RESEARCH ARTICLE

Optimal decisions and Pareto improvement for green supply chain considering reciprocity and cost-sharing contract

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Abstract

With the rapid development of green consumption demand, more and more consumers choose to purchase green products. Incorporating consumers' environmental awareness into a green supply chain, this paper studies the decisions and coordination of the green supply chain under the retailer's reciprocal preference. The decentralized models with and without reciprocity are constructed and analyzed with consideration of product green degree and pricing. Then, the cost-sharing joint commission contract is proposed to realize Pareto improvement. Finally, propositions and conclusions are verified by numerical simulation. The results indicate that improving consumers' environmental awareness is favorable to the profit of the whole supply chain and environment. Besides, within the reasonable range of retailer's reciprocal preference, higher value of the retailer's reciprocal preference is conductive to the better realization of environmental protection and the improvement of the economic welfare of the whole society. The cost-sharing contract exerts a positive effect in improving the environmental and economic performance in the green supply chain (GSC). The paper provides a theoretical foundation for the design of cooperative contracts in the GSC, especially the GSC with retailer's reciprocal preference.

Introduction

With the aggravation of the global greenhouse effect, it is urgently necessary to achieve the emissions reduction targets (Lotfi et al. 2020). Consumer's increasing preference for green products is the primary incentive for enterprises

Highlights
• Both environmental preference and retailer's reciprocal preference are considered.
• Retailer's positive reciprocity is good for environment and supply chain.
• Channel profits can realize Pareto improvement by cost-sharing contract.
• Green products provide more value-add for the GSC system.

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to reduce carbon emissions (Mehrjerdi and Lotfi 2019; Banik et al. 2020). In recent years, a growing body of literature shows that consumer's awareness and preference of green products will affect their consume behavior and market demand (Aslani and Heydari 2019; Mehrbakhsh and Ghezavati 2020). As enterprises in the green supply chain (GSC) face a particular market demand, consumers tend to have low-carbon preferences (Xu et al. 2018; Tang et al. 2020). Faced with the double pressure of governmental controls on carbon emission and demand growth for green products, the core enterprises in the GSC take green transformation strategies, such as adopting advanced energy-saving and emission-reduction production technology, encouraging cooperators to participate in energy conservation and emission reduction, and stimulating consumer-facing retailers to strengthen the propaganda low-carbon products (Lotfi et al. 2017a, b). These strategies will lead to an increase in operating costs more or less and even a reduction in supply chain performance. Therefore, it is of great significance for enterprises to take consumers' environmental preference into account when making operational decisions.

The psychology of decision-makers is still a key issue in supply chain coordination. At present, a large number of research is based on the low-carbon supply chain, most of which assume that decision-makers are rational economic men (Xiao et al. 2020). However, a growing number of researches suggest that this assumption is at odds with reality. They propose the theories of finite rationality and illustrate that people have social preferences. A prime difference of finite rationality hypothesis model from rational hypothesis model is that decision-makers with social preferences target the maximum utility functions which include cooperators' profits and their profits, rather than just maximizing their profits. Reciprocal preference is one of the most critical social preferences, which is defined as an attitude of the decision-maker to "repay the kindness of others, revenge on the spite of others" (Fehr and Gächter 2000). In practice, many firms reward partners who are kind to them, even if they cannot foresee whether reciprocal behavior between firms will improve economic benefits. Enterprises' reciprocal preferences impact not only their own decisions but also cooperators' decisions in the GSC. For example, companies in a reciprocal social network tend to adopt kinder strategies, and any company adopting kind strategy can increase the efficiency of the whole supply chain (Xia et al. 2018). Furthermore, to reflect the realistic conditions truer, Xia et al. (2018) assume that the retailer has a reciprocal preference. In practice, it is usually the core enterprises in the GSC, namely manufacturers, that play leading roles in reducing carbon emissions. For instance, Huawei Technologies Co., Ltd., has cooperated with suppliers in energy conservation and emission reduction innovation, and actively participated in relevant industry organization activities and the formulation of relevant standards to build a GSC in an all-round way. This company has achieved a carbon emission reduction of about 450,000 t by 2018. Similarly, Dell works closely with Chinese suppliers to help them meet strict international standards in environmental protection and enhance competitiveness in the international environment. And it ranked second in the 2017 CITI index of green supply chain released by the Institute of Public and Environmental Affairs (IPE). However, the dominant manufacturer tends to decide the most self-interest way, such as deliberately improve the wholesale price or share the less environmental cost, which is not conducive to the long-term development of the GSC (Zhao et al. 2016). Therefore, the manufacturer needs to consider the reciprocity preference of retailers so that the retailer can better serve manufacturer's green transformation strategies. In this paper, we focus on a GSC in which the retailer wholesales green products from a manufacturer to meet consumers' demand for low-carbon products. More specifically, we focus on four issues: (1) How do players determine the optimal price of green products and emission abatement level in a GSC considering reciprocal preference? (2) How does consumers' environmental awareness influence management decisions in a GSC? Can green products provide more value-add for the GSC system? (3) How does retailer's reciprocal behavior affect environment, members' decision-makings, and their profits? (4) Can the channel profits realize Pareto improvement under the cost-sharing contract? Can a cost-sharing contract improve the environmental and economic performance in the GSC?

Motivated by the above issues, several analytical models are proposed under the framework of the Stackelberg game to obtain the optimal equilibrium in the GSC. Based on these equilibrium results, decision-makers can develop specific computer programs and introduce them to management information systems, then use mass data stored in the information system to predict model parameters, so as to realize the optimal pricing and emission-reduction scheme. For this purpose, we first develop two decentralized models based on whether the retailer has reciprocal preference. Then, we introduce the cost-sharing contract to investigate whether contracts can realize the Pareto improvement with and without the retailer's reciprocal preference. The backward induction method and the Kuhn-Tucker condition (KT condition) are used to solve the decision variables in our models. Our results lead to the creation of new operation and management perspectives for the decision-making and contract design in the GSC. The results show that both the emission abatement level and the profits of retailer and manufacturer increase with the consumer's environmental preference; thus, improving consumer environmental preference is beneficial to the construction of energy-saving society. In addition, we obtain a reasonable range of retailer's reciprocal preference. The results show that the higher value of the retailer's reciprocal preference can lead to improvement in environmental protection and economic welfare of the whole society within this reasonable range. Besides, the manufacturer can make more profit when the retailer is kind to him, while both the manufacturer and entire GSC would make less profit when the retailer takes a hostile attitude. Furthermore, we discuss the cost-sharing contract, especially focus on exploring how this contract affects optimal decisions and whether it can realize Pareto improvement. Interestingly, we find that the channel profits can realize Pareto improvement under certain conditions regardless of the presence of the retailer's reciprocal preference.

The remainder of the paper is organized as follows. The "Literature review" section presents the relevant literature. "The models" section introduces the problem description and assumptions, besides elaborating the basic models' formulation and solution. Subsequently, "The models" section introduces the contract mechanism to explore whether cost-sharing contract can improve the performance of GSC or achieve Pareto improvement. The "Numerical analysis" section presents some numerical examples to analyze the equilibrium in "The models" section by several numerical examples. The "Conclusions" section summarizes conclusions of our

work as well as proposes further research work direction of the related research.

Literature review

In this section, the most relevant topics and research (including three aspects) are presented that will help to continue the discussion. Table 1 lists part of the literature, which is the highly relevant to our research and shows our contributions.

