B-A)\ \ (c_n - c_r - B))/(4(2k_T - (B-A)\ \ (c_n - c_r - B))\ \ (4k_M - (c_n - c_r - A)^2) > 0$ and $\pi_M^{YR*} - \pi_M^{YT*} = (1 - \alpha s - c_n - 2b)^2 (B-A)\qquad (k_T(c_n - c_r - A) - k_R(c_n - c_r - B))/(4(2k_T - (B-A)(c_n - c_r - B))(2k_R - (B-A)(c_n - c_r - A))) > 0$. □

L. Proof of Proposition 12

Proof of Proposition 12. Comparing the CS in the six models, we have

$CS^{YM*} - CS^{NM*} = k_M^2\quad (a - s - c_n + a - \alpha s - c_n - 2b)\ ((1-\alpha)\quad s - 2b)/(2(4k_M - (c_n - c_r - A)^2)^2)$, $CS^{YR*} - CS^{NR*} = k_R^2 (a - s - c_n + a - \alpha s - c_n - 2b)\ \ ((1-\alpha)s - 2b)/(8(2k_R - (B-A)(c_n - c_r - A))^2)$, $CS^{YT*} - CS^{NT*} = k_T^2 (a - s - c_n + a - \alpha s - c_n - 2b)\ \ ((1-\alpha)s - 2b)/(8(2k_T - (B-A)(c_n - c_r - A))^2)$.

If $b < (1-\alpha)s/2$, then $CS^{YM*} > CS^{NM*}$, $CS^{YR*} > CS^{NR*}$, and $CS^{YT*} > CS^{NT*}$. □

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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