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PRICING AND COLLECTION DECISIONS OF A CLOSED-LOOP SUPPLY CHAIN WITH REMANUFACTURING UNDER RECIPROCAL PREFERENCES

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Abstract. This paper examines the effects of reciprocal preferences on the performances of a closed-loop supply chains (CLSC) with remanufacturing. Specifically, we incorporate reciprocal preferences into a two-echelon CLSC in which the manufacturer collects used products and then remanufactures the other parts except for key components as well as producing new products, and must purchase such key components from the supplier. Using a supplier-led Stackelberg game framework, the models are constructed with and without reciprocity, and then the effects of reciprocity on channel efficiency, consumers, environment and society are examined. We show that, (i) if the supplier reciprocates, the collection rate, the CLSC's total profit, the channel efficiency and the consumer surplus enhance. Additionally, if only the manufacturer reciprocates, the CLSC's profit remains constant; (ii) under certain conditions, the reciprocal preferences of both channel members aggravate environmental impact, while benefit social welfare; (iii) Pareto improvement can be achieved if the reciprocity parameters of both channel members are relatively high, and a simple procurement price contract can conditionally coordinate the CLSC. Finally, two extensions are studied by considering consumer heterogeneity and solving a two-period game problem, and the results characterize how reciprocal behaviors drive the performances of channel members.

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1. Introduction

The advance of economy and technology has made product life cycles shorter and shorter, and the huge market demand has stimulated firms to produce more products. However, this has also led to a series of environmental issues, including energy consumption and waste of resources. Such issues, causing climate change and a rise in sea level, have raised widespread concerns from the public and policy makers. In response, many firms have implemented closed-loop supply chain (CLSC) management, such as Caterpillar, Kodak and Xerox [1]. Firms conduct CLSC management not only to respond to the policies and laws regulated by policy makers, but also to pursuit huge economic and environmental benefits. Since several parts of used products are reusable and have great economic value, remanufacturing strategy can help firms reduce costs and mitigate environmental impacts [2–5].

Keywords. Closed-loop supply chain, remanufacturing, reciprocal preferences, consumer surplus, social welfare.

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On CLSC management, many scholars have conducted in-depth research, including pricing policies (*e.g.*, [5–7]), collecting and remanufacturing modes (*e.g.*, [8, 9]). Most of the aforesaid studies, however, assume that the entire used product can be remanufactured. As reported by Fleischmann *et al.* [10] and Du *et al.* [11], it is unreasonable to remanufacture entire used product from either the technical aspect or the economical aspect. Consequently, several key components of used products cannot be remanufactured [12]. In real industries, especially the machine tool remanufacturing industry and the auto parts remanufacturing industry, due to technical level or research and development (R&D) patent, several key components must be purchased from upstream suppliers and cannot be manufactured or remanufactured independently by firms [11]. Analogously, Huawei, one of the world's largest manufacturers of smartphone and IT products, has engaging in remanufacturing activities due to economic and environmental benefits. Annually, Huawei purchases a great many chips from a very limited number of suppliers, such as Qualcomm, to produce final products. In addition to being assembled in new smartphones, such new chips are also assembled in remanufactured smartphones due to the un-remanufacturibility of used chips. Facing the un-remanufacturable key components, firms have to purchase them from their suppliers when producing new and remanufactured products. Hence, we formulate a supplier-manufacturer CLSC model where the key components cannot be remanufactured in this study.

Additionally, most of previous CLSC models assume that the channel players are completely rational, and all of them pursuit personal maximizing profits and, therefore, the results they obtained are based on "homo economicus" [13]. Relevant studies on behavior operations, however, show that this assumption is usually disconnected with actual operational modes, and firms' decisions are often affected by social preferences in a supply chain [14, 15]. Hence, the assumption based on complete rationality does not hold in practice [16]. Economists have also collected a lot of evidence to refute this hypothesis, and found that many firms or individuals have social preferences. Among social preferences, fairness plays a vital role in operations management and has received considerable attention of researchers. Firms who behave fairness preferences focus not only on their own profits, but also on the outcome of profit allocation with other participants [17]. Examining the effects of social preferences on supply chain performances, Loch and Wu [14] have ever proposed a utility function with fairness and altruism for each player by introducing other-regarding parameters. Recently, such parameters have been updated through reciprocity and status updates [18]. Xia *et al.* [13] use such parameters to capture channel players' extent of reciprocal concerns for the participant, and state that reciprocity is regarded as one of the most important social preferences. Substantial evidences have verified that reciprocal behavior is of omnipresence [19–21]. For instance, a firm may be punished by its clients due to mean or less kind behaviors, and *vice versa* [22].

In practice, there are several industrial cases where channel relationship is reinforced because manufacturers reciprocate theirs suppliers with kindness concerns. As we mentioned above, for example, Huawei rewarded and strengthened cooperation with its supplier, Qualcomm, one of the world's largest chip suppliers, in 2018, because Qualcomm finished their projects earlier than schedule in a 90-days period, which saved costs for Huawei. Such behaviors made Huawei feel to be kindly treated in the transaction. In addition, there are also several industrial cases where channel relationship is broken due to firms' mean or unfair behaviors in CLSCs [23]. Evidently, firms' kind or mean behaviors have significant impacts on their counterparts in CLSCs. In this study, we employ reciprocity as a magnitude to measure firms' kind and mean behaviors, and analyze the impacts of reciprocal preferences on the performances of the CLSC. We focus mainly on addressing the following questions in this study:

- What are the optimal strategies of both channel members, including the procurement price of key components, the selling price of final products, and the collection rate of used products?
- How do reciprocal preferences of both channel members affect the optimal strategies, profits as well as channel efficiency?
- Can reciprocal behaviors achieve Pareto improvement for the channel members?
- How do reciprocal preferences of both channel members influence consumers, environment and the society?

Motivated by the above issues and business environment, we develop a CLSC model where a single supplier provides key components which cannot be remanufactured, and a single manufacturer collects used products and then remanufactures the other parts of used products except for the key components, and finally sells final products (new and remanufactured ones) to consumers. We first analyze the reciprocity-neutral scenario and the scenario with bilateral reciprocity. In addition, we also investigate the scenarios where only one channel member has reciprocal behavior. Second, we examine the impact of reciprocity on equilibrium decisions and profits of channel members. Besides, we discuss the impacts of reciprocal preferences on consumers, environment and society. Finally, the base model is extended by examining consumer heterogeneity and exploring a two-period scenario. The novelties of this study are as follows.

- Incorporating reciprocal preferences into a CLSC model comprised of a supplier and a manufacturer.
- Considering the un-remanufacturable feature of key components in used products.
- Studying the optimal pricing and collecting policies under the scenarios with and without reciprocal preferences.
- Examining the impacts of reciprocity on consumer surplus, environment performance and social welfare.

The rest of this paper is organized as follows. We review related literature in the next section. In Section 3, we present assumptions and related notation. Section 4 develops decentralized models with and without reciprocal preferences. We then examine the impacts of reciprocal preferences on equilibrium decisions, profits, channel efficiency, consumers, environment and society in Section 5. Section 6 conducts numerical analysis. Section 7 extends our base model. Section 8 further discusses the impacts of social preferences on equilibrium solutions. Finally, we conclude this paper and provide significant economic and environmental implications for different stakeholders in Section 9.

2. Literature review

This study builds on and contributes to previous literature on two streams, including pricing and remanufacturing strategies in CLSCs and social preferences in operations management as discussed in the following subsections.

2.1. Pricing and remanufacturing strategies in CLSCs

The literature on CLSC is rich and growing rapidly. Govindan *et al.* [24] comprehensively review the literature on reverse logistics and CLSC, and then explore the directions of future research. Atasu *et al.* [25] report that remanufacturing is considered as a profitable strategy. Therefore, many firms have begun to collect their own used products and then remanufacture them, and such a strategy helps firms save a lot of costs [2,3,26]. Thus, many researchers have focused on pricing and collecting strategies in CLSCs (*e.g.*, [6,8,12,27–30]).

In a supply chain network, there are two common vertical relationships at different levels: (i) the structure including manufacturers and retailers, and (ii) the structure including suppliers and manufacturers [31]. Also, many researchers develop CLSC models based on these two streams. In the first stream, Savaskan *et al.* [29] study three collection strategies in a CLSC, including manufacturer-collecting, retailer-collecting, and furthermore, third-party-collecting. In their model, the manufacturer is the Stackelberg leader and the retailer is the follower. They find that the collection rate is largest if the downstream retailer, who is closer to consumers, undertakes collection responsibility. Wu [32] investigates price and service decisions of manufacturers and retailer in a two-echelon CLSC, of which the competition between two manufacturers is considered. Several economic and managerial insights are provided in such an environment. Considering collection quality, Zhou *et al.* [33] study the optimal pricing and quality improvement decisions in a CLSC comprised of a manufacturer and a retailer under different collection modes. In the second stream, Reimann *et al.* [34] consider process innovation for remanufacturing management in a CLSC where the remanufacturing cost can be decreased *via* process innovation. In addition, several studies introduce third-party remanufacturer as the Stackekberg follower in manufacturer–remanufacturer CLSC models (*e.g.*, [35–37]).

The aforementioned studies are based on an ideal assumption that the entire used products can be completely remanufactured. In reality, many manufacturers have to purchase key components from a very limited number of suppliers due to the uneconomic characteristics of entire product remanufacturing [10,11]. Therefore, several scholars introduce suppliers in CLSC models with remanufacturing, which is closer to the second stream. Aras *et al.* [38] consider a hybrid manufacturing and remanufacturing system that buys core components from a supplier and there is only one decision-maker, but they ignore the interaction of the supplier. Following Aras *et al.* [38], Xiong *et al.* [39] examine the interactions of a key component supplier and an integrated manufacturer. Xiong *et al.* [40] further develop two different models in which the manufacturer and the retailer are responsible for remanufacturing, respectively, and then compare the performances of different channel members. Wu and Zhou [12] assume that the key components cannot be remanufactured and then study the optimal pricing policies in a CLSC, in which a third-party remanufacturer is introduced. Liu *et al.* [41] assumes that remanufactured products do not need the key components from suppliers, and then they investigate product-design strategies in a CLSC. According to their study, the condition that environmental benefits are improved by product design is derived.

Overall, nearly all the above studies assume that all the channel members are maximizing self-interests. Additionally, most of the studies on CLSC assume that the key components can be also remanufactured, and ignore the social preferences of CLSC channel members, especially the reciprocal preferences. In this study, we introduce reciprocity as a magnitude to measure kind and mean behaviors to examine the impacts of reciprocal preferences on the CLSC where the key components cannot be remanufactured.

2.2. Social preference in operations management

Our work is also relevant to the literature on social preference in operations management. Social preference of individuals and firms, such as reciprocity, fairness and status, can influence firms' decisions [14,15]. Many researchers have studied the behavior of channel members in supply chain management and most of them focus only on fairness concerns [42]. According to Cui *et al.* [43], fairness plays a vital role in maintaining channel relationships in operations management. Du *et al.* [18] study the newsvendor problem in a supply chain where both the manufacturer and the retailer are fairness-concerned. They employ Nash bargaining solution as the fairness reference point, and the results show that fairness concerns can decrease channel efficiency. Following Du *et al.* [18], Sharma *et al.* [44] adopt Nash bargaining solution as fairness criterion in an option contract setting. Provided that a retailer has fairness concerns, Li *et al.* [45] investigate the optimal price and carbon emission reduction decisions in a supply chain, and reveal that fairness concerns have great effects on equilibrium decisions. Further, Ganguly *et al.* [46] comprehensively study how fairness and overconfidence influence pricing strategy of substitute bundles. In addition, limited studies focus on fairness preferences in CLSCs. For instance, Ma *et al.* [47] analyze the influence of fairness concerns on optimal pricing decisions in CLSC with marketing effort, and find that fairness concerns do significantly affect the decisions and profits under CLSC context. Zheng *et al.* [48] study the coordination mechanisms in a three-echelon CLSC where only the retailer is fairness-concerned, and then examine the impact of fairness concerns on decisions and profit allocation. Recently, several scholars have investigated the role of fairness concerns in CLSC coordination (*e.g.*, [49]). Additionally, Suvadarshini *et al.* [50] investigate the impacts of individual rationality on CLSC design, and show that under the constraints of individual rationality, the manufacturer and retailer do not trade of their costs are lower than certain values. Several researchers explore the role of reciprocal preferences using empirical approaches (*e.g.*, [19,20]), while few studies focus on reciprocal preferences in operations management. Du *et al.* [42] hold that the existing models of fairness based only on consequence cannot explain why the same consequence of an action is perceived and reciprocated differently. In view of this, they develop a model taking such consequence and intention into account to investigate how reciprocity affects the optimal decisions of supply chain players. Xia *et al.* [13] study the effects reciprocal preferences on the decisions of a manufacturer and a retailer in a low-carbon supply chain, in which both of the channel members have reciprocal behaviors. Results show that the reciprocal preferences have significant impacts on the decisions, profits and utilities of channel members. Their work, however, ignore the effects of reciprocal preferences on consumers, environment, and society.

Table 1. Relevant literature *vs.* this paper.

Reference	Supply chain structure	Remanufacturing type	Social preferences
Savaskan *et al.* [29]	M–R–3P	Entire remanufacturing	None
Kaya [35]	M–3P	Entire remanufacturing	None
Reimann *et al.* [34]	M–R	Entire remanufacturing	None
Liu *et al.* [41]	S–M	Entire remanufacturing	None
Xiong *et al.* [39]	S–M	Partial remanufacturing	None
Ma *et al.* [47]	M–R–3P	Entire remanufacturing	Fairness
Sharma *et al.* [44]	S–R	None	Fairness
Sarkar and Bhala [49]	M–R	Entire remanufacturing	Fairness
Suvadarshini *et al.* [50]	M–R–3P	Entire remanufacturing	Individual rationality
Ganguly *et al.* [46]	M–R	None	Fairness and overconfidence
Du *et al.* [42]	S–R	None	Reciprocity
Xia *et al.* [13]	M–R	None	Reciprocity
This paper	S–M	Partial remanufacturing	Reciprocity

Notes. S, M, R, and 3P denote supplier, manufacturer, retailer, and third-party remanufacturer, respectively.