Consumer environmental preference The first stream of literature studies consumer environmental preference in the supply chain. Chen et al. (2014) analyze the influence of consumer environmental preference on their purchase decisions, and conclude that the low-carbon awareness, wage levels, cultural diversity, and geographical position are influential in the consumer's purchase intentions. Wang et al. (2017) show that increasing consumer environmental preference makes them pay more attention to the carbon performance of products and even would like to shell out more money for green products. Hence, consumer environmental preference exerts influence on consumer's purchase intentions, which will affect enterprises' decision-making in turn. There are a couple of studies similar to that of Wang et al. (2017) as they all illustrate the effects of consumer environmental preference on the supply chain based on the demand of emission abatement level (see for example Ghosh and Shah 2012; Du et al. 2016; Zhao et al. 2016; Cui et al. 2017; Du et al. 2017). Ghosh and Shah (2012) investigate the influences of different power structures on pricing and emission-reduction decision. Du et al. (2016) present the effects of emissions and environmental preference on the production decisions in the carbon cap-and-trade system. Zhao et al. (2016) construct a remanufacturing model considering low-carbon preference

to achieve harmonious development of economy. Cui et al. (2017) study the selection model of remanufacturing quality and introduce a demand function of remanufactured products generated by environmental preference. The results show that the optimal decision relates to consumer environmental preference. In the findings of Du et al. (2017), the environmental performance of products in the low-carbon supply chain is studied, and price discount sharing is designed to achieve Pareto improvement. The above-cited work uses a similar linear demand function dependent on retail price and emission abatement level. However, we consider a GSC where both retailer's reciprocal preference and consumer environmental preference affect the channel decisions, rather than disregarding reciprocity as the existing literature does.

Reciprocal preference in the supply chain The previous literatures related to the reciprocal preference mainly involved two aspects. One aspect conducts various surveys and experimental games to prove that reciprocity exists and has a significant effect on human behavior. For instance, Fehr and Gächter (2000) show that individuals with reciprocal preferences are willing to make the material sacrifice to reward others who are kind to them and punish those who are not. The model of reciprocity can explain games such as the gift exchange game (Fehr et al. 1993), ultimatum game (Camerer and Thaler 1995), trust game (Camerer 2003), and mini-ultimatum game (Falk et al. 2003), while the widely studied fairness-based models cannot. Fehr et al. (1993) find that the employer will reciprocate with a generous remuneration package, and the employer expects reciprocity in return for a generous wage offer in the gift exchange game. Camerer and Thaler (1995) illustrate that responders continually reject low offers and always sanction defectors for unfair behavior, which is manifested as negative reciprocity in the ultimatum game. In Camerer (2003), there is a positive reciprocal relationship between the investor and the

Table 1 Highly related literatures

Research paper	Pricing strategy	Low-carbon preference	reciprocity	Cost-sharing
Aslani and Heydari (2019)	√	√		
Du et al. 2014	√		√	
Du et al. (2016)	√	√		
Du et al. (2017)	√	√		
Ghosh and Shah (2012)	√	√		
Ghosh and Shah (2015)	√	√		√
Wang and Shin (2015)	√			√
Wang et al. (2017)	√	√		√
Wang et al. (2017)	√	√		
Xia et al. (2018)	√	√	√	
Xiao et al. (2020)	√	√		√
Our paper	√	√	√	√

trustor in the absence of a formal contract or a perfect contract. The other aspect focuses on constructing various reciprocity models and putting reciprocal preference into the study of the supply chain. Many existing papers have proved that some social preference behaviors, especially fairness concerns (Chen et al. 2018; Liu et al. 2018), can affect supply chain's performances. Many contracts related to fairness concerns in these literatures have been proved to be able to achieve channel profits' Pareto improvement, while it is difficult to implement these contracts effectively in reality. Although the above works are not about reciprocity, they have an important reference value to this paper. A prime difference between the fairness-based model and the reciprocity-based model is that in the fairness-based model, the follower only punishes others if they are possible to reduce such unfairness. While in the reciprocity-based model, decision-makers reward or punish others based on their perceived kindness or spite (Du et al. 2014). In practice, large-scale automobile manufacturers with reciprocal preferences for suppliers, such as Toyota and GM, are not only committed to profit-maximization but also concerned about the profit of upstream suppliers. Therefore, a few scholars introduce reciprocal preference into the supply chain decision-making and further explore the performances of the supply chain (Du et al. 2014; Xia et al. 2018; Yan et al. 2017). Du et al. (2014) study the effects of reciprocal preferences on players' optimal decision-making by using the modeling quantitative analysis method. Xia et al. (2018) investigate a two-level low-carbon supply chain in the trading scheme considering reciprocity theory. Yan et al. (2017) propose the allocation game framework model under reciprocity. In our paper, the similar reciprocity theory and different contract design to study the optimal pricing and emission abatement problem in the GSC.

Cost-sharing contract in the supply chain Revenue-sharing and cost-sharing have been widely studied in related literature (Wang and Shin 2015) to encourage supply chain coordination. There are many papers similar to that of Wang and Shin (2015) because they all consider the cost-sharing contract in the non-green supply chain (see for example Cavusoglu et al. 2008; Chao et al. 2009; Frisk et al. 2010; Panda 2013). Cavusoglu et al. (2008) assume that cost-sharing may realize optimal social benefits even in the presence of information asymmetry. Chao et al. (2009) present that cost-sharing contract could raise the quality of the non-green product. Frisk et al. (2010) propose an allocation method in a collaborative forest transportation to achieve a balanced distribution of profits among participants. Compared with the revenue sharing contract, the cost-sharing contract proposed in Panda (2013) can effectively coordinate the two-level supply chain. Panda (2013) presents a cost-sharing contract that can effectively coordinate the two-level supply chain, while the revenue-sharing contract cannot. With the widespread

application of cost-sharing in reality, more and more academics start to study cost-sharing contracts in the field of the GSC. Faced with the low-carbon demand in the GSC, the retailers have the motivation to encourage manufacturers to take steps to reduce carbon emission and protect the environment (Jaber et al. 2013). The manufacturers make unique infinitely divisible green products and engage in emission reduction by adopting green technology, which could not only bring economic benefits and enhance enterprises' competitiveness but also increase investment costs (Xu et al. 2016). In the work of Wang et al. (2017), the cost-sharing contract is regarded as an effective coordinated mechanism under low-carbon behavior. We refer the reader to Ghosh and Shah (2015) for a recent review of practically implemented cost-sharing contract. The authors develop two cost-sharing models to compare and analyze performances of the supply chain. A similar cost-sharing contract enables us to research the influence of cost-sharing on the optimal decisions in the GSC considering the retailer's reciprocal preference.

The models

The paper focuses on a GSC considering reciprocity and cost-sharing contract. We consider a make-to-order production system in which the downstream retailer wholesales green products from an upstream manufacturer to satisfy environmentally friendly market demand. The inventory is not taken into account, and the information between supply chain members is assumed to be completely symmetric. Table 2 shows the notations that are used in the subsequent models. Figure 1 depicts the corresponding strategies of the five models proposed in this paper.

Based on practical considerations, we give the following three assumptions.

Assumption 1

The improvement of emission abatement level of low-carbon products affects the market demand function. As in the work of Tang et al. (2020), the manufacturer has a quadratic abatement cost function, which is a convex and increasing function with emission abatement level. So the manufacturer's cost function of investing emission abatement is expressed as $\beta\theta^2$, where β denotes the difficulty level of carbon emission abatement, and θ denotes emission abatement level of the manufacturer. In the actual situation, the cost of emission abatement is diseconomies of scale for green technology (Mehrbakhsh and Ghezavati 2020), which means huge losses of profits. Therefore, we have to ensure that the difficulty level of emission abatement is high enough to reduce the loss of profits. Following Xiao et al. (2020), we give the assumption of $e^2 < 4b\beta$ to keep the existence of optimal

Table 2 Concept of parameters

|	Notation	Definition
Parameter	a	The total market potential, $a>bp>0$
	b	Price elasticity of demand, $b>0$
	c	Manufacturer's variable cost of production, $c>0$
	e	Consumer's environmental preference, $e>0$
	D	Actual market demand
	β	The investment coefficient of emission abatement, $\beta>0$
	π_i	Profit, $i\in\{m,r,\mathrm{sc}\}$ refers to manufacturer, retailer, and supply chain
	γ_r	Retailer's reciprocal preference, $-1<\gamma_r<1$
	U_r	Retailer's utility
Decision variable	p	Retail price for unit product
	θ	Emission abatement level, $\theta>0$
	w	Wholesale price for unit product, $p>w>c$
	ϕ	Retailer's cost-sharing ratio of emission reduction, $\phi\in(0,1)$

solutions, besides, the values of total market potential a and the investment coefficient of emission abatement β are far higher than other parameters in this paper.

Assumption 2

The green supply chain faces the oligopoly market of single low-carbon product, and each member is risk-neutral. The manufacturer strengthens reduction efforts of carbon emission by adopting various green measures, such as using green raw materials and applying clean manufacturing technology, to meet consumer demand for green products. The unique manufacturer is directly exposed to the pressure of emission reduction, and the emission abatement level of manufacturer immediately affects the carbon emissions. According to Xu et al. (2018), we assume that the manufacturer bears the whole emission abatement cost without cooperative contracts, and retailer's carbon emissions are neglected. Given that cost-sharing contract plays a critical role in encouraging the manufacturer to participate in the green channel (Ghosh and Shah 2015; Yang and Chen 2018), we assume that the retailer determines a ratio of sharing emission abatement cost, namely φ. Under the cost-sharing contract, the retailer's abatement cost is $\phi\beta\theta^2$, and the manufacturer's abatement cost is $(1-\phi)\beta\theta^2$, where $0<\phi<1$.

Fig. 1 The corresponding strategies of the five models
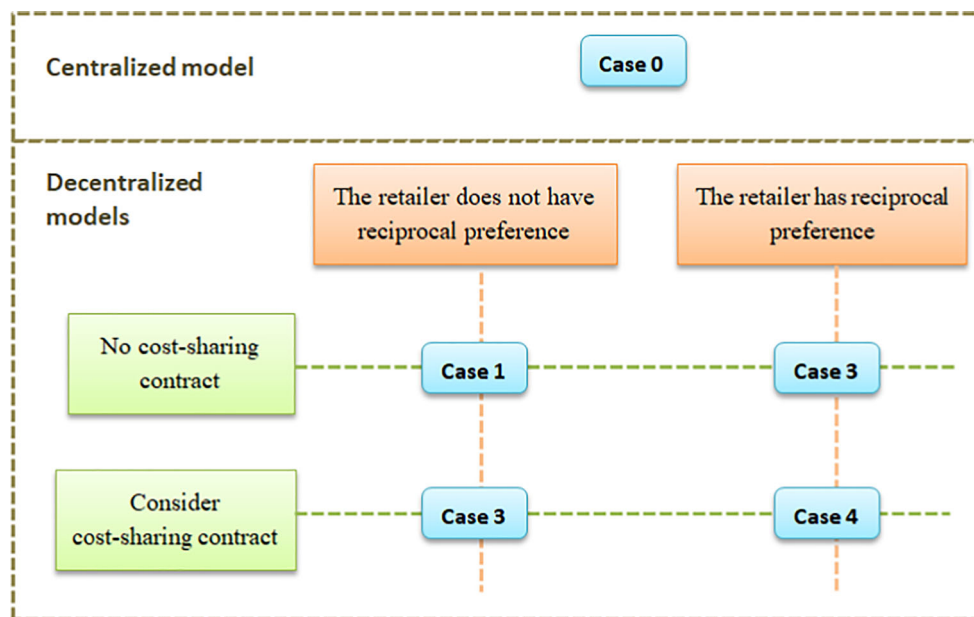
Assumption 3

Consumers have low-carbon preferences and the market demand is related to retail price and emission abatement level. Demand function is linearly correlated with emission abatement level and negatively linearly related to the retail price. Following Xia et al. (2018), the demand function is characterized as $D = a - bp + e\theta$, where a is the total market potential, b is the price elasticity of demand, and e denotes consumer's environmental preference and the extent to which demand responds to changes in the emission abatement level. The higher e is, the more willing consumers are to buy low-carbon products and the more insensitive demand function is to the retail price.

Case 0: Benchmark model

In this scenario, the retailer and manufacturer under the centralized decision-making are considered as a centralized system. This is an ideal model that is practically impossible to implement, as all the participants are committed to maximizing their profits. However, the achieved result by this model can serve as a benchmark for the following decentralized models. We index this case by superscript B. The whole supply chain's objective function with constraints is:

$$\max_{p^B > c, 0 < \theta^B < 1} \pi_{sc}^B = \max_{p^B, \theta^B} \left[(p^B - c)D - \beta(\theta^B)^2 \right] \quad (1)$$

By Eq. (1), we can derive the Hessian matrix of π_{sc}^C with respect to p^C and θ^C:

$$H_1 = \begin{bmatrix} \dfrac{\partial^2 \pi_{sc}^B}{\partial p^{B2}} & \dfrac{\partial^2 \pi_{sc}^B}{\partial p^B \partial \theta^B} \\ \dfrac{\partial^2 \pi_{sc}^B}{\partial \theta^B \partial p^B} & \dfrac{\partial^2 \pi_{sc}^B}{\partial \theta^{C2}} \end{bmatrix} = \begin{bmatrix} -2b & e \\ e & -2\beta \end{bmatrix}.$$

In real-life, $b\beta$ is much bigger than e, then we can derive that H_1 is negative definite; thus, the GSC's profit function is jointly concavity for the above decision variables. Therefore, the optimal solutions for Eq. (1) exist. Next, we can derive this optimal solution with the Kuhn-Tucker condition (KT condition), and the optimal decisions can be derived from equating the first derivatives concerning p^B and θ^B to zero. The optimal solutions and profit of GSC are $p^{B*} = \frac{ce^2 - 2a\beta - 2bc\beta}{e^2 - 4b\beta}$, $\theta^{B*} = (-a + bc) \frac{e}{e^2 - 4b\beta}, \pi_{sc}^{B*} = (a - bc) \frac{2\beta}{-e^2 + 4b\beta}$.

Case 1: Decentralized model without the retailer's reciprocal preference

In this case, the retailer has no reciprocal preference. Both the retailer and manufacturer are completely rational and in

pursuit of the maximum profits (Lotfi et al. 2017a). Supposing the manufacturer is the leader and bears all emission abatement cost, we solve the optimal decisions by the backward induction method.

The sequence of events in the following decentralized games is in the first stage; the manufacturer makes decisions of the emission abatement level (θ) and wholesale price (w). In the second stage, the retailer determines the retail price (p) based on the manufacturer's decisions in the first stage. Then, the market demand and the profits of each member are realized. Figure 2a depicts the decision process.

We propose a Stackelberg game model to study the management decisions with no reciprocal preference, which lays a foundation for the research later in this section. We index case 1 by superscript N. The objective functions of each player are stated as follows:

$$\max_{w^N > c, 0 < \theta^N < 1} \pi_m^N = \max_{w^N > c, 0 < \theta^N < 1} \left[(w^N - c)D - \beta(\theta^N)^2 \right] \quad (2)$$

$$\max_{p^N > w^N} \pi_r^N = \max_{p^N > w^N} \left[(p^N - w^N)D \right] \quad (3)$$

The optimal solutions can be obtained by backward induction method. Firstly, we can derive the retailer's optimal response function from the first-order condition for $p^{N*} = (a + bw + e\theta)/2b$. Then, the manufacturer maximizes its profit based on p^{N*}. Substituting p^{N*} into Eq. (2). The Hessian matrix with respect to w and θ is:

$$H_2 = \begin{bmatrix} \dfrac{\partial^2 \pi_m^N}{\partial w^{N2}} & \dfrac{\partial^2 \pi_m^N}{\partial w^N \partial \theta^N} \\ \dfrac{\partial^2 \pi_m^N}{\partial \theta^N \partial w^N} & \dfrac{\partial^2 \pi_m^N}{\partial \theta^{N2}} \end{bmatrix} = \begin{bmatrix} -b & \dfrac{e}{2} \\ \dfrac{e}{2} & -2\beta \end{bmatrix}.$$

According to the "Case 0: Benchmark model" section, we derive $e^2 < 8b\beta$, so H_2 Hessian matrix is negative definite. Then we can derive the optimal decisions of the manufacturer by equating the first derivatives concerning w^N and θ^N to zero. The equilibrium solutions of decision variables in case 1 are $p^{N*} = \frac{ce^2 - 6a\beta - 2bc\beta}{e^2 - 8b\beta}$, $w^{N*} = \frac{-ce^2 + 4a\beta + 4bc\beta}{-e^2 + 8b\beta}$, and $\theta^{N*} = (-a + bc) \frac{e}{e^2 - 8b\beta}$. The players' optimal profits are $\pi_m^{N*} = (a - bc) \frac{2\beta}{-e^2 + 8b\beta}$ and $\pi_r^{N*} = 4b(a\beta - bc\beta) \frac{2}{(e^2 - 8b\beta)^2}$. The entire profit of the GSC is $\pi_{sc}^{N*} = (a - bc) \frac{2\beta(-e^2 + 12b\beta)}{(e^2 - 8b\beta)^2}$.

Proposition 1 The optimal decisions (p^{N*}, w^{N*} and θ^{N*}) and the optimal profits (π_m^{N*}, π_r^{N*} and π_{sc}^{N*}) are increasing with the consumer environmental preference (e).

We can derive these relationships from the algebraic calculation of the corresponding first-order conditions. Proposition 1 implies that consumers' environmental preference pushes the manufacturer to increase emission-reduction efforts. Intriguingly, the retail price, wholesale price, and emission-
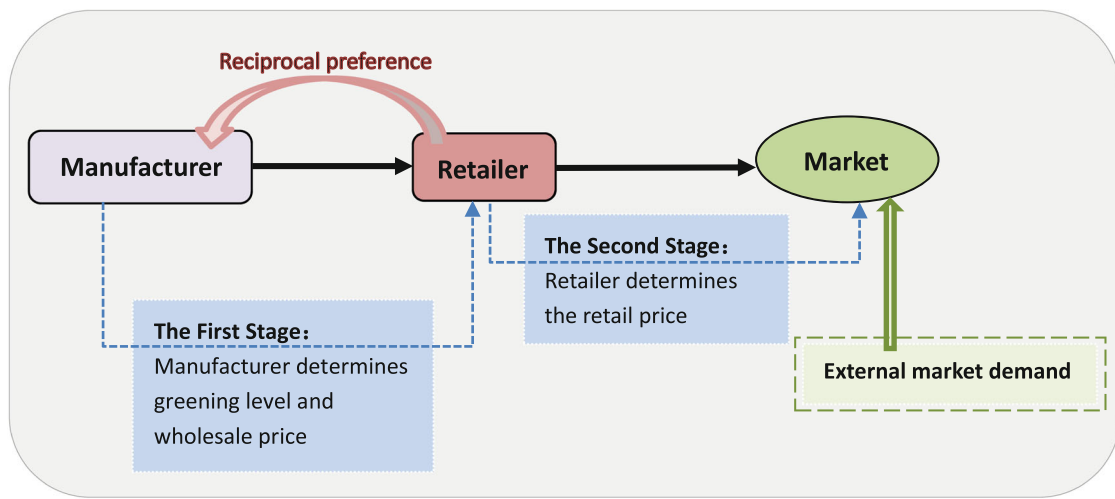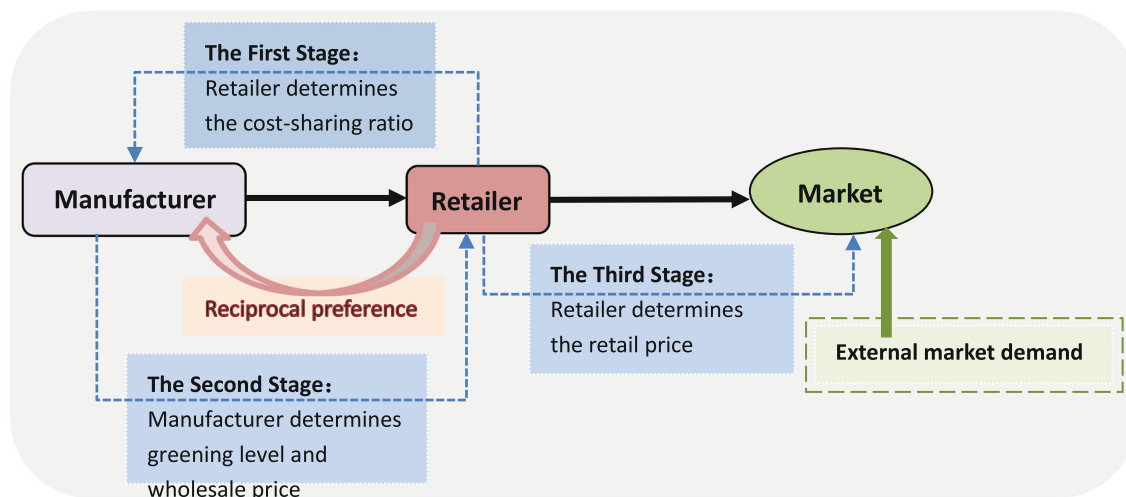
Fig. 2 Decision process. **a** Two-stage decision process. **b** Three-stage decision process under cost-sharing contract

reduction level increase with consumer environmental preference. Consumer's low-carbon awareness affects demand as well as the profits of channel members. Both the retailer's and manufacturer's profits increase with the consumer's environmental preference, so the GSC's profit also increases. Thus, improving consumer environmental preference is favorable to the construction of resource service–oriented and environmentally friendly society. How to improve consumers' awareness of protecting the environment will be a major challenge facing the national environmental administrations.

Case 2: Decentralized model with the retailer's reciprocal preference

The theory of self-interest is often proved to be contradictory in human's decision-making process. To deal with these contradictions, economists have tried to reconstruct utility functions that can explain human's behavior. Frequently studied fairness concerns are defined over outcomes, while the reciprocity highlights both outcomes and human beliefs about the individual intentions or types of people they deal with (Loch and Wu 2008).

If the retailer in the GSC has the reciprocal preference, then the retailer takes the manufacturer's profit into his/her utility and aims to maximize the utility function. The retailer's utility function is expressed as $U_r = \pi_r + \gamma_r * \pi_m$, where γ_r is the retailer's reciprocal preference parameter, and it denotes the retailer's extent of reciprocity to the manufacturer. The range of values of γ_r is −1 to 1 and does not include 0. Especially, $\gamma_r = 0$ means that the retailer has no reciprocal preference, which is similar to the model in case 1. Importantly, if $0 < \gamma_r \leq 1$, the retailer has positive reciprocity behavior and is kind to the manufacturer. A higher γ_r implies a greater reciprocal preference of the retailer for the manufacturer's profit. On the contrary, $-1 \leq \gamma_r < 0$ indicates that the retailer has negative reciprocity behavior and shows hostility to

the manufacturer, and a higher γ_r implies a smaller reciprocal preference of the retailer for the manufacturer's profit. Besides, the manufacturer who has no reciprocal preference aims to maximize the profit function. We index this case by superscript Y. The player's objective functions are:

$$\max_{w^Y>c,0<\theta^Y<1} \pi_m^Y = \max_{w^Y>c,0<\theta<1} \left[(w^Y-c)D-\beta(\theta^Y)^2 \right] \quad (4)$$

$$\max_{p^Y>w^Y} U_r^Y = \max_{p^Y>w^Y} \left\{ (p^Y-w^Y)D + \gamma_r \left[(w^Y-c)D-\beta(\theta^Y)^2 \right] \right\} \quad (5)$$

We substitute the best retailer's response function $p^{Y*} = (a + bw + e\theta + b(c-w)\gamma_r)/2b$ into Eq. (4). The Hessian matrix with respect to w^Y and θ^Y is:

$$H_3 = \begin{bmatrix} \dfrac{\partial^2 \pi_m^Y}{\partial w^{Y2}} & \dfrac{\partial^2 \pi_m^Y}{\partial w^Y \partial \theta^Y} \\ \dfrac{\partial^2 \pi_m^Y}{\partial \theta^Y \partial w^Y} & \dfrac{\partial^2 \pi_m^Y}{\partial \theta^{Y2}} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{2}(-2b + 2b\gamma_r) & \dfrac{e}{2} \\ \dfrac{e}{2} & -2\beta \end{bmatrix}$$

$e^2 < 8b\beta(1 - \gamma_r)$ is assumed to ensure that this model has an optimal solution. Then the optimal decisions of the manufacturer can be derived by equating the first derivatives concerning w^Y and θ^Y to zero. The equilibrium solutions of decision variables in case 2 are $p^{Y*} = -6a\beta + c(e^2-2b\beta) + 2(3a + bc) \dfrac{\beta\gamma_r}{e^2-8b\beta+8b\beta\gamma_r}$, $w^{Y*} = c-4(ae-bce) \dfrac{\beta}{e(e^2-8b\beta+8b\beta\gamma_r)}$, $\theta^{Y*} = -\dfrac{ae-bce}{e^2-8b\beta+8b\beta\gamma_r}$. The optimal profits are $\pi_m^{Y*} = -(a-bc) \dfrac{^2\beta}{e^2-8b\beta+8b\beta\gamma_r}$, $\pi_r^{Y*} = 4b(a-bc) \, ^2\beta^2(-1 + \gamma_r) \dfrac{(-1+3\gamma_r)}{(e^2-8b\beta+8b\beta\gamma_r)} \, ^2$ and $\pi_{sc}^{Y*} = (a-bc) \dfrac{^2\beta(-e^2+12b\beta-24b\beta\gamma_r+12b\beta\gamma_r^2)}{(e^2-8b\beta+8b\beta\gamma_r)} \, ^2$.

Theorem 1 The reasonable range of the retailer's reciprocal preference is $\Omega_r^Y = \{\gamma_r | -1 \le \gamma_r < 0 \text{ and } 0 < \gamma_r \le 1/3 \}$.

We derive Ω_r^Y from the inequality $p^Y - w^Y = [2(a - bc)\beta(-1 + 3\gamma_r)]/[e^2 - 8b\beta + 8b\beta\gamma_r] \ge 0$. The manufacturer is the market leader and is in a competitive position, the minimum for the retailer to participate in the cooperation with the manufacturer is to profit from it.

The manufacturer is the market leader and in a competitive position. As a follower, the retailer hopes to profit from cooperating with the manufacturer. The reasonable range of the retailer's reciprocal preference (Ω_r^Y) is a mutually beneficial area for the manufacturer and retailer to maintain stability. The following propositions in case 2 are based on this reasonable range.

Proposition 2 In case 2, the optimal decisions (p^{Y*}, w^{Y*} and θ^{Y*}) and the optimal profits (π_m^{Y*}, π_r^{Y*} and π_{sc}^{Y*}) are increasing with the consumer's environmental preference (e).

This relationship can be derived from the algebraic calculation of the first-order partial conditions. Interestingly, the

relationship is similar to that of proposition 1. Proposition 2 means that the consumers' low-carbon conscious make them prefer to afford additional payment for green products, regardless of whether the retailer has reciprocal preference. If consumers are more green-minded, greater emission abatement could affect market demand. Meanwhile, emission abatement level, members' profit, and GSC's profit tend to rise with consumers' environmental preference.

Proposition 3 The optimal decisions (p^{Y*}, w^{Y*} and θ^{Y*}), manufacturer's profit (π_m^{Y*}) and GSC's profit (π_{sc}^{Y*}) are increasing with the retailer's reciprocal preference parameter (γ_r).

Proposition 3 means that within the reasonable range of the retailer's reciprocal preference (Ω_r^Y), the retailer's reciprocal preference can be an effective incentive for the manufacturer to do more to reduce carbon emissions. Interestingly, the retail price, wholesale price, and emission abatement level increase with the retailer's reciprocal preference. To encourage the manufacturer to make efforts to enhance emission abatement level, the retailer needs to show more kindness to him. This means that the manufacturer's profit has a greater impact on the retailer's utility. The retailer's reciprocal concern not only affects the low-carbon market demand but also affects manufacturer's profit and GSC's profit. More specifically, the profits of manufacturer and GSC increase with retailer's reciprocal preference. Therefore, the increasing reciprocal concern of the retailer is beneficial to the GSC within the reasonable range (Ω_r^Y). The realization of environmental protection and the improvement of economic welfare of the whole society would benefit greatly by the high-value retailer reciprocal preference. In particular, the closer γ_r is to the maximum value of 1/3, the larger the optimal decisions and GSC's profit will be in case 2.

Proposition 4 Within the reasonable range of retailer's reciprocal preference (Ω_r^Y), the comparison results of optimal decisions in case 1 and case 2 are:

(i) if $\gamma_r < 0$, we have $\theta^{Y*} < \theta^{N*}, w^{Y*} < w^{N*}, p^{Y*} < p^{N*}, \pi_m^{Y*} < \pi_m^{N*}, \pi_r^{Y*} > \pi_r^{N*}, \pi_{sc}^{Y*} < \pi_{sc}^{N*}$;

(ii) if $0 < \gamma_r \le 1/3$, we have $\theta^{Y*} > \theta^{N*}, w^{Y*} > w^{N*}, p^{Y*} > p^{N*}, \pi_m^{Y*} > \pi_m^{N*}, \pi_r^{Y*} < \pi_r^{N*}, \pi_{sc}^{Y*} > \pi_{sc}^{N*}$.

Proposition 4 means that the retailer would make the manufacturer more profitable if the retailer is kind to the manufacturer ($0 < \gamma_r \le 1/3$). By contrast, if the retailer is mean to the manufacturer ($-1 \le \gamma_r < 0$), the manufacturer and GSC would gain less profit. Especially, when the retailer shows positive reciprocal concern to the cooperator, he/she is willing to sacrifice own interest to improve the manufacturer's profit, which can also enhance the entire GSC's profit. Hence, as a leader,

the manufacturer tends to collaborate with a retailer who has a positive reciprocal preference.

Proposition 5 Within the reasonable range of retailer's reciprocal preference (Ω_r^Y), the optimal emission abatement level and GSC's profit in the benchmark are greater than those in the decentralized cases (case 1 and case 2), that is: $\pi_{sc}^{B*} > \pi_{sc}^{Y*}$, $\pi_{sc}^{B*} > \pi_{sc}^{N*}, \theta^{B*} > \theta^{Y*}, \theta^{B*} > \theta^{N*}$.

Proposition 5 indicates that the centralized model is an ideal case, as both emission abatement level and GSC's profit in such a case are larger than those of the other two decentralized cases. This also explains why this paper uses centralized model as a benchmark to help us characterize equilibrium decisions. However, in reality, enterprises do not make decisions based on the goal of maximizing the profit of the entire GSC. The differences of enterprises' goals lead to an inability to reach the ideal state in the benchmark, namely, supply chain maladjustment. Although it cannot achieve the optimal decisions of the centralized case, enterprises can adopt effective cooperative contracts, which will be a promising way to approach it infinitely. Therefore, next, we will introduce the contract mechanism to further explore whether cost-sharing contract can improve performance of the GSC or achieve Pareto improvement in the above decentralized models.

Case 3: Cost-sharing contract without the retailer's reciprocal preference

The above cases illustrate the GSC's performance with and without retailer's reciprocal preference. In this section, we will introduce the contract mechanism to explore whether cost-sharing contract can improve performance of GSC or achieve Pareto improvement in the decentralized models. According to Xu et al. (2016), the cost-sharing contract can coordinate the supply chain with environment-concerned consumers and plays a significant role in encouraging the manufacturer to participate in the green channel. Therefore, we propose a cost-sharing contract in the GSC where the retailer shares investment cost of emission abatement. Contract analysis is important in this section. More importantly, we need to determine whether the retailer benefits from this cost-sharing contract. The following models reflect the collaborative development of low-carbon products. Figure 2b describes the decision process with the cost-sharing contract. The sequence of the game to understand the cost-sharing contract:

Step 1: The retailer sets a cost-sharing ratio (ϕ), then the retailer's abatement cost and manufacturer's abatement cost can be obtained as $\phi\beta\theta^2$ and $(1-\phi)\beta\theta^2$, respectively.

Step 2: The manufacturer determines the emission abatement level (θ) and wholesale price (w) based on the new abatement cost functions in Step 1.

Step 3: Finally, the retailer decides the retail price (p) based on the emission abatement level and wholesale price in STEP-2.

Under the above game sequence, the optimal decisions in two cases can be derived.

In this case, players are completely rational and pursue maximum profits. We index this case by superscript NS. The objective functions of each player can be described as follows:

$$\max_{w^{NS}>c,0<\theta^{NS}<1} \pi_m^{NS}$$

$$= \max_{w^{NS}>c,0<\theta^{NS}<1} \left[(w^{NS}-c)D-(1-\phi)\beta\,\theta^{NS2} \right] \quad (6)$$

$$\max_{p^{NS}>w^{NS}} \pi_r^{NS} = \max_{p^{NS}>w^{NS}} \left[(p^{NS}-w^{NS})D-\phi\beta\theta^{NS2} \right] \quad (7)$$

By substituting the best retailer's response $p^{NS*} = (a + bw^{NS} + e\theta^{NS} + b(c - w^{NS})\gamma_r)/2b$ into Eq. (6), the Hessian matrix with respect to w^{NS} and θ^{NS} can be expressed as:

$$H_4 = \begin{bmatrix} \dfrac{\partial^2 \pi_m}{\partial w^{NS2}} & \dfrac{\partial^2 \pi_m}{\partial w^{NS}\partial\theta^{NS}} \\ \dfrac{\partial^2 \pi_m}{\partial\theta^{NS}\partial w^{NS}} & \dfrac{\partial^2 \pi_m}{\partial\theta^{NS2}} \end{bmatrix} = \begin{bmatrix} -b & \dfrac{e}{2} \\ \dfrac{e}{2} & 2\beta(-1+\phi) \end{bmatrix}.$$

We assume $3e^2 - 16b\beta < 0$ to ensure the existence of optimal solutions. By first-order conditions, the optimal solutions can be derived as $p^{NS*} = \frac{3ae^2+9bce^2-48ab\beta-16b^2c\beta}{12be^2-64b^2\beta}$, $w^{NS*} = a(e^2-16b\beta)\frac{+bc(5e^2-16b\beta)}{6be^2-32b^2\beta}$, $\theta^{NS*} = 2(a-bc)\frac{e}{-3e^2+16b\beta}$. Then, we substitute above optimal solutions to Eq. (7). Since $d^2\pi_r^{NS}/d\phi^2 = 8b(a-bc)\frac{2e^2\beta^2(-5e^2+16b\beta(1+2\phi))}{-(e^2+8b\beta(-1+\phi))}4 < 0$, the optimal cost-sharing ratio exists. We derive $\phi^{NS*} = \frac{e^2}{16b\beta}$ by the first-order condition.

Substituting the optimal decisions into Eq. (6) and Eq. (7), we can derive the optimal profits $\pi_m^{NS*} = (a-bc)\frac{2(-e^2+16b\beta)}{8b(-3e^2+16b\beta)}$, $\pi_r^{NS*} = (a-bc)\frac{2(e^2+16b\beta)}{16b(-3e^2+16b\beta)}$ and $\pi_{sc}^{NS*} = (a-bc)\frac{2(-e^2+48b\beta)}{16b(-3e^2+16b\beta)}$.

Proposition 6 The optimal decisions (p^{NS*}, w^{NS*}, θ^{NS*} and ϕ^{NS*}) and the optimal profits (π_m^{NS*}, π_r^{NS*} and π_{sc}^{NS*}) increase with consumer environmental preference (e).

The above relationships can be derived from the algebraic calculation of the first-order partial conditions. Interestingly, the relationship in proposition 6 is similar to that of proposition 1 and proposition 2. This means consumers' strong low-carbon preference consciousness can also be beneficial to environmental protection and

Table 3 Numerical example of parameters in the "Influence of retailer's reciprocal preference" section

Parameter	Values
The total market potential	$a=1500$
Price elasticity of demand	$b=20$
Manufacturer's variable cost of production	$c=10$
Consumer's environmental preference	$e=80$
The investment coefficient of emission abatement	$\beta=100$

supply chain interests even considering the cost-sharing contract.

Proposition 7 The optimal decision variables and profits in case 3 are greater than those in case 1, thus $\theta^{NS*} > \theta^{N*}$, $w^{NS*} > w^{N*}$, $p^{NS*} > p^{N*}$, $\pi_m^{NS*} > \pi_m^{N*}$, $\pi_r^{NS*} > \pi_r^{N*}$, $\pi_{sc}^{NS*} > \pi_{sc}^{N*}$;

the optimal emission abatement level and GSC's profit in the benchmark are greater than those in the case 3, thus $\theta^{NS*} < \theta^{B*}$, $\pi_{sc}^{NS*} < \pi_{SC}^{B*}$.

Proposition 7 demonstrates the cost-sharing contract makes for higher emission abatement level than the decentralized channel of case 1; that is, the cost-sharing contract can promote environmental protection. Interestingly, both the retailer and

Table 4 Equilibrium solutions and profits in different cases

Model	ϕ^*	p^*	θ^*	w^*	π_m^*	π_r^*	π_{sc}^*
Centralized case	–	172.5	65	–	–	–	105625
Case 1	–	91.25	10.83	64.17	17604.2	14670.1	32274.3
Case 2							
$\gamma_r=-1$	–	70.93	4.06	30.31	6601.56	16503.9	23105.5
$\gamma_r=-0.8$	–	72.68	4.64	33.21	7544.64	16490.4	24035.1
$\gamma_r=-0.6$	–	75	5.42	37.08	8802.08	16430.6	25232.6
$\gamma_r=-0.4$	–	78.25	6.5	42.5	10562.5	16266.2	26828.7
$\gamma_r=-0.2$	–	83.13	8.13	50.63	13203.1	15843.8	29046.9
$\gamma_r=0.03$	–	92.96	11.40	67.02	18530.7	14348.3	32879
$\gamma_r=0.06$	–	94.86	12.04	70.19	19560.2	13960.2	33520.4
$\gamma_r=0.09$	–	96.99	12.75	73.73	20710.8	13488.4	34199.2
$\gamma_r=0.12$	–	99.38	13.54	77.71	22005.2	12909.7	34914.9
$\gamma_r=0.15$	–	102.08	14.44	82.22	23472.2	12192.5	35664.5
$\gamma_r=0.18$	–	105.18	15.48	87.38	25148.8	11293	36441.8
Case 3	0.2	107.5	16.25	75	21125	15843.8	36968.8
Case 4							
$\gamma_r=-1$	0.6	107.5	16.25	42.5	10562.5	26406.3	36968.8
$\gamma_r=-0.8$	0.56	107.5	16.25	46.11	11736.1	25232.6	36968.8
$\gamma_r=-0.6$	0.5	107.5	16.25	50.63	13203.1	23765.6	36968.8
$\gamma_r=-0.4$	0.43	107.5	16.25	56.43	15089.3	21879.5	36968.8
$\gamma_r=-0.2$	0.33	107.5	16.25	64.17	17604.2	19364.6	36968.8
$\gamma_r=0.03$	0.18	107.5	16.25	77.01	21778.4	15190.4	36968.8
$\gamma_r=0.06$	0.15	107.5	16.25	79.15	22473.4	14495.3	36968.8
$\gamma_r=0.09$	0.12	107.5	16.25	81.43	23214.3	13754.5	36968.8
$\gamma_r=0.12$	0.09	107.5	16.25	83.86	24005.7	12963.1	36968.8
$\gamma_r=0.15$	0.06	107.5	16.25	86.47	24852.9	12115.8	36968.8
$\gamma_r=0.18$	0.02	107.5	16.25	89.27	25762.2	11206.6	36968.8

Note: γ_r denotes the retailer's reciprocal preference parameter; ϕ^* represents the optimal retailer's cost-sharing ratio of emission reduction; p^* is the optimal retail price for unit product; θ^* denotes the optimal emission abatement level; w^* is the optimal wholesale price for unit product; π_i^* is the optimal profit; $i \in \{m, r, sc\}$ refer to manufacturer, retailer, and supply chain
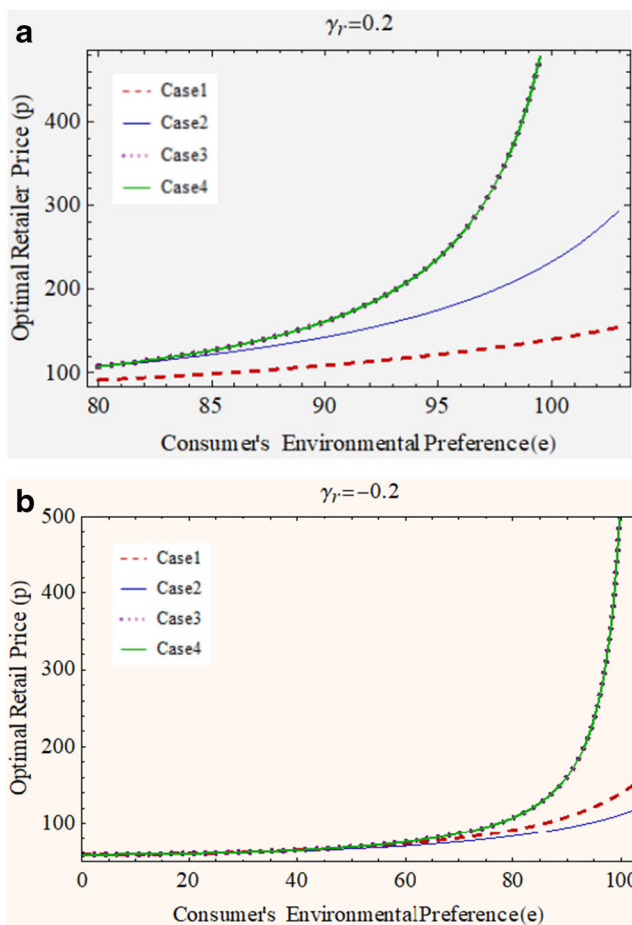
Fig. 3 Influence of e on p. **a** $\gamma_r = 0.2$. **b** $\gamma_r = -0.2$

manufacturer in case 3 make higher profits than those of the decentralized GSC in case 1. The manufacturer benefits from the abatement cost-sharing of the retailer. The main reason is that the manufacturer can improve the greening level when the abatement costs are lowered. Importantly, the retailer though bears a portion of the abatement costs makes a higher profit than that of the decentralized channel in case 1, which helps explain why the retailer enters into this cost-sharing contract. More importantly, sharing responsibility for reducing emission with manufacturer can improve profits for each participant and the entire GSC, which indicates that both of them can achieve Pareto improvement through the cost-sharing contract without considering retailer's reciprocal preference. The above results serve as reminders to managers and policymakers to establish reasonable incentives for the GSC.

Case 4: Cost-sharing contract with the retailer's reciprocal preference

To further explore whether members can achieve Pareto improvement through the cost-sharing contract, we focus on a cost-sharing contract with the retailer's reciprocal preference. We first illustrate the necessary and sufficient conditions for

Pareto improvement in a GSC considering the retailer's reciprocal preference. Next, we investigate how a cost-sharing contract that realizes Pareto improvement affects GSC's performances. The retailer aims to maximize the utility function, while the manufacturer pursues the maximum profit. We index this case by superscript YS. The player's objective functions are:

$$\max_{w^{YS}>c,0<\theta^{YS}<1} \pi_m^{YS}$$

$$= \max_{w^{YS}>c,0<\theta^{YS}<1} \left[(w^{YS}-c)D-(1-\phi)\beta(\theta^{YS})^2 \right] \quad (8)$$

$$\max_{p^{YS}>w^{YS}} U_r^{YS}$$

$$= \max_{p^{YS}>w^{YS}} \left\{ (p^{YS}-w^{YS})D-\phi\beta(\theta^{YS})^2 + \gamma_r \left[(w^{YS}-c)D-(1-\phi)\beta(\theta^{YS})^2 \right] \right\} \quad (9)$$

By substituting the best retailer's response $p^{YS*} = (a + bw^{YS} + e\theta^{YS} + b(c - w^{YS})\gamma_r)/2b$ into Eq. (8), the optimal emission abatement level and wholesale price can be solved. The Hessian matrix with respect to w^{YS} and θ^{YS} is:
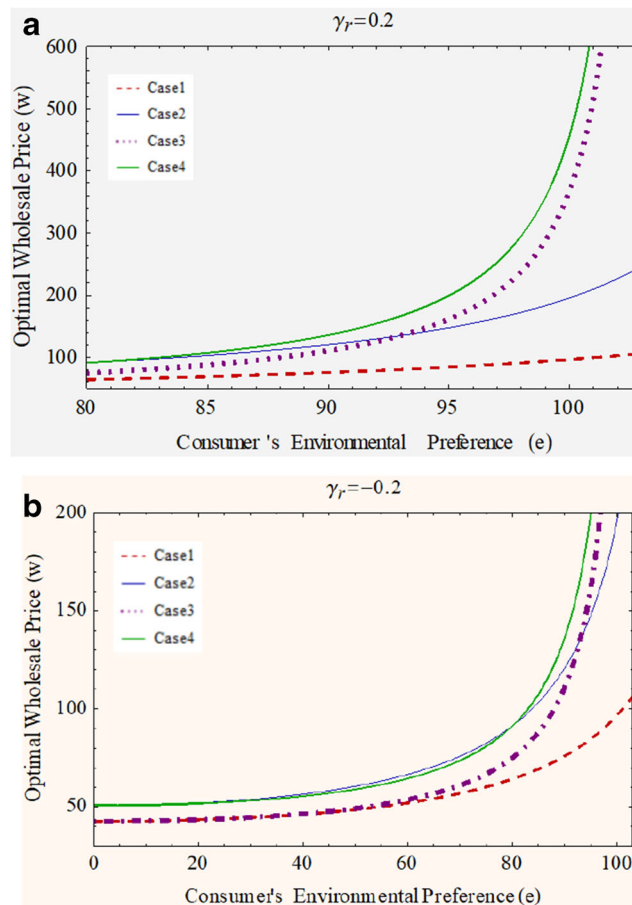

Fig. 4 Influence of e on w. **a** $\gamma_r = 0.2$. **b** $\gamma_r = -0.2$
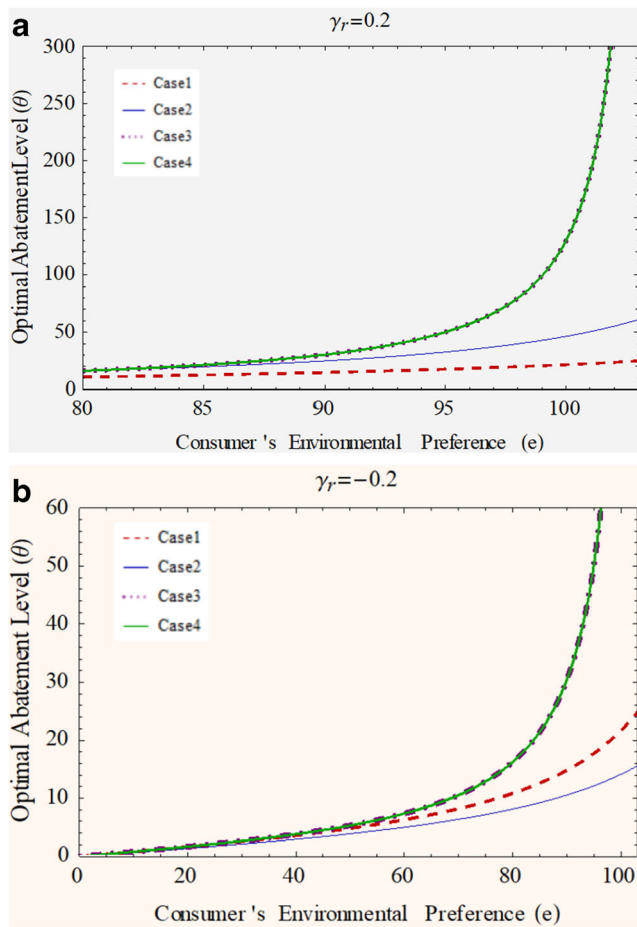
Fig. 5 Influence of e on θ. **a** $\gamma_r = 0.2$. **b** $\gamma_r = -0.2$

$$H_5 = \begin{bmatrix} \dfrac{\partial^2 \pi_m^{YS}}{\partial(w^{YS})^2} & \dfrac{\partial^2 \pi_m^{YS}}{\partial w^{YS} \partial \theta^{YS}} \\ \dfrac{\partial^2 \pi_m^{YS}}{\partial \theta^{YS} \partial w^{YS}} & \dfrac{\partial^2 \pi_m^{YS}}{\partial(\theta^{YS})^2} \end{bmatrix} = \begin{bmatrix} b\gamma_r & \dfrac{e}{2} \\ \dfrac{e}{2} & 2\beta(1-\phi) \end{bmatrix},$$

Under the assumption of $e^2 < 8b\beta(1-\phi)(1-\gamma_r)$, the Hessian matrix is negative definite; thus the decentralized model has the optimal solutions. We derive the optimal retail price and emission abatement level by equaling the first derivatives concerning to 0. Then, we substitute the optimal decision above to Eq. (9). The retailer's utility function U_r^{YS} is concave in ϕ if the second-order condition $d^2 U_r^{YS}/d\phi^2 = 5 e^2 - 16b\beta(1+2\phi) + 32b\beta(-1+\phi)\gamma_r < 0$ is satisfied. The optimal cost-sharing ratio ϕ^{YS*} can be derived from setting the first-order condition equal to 0. Especially, we can get the necessary condition $3e^2 < 16b\beta$, which ensures the existence of the optimal decisions, by substituting the optimal cost-sharing proportion ϕ^{YS*} into $e^2 < 8b\beta(1-\phi)(1-\gamma_r)$ and $d^2 U_r^{YS}/d\phi^2 < 0$, the optimal solutions in this case can be calculated as: $w^{YS*} = a(e^2-16b\beta) + bc(5e^2-16b\beta)$

$\dfrac{+2bc(-3e^2+16b\beta)\gamma_r}{2b(-3e^2+16b\beta)}$ $(-1+\gamma_r)$, $\theta^{YS*} = 2(a-bc)\dfrac{e}{-3e^2+16b\beta}$, ϕ^{YS*} $= \dfrac{-e^2+16b\beta\gamma_r}{16b\beta(-1+\gamma_r)}$ and $p^{YS*} = \dfrac{3ae^2+9bce^2-48ab\beta-16b^2c\beta}{12be^2-64b^2\beta}$.

Next, substituting the optimal decisions into Eq. (8) and Eq. (9), the optimal profits are derived as: $\pi_m^{YS*} = (a-bc)$ $\dfrac{^2(e^2-16b\beta)}{8b(-3e^2+16b\beta)}(-1+\gamma_r)$, $\pi_r^{YS*} = (a-bc)\dfrac{^2(e^2+16b\beta+(e^2-48b\beta)\gamma_r)}{-16b(-3e^2+16b\beta)}$ $(-1+\gamma_r)$ and $\pi_{sc}^{YS*} = (a-bc)\dfrac{^2(-e^2+48b\beta)}{16b(-3e^2+16b\beta)}$.

More interestingly, by solving inequalities $p^{YS*} - w^{YS*} \geq 0$, and $0 < \phi^{YS*} < 1$, the reasonable range of the retailer's reciprocity can be derived as: $\Omega_r^{YS} = \{\gamma_r| -1 \leq \gamma_r < 0 \text{ and } 0 < \gamma_r < e^2/16b\beta\}$. This reasonable range (Ω_r^{YS}) is a mutually beneficial area for manufacturer and retailer to maintain stability. The following propositions in case 4 are based on this reasonable range.

Proposition 8 In the decentralized channel under cost-sharing contract, the optimal decisions ((p^{YS*}, w^{YS*}, θ^{YS*} and ϕ^{YS*}) and the optimal profits (π_m^{YS*}, π_r^{YS*} and π_{sc}^{YS*}) are increasing with the consumer