Although the above studies have focused on the social preferences in operations management, none of them incorporates reciprocal preferences into CLSC models with product remanufacturing. In this study, we incorporate reciprocity into a CLSC in which the supplier provides the manufacturer with key components that cannot be remanufactured, and the manufacturer focuses on collecting used products and then remanufacturing as well as producing new products.

2.3. Summary of research gaps

Table 1 summarizes the differences between our work and previous studies. As shown in Table 1, we present the research gaps in the following two aspects. First, most studies on CLSCs assume that one used product can be entirely remanufactured and ignore the un-remanufacturable feature of key components. Second, most studies on social preferences study fairness concerns in supply chains, and few of them discuss the role of reciprocity, especially in CLSCs. To fill these gaps, we incorporate reciprocal preferences into a CLSC model consisting of one supplier and one manufacturer, in which the key components produced by the supplier cannot be remanufactured. Thus the manufacturer has to purchase the key components from the supplier when producing the final products (new and remanufactured ones). Subsequently, the impacts of reciprocal preferences on CLSC performances are explored to provide managerial implications for different stakeholders.

3. Assumptions and notation

We consider a two-echelon CLSC incorporating a supplier and a manufacturer. Due to technical level or R&D patent, one key component of the final product cannot be produced by the manufacturer independently, let alone remanufacturing. The other parts of the final products, however, can be independently manufactured and remanufactured. Consequently, the main feature of proposed model is that such key components must be purchased by the manufacturer from a certain supplier before producing final products (new and remanufactured ones). In other words, the manufacturer relies extremely on the supplier when producing. Accordingly, the supplier, who has sufficient bargaining power over the manufacturer, acts as a leader in the game with the manufacturer who plays the role of a follower [39, 41]. As shown in Figure 1, the supplier provides the manufacturer with key components, and the manufacturer collects used products and then produces the final products among which the key components of new and remanufactured products are brand-new, and finally sells to end consumers. Note that all information, including the costs and the reciprocity parameters of both channel members, is common knowledge [12, 13].

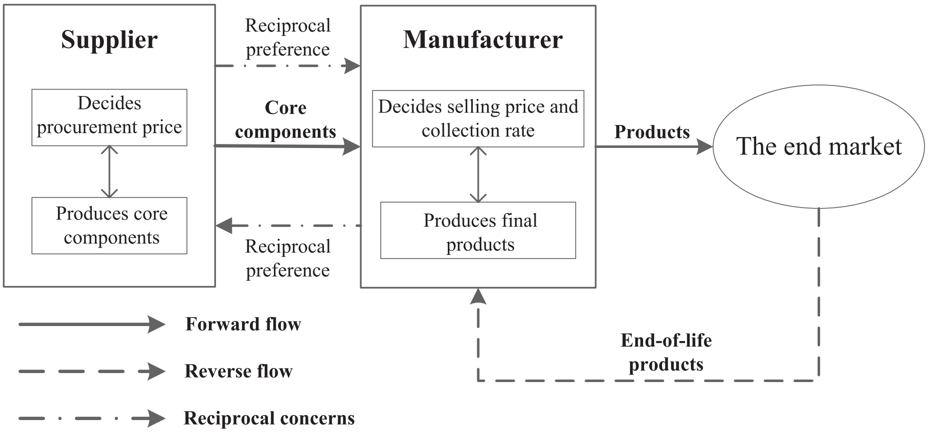

FIGURE 1. General structure of closed-loop supply chain.

The notation in this study is listed in Table 2.

TABLE 2. Notation.

Symbol	Description
Decision variables	
w	Unit procurement price of key components
p	Unit selling price of final products
τ	Collection rate of used products
Parameters	
k	Scale parameter of collecting used products
b	Price elasticity coefficient
c_0	Unit cost of producing a key component
c_n	Unit cost of producing a new product
c_r	Unit cost of producing a remanufactured product (including the costs of collecting and remanufacturing)
Δ	Unit cost advantage of remanufactured product, *i.e.*, $\Delta = c_n - c_r$
γ	Environmental benefit of each remanufactured product during life cycle
θ_i	Reciprocal preference parameter of i
Defined functions	
q	$q = a - p$, demand function of final products, where a is the potential demand size
π_i, u_i	Profit and utility of i

Notes. $i = s, m, t$ indicates supplier, manufacturer, and CLSC, respectively.

In addition, several key assumptions are made to formulate our model as follows.

Assumption 1. *The unit cost of remanufacturing a product is lower than that of producing a new one, i.e.,* $c_r < c_n$*. Herein, we normalize the unit cost of remanufactured products to* c_r*, which includes the costs of collection, inspection, disassembly, and remanufacturing [35]. Remanufacturing strategy is always profitable, and that is the reason why many firms enter the remanufacturing market. As studied by Giuntini and Gaudette [3], the remanufacturing strategy can save 40%–65% of cost compared with traditional manufacturing. Therefore, following the research of Savaskan et al. [29], Souza [51], and Reimann et al. [34], we adopt this assumption.*

Assumption 2. *Consumers have the same willingness to pay for new and remanufactured products, and therefore the market demand function is assumed to be* $q = a - bp$*, with* a *being the potential demand size and* b *being the price elasticity coefficient. Without loss of generality, we assume* $b = 1$.

The market demand is depending upon selling price of final products [52]. Consumer homogeneity on new and remanufactured products has been widely considered in previous studies (*e.g.*, [8, 29, 36, 49]). Such an assumption is reasonable in practice. For instance, many firms, manufacturing mobile phones, usually collect used products and extract available materials in the process of producing new mobile phones, rather than producing second-hand ones [53]. In our study, the key components are always brand-new in new and remanufactured products. Therefore, this assumption about consumer homogeneity on new and remanufactured products is more applicable in the proposed model of this paper. Such an assumption is relaxed in Section 7.1 to study consumer heterogeneity on new and remanufactured products, *i.e.*, consumers have different willingness to pay for the two types of products, and then explore the impacts of reciprocal behaviors on CLSC performances.

Based on the assumption of homogenous features, the linear demand function has been widely used in the literature (*e.g.*, [8,29,49,54]). Note that the price elasticity coefficient b means the sensitivity of demand to price, and higher b means that the price has higher influence on the demand. In previous studies, the price elasticity coefficient is usually assumed to be 1 for simplification (*e.g.*, [14,37]). Note also that all the conclusions would also hold if such an assumption is relaxed. Combining with Assumption 1, the unit average cost of producing a final product is $c_n - \tau\Delta$. In Section 7.1, we separately consider the demand functions for new and remanufactured products by examining consumer heterogeneity on the two types of products.

Assumption 3. *The fixed investment cost of collecting used products is convex in the collection rate* τ*. Without loss of generality, we assume the fixed investment cost is* $\frac{1}{2}k\tau^2$*, where* k *is the scale parameter of collecting used products.*

The investment cost structure has been widely used in literature (*e.g.*, [29,36,55]). The convex function means that the cost increases in the collection rate nonlinearly up to a certain level. In fact, there are two main costs in the collecting process, namely, variable cost and fixed cost. The variable cost is the processing cost of unit used product, which is normalized to c_r as shown in Assumption 1. The fixed cost, also called fixed investment cost or collection effort cost, includes infrastructure construction cost for collecting used products, and it is a quadratic function on the collection rate τ.

Assumption 4. *The game between the supplier and the manufacturer is considered in a steady-state single period. The game problem of single period is usually regarded as a steady-state period in an infinite horizon, and is widely used in Stackelberg game models (e.g., [2, 13, 29, 34, 43, 49]). On the basis of this assumption, we can focus on studying the impacts of reciprocal preferences on the CLSC's performances [23]. Such an assumption is relaxed in Section 7.2 to investigate the impacts of reciprocal behaviors on the optimal performances of a two-period game model.*

Assumption 5. *The quantity of final products is utilized as a proxy of the environmental performance of the CLSC.*

In practice, remanufacturing strategy not only brings benefits to the firms, but also has great environmental performance. This is also the reason why policymakers motivate firms to undertake remanufacturing. It is acknowledged that unit remanufactured products have less environmental impact than a new one. Thus, we employ $(1-\tau)q + \gamma\tau q$ as the total environmental impact, where $\gamma\,(0 < \gamma < 1)$ indicates the environmental benefit of each remanufactured product during its life cycle [12, 41, 56, 57].

Based on the above problem description and assumptions, the profits of the supplier and the manufacturer are given as follows, respectively:

$$\pi_s = (w - c_0)(a - p) \tag{1}$$

$$\pi_m = (p - w - c_n + \tau\Delta)(a - p) - \frac{1}{2}k\tau^2. \tag{2}$$

Further, the total profit of the CLSC system is given by

$$\pi_t = (p - c_0 - c_n + \tau\Delta)(a - p) - \frac{1}{2}k\tau^2. \tag{3}$$

4. Decentralized models

In the decentralized models, both the supplier and the manufacturer maximize their individual utilities. The sequence of events is described below: (i) the supplier first decides the procurement price of unit key component; (ii) the manufacturer then determines the selling price of final products and the collection rate of used products.

4.1. Game of reciprocity-neutral channel (Scenario N)

As a benchmark, we investigate the scenario that both the supplier and the manufacturer are reciprocity-neutral. The channel members maximize their own profits which are given as follows:

$$\max_{w} \pi_s = (w - c_0)(a - p) \tag{4}$$

$$\max_{p,\tau} \pi_m = (p - w - c_n + \tau\Delta)(a - p) - \frac{1}{2}k\tau^2. \tag{5}$$

The equilibrium solutions can be derived in Lemma 1. Note that the superscripts C, N, S, M, SM indicate the optimal outcomes of the centralized scenario, the scenario of reciprocity-neutral channel, the scenario that only the supplier reciprocates, the scenario that only the manufacturer reciprocates, and the scenario of bilateral reciprocal preferences, respectively.

Lemma 1. *Under the decentralized model of reciprocity-neutral channel, the equilibrium solutions of procurement price, selling price, and collection rate are*

$$w^N = \frac{a - c_n + c_0}{2}, \quad p^N = a - \frac{k(a - c_n - c_0)}{2(2k - \Delta^2)} \quad \text{and} \quad \tau^N = \frac{\Delta(a - c_n - c_0)}{2(2k - \Delta^2)},$$

respectively.

The proofs of Lemmas 1–3 can be seen in Appendix A.

Lemma 1 shows the optimal decisions when both the supplier and manufacturer are reciprocity-neutral. As the Stackelberg leader, the supplier only takes into account the production cost of new product and pays no attention to the scale parameter of collecting used products and the remanufacturing cost. The manufacturer, however, has to consider these factors comprehensively as well as the supplier's response.

Substituting the equilibrium solutions of Lemma 1 into equations (1)–(3), the profits of the supplier, the manufacturer and the CLSC system can be derived as follows, respectively

$$\pi_s^N = \frac{k(a - c_n - c_0)^2}{4(2k - \Delta^2)} \tag{6}$$

$$\pi_m^N = \frac{k(a - c_n - c_0)^2}{8(2k - \Delta^2)} \tag{7}$$

$$\pi_t^N = \frac{3k(a - c_n - c_0)^2}{8(2k - \Delta^2)}. \tag{8}$$

4.2. Game of decentralized model with bilateral reciprocal preferences (Scenario SM)

In this business operating environment, the complete self-interest mode is no longer adopted by firms, and the strategy of win-win cooperation is gradually popular among most firms. Therefore, economists are trying to use utility functions to explain the cooperation behavior of people or firms. Unlike fairness preferences, which are defined over outcomes, reciprocal preferences focus not only on the outcomes, but on people's intentions [58].

With reciprocity, channel members also take their cooperator's profit into account as well as their own profits to maximize their utilities. According to Loch and Wu [14], the supplier's utility function can be written as

$u_s = \pi_s + \theta_s \pi_m$, in which the reciprocity parameter, θ_s, indicates the supplier's extent of reciprocity for the manufacturer and $-1 \leq \theta_s \leq 1$. $\theta_s > 0$ means that the supplier is kind to the manufacturer. On the contrary, $\theta_s < 0$ means that the supplier is mean to the manufacturer. Analogously, the manufacturer's utility function is $u_m = \pi_m + \theta_m \pi_s$, where θ_m indicates the manufacturer's extent of reciprocity for the supplier.

Substituting equations (1) and (2) into the utility functions u_s and u_m, the objective functions of the supplier and the manufacturer can be rewritten as follows

$$\max_{w} u_s = (w - c_0)(a - p) + \theta_s \left[(p - w - c_n + \tau\Delta)(a - p) - \frac{1}{2}k\tau^2 \right] \tag{9}$$

$$\max_{p,\tau} u_m = (p - w - c_n + \tau\Delta)(a - p) - \frac{1}{2}k\tau^2 + \theta_m (w - c_0)(a - p). \tag{10}$$

The equilibrium outcomes are derived in Lemma 2.

Lemma 2. *Under the decentralized model of bilateral reciprocal preferences, the equilibrium solutions of procurement price, selling price, and collection rate are as follows:*

$$\begin{aligned} w^{SM} &= \frac{(1-\theta_s)(a-c_n) + (1 - 2\theta + \theta_s^2\theta_m)c_0}{(1-\theta_m)(2-\theta_s-\theta_m\theta_s)} \\ p^{SM} &= a - \frac{k(1-\theta_m\theta_s)(a-c_n-c_0)}{(2-\theta_s-\theta_m\theta_s)(2k-\Delta^2)} \\ \tau^{SM} &= \frac{(1-\theta_m\theta_s)(a-c_n-c_0)\Delta}{(2-\theta_s-\theta_m\theta_s)(2k-\Delta^2)}. \end{aligned}$$

The proofs of Lemmas 1–3 can be seen in Appendix A.

Lemma 2 shows the equilibrium decisions of the supplier and the manufacturer. With the equilibrium solutions, the equilibrium profits of the supplier, the manufacturer and the CLSC system are as follows:

$$\pi_s^{SM} = \frac{k(1-\theta_s)(1-\theta_m\theta_s)(a-c_n-c_0)^2}{(1-\theta_m)\left(2-\theta_s-\theta_m\theta_s\right)^2\left(2k-\Delta^2\right)} \tag{11}$$

$$\pi_m^{SM} = \frac{k(1-\theta_m\theta_s)\left[(1+\theta_s)\left(1+\theta_m\theta_s\right)-4\theta_m\right](a-c_n-c_0)^2}{2(1-\theta_m)\left(2-\theta_s-\theta_m\theta_s\right)^2\left(2k-\Delta^2\right)} \tag{12}$$

$$\pi_t^{SM} = \frac{k(1-\theta_m\theta_s)[3-\theta_s(2+\theta_m)](a-c_n-c_0)^2}{2(2-\theta_s-\theta_m\theta_s)^2(2k-\Delta^2)}. \tag{13}$$

Although the manufacturer reciprocates and maximizes the actual utility as its objective, it must be satisfied that its profit is positive, namely, $\pi_m^{SM} > 0$. Thus, the reciprocity parameters must satisfy $(1+\theta_m)(1+\theta_m\theta_s) - 4\theta_m > 0$. Since $-1 \leq \theta_s \leq 1$, we thus obtain the reasonable region about reciprocity parameters, *i.e.*,

$$\Omega = \left\{ (\theta_s, \theta_m) \,\middle|\, -1 \leq \theta_s \leq 1, -1 \leq \theta_m < \sqrt{5} - 2 \right\}.$$

Next, we analyze the scenarios that only the supplier reciprocates (Scenario S) and only the manufacturer reciprocates (Scenario M). Both the two scenarios are special cases of bilateral reciprocal preferences scenario. As long as the reciprocity parameters are slightly constrained, the equilibrium solutions of unilateral reciprocal preference can be derived, as shown in Table 3.

In what follows, we investigate the effects of reciprocal behaviors on the decisions and profits of channel members.

5. RESULTS ANALYSES

In this section, we firstly examine the effects of reciprocity on the decisions and profits of CLSC players, and then compare the equilibrium solutions of different scenarios. Further, we discuss the impact of reciprocity on channel efficiency, consumers, environment and society.

Table 3. Equilibrium outcomes of unilateral reciprocal preference.

Variables	Scenario S $(\theta_m = 0)$	Scenario M $(\theta_s = 0)$
w	$\dfrac{(1-\theta_s)(a-c_n)+c_0}{2-\theta_s}$	$\dfrac{a-c_n+(1-2\theta_m)c_0}{2(1-\theta_m)}$
p	$a-\dfrac{k(a-c_n-c_0)}{(2-\theta_s)(2k-\Delta^2)}$	$a-\dfrac{k(a-c_n-c_0)}{2(2k-\Delta^2)}$
τ	$\dfrac{(a-c_n-c_0)\Delta}{(2-\theta_s)(2k-\Delta^2)}$	$\dfrac{(a-c_n-c_0)\Delta}{2(2k-\Delta^2)}$
π_s	$\dfrac{k(1-\theta_s)(a-c_n-c_0)^2}{(2-\theta_s)^2(2k-\Delta^2)}$	$\dfrac{k(a-c_n-c_0)^2}{4(1-\theta_m)(2k-\Delta^2)}$
π_m	$\dfrac{k(a-c_n-c_0)^2}{2(2-\theta_s)^2(2k-\Delta^2)}$	$\dfrac{k(1-3\theta_m)(a-c_n-c_0)^2}{8(1-\theta_m)(2k-\Delta^2)}$
π_t	$\dfrac{k(3-2\theta_s)(a-c_n-c_0)^2}{2(2-\theta_s)^2(2k-\Delta^2)}$	$\dfrac{3k(a-c_n-c_0)^2}{8(2k-\Delta^2)}$

5.1. Impacts on equilibrium solutions

Analyzing the effects of reciprocity on the equilibrium decisions of chain members, we derive the following results. Note that all the proofs of propositions and corollaries in this study are presented in Appendix B.

Proposition 1. *In Scenario SM, (i)* $\frac{\partial w^{SM}}{\partial \theta_s} < 0$, $\frac{\partial p^{SM}}{\partial \theta_s} < 0$ *and* $\frac{\partial \tau^{SM}}{\partial \theta_s} > 0$, *(ii) if* $\theta_s < 0$, *then* $\frac{\partial \pi_s^{SM}}{\partial \theta_s} > 0$, *or else* $\frac{\partial \pi_s^{SM}}{\partial \theta_s} < 0$. *While* $\frac{\partial \pi_m^{SM}}{\partial \theta_s} > 0$ *and* $\frac{\partial \pi_t^{SM}}{\partial \theta_s} > 0$ *always hold.*

Proposition 1 indicates that, for a given reciprocity parameter of the manufacturer, as the supplier becomes kinder or less mean to the manufacturer, both the procurement price of key components and the selling price of final products decrease, but the collection rate of used products increases. This is because the supplier will lower procurement price so that the manufacturer can gain more profit if the supplier is increasingly concerned about the manufacturer's profit. In return, the manufacturer lowers the selling price of products to stimulate market demand, and also make more efforts to collect used products, thereby increasing the procurement quantity of core components. From the perspective of used products, the supplier's reciprocal behavior can effectively improve collection rate.

In addition, the manufacturer can always benefit if the supplier becomes kinder or less mean. The supplier's reciprocity, however, cannot always improve its own benefits. As the reciprocity parameter of the supplier θ_s increases, if the supplier is mean to the manufacturer, the supplier's profit increases. Otherwise, its profit decreases. Thereby, the supplier's profit is concave in θ_s. The supplier's mean behavior affects not only the manufacturer's profit, but also its own profit. The kind behavior of the supplier, however, leads to a profit loss to itself. Although such a behavior hurts the supplier, it can improve the total profit of the CLSC.

Proposition 2. *In Scenario SM, (i)* $\frac{\partial w^{SM}}{\partial \theta_m} > 0$, $\frac{\partial p^{SM}}{\partial \theta_m} < 0$ *and* $\frac{\partial \tau^{SM}}{\partial \theta_m} > 0$, *or else* $\frac{\partial p^{SM}}{\partial \theta_m} > 0$ *and* $\frac{\partial \tau^{SM}}{\partial \theta_m} < 0$, *(ii)* $\frac{\partial \pi_s^{SM}}{\partial \theta_m} > 0$*; If* $\theta_s < 0$, *then* $\frac{\partial \pi_m^{SM}}{\partial \theta_m} < 0$ *and* $\frac{\partial \pi_t^{SM}}{\partial \theta_m} < 0$.

Proposition 2 demonstrates that, for a given reciprocity parameter of the supplier, the procurement price of key components increases if the manufacturer becomes kinder or less mean to the supplier. This is because the manufacturer gets more eager to accept a higher procurement price. Additionally, the manufacturer's decisions are also affected by the supplier's reciprocity. This is a counter-intuitive result, that is, when the supplier is mean (kind) towards the manufacturer, the selling price decreases (increases), but the collection rate increases (decreases). Recall Proposition 1, if the supplier is mean, namely, $\theta_s < 0$, the selling price is relatively high. When the manufacturer becomes kinder or less mean, it has sufficient room to adjust pricing strategy and, therefore, it will lower selling price and enhance collection rate to stimulate demand. However, if $\theta_s > 0$, the selling price is relatively low. Moreover, the procurement price increases in θ_m. For the manufacturer, the selling price has to be enhanced to pursue benefits and reduce collection rate to lower costs, thereby maintaining actual utility.

Besides, the supplier always benefits if the manufacturer is kinder or less mean, but the manufacturer suffers a profit loss due to its kind behavior. The reason relies on that the supplier takes the initiative in decision-making, and the manufacturer is willing to accept a higher procurement price, which brings more benefits to the supplier. The manufacturer, however, suffers a profit loss although it gets higher actual utility. From the CLSC' perspective, if the supplier is mean (kind) to the manufacturer, the profit suffered by the manufacturer is lower than (larger) the additional profit gained by the supplier. Therefore, the manufacturer should balance the trade-off between the profit loss and reciprocal behavior. Comparing the profits of CLSC players under the scenario of bilateral reciprocity, we obtain the following results.

Corollary 1. *(i) if* $\theta_m > \theta_s$, *then* $\pi_s^{SM} > \pi_m^{SM}$ *always holds, (ii) if* $-1 \leq \theta_s \leq 1/2$, *then* $\pi_s^S > \pi_s^{SM}$*; if* $1/2 \leq \theta_s \leq 1$, *then* $\pi_s^S < \pi_m^S$, *(iii) if* $-1 \leq \theta_m \leq -1/3$, *then* $\pi_s^M < \pi_m^M$*; if* $-1/3 \leq \theta_m < \sqrt{5}-2$, *then* $\pi_s^M > \pi_m^M$.

Corollary 1(i) indicates that the supplier always gains more profit than the manufacturer in the scenario of bilateral reciprocity if the manufacturer is kinder (or less mean) than the supplier. Otherwise, the supplier's profit may be less than that of the manufacturer even though the supplier dominates the CLSC. Corollaries 1(ii) and 1(iii) show that, the trade-off between the supplier and manufacturer's profits can be disposed by reciprocity parameters if only one channel member reciprocates. As the Stackelberg leader, the supplier earns more than the manufacturer if the supplier performs a relatively low reciprocity in Scenario S, or if the manufacturer behaves a relatively high reciprocity in Scenario M. On the contrary, the manufacturer gets more profit than the supplier.

We then analyze the effects of reciprocity on the scenarios that only the supplier or manufacturer reciprocates.

Proposition 3. *In Scenario* S, *(i)* $\frac{\partial w^S}{\partial \theta_s} < 0$, $\frac{\partial p^S}{\partial \theta_s} < 0$ *and* $\frac{\partial \tau^S}{\partial \theta_s} > 0$, *(ii)* $\frac{\partial \pi_s^S}{\partial \theta_s} < 0$, $\frac{\partial \pi_m^S}{\partial \theta_s} > 0$ *and* $\frac{\partial \pi_t^S}{\partial \theta_s} > 0$.

Proposition 3 suggests that if only the supplier reciprocates and as it becomes kinder or less mean to the manufacturer, the procurement price and the selling price decrease, but the collection rate increases, which are consistent with Proposition 1. Furthermore, the supplier will suffer a profit loss, while the manufacturer and the CLSC system can gain more profits if the supplier is relatively kind.

Proposition 4. *In Scenario* M, *(i)* $\frac{\partial w^M}{\partial \theta_m} > 0$, $\frac{\partial p^M}{\partial \theta_m} = 0$ *and* $\frac{\partial \tau^M}{\partial \theta_m} = 0$, *(ii)* $\frac{\partial \pi_s^M}{\partial \theta_m} > 0$, $\frac{\partial \pi_m^M}{\partial \theta_m} < 0$ *and* $\frac{\partial \pi_t^M}{\partial \theta_m} = 0$.

Proposition 4 manifests that if only the manufacturer reciprocates and as it becomes kinder or less mean to the supplier, the procurement price increases, but the selling price and collection rate remain unchanged, which are different from Proposition 1. Under this setting, the manufacturer will adopt the same decision strategy with that in the absence of reciprocity. In addition, the reciprocity in this case only changes the profit distribution of the CLSC, but has no effects on the total profit. Specifically, the higher procurement price allows the supplier to earn more profits, but the manufacturer will suffer a profit loss.

By comparing the solutions of Scenario S and Scenario M with those of Scenario N, we have the following conclusions.

Corollary 2. *If* $\theta_s < 0$, *then* $w^S > w^N$, $p^S > p^N$, $\tau^S < \tau^N$, $\pi_s^S > \pi_s^N$, $\pi_m^S < \pi_m^N$ *and* $\pi_t^S < \pi_t^N$. *If* $\theta_s > 0$, $w^S < w^N$, $p^S < p^N$, $\tau^S > \tau^N$, $\pi_s^S < \pi_s^N$, $\pi_m^S > \pi_m^N$ *and* $\pi_t^S > \pi_t^N$.

Corollary 2 shows that if only the supplier reciprocates and is mean (kind) to the manufacturer, the procurement price and the selling price are higher (lower) than those without reciprocity, but the collection rate is lower (higher) than the scenario in the absence of reciprocity. In addition, compared with the scenario without reciprocity, the supplier earns more (less) profits, but the manufacturer and CLSC system obtain less (more) profits. From the above analysis, we know that the collection rate of used products and the total profits of CLSC can be improved if the supplier exhibits kindness to the manufacturer.

Corollary 3. *$p^M = p^N$, $\tau^M = \tau^N$ and $\pi_t^M = \pi_t^N$ always hold. If $\theta_m < 0$, then $w^M < w^N$, $\pi_s^M < \pi_s^N$ and $\pi_m^M > \pi_m^N$. If $\theta_m > 0$, $w^M > w^N$, $\pi_s^M > \pi_s^N$ and $\pi_m^M < \pi_m^N$.*

Corollary 3 declares that if only the manufacturer reciprocates, the selling price is not affected by the reciprocal preference. However, if the manufacturer is mean (kind) to the supplier, the procurement price is lower (higher) than that without reciprocity. Moreover, compared with the scenario without reciprocity, the supplier earns more (less) and the manufacturer earns less (more) profits, but the total profit of CLSC does not change. Under such a scenario, the reciprocal behavior of the manufacturer only plays the role of profit distribution mechanism in the CLSC.

In particular, when the supplier performs the greatest reciprocal preference, we have the following conclusion.

Corollary 4. *If $\theta_s = 1$, θ_m has no effects on the equilibrium solutions of bilateral reciprocity.*

Corollary 4 indicates that if $\theta_s = 1$, which means that the supplier treats the manufacturer's profit as its own benefits, the manufacturer's reciprocal behavior does not affect the decisions of channel members. From $u_s = \pi_s + \theta_s \pi_m$, we know that the supplier maximizes its utility from the perspective of the CLSC system. As a result, the reciprocity parameter of the manufacturer does not affect the equilibrium decisions of both channel members. Note also that $w^{SM} = c_0$ if $\theta_s = 1$, implying that the supplier determines the optimal procurement price which remains the same as its cost. Such a special case indicates that the supplier earns nothing in the channel, and all the benefits are attained by the manufacturer.

5.2. Impacts on the channel efficiency

Before analyzing the channel efficiency, we firstly consider the centralized scenario. The reciprocal behavior is not considered in a centralized model since there is only one decision maker. The optimization objective is given by

$$\max_{p,\tau} \pi_t = (p - c_0 - c_n + \tau\Delta)(a - p) - \frac{1}{2}k\tau^2. \tag{14}$$

Solving the optimization problem, the optimal outcomes can be derived in Lemma 3.

Lemma 3. *Under the centralized scenario, the optimal selling price and collection rate are $p^C = a - \frac{k(a-c_n-c_0)}{2k-\Delta^2}$ and $\tau^C = \frac{\Delta(a-c_n-c_0)}{2k-\Delta^2}$, respectively.*

With Lemma 3, we can obtain the total profit of the CLSC system as follows.

$$\pi_t^C = \frac{k(a-c_n-c_0)^2}{2(2k-\Delta^2)}. \tag{15}$$

According to the research of Xia *et al.* [13], we define $\eta^j = \frac{\pi_t^j}{\pi_t^C}$ as the channel efficiency, in which π_t^j denotes the total profit of CLSC under Scenario j. To investigate the impact of bilateral reciprocity on channel efficiency, we focus only on Scenario SM. Thus, the channel efficiency under Scenario SM can be derived as follows:

$$\eta^{SM} = \frac{(1-\theta_m\theta_s)\left[3-\theta_s(2+\theta_m)\right]}{(2-\theta_s-\theta_m\theta_s)^2}.$$

Investigating the effects of reciprocal preferences on channel efficiency, we obtain the following result.

Proposition 5. *In Scenario SM,* $\frac{\partial \eta^{SM}}{\partial \theta_s} > 0$ *always holds. If* $\theta_s < 0$*, then* $\frac{\partial \eta^{SM}}{\partial \theta_m} > 0$*, or else,* $\frac{\partial \eta^{SM}}{\partial \theta_m} < 0$*.*

Proposition 5 reveals that the channel efficiency enhances if the supplier is kinder or less mean to the manufacturer, which also indicates that the supplier's reciprocity can increase the total profits and improve the efficiency of decentralized channel. This is because the supplier's reciprocity can motivate the manufacturer to lower selling price and raise collection rate, and further increase the channel efficiency. The effect of manufacturer's reciprocity on the channel efficiency, however, depends also on the supplier's behavior. Specifically, when the supplier is mean (kind) to the manufacturer, the channel efficiency increases (decreases) as the manufacturer becomes kinder or less mean. This is because the profit loss suffered by the manufacturer is lower (higher) than the additional profit earned by the supplier, which is consistent with Propositions 1 and 2. In addition, compared with the scenario of without reciprocity, Proposition 5 indicates that the reciprocity behaviors of channel members can improve channel efficiency in a CLSC under certain conditions. Particularly, if the supplier determines the optimal procurement price from the whole CLSC perspective, *i.e.*, $\theta_s = 1$, the channel efficiency reaches the centralized value irrespective of the manufacturer's reciprocal behavior. The reasons are twofold: first, the analysis of Corollary 4 tells that the procurement price is equivalent to the production cost; second, the equilibrium selling price and collection rate of Scenario SM reduce to those in Lemma 3, indicating that the equilibrium decisions are exactly the same as the centralized scenario. Although the supplier earns nothing, the manufacturer earns excessive profit, thereby leading to a higher profit to the CLSC compared with $\theta_s < 1$.

The preceding analysis leads to the following result.

Corollary 5. *The two-echelon CLSC with bilateral reciprocal preferences can be conditionally coordinated by a simple procurement price contract.*

Corollary 5 reveals the role of reciprocal behaviors in coordinating the CLSC. Our result echoes certain parts of Cui *et al.* [43], of which they studied the fairness and coordination in a general supply chain. Our work, however, extends their study to a CLSC environment, and measures the fairness with reciprocity. In addition, recalling Proposition 1, coordinating the CLSC perfectly would lead to a heavy profit loss to the supplier, who earns nothing from the transaction with the manufacturer. Thus, we have the following conclusion.

Corollary 6. *Pareto improvement cannot be achieved when the channel efficiency reaches the maximum.*

Our prior analysis shows that the CLSC can be coordinated by a simple procurement price contract if the supplier sacrifices all of its profits to keep a high degree of reciprocity. Consequently, it is of great significance for the manufacturer to share additional benefits with the supplier to further motivate the supplier to keep kind behaviors. Otherwise, the supplier may become mean to the manufacturer, thereby leading to profit losses to the manufacturer and the CLSC. Even worse, the stable business partnership between them will be broken up.

5.3. Impacts on the consumers

Herein, we show the effects of reciprocal behaviors on consumers. Let CS^j denote the consumer surplus of Scenario j. Following Mankiw [59] and Zhou *et al.* [60], the consumer surplus can be expressed as follows:

$$\mathrm{CS}^j = \int_0^{q^j} (a - x)\,\mathrm{d}x - q^j\left(a - q^j\right) \tag{16}$$

where $\int_0^{q^j} (a - x)\,\mathrm{d}x$ indicates the total consumer utility and $q^j(a - q^j)$ is the actual payment of consumers.

Substituting the equilibrium solutions of Lemma 2 into equation (16), the consumer surplus under bilateral reciprocity is derived as follows:

$$\mathrm{CS}^{SM} = \frac{1}{2}\left[\frac{k(1-\theta_m\theta_s)(a-c_n-c_0)}{(2-\theta_s-\theta_m\theta_s)(2k-\Delta^2)}\right]^2.$$

The following result can be then obtained.

Proposition 6. *(i) In Scenario SM,* $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_s} > 0$ *always holds. If* $\theta_s < 0$*, then* $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_m} > 0$*, or else,* $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_m} < 0$*. (ii) In Scenario S,* $\frac{\partial \mathrm{CS}^{S}}{\partial \theta_s} > 0$ *holds. (iii) In Scenario M,* $\frac{\partial \mathrm{CS}^{M}}{\partial \theta_m} = 0$ *holds.*

Proposition 6(i) clears that, under Scenario SM, the consumer surplus increases in the reciprocity parameter of the supplier θ_s. This reason is that the selling price decreases in θ_s, which then stimulates market demand. The manufacturer's reciprocity, however, cannot always increase consumer surplus. Recall the findings in Proposition 2 that if the supplier is mean to the manufacturer ($\theta_s < 0$), the selling price decreases if θ_m increases. Hence, the market demand increases and then the consumer surplus raises. Nevertheless, if $\theta_s > 0$, the selling price increases. Thus, the demand decreases and then the consumer surplus declines.

Specially, if only the supplier reciprocates, Propositions 6(ii) and 6(iii) indicates that the consumers are better-off when the supplier becomes kinder or less mean. The consumer surplus, however, is indifferent to θ_m if only the manufacturer reciprocates. Since the quantity of products is independent on θ_m, the consumer surplus thus remains constant.

5.4. Impacts on the environment

In this section, we analyze the influences of reciprocal preferences on environmental benefits. The firms who conduct remanufacturing focus not only on the low-cost characteristic of remanufactured products, but also on the environmentally-friendly features. Following environmental economics and operations literatures (*e.g.*, [12, 40, 56, 57]), let the environmental impact of each remanufactured product during its life cycle be a portion γ $(0 < \gamma < 1)$ of that of a new one. Combining with Assumption 4, we utilize the weighted production quantity of both new products and remanufactured ones as a proxy for the total environmental impact of the CLSC under Scenario j, which is given by

$$E^j = (1 - \tau^j)q^j + \gamma\tau^j q^j$$

where larger quantity of final products means heavier environmental impact.

Proposition 7. *When* $\gamma \in (1/2, 1)$*, (i)* $\frac{\partial E^{SM}}{\partial \theta_s} > 0$ *always holds, (ii) if* $\theta_s < 0$*, then* $\frac{\partial E^{SM}}{\partial \theta_m} > 0$*, or else,* $\frac{\partial E^{SM}}{\partial \theta_m} < 0$*.*

Proposition 7 states that the environment is worse-off as the degree of reciprocity of the supplier increases if the remanufactured products are less environment-friendly, *i.e.*, $\gamma \in (1/2, 1)$. The main reason relies on the increment of the total quantity of products, although the collection rate increases. In addition, if the supplier is mean ($\theta_s < 0$), although the total quantity of products decreases, the environmental impact decreases as the reciprocity parameter of the manufacturer increases. This is because the quantity of remanufactured products grows more rapidly, and then the proportion of remanufactured products in the final products improves. The environment, however, is worse-off as the manufacturer is kinder or less mean if the supplier is kind. Under such conditions, although the environmental benefits decline, the collection rate of used products enhances as is shown in Proposition 1. Consequently, the trade-off between environmental impact and collection rate should be well balanced by the channel members of CLSC when exhibiting reciprocal behaviors.

5.5. Impacts on the society

Finally, we focus on the impacts of reciprocity on the society. Following Atasu *et al.* [61] and Esenduran *et al.* [62], we define the social welfare as the sum of total profits of CLSC and consumer surplus minus environmental impact, which is given by

$$W = \pi_t + \mathrm{CS} - eE \tag{17}$$

where ε represents the economic value of unit environmental impact.

Substituting the results of Lemma 2 into equation (17), we firstly examine the case that the social welfare does not contain environmental impact ($\varepsilon = 0$).

Proposition 8. *When* $\varepsilon = 0$*, (i)* $\frac{\partial W^{SM}}{\partial \theta_s} > 0$ *always holds, (ii) if* $\theta_s < 0$*, then* $\frac{\partial W^{SM}}{\partial \theta_m} > 0$*, or else,* $\frac{\partial W^{SM}}{\partial \theta_m} < 0$*.*

Proposition 8 demonstrates that when the environmental impact is not considered as a factor influencing the society, the social welfare increases in the reciprocity parameter of the supplier. The impact of the manufacturer's reciprocity on the social welfare, however, depends on the supplier's behavior as well as its own. Hence, as the leader of CLSC, the supplier is supposed to exhibit kindness to the manufacturer from the perspective of the society. Meanwhile, the manufacturer can reciprocate less but should reward the supplier with additional benefits in order to motivate the supplier to keep kind behaviors and achieve the level of the centralized scenario as is shown in Section 5.2.

Due to the complexity of W^{SM} if $\varepsilon \neq 0$, numerical studies are conducted to examine the impact of θ_s and θ_m on W^{SM} in the section of numerical analyses.

5.6. Sensitivity analysis on parameters

Firstly, we examine the impacts of scale parameter k on the equilibrium solutions under decentralized models, and the results are characterized in Corollary 7.

Corollary 7. $\frac{\partial w^i}{\partial k} = 0$, $\frac{\partial p^i}{\partial k} > 0$, $\frac{\partial \tau^i}{\partial k} < 0$, $\frac{\partial \pi_s^i}{\partial k} < 0$, $\frac{\partial \pi_m^i}{\partial k} < 0$ *and* $\frac{\partial \pi_t^i}{\partial k} < 0$, *where* $i = N, S, M, SM$.

Corollary 7 shows that regardless of whether the channel members have reciprocal behaviors or not, the scale parameter does not affect the procurement price of key components. The profit of the supplier, however, always decreases in the scale parameter. This is because an increase in the scale parameter leads to a higher selling price of the final products, and then lowers the total market demand (the order quantity of key components), thereby resulting in a lower profit to the supplier. Additionally, the manufacturer becomes unwilling to perform collection responsibility, and thus the collection rate declines, as the scale parameter increases. Although the selling price enhances, the increase of collection cost and the decrease of demand make the manufacturer suffer a profit loss. Preceding analysis shows that the double marginalization aggravates between the supplier and the manufacturer if the used products become increasingly difficult to collect (an increase in k), and therefore, the total profits of the CLSC decrease. Thus, it is necessary for the manufacturer to invest on collection technology to lessen the scale parameter of collecting used products. Subsequently, we discuss how the cost advantage of remanufactured product Δ affects the equilibria of different scenarios, as is characterized in Corollary 8.

Corollary 8. $\frac{\partial w^i}{\partial \Delta} = 0$, $\frac{\partial p^i}{\partial \Delta} < 0$, $\frac{\partial \tau^i}{\partial \Delta} > 0$, $\frac{\partial \pi_s^i}{\partial \Delta} > 0$, $\frac{\partial \pi_m^i}{\partial \Delta} > 0$ *and* $\frac{\partial \pi_t^i}{\partial \Delta} > 0$, *where* $i = N, S, M, SM$.

Corollary 8 indicates that, regardless of the reciprocal preferences of both the supplier and the manufacturer, as the cost advantage of remanufactured product increases, the procurement price remains constant, but the supplier's profit enhances. This is due to the fact that the manufacturer lowers the selling price of final products, thereby stimulating market demand. An increase in the cost advantage also motivates the manufacturer to hold responsible for collecting used products and then remanufacture, which further reduces the production cost of the manufacturer. As a result, the manufacturer receives more benefits from a larger cost advantage than from a low one. Combining with Corollary 7, although the supplier's decision is indifferent to the scale parameter and the cost advantage of remanufactured product, to which its profit is closely geared. Preceding analysis on the cost advantage also echoes the managerial insights of Corollary 7. That is, both the supplier and the manufacturer have incentives to reduce the scale parameter of collecting used products and improve the cost advantage of remanufactured product.

6. NUMERICAL ANALYSES

The above findings have provided adequate clues to examine the issues motivating our study. In this section, we perform numerical examples to examine the effects of reciprocal preferences, and then compare the profits, actual utilities and channel efficiency of different scenarios. Assuming $a = 20$, $c_n = 6$, $c_r = 5$, $c_0 = 4$ and $k = 1$, we investigate the impacts of reciprocal behaviors within a fixed scope $\Omega = \left\{(\theta_s, \theta_m) \,\middle|\, -1 \leq \theta_s \leq 1, -1 \leq \theta_m < \sqrt{5} - 2\right\}$.

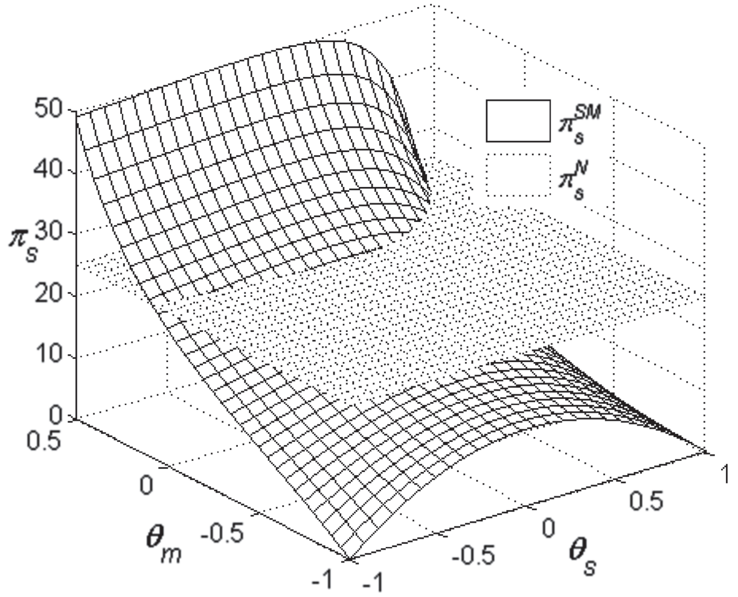

FIGURE 2. Effects of reciprocal behaviors on the profit of the supplier.

6.1. Analysis on profits

Herein, we analyze the impacts of reciprocal behaviors on the profits of channel members, as shown in Figures 2 and 3. Figure 2 graphically illustrates that the supplier's profit increases in the manufacturer's reciprocity parameter if the supplier's reciprocity parameter is lower than one. However, as the supplier's reciprocity coefficient increases, its profit firstly increases and then decreases, which is in line with Proposition 1. This also indicates that if the supplier focuses only on its own profits and does not consider the interests of the manufacturer, that is, if the attitude towards the manufacturer is neither much mean nor much kind, it can gain the most profits. In addition, when the reciprocity parameters of the supplier and manufacturer are relatively small and large, respectively, the supplier can earn more profits with reciprocal behavior than that of without reciprocal behavior.

Figure 3 demonstrates that the manufacturer's profit increases in the supplier's reciprocity parameter θ_s. This is because the kind supplier drops the procurement price of key components. Additionally, the manufacturer may suffer a profit loss if it becomes kinder or less mean to the supplier. Specifically, if $\theta_s > 0$, the manufacturer's profit drops with its reciprocity parameter θ_m, which is consistent with Proposition 2. Nevertheless, if $\theta_s < 0$, the manufacturer's profit is concave in θ_m. The reason relies on that although the procurement price is high relatively, the manufacturer can drop selling price and then stimulate demand as well as exerting more efforts to collect used products to lower its total costs, in order to earn more profit. However, if θ_m is very large, the excessive procurement price leads to a heavy profit loss to the manufacturer.

Additionally, we can also see from Figure 3 that the manufacturer's profit is negative if θ_m exceeds the scope, *i.e.*, $\theta_m > \sqrt{5} - 2$. The result signifies that the manufacturer is also supposed to pay attention to its profit while focusing on actual utility. The illustrations of Figures 2 and 3 lead to Observation 1.

Observation 1. Pareto improvement can be achieved if the reciprocity parameters of both the supplier and the manufacturer are relatively high.

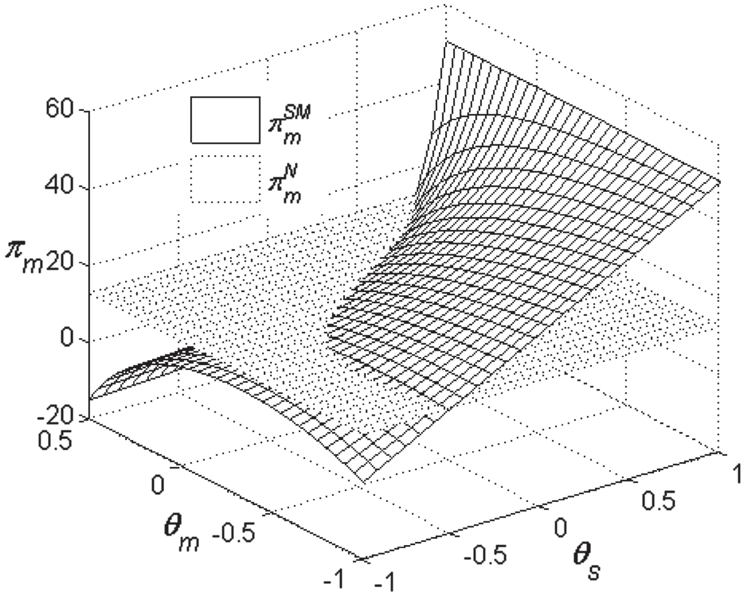

Figure 3. Effects of reciprocal behaviors on the profit of the manufacturer.

6.2. Analysis on actual utilities

Reciprocal behaviors make the supplier and the manufacturer focus on their own utilities rather than monetary payoffs. In this subsection, we examine the effects of reciprocal behaviors on the actual utilities of channel members, as illustrated in Figures 4 and 5.

As depicted from Figure 4, if θ_m is relatively small, the supplier's utility increases if it becomes kinder or less mean. Combined with Figures 2 and 3, although the supplier may suffer a profit loss, the manufacturer's profit significantly increases, thus enhancing the supplier's actual utility. However, if the reciprocity parameter of the manufacturer θ_m is large relatively, the supplier's utility drops with the reciprocity parameter of the supplier θ_s. The reason relies on that the supplier's profit significantly reduces which is greater than the added profit obtained by the manufacturer, ultimately leading to a decrease to the supplier's actual utility. In addition, the supplier's utility increases with θ_m, but it becomes less sensitive to θ_s.

Figure 5 shows that the manufacturer's utility always increases in the supplier's reciprocity parameter. Additionally, as the manufacturer is kinder or less mean, it can obtain higher utility. In general, the manufacturer's utility is more sensitive to the supplier's reciprocity than its own.

Figures 4 and 5 jointly demonstrate that the reciprocal preferences of the channel member encourage its cooperators to be kinder in the social network, which also has practical significance to stakeholders.

6.3. Analysis on channel efficiency and social welfare

Finally, we investigate the impact of reciprocity on channel efficiency and social welfare, which are displayed in Figures 6 and 7.

Figure 6 illustrates that, when both the supplier and the manufacturer are kinder to each other, the channel efficiency is always higher with reciprocity concerns than without, implying that the reciprocal behaviors positively affect the CLSC and improves channel efficiency. Specially, if $\theta_s = 1$, the channel efficiency is close to one, which reveals that the total profit is the highest if the supplier makes decisions from the whole CLSC's perspective. With Figures 2 and 3, the most of the system's profits is obtained by the manufacturer in the case of $\theta_s = 1$. Hence, when the supplier is very kind to the manufacturer, how to redistribute the profits becomes a

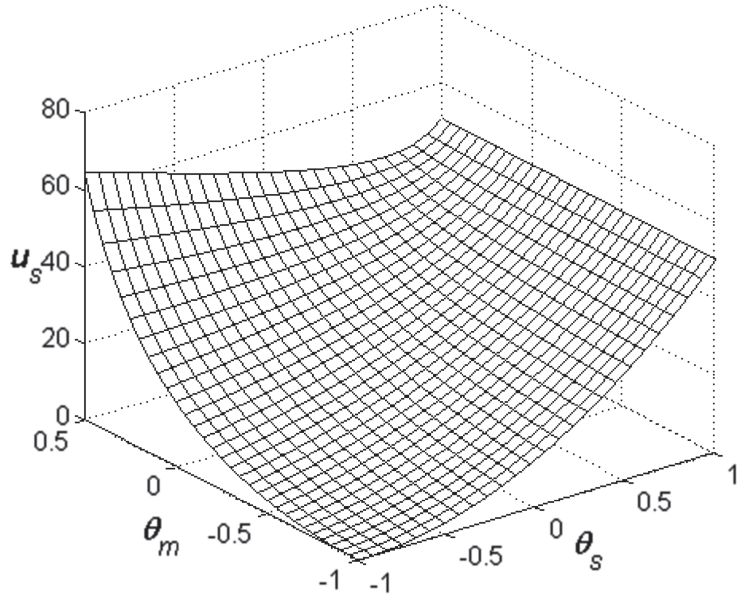

FIGURE 4. Effects of reciprocal behaviors on the utility of the supplier.

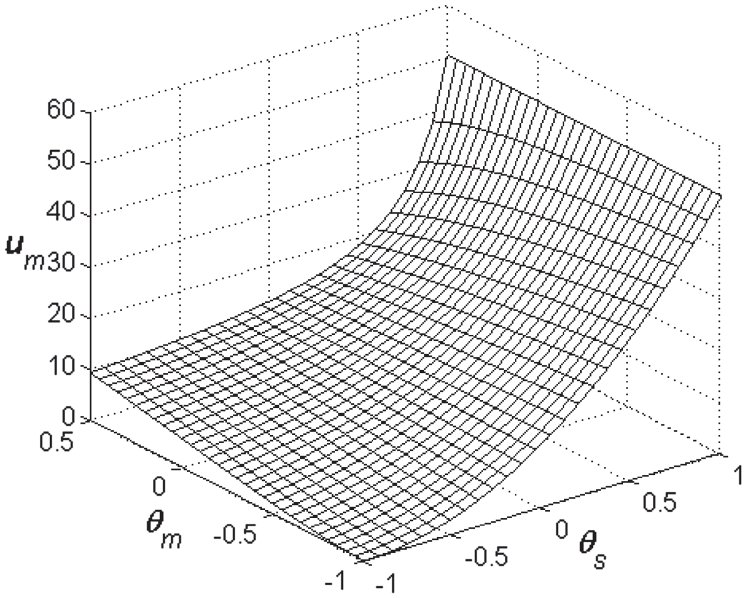

FIGURE 5. Effects of reciprocal behaviors on the utility of the manufacturer.

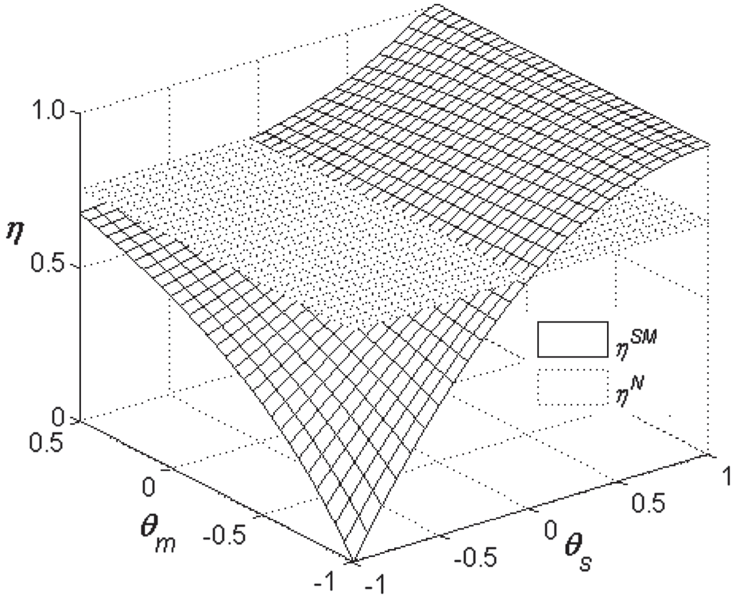

FIGURE 6. Effects of reciprocal behaviors on channel efficiency.

main issue that should be well addressed by both game participants, for whom a reasonable profit distribution mechanism can reach a win–win situation between them.

Figure 6 also reflects the effects of reciprocity concerns on the CLSC's total profit. Specifically, the total profit increases with the reciprocity parameter of the supplier θ_s, which is in line with Proposition 1. On the one hand, if $\theta_s < 0$, the total profit increases significantly in the reciprocity parameter of the manufacturer θ_m. According to Figure 3, although the manufacturer may suffer a profit loss, the supplier can earn more profit, which in turn promotes the total profit of the CLSC. On the other hand, if $\theta_s > 0$, the total profit drops with θ_m, but is less sensitive to θ_m. From Proposition 2, the manufacturer's profit reduces when $\theta_s < 0$. Since the increased profit of the supplier is less than the profit loss of the manufacturer, the total profit of the CLSC thus declines.

We then examine the impact of reciprocal preferences on social welfare, which is vividly illustrated in Figure 7. Herein, we set $\varepsilon = 1$, which means that the environmental impact is as important as the total profit and the consumer surplus towards the social welfare. Figure 7 depicts that the social welfare increases in θ_s and θ_m. According to Proposition 7, although reciprocity concerns may make the environment worse-off, the increased values of the CLSC's profit and consumer surplus are much higher than the increased value of environmental impact, thus leading to an increase in the social welfare. Additionally, as the impact of remanufactured products on environment (γ) enhances, the social welfare reduces, which is in line with our intuition. The social welfare, however, always benefits from the reciprocity of both channel members. Hence, from the perspective of the society, the firms' reciprocal behaviors can bring more benefits to society.

7. EXTENSIONS

In this section, we explore two extensions to our model, among which, the first one studies consumer heterogeneity on new and remanufactured products, and the other solves a two-period game model. We investigate separately each extension, rather than integrating into a model.

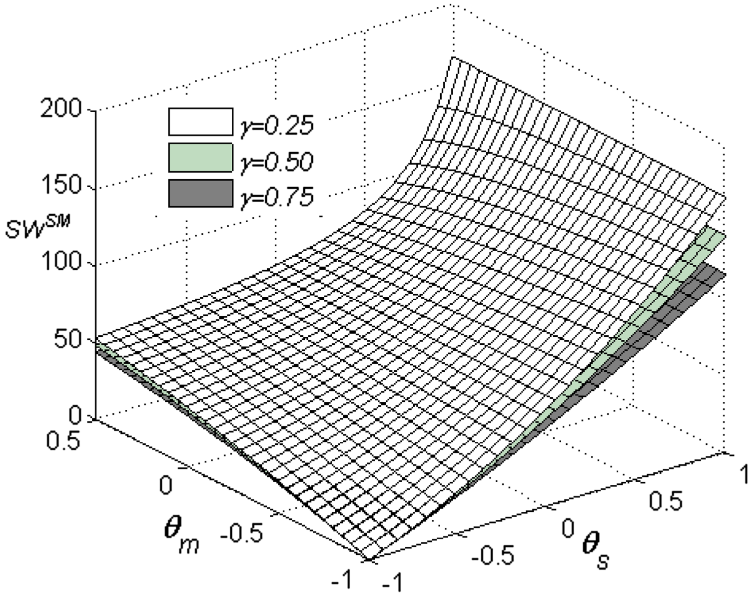

Figure 7. Effects of reciprocal behaviors on social welfare.

7.1. Consumer heterogeneity

Up to now, we have assumed that the qualities of new and remanufactured products are homogenous. Now we relax this assumption by considering the heterogeneous feature of the two types of products. In other words, consumers have different willingness to pay for new and remanufactured products. Herein, the selling prices of unit new and remanufactured product are denoted by p_n and p_r, respectively, and corresponding production quantities are q_n and q_r, respectively.

Assume consumer valuation for new product v is uniformly distributed in the range $[0, a]$, and the consumer valuation for remanufactured product is a fraction of v, *i.e.*, δv. Therefore, the net utility for the consumer purchasing unit new product is $v_n = v - p_n$, and that buying unit remanufactured product is $v_r = \delta v - p_r$. By comparing the net utilities from buying new and remanufactured product, the inverse demand functions of new and remanufactured products are $p_n = a - q_n - \delta q_r$, and $p_r = \delta(a - q_n - q_r)$, respectively. Such an assumption has been widely used in previous studies (*e.g.*, [28,39,62,63]), and we refer the reader to Ferrer and Swaminathan [27] and Ferguson and Toktay [26] for detailed derivation process.

Additionally, following the research of Atasu *et al.* [25], we assume $\delta c_n > c_r$, which ensures that remanufacturing is profitable. On the basis of above analysis, the profit functions of the supplier and the manufacturer are respectively

$$\pi_s = (w - c_0)(q_n + q_r) \tag{18}$$

$$\pi_m = (p_n - w - c_n)q_n + (p_r - w - c_r)q_r. \tag{19}$$

Then, the objective functions of both channel members under bilateral reciprocity in the presence of consumer heterogeneity are as follows, respectively

$$\max_{w} u_s = (w - c_0)(q_n + q_r) + \theta_s\left[(p_n - w - c_n)q_n + (p_r - w - c_r)q_r\right] \tag{20}$$

$$\max_{q_n, q_r} u_m = (p_n - w - c_n)q_n + (p_r - w - c_r)q_r + \theta_m(w - c_0)(q_n + q_r). \tag{21}$$

Using backward induction, the equilibrium solutions can be derived. Lemma 4 characterizes how the reciprocal behaviors affect such equilibrium solutions. The solving process and corresponding proof are presented in Appendix C. Note that the superscript "*" denotes the case of consumer heterogeneity.

Lemma 4. *In the presence of consumer heterogeneity, (i) the equilibrium decisions of procurement price, the quantities of new and remanufactured products are*

$$w^{SM^*} = \frac{(1-\theta_s)\delta a + (1-2\theta_m+\theta_s\theta_m^2)c_0 - (1-\theta_s)c_r}{2-\theta_s-2\theta_m-\theta_s\theta_m^2}, \quad q_n^{SM^*} = \frac{(1-\delta)a - c_n + c_r}{2(1-\delta)}$$

and

$$q_r^{SM^*} = \frac{\delta c_n - c_r - (1-\delta)[(1-\theta_m)w^{SM^*} + \theta_m c_0]}{2\delta(1-\delta)},$$

respectively; (ii) the impacts of reciprocal behaviors on the procurement price and the profits of both channel members are the same as the scenario of consumer homogeneity; (iii) the reciprocal behaviors of both the supplier and the manufacturer have no effects on the quantity of new products.

Lemma 4(i) gives the equilibrium solutions of the supplier and the manufacturer under consumer heterogeneity on new and remanufactured products. By the first derivatives of such solutions with respect to different reciprocity parameters, Lemma 4(ii) describes that the impacts of reciprocal behaviors on the procurement price and the profits of channel members are independent on the differences between new and remanufactured products.

Interestingly, Lemma 4(iii) reveals that the quantity of new products always remains constant regardless of the reciprocal behaviors of the supplier and the manufacturer, suggesting that the influence of reciprocal behaviors on total quantity relies only on that on remanufactured products. Besides, by the first-order conditions of $q_r^{SM^*}$ concerning θ_s and θ_m, we obtain that the remanufactured quantity increases in the reciprocity parameter of the supplier and decreases in that of the manufacturer. Let $\tau^{SM^*} = q_r^{SM^*}/q_n^{SM^*}$ be the collection rate under consumer heterogeneity, and then τ^{SM^*} increases. According to the above analysis, it is derived that as the supplier (manufacturer) becomes kinder or less mean, the collection rate improves (declines), which is consistent with that under consumer homogeneity.

7.2. A two-period game model

Thus far the game problem has been solved in a steady-state single period. We now extend to a two-period game model. As reported by Atasu *et al.* [25] and Wang *et al.* [36], there exist only new products in the initial stage, and used products can be collected and remanufactured in the subsequent periods. Following the above studies, we consider a two-period game problem where the manufacturer produces only new products in the first period and produces new and remanufactured products in the second period, and must purchase key components from the supplier when producing new or remanufactured products at both periods.

The demand function of period i is $q_i = a - p_i$ where a is the market size and p_i is the unit selling price of final products. The linear function has been widely adopted in literature (*e.g.*, [6,25,27,36,49]). Assume the unit procurement price of key components of period i is w_i, the profit functions of the supplier and the manufacturer are given by, respectively

$$\pi_s = \sum_{i=1}^{2}(w_i - c_0)(a - p_i) \tag{22}$$

$$\pi_m = (p_1 - w_1 - c_n)(a - p_1) + (p_2 - w_2 - c_n + \tau\Delta)(a - p_2) - \frac{1}{2}k\tau^2. \tag{23}$$

Then, the utility functions of the supplier and the manufacturer are expressed by, respectively

$$\max_{w_1,w_2} u_s = \sum_{i=1}^{2}(w_i - c_0)(a - p_i) + \theta_s\left[(p_1 - w_1 - c_n)(a - p_1) + (p_2 - w_2 - c_n + \tau\Delta)(a - p_2) - \frac{1}{2}k\tau^2\right]. \tag{24}$$

Then, the utility functions of the supplier and the manufacturer are expressed by, respectively

$$\max_{w_1,w_2} u_s = \sum_{i=1}^{2}(w_i - c_0)(a - p_i) + \theta_s \left[(p_1 - w_1 - c_n)(a - p_1) + (p_2 - w_2 - c_n + \tau\Delta)(a - p_2) - \frac{1}{2}k\tau^2\right] \quad (25)$$

$$\max_{p_1,p_2,\tau} u_m = (p_1 - w_1 - c_n)(a - p_1) + (p_2 - w_2 - c_n + \tau\Delta)(a - p_2) - \frac{1}{2}k\tau^2 + \theta_m \sum_{i=1}^{2}(w_i - c_0)(a - p_i). \quad (26)$$

Similar to Section 7.1, the equilibrium solutions are derived in Lemma 5. The solving process and corresponding proof are presented in Appendix D. Note that the superscript "**" denotes the two-period case.

Lemma 5. *In a two-period game model, (i) the equilibrium solutions are*

$$\begin{aligned} w_1^{SM^{**}} &= w_2^{SM^{**}} = w^{SM}, \\ p_1^{SM^{**}} &= a - \frac{(1-\theta_m\theta_s)(a - c_n - c_0)}{2(2 - \theta_s - \theta_m\theta_s)}, \\ p_2^{SM^{**}} &= p^{SM}, \\ \tau^{SM^{**}} &= \tau^{SM}, \end{aligned}$$

(ii) the reciprocal behaviors have similar impacts on the selling price of the first period with that of the second period.

Lemma 5(i) shows the equilibrium solutions of the procurement prices, the selling prices of two periods, and the collection rate of used products. Surprisingly, we find that all the equilibrium solutions of the second period remain the same as those of the single period, which means that the optimal decisions tend to stay constant in steady periods. Consequently, the impacts of reciprocal behaviors on the equilibrium decisions and the profits of both channel members are the same as the scenario of the single period.

Additionally, the procurement prices of key components are always the same in two periods, implying that the supplier is indifferent to whether the manufacturer adopts remanufacturing strategy when determining procurement prices. The selling prices of final products, however, differ in two periods. This is because the cost advantage of remanufacturing enables the manufacturer to lower the selling price of the second period. Although the selling prices of two periods are various, Lemma 5(ii) confirms that the impacts of reciprocal behaviors on them are similar. That is, the selling price of the first period increases in the supplier's reciprocity parameter, but decreases in the manufacturer's reciprocity parameter.

Comparing the impacts of reciprocal behaviors on the selling prices of two periods, we observe the following results.

Observation 2. Remanufacturing weakens (strengthens) the impacts of reciprocal behavior of the supplier (manufacturer) on the selling price of the second period compared with that of the first period.

Observation 2 implies that, from the perspective of selling price, implementing remanufacturing strategy will help the manufacturer mitigate the impact of external factors and promote the impact of its own reciprocal behavior.

8. DISCUSSION

In this study, we utilized a normalized utility function for player i by referring to Loch and Wu [14] as follows: $u_i = \pi_i + \theta_i\pi_j$. Preceding analysis focuses only on examining the overall effects of reciprocal behaviors on the performances of channel members. In fact, θ_i is identified by several related parameters, such as altruism and fairness. We refer the readers to Loch and Wu [14] for details. Therein the reciprocity parameter is expressed

TABLE 4. Effects of the parameters of social preferences on equilibrium outcomes.

Parameter	w^{SM}	p^{SM}	τ^{SM}	π_s^{SM}	π_m^{SM}	π_t^{SM}
α_s	$-$	$-$	$+$	$\pm$	$+$	$+$
β_s	$+$	$+$	$\approx$	m	$-$	$-$
α_m	$+$	m	$\pm$	$\approx$	$\pm$	$\approx$
β_m	$\approx$	$\pm$	m	$-$	$\approx$	m

Notes. The marks $+$ and $-$ indicate positive effect and negative effect, respectively; $\pm$ means positive effect if $\alpha_s < \beta_s$ and *vice versa*; m means negative effect if $\alpha_s < \beta_s$ and *vice versa*; $\approx$ means that the result is unclear.

by $\theta_i = \frac{\alpha_i - \beta_i}{1+\beta_i}$, where α_i is the relationship parameter, reflecting that player i exhibits altruism or spitefulness and $-1 < \alpha_i < 1$; β_i is the fairness concern parameter reflecting that player i cares about profit distributional fairness and $-1 < \beta_i < 1$. In this section, we further discuss how the two parameters of social preferences (especially the fairness-regarding parameter) affect the equilibrium solutions of our model. To do so, we change the value of one parameter and fix that of the other one.

Taking derivatives of θ_i with respect to α_i and β_i, we have $\frac{\partial \theta_i}{\partial \alpha_i} > 0$ and $\frac{\partial \theta_i}{\partial \beta_i} < 0$, respectively. Note that both the results are monotonic, which allows us to concentrate only on the impacts of α_i and β_i on θ_i rather than on equilibrium solutions. By means of the results of Propositions 1 and 2, we examine the impacts of α_i and β_i on equilibria of both channel members, as shown in Table 4.

Since the impacts of the relationship parameter α_i and the distributional fairness concern parameter β_i on equilibria are always opposite, we thus focus mainly on β_i for given α_i. Table 4 characterizes the impacts of social preferences on equilibrium solutions. Firstly, we analyze the impacts of the distributional fairness concern of the supplier. As the Stackelberg leader, as her sensitivity on concerning with the fairness of profit distributions increases, both the procurement price and the selling price heighten, while the collection rate lessens regardless of the social preferences of the manufacturer. The reasons are straightforward: if the supplier feels strongly unfair about the distribution of profits, she will set a relatively high procurement price of key components to obtain more profits. As such, the manufacturer has to lessen collection effort to save cost and raise the selling price of his products to pursuit profit. Such a behavior leads to a profit loss to the manufacturer and also to the total CLSC. The supplier's profit, however, relies also on the relationships of two different social preferences. Specifically, if the fairness concern dominates the altruism, the supplier benefits from her concern on the fairness of profit distributions. Otherwise, she suffers a profit loss from such behaviors.

Subsequently, we investigate the impacts of the manufacturer's fairness concern on the performances of the CLSC. As characterized in Table 4, the procurement price of key components always decreases in the manufacturer's fairness concern, thereby making the supplier suffer a profit loss. The manufacturer's equilibrium decisions, however, depend also on the social preferences of the supplier. If the supplier's fairness concern dominates the altruism, as the manufacturer's fairness concern increases, the selling price enhances and the collection rate reduces. Otherwise, the selling price reduces and the collection rate enhances. Such results are more intuitive in a special case, *i.e.*, $\alpha_s = 0$. Under this condition, $\beta_s > 0$ means the supplier has an aversion to disadvantageous inequality, and $\beta_s < 0$ means the supplier has an aversion to advantageous inequality. Preceding analysis demonstrates that the procurement price of key components always increases in the supplier's fairness concern. If the supplier has an aversion to disadvantageous inequality, the procurement price is relatively high. Consequently, the manufacturer will improve the selling price of his products and exert less collection effort on used products as his distributional fairness concern increases, and then such behaviors make the CLSC suffer a profit loss. Otherwise, the manufacturer has an incentive to reduce selling price and improve collection rate, thereby benefiting the CLSC. Although the complete effects of the manufacturer's fairness concern on his profit are not clear, it follows from Proposition 2 that the manufacturer benefits from his fairness concern if the supplier's altruism dominates fairness concern.

9. CONCLUSIONS

In this study, we examine the impacts of reciprocal behaviors on the performances of a CLSC incorporating a supplier and a manufacturer, wherein both of them are reciprocity-concerned. The supplier provides key components which cannot be remanufactured, and the manufacturer produces new products and remanufactures the other parts except for the key components of collected used products. Subsequently, we analyze the scenarios with and without reciprocal preferences. The equilibrium solutions of procurement price, selling price and collection rate are derived, and the impacts of reciprocal preferences on such solutions, the profits of channel members, channel efficiency, consumers, environment and society are then examined. Finally, we extend our model by considering the scenarios of consumer heterogeneity and a two-period game. Through mathematical results and numerical analysis, our main findings include the following:

(i) The supplier's kind behavior can prompt the manufacturer to increase collection rate and increase the CLSC's total profit. The impact of the manufacturer's reciprocity on collection rate, however, depends also on the supplier's reciprocal behavior. (ii) If only the manufacturer reciprocates, the total profit of CLSC is indifferent to such behavior of reciprocity. (iii) The channel efficiency and consumer surplus always increase with the supplier's reciprocity, while the effect of the manufacturer's reciprocity on them also depends on the supplier's attitude. Additionally, under certain conditions, the reciprocal behaviors of both the supplier and manufacturer have negative impacts on environment, but have positive impacts on social welfare. (iv) Pareto improvement can be achieved if the reciprocity parameters of both the supplier and the manufacturer are relatively high, and the CLSC can be conditionally coordinated by a simple procurement price contract. (v) The impacts of reciprocal behaviors on the procurement price and the profits of both channel members are the same as the scenario of consumer homogeneity and the scenario of two-period game. Additionally, the reciprocal behaviors of both the supplier and the manufacturer have similar impacts on the selling price of the first period with that of the second period in the two-period scenario, but have no effects on the quantity of new products under consumer heterogeneity.

Our work also provides several significant economic and environmental managerial implications for different stakeholders. To begin with, a firm's reciprocal behavior can motivate its cooperators to express more kindly in the social network. A mean firm may face revenge from its cooperators, which can drop its utility and profits. Second, a firm's reciprocity always makes its cooperator better off, while the firm itself is worse off. More importantly, Pareto improvement can be achieved if the reciprocity parameters of both channel members are relatively high. Thus, such kind behaviors lead to a profit increase to both firms and then reach a win-win situation, which is more applicable in the business. Xia *et al.* [13] reported that several suppliers exerted more efforts to complete the project for their clients even if they suffered from heavy cost difficulties, thereby saving cost for their clients. Finally, their clients rewarded them and strengthened cooperation. Third, as the leader, the supplier's reciprocity can effectively enhance the collection rate of used products, the channel efficiency and the consumer surplus. To do so, the supplier should be incited to exhibit reciprocity. In addition, if the firm behaves great social responsibility, it can adopt this reciprocal strategy. This may in turn stimulate market demand and finally gain more profits. For the manufacturer, if the supplier is much kinder, it should give up some benefits and reward its cooperator. This is because the total profit of CLSC is much more with reciprocity than without, and most of the profit is obtained by the manufacturer. Hence, a reasonable profit distribution mechanism can strengthen the cooperation between them to achieve Pareto improvement. In other words, if the manufacturer shares benefits with the supplier, the supplier will be increasingly kind to make the total CLSC profit achieve the level of centralized scenario. Besides, from the perspective of selling price, remanufacturing helps the manufacturer mitigate the impact of external factors and promote the impact of its own reciprocal behavior. Finally, the reciprocal behaviors of both firms benefit the society. For policymakers, it is necessary to motivate the firms to adopt reciprocal strategy to enhance the social welfare, in addition to increasing the collection rate of used products to improve environment performances.

Several limitations and future directions are worth mentioning. First, we assume that the manufacturer is responsible for collecting and remanufacturing activities in the CLSC. In practice, manufacturers usually authorize third-party remanufacturers to take charge of such activities. Thus we can incorporate a third-party remanufacturer into our model framework to examine the impacts of reciprocal preferences on CLSC performances. Second, there are only a monopolistic supplier and a monopolistic manufacturer in our model. Therefore, taking the fierce competition of suppliers or manufacturers into account may be more applicable in practice and is also a direction for future research. Third, we consider only the reciprocal preferences of channel members in our model. There are many other types of social preferences, such as altruism, inequality aversion and identification, and other irrational behaviors, such as overconfidence. Therefore, exploring the impacts of double social preferences or irrational behavior on CLSC performances may be an interesting research topic.

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APPENDIX A.

Proof of Lemma 1

The objective functions of the supplier and the manufacturer are expressed as follows, respectively

$$\max_{w} \pi_s = (w - c_0)(a - p) \tag{A.1}$$

$$\max_{p,\tau} \pi_m = (p - w - c_n + \tau\Delta)(a - p) - \frac{1}{2}k\tau^2. \tag{A.2}$$

We use backwards induction to solve the dynamic game problem. Firstly, the manufacturer decides p and τ simultaneously to maximize π_m. The Hessian matrix of equation (A.2) is

$$H = \begin{bmatrix} \frac{\partial^2 \pi_s}{\partial p^2} & \frac{\partial^2 \pi_s}{\partial p \partial \tau} \\ \frac{\partial^2 \pi_s}{\partial \tau \partial p} & \frac{\partial^2 \pi_s}{\partial \tau^2} \end{bmatrix}$$

which can be rewritten as $H = \begin{bmatrix} -2 & -\Delta \\ -\Delta & -k \end{bmatrix}$. Since k is greater than other parameters, it is reasonable to assume $2k - \Delta^2 > 0$. With $H_{11} = -2 < 0$ and $det(H) = 2k - \Delta^2 > 0$, π_m is jointly concave in p and τ. From the first-order conditions of π_m regarding p and τ, respectively, it follows that

$$p = \frac{a + w + c_n - \tau\Delta}{2} \tag{A.3}$$

$$\tau = \frac{\Delta(a - p)}{k} \cdot \tag{A.4}$$

Solving (A.3) and (A.4) jointly, we can obtain

$$p = a - \frac{k(a - w - c_n)}{2k - \Delta^2} \tag{A.5}$$

$$\tau = \frac{\Delta(a - w - c_n)}{2k - \Delta^2} \cdot \tag{A.6}$$

Substituting (A.5) into (A.1), we have the supplier's profit function as follows.

$$\max_{w} \pi_s = \frac{k(a - w - c_n)(w - c_0)}{2k - \Delta^2} \cdot \tag{A.7}$$

Since $\frac{\partial^2 \pi_s}{\partial w^2} = -\frac{2k}{2k - \Delta^2} < 0$, π_s is thus concave in w. Solving the first-order condition of π_s with respect to w, $w^N = \frac{a - c_n + c_0}{2}$ can be then derived.

Substituting $w^N = \frac{a - c_n + c_0}{2}$ into equations (A.5) and (A.6), we can obtain

$$p^N = a - \frac{k(a - c_n - c_0)}{2(2k - \Delta^2)} \quad \text{and} \quad \tau^N = \frac{\Delta(a - c_n - c_0)}{2(2k - \Delta^2)} \cdot$$

Proof of Lemma 2

The proof is similar to that of Lemma 1, so it is omitted.

Proof of Lemma 3

The optimization objective is

$$\max_{p,\tau} \pi_t = (p - c_0 - c_n + \tau\Delta)(a - p) - \frac{1}{2} k \tau^2. \tag{A.8}$$

From the first-order conditions of π_t with respect to p and τ, it follows that

$$p = \frac{a + c_0 + c_n - \tau\Delta}{2} \tag{A.9}$$

$$\tau = \frac{\Delta(a - p)}{k} \cdot \tag{A.10}$$

Solving equations (A.9) and (A.10) jointly, we have

$$p^C = a - \frac{k(a - c_n - c_0)}{2k - \Delta^2} \tag{A.11}$$

$$\tau^C = \frac{\Delta(a - c_n - c_0)}{2k - \Delta^2} \cdot \tag{A.12}$$

Appendix B.

Proof of Proposition 1

In Scenario SM, by the first-order condition of equilibrium solutions with respect to θ_s, we have

$$\frac{\partial p^{SM}}{\partial \theta_s} = -\frac{k(1-\theta_m)(a-c_n-c_0)}{(2-\theta_s-\theta_m\theta_s)^2(2k-\Delta^2)} < 0, \quad \frac{\partial w^{SM}}{\partial \theta_s} = -\frac{(a-c_n-c_0)}{(2-\theta_m\theta_s-\theta_s)^2} < 0$$

and

$$\frac{\partial \tau^{SM}}{\partial \theta_s} = \frac{(1-\theta_m)(a-c_n-c_0)\Delta}{(2-\theta_s-\theta_m\theta_s)^2(2k-\Delta^2)} > 0.$$

Since

$$\frac{\partial \pi_s^{SM}}{\partial \theta_s} = -\frac{k\theta_s(1-\theta_m)(a-c_n-c_0)^2}{(2-\theta_m\theta_s-\theta_s)^3(2k-\Delta^2)},$$

it is thus derived that $\frac{\partial \pi_s^{SM}}{\partial \theta_s} < 0$, if $\theta_s > 0$, or else $\frac{\partial \pi_s^{SM}}{\partial \theta_s} > 0$. In addition, it follows from the first derivatives of π_s^{SM} and π_t^{SM} concerning θ_s that

$$\frac{\partial \pi_m^{SM}}{\partial \theta_s} = \frac{k(1-\theta_m)\left(a-c_n-c_0\right)^2}{\left(2-\theta_m\theta_s-\theta_s\right)^3\left(2k-\Delta^2\right)} > 0, \quad \text{and} \quad \frac{\partial \pi_t^{SM}}{\partial \theta_s} = \frac{k\left(1-\theta_m\right)\left(1-\theta_s\right)\left(a-c_n-c_0\right)^2}{\left(2-\theta_m\theta_s-\theta_s\right)^3\left(2k-\Delta^2\right)} > 0.$$

Proof of Proposition 2

In Scenario SM, by the first-order conditions of equilibrium solutions with respect to θ_m, we have

$$\begin{aligned} \frac{\partial w^{SM}}{\partial \theta_m} &= \frac{2\left(1-\theta_s\right)\left(1-\theta_m\theta_s\right)\left(a-c_n-c_0\right)}{\left(1-\theta_m\right)^2\left(2-\theta_m\theta_s-\theta_s\right)^2} > 0, \\ \frac{\partial p^{SM}}{\partial \theta_m} &= -\frac{k\theta_s(1-\theta_s)(a-c_n-c_0)}{(2-\theta_s-\theta_m\theta_s)^2(2k-\Delta^2)} < 0, \quad \text{and} \quad \frac{\partial \tau^{SM}}{\partial \theta_m} = -\frac{\theta_s(1-\theta_s)(a-c_n-c_0)\Delta}{(2-\theta_s-\theta_m\theta_s)^2(2k-\Delta^2)}. \end{aligned}$$

Further we obtain that, if $\theta_s > 0$, then $\frac{\partial p^{SM}}{\partial \theta_m} > 0$ and $\frac{\partial \tau^{SM}}{\partial \theta_m} < 0$, or else, $\frac{\partial p^{SM}}{\partial \theta_m} < 0$ and $\frac{\partial \tau^{SM}}{\partial \theta_m} > 0$. Moreover, the partial derivative of π_s^{SM} regarding θ_m gives

$$\frac{\partial \pi_s^{SM}}{\partial \theta_m} = \frac{k\left(1-\theta_s\right)\left[2(1-\theta_m\theta_s)^2-\theta_s(1-\theta_m)\left(1-\theta_s\right)\right]\left(a-c_n-c_0\right)^2}{\left(2-\theta_m\theta_s-\theta_s\right)^3\left(2k-\Delta^2\right)}.$$

Letting $f_1(\theta_m) = 2(1-\theta_m\theta_s)^2-\theta_s(1-\theta_m)(1-\theta_s)$, by the maximum value formula and $\theta_s \in [-1,1]$, we can get $f_1(\theta_m) > 0$ and then $\frac{\partial \pi_s^{SM}}{\partial \theta_m} > 0$ can be obtained. For the manufacturer's profit, the partial derivative of π_m^{SM} regarding θ_m gives

$$\frac{\partial \pi_m^{SM}}{\partial \theta_m} = -\frac{k(1-\theta_s)\left[(1-\theta_m\theta_s)(2-\theta_m-\theta_s)-\theta_s(2-\theta_m-\theta_s)\right]\left(a-c_n-c_0\right)^2}{(1-\theta_m)^2(2-\theta_m\theta_s-\theta_s)^3(2k-\Delta^2)}.$$

Similarly, letting $f_2(\theta_m) = (1-\theta_m\theta_s)(2-\theta_m-\theta_s)-\theta_s(2-\theta_m-\theta_s)$, by the maximum value formula...

Proof of Corollary 1

With the equilibrium profits of the supplier and the manufacturer in Scenario SM, we have

$$\pi_s^{SM} - \pi_m^{SM} = \frac{k(1-\theta_m\theta_s)[(1+\theta_m)(1-\theta_m\theta_s)+2(\theta_m-\theta_s)](a-c_n-c_0)^2}{2(1-\theta_m)(2-\theta_s-\theta_m\theta_s)^2(2k-\Delta^2)}.$$

By the scope of $\Omega = \{(\theta_s,\theta_m) | -1 \le \theta_s \le 1, -1 \le \theta_m < \sqrt{5}-2\}$, we thus obtain $\pi_s^{SM} > \pi_m^{SM}$ always holds if $\theta_m > \theta_s$. Similarly, by Table 3, we have $\pi_s^S > \pi_s^m$ ($\pi_s^s < \pi_s^m$) if $-1 \le \theta_s \le 1/2$ ($1/2 \le \theta_s \le 1$), and $\pi_s^s < \pi_s^m$ ($\pi_s^s > \pi_s^m$) if $-1/3 \le \theta_m < \sqrt{5}-2$.

Proof of Proposition 3

In Scenario S, by the first-order conditions of equilibrium solutions regarding θ_s, we have

$$\frac{\partial w^S}{\partial\theta_s}=-\frac{(a-c_n-c_0)}{(2-\theta_s)^2}<0,\quad \frac{\partial p^S}{\partial\theta_s}<0,\quad \frac{\partial\tau^S}{\partial\theta_s}>0,\quad \frac{\partial\pi_s^S}{\partial\theta_s}=\frac{k\theta_s(a-c_n-c_0)^2}{(2-\theta_s)^3(2k-\Delta^2)}<0,$$

and

$$\frac{\partial\pi_m^S}{\partial\theta_s}=\frac{k(1-\theta_s)(a-c_n-c_0)^2}{(2-\theta_s)^3(2k-\Delta^2)}>0.$$

Proof of Proposition 4

In Scenario M, by the first-order conditions of the equilibrium solutions regarding θ_m, we have

$$\frac{\partial w^M}{\partial\theta_m}=\frac{a-c_n-c_0}{2(1-\theta_m)^2}>0,\quad \frac{\partial p^M}{\partial\theta_m}=\frac{\partial\tau^M}{\partial\theta_m}=0,\quad \frac{\partial\pi_s^M}{\partial\theta_m}=-\frac{k(a-c_n-c_0)^2}{4(1-\theta_m)^2(2k-\Delta^2)}>0,$$
$$\frac{\partial\pi_m^M}{\partial\theta_m}=-\frac{k(a-c_n-c_0)^2}{4(1-\theta_m)^2(2k-\Delta^2)}<0\quad\text{and}\quad\frac{\partial\pi_t^M}{\partial\theta_m}=0.$$

Proof of Corollaries 2 and 3

It is very simple to prove them according to Propositions 3 and 4, so we omit them.

Proof of Corollary 4

By the equilibrium solutions in Lemma 2 and $\theta_s=1$, we obtain $w^{SM}=c_0$, $p^{SM}=a-\frac{k(a-c_n-c_0)}{2k-\Delta^2}$ and $\tau^{SM}=\frac{(a-c_n-c_0)\Delta}{2k-\Delta^2}$. It is easy to find that θ_m has no effect on...

Proof of Proposition 5

Since

$$\frac{\partial\eta^{SM}}{\partial\theta_s}=\frac{2\left(1-\theta_s\right)\left(1-\theta_m\right)}{\left(2-\theta_s-\theta_m\theta_s\right)^3}$$

and

$$\frac{\partial\eta^{SM}}{\partial\theta_m}=\frac{-2\theta_s(1-\theta_s)^2}{\left(2-\theta_s-\theta_m\theta_s\right)^3},$$

according to

$$\Omega=\left\{(\theta_s,\theta_m)\middle|-1\le\theta_s\le1,-1\le\theta_m<\sqrt{5}-2\right\},$$

it is derived that $\frac{\partial\eta^{SM}}{\partial\theta_s}>0$, and if $\theta_s<0$, then $\frac{\partial\eta^{SM}}{\partial\theta_m}>0$, or else $\frac{\partial\eta^{SM}}{\partial\theta_m}<0$.

Proof of Proposition 6

With the expression of consumer surplus, we obtain

$$\mathrm{CS}^{SM}=\frac{\left(q^{SM}\right)^2}{2}.$$

The first-order conditions of CS^{SM} with respect to θ_s and θ_m,

$$\frac{\partial\mathrm{CS}^{SM}}{\partial\theta_s}=q^{SM}\frac{\partial q^{SM}}{\partial\theta_s}\quad\text{and}\quad\frac{\partial\mathrm{CS}^{SM}}{\partial\theta_m}=q^{SM}\frac{\partial q^{SM}}{\partial\theta_m}$$

are derived, respectively. Since $p = a - q$, $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_m}$ can be rewritten as

$$\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_s} = -q^{SM}\frac{\partial p^{SM}}{\partial \theta_s} \quad \text{and} \quad \frac{\partial \mathrm{CS}^{SM}}{\partial \theta_m} = -q^{SM}\frac{\partial p^{SM}}{\partial \theta_m},$$

respectively. Recall the results of Propositions 1 and 2, we acquire that $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_s} > 0$ always holds and if $\theta_s < 0$, then $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_m} > 0$, or else, $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_m} < 0$. Analogously,

$$\frac{\partial \mathrm{CS}^{S}}{\partial \theta_s} > 0 \quad \text{and} \quad \frac{\partial \mathrm{CS}^{M}}{\partial \theta_m} = 0$$

can be proved.

Proof of Proposition 7

Substituting the equilibrium solutions of Lemma 2 into

$$E^j = (1 - \tau^j)q^j + \gamma\tau^j q^j,$$

we obtain

$$E^{SM} = \left(1 - \tau^{SM}\right) q^{SM} + \gamma\tau^{SM} q^{SM}.$$

The first-order condition of E^{SM} with respect to θ_s gives

$$\frac{\partial E^{SM}}{\partial \theta_s} = [1 - 2(1-\gamma)\tau^{SM}]\frac{\partial q^{SM}}{\partial \theta_s}\cdot$$

Since $\frac{\partial q^{SM}}{\partial \theta_s} > 0$ and $\tau^{SM} \in (0,1)$, we then obtain $\frac{\partial E^{SM}}{\partial \theta_s} > 0$ if $\gamma \in (1/2, 1)$ holds. Analogously, when $\gamma \in (1/2, 1)$ holds,

$$\frac{\partial E^{SM}}{\partial \theta_m} > 0 \quad \text{if} \quad \theta_s < 0, \quad \text{otherwise,} \quad \frac{\partial E^{SM}}{\partial \theta_m} < 0.$$

Proof of Proposition 8

When $\varepsilon = 0$, the social welfare can be rewritten as

$$W^{SM}_{\varepsilon=0} = \pi_t^{SM} + \mathrm{CS}^{SM}.$$

By the first-order condition of $W^{SM}_{\varepsilon=0}$ with respect to θ_s,

$$\frac{\partial W^{SM}_{\varepsilon=0}}{\partial \theta_s} = \frac{\partial \pi_t^{SM}}{\partial \theta_s} + \frac{\partial \mathrm{CS}^{SM}}{\partial \theta_s}$$

can be derived. Recall that $\frac{\partial \pi_t^{SM}}{\partial \theta_s} > 0$ and $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_s} > 0$ in Propositions 1 and 6,

$$\frac{\partial W^{SM}_{\varepsilon=0}}{\partial \theta_s} > 0$$

yields. In addition, by Propositions 2 and 6, we have $\frac{\partial \pi_t^{SM}}{\partial \theta_m} > 0$ and $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_m} > 0$ if $\theta_s < 0$, otherwise, $\frac{\partial \pi_t^{SM}}{\partial \theta_m} < 0$ and $\frac{\partial \mathrm{CS}^{SM}}{\partial \theta_m} < 0$. We thus have

$$\frac{\partial W^{SM}_{\varepsilon=0}}{\partial \theta_m} > 0 \quad \left(\frac{\partial W^{SM}_{\varepsilon=0}}{\partial \theta_m} < 0\right) \quad \text{if } \theta_s < 0 \ (\theta_s > 0) \text{ is satisfied.}$$

Proof of Corollary 7

In Scenario SM, by the first-order conditions of equilibrium solutions with respect to k, we have

$$\frac{\partial w^{SM}}{\partial k} = 0, \quad \frac{\partial p^{SM}}{\partial k} = \frac{(1-\theta_m\theta_s)(a-c_n-c_0)\Delta^2}{(2-\theta_s-\theta_m\theta_s)^2(2k-\Delta^2)} > 0,$$
$$\frac{\partial \tau^{SM}}{\partial k} = \frac{-2(1-\theta_s)(a-c_n-c_0)\Delta}{(2-\theta_s-\theta_m\theta_s)(2k-\Delta^2)^2} < 0, \quad \frac{\partial \pi_s^{SM}}{\partial k} = \frac{-k(1-\theta_m\theta_s)(a-c_n-c_0)^2}{(2-\theta_s-\theta_m\theta_s)^2(2k-\Delta^2)} < 0.$$

Since $\frac{\partial \pi_s^{SM}}{\partial k} < 0$ and $\frac{\partial \pi_m^{SM}}{\partial k} < 0$ can thus be derived. Letting $\theta_s = \theta_m = 0$, $\theta_m = 0$ and $\theta_s = 0$, we can obtain the same results under Scenario N, Scenario S, and Scenario M, respectively.

Proof of Corollary 8

In Scenario SM, by the first-order conditions of equilibrium solutions regarding Δ, we have

$$\frac{\partial w^{SM}}{\partial \Delta} = 0, \quad \frac{\partial p^{SM}}{\partial \Delta} = \frac{-2k(1-\theta_m\theta_s)(a-c_n-c_0)\Delta}{(2-\theta_s-\theta_m\theta_s)(2k-\Delta^2)} < 0,$$
$$\frac{\partial \tau^{SM}}{\partial \Delta} = \frac{(1-\theta_m\theta_s)(a-c_n-c_0)(2k+\Delta)}{(2-\theta_s-\theta_m\theta_s)(2k-\Delta^2)^2} > 0.$$

Besides, from the equilibrium solutions of the profits of the supplier and the manufacturer, it is simple to derive $\frac{\partial \pi_s^{SM}}{\partial \Delta} > 0$ and $\frac{\partial \pi_m^{SM}}{\partial \Delta} > 0$.

APPENDIX C.

The maximization problems of the supplier and the manufacturer are as follows, respectively:

$$\max_{w} u_s = (w-c_0)(q_n+q_r) + \theta_s[(p_n-w-c_n)q_n + (p_r-w-c_r)q_r], \tag{C.1}$$
$$\max_{q_n,q_r} u_m = (p_n-w-c_n)q_n + (p_r-w-c_r)q_r + \theta_m(w-c_0)(q_n+q_r). \tag{C.2}$$

The Hessian matrix of equation (C.2) is

$$H = \begin{bmatrix} -2 & -2\delta \\ -2\delta & -2\delta \end{bmatrix}.$$

With $H_{11} = -2 < 0$ and $\det(H) = 4\delta(1-\delta) > 0$, it can be thus proved that u_m is jointly concave in q_n and q_r. Then, the rest of the proof process is similar to that of Appendix A, so it is omitted.

Subsequently, we prove the second and the third parts of Lemma 4.

By solving the first partial derivatives of w^{SM^*} regarding θ_s and θ_m, we obtain

$$\frac{\partial w^{SM^*}}{\partial \theta_s} = \frac{-\delta(a-c_r-c_0)}{(2-\theta_s\theta_m)^2}, \quad \frac{\partial w^{SM^*}}{\partial \theta_m} = \frac{2(1-\theta_s)(1-\theta_s\theta_m)\delta(a-c_r-c_0)}{(1-\theta_m)^2(2-\theta_s-\theta_m\theta_s)^2}.$$

Further, $\frac{\partial w^{SM^*}}{\partial \theta_s} < 0$ and $\frac{\partial w^{SM^*}}{\partial \theta_m} > 0$ can be proved.

Analogously, we can prove the effects of reciprocity parameters of the supplier and the manufacturer on the other equilibrium solutions.

Appendix D.

The objective functions of the supplier and the manufacturer are as follows, respectively:

$$\begin{aligned}\max_{w_1,w_2} u_s &= \sum_{i=1}^{2}(w_i - c_0)(a-p_i) + \theta_s\left[(p_1 - w_1 - c_n)(a-p_1) + (p_2 - w_2 - c_n + \tau\Delta)(a-p_2)\right]\\ &\quad - \frac{1}{2}k\tau^2, \qquad \text{(D.1)}\\ \max_{p_1,p_2,\tau} u_m &= (p_1 - w_1 - c_n)(a-p_1) + (p_2 - w_2 - c_n + \tau\Delta)(a-p_2)\\ &\quad - \frac{1}{2}k\tau^2 + \theta_m\sum_{i=1}^{2}(w_i - c_0)(a-p_i). \qquad \text{(D.2)}\end{aligned}$$

Then, we solve this game problem using backwards induction. The Hessian matrix of equation (D.2) is

$$H = \begin{bmatrix} -2 & 0 & 0\\ 0 & -\Delta & 0\\ 0 & 0 & -k\end{bmatrix}.$$

Because $2k - \Delta^2 > 0$, it can be thus proved that u_m is jointly concave in p_1, p_2, and τ. Then, the rest of the proof process is similar to that of Appendix A, so it is omitted.

Subsequently, we prove the second part of Lemma 5.

By the first partial derivatives of $P_1^{SM^{**}}$ with respect to θ_s and θ_m, we receive

$$\frac{\partial P_1^{SM^{**}}}{\partial\theta_s} = \frac{-(1-\theta_m)(a-c_n-c_0)}{2(2-\theta_s-\theta_m\theta_s)^2}, \quad \frac{\partial P_1^{SM^{**}}}{\partial\theta_m} = \frac{\theta_s(1-\theta_s)(a-c_n-c_0)}{2(2-\theta_s-\theta_m\theta_s)^2}.$$

Thus, $\frac{\partial P_1^{SM^{**}}}{\partial\theta_s} < 0$ and $\frac{\partial P_1^{SM^{**}}}{\partial\theta_m} > 0$ are proved. Recall the findings of Propositions 1 and 2 that $\frac{\partial P^{SM}}{\partial\theta_s} < 0$ and $\frac{\partial P^{SM}}{\partial\theta_m} > 0$, Lemma 5(ii) is proved because $P_2^{SM^{**}} = P^{SM}$.

Finally, the result of Observation 2 can be proved by comparing the first-order conditions of the selling prices of two periods regarding θ_s and θ_m. Since

$$\frac{\partial P_2^{SM^{**}}}{\partial\theta_s} - \frac{\partial P_1^{SM^{**}}}{\partial\theta_s} = \frac{-(1-\theta_m)(a-c_n-c_0)\Delta^2}{2(k\Delta-\Delta^2)(2-\theta_s-\theta_m\theta_s)^2} < 0$$

and

$$\frac{\partial P_2^{SM^{**}}}{\partial\theta_m} - \frac{\partial P_1^{SM^{**}}}{\partial\theta_m} = \frac{\theta_s(1-\theta_s)(a-c_n-c_0)\Delta^2}{2(k\Delta-\Delta^2)(2-\theta_s-\theta_m\theta_s)^2} > 0,$$

the result can be proved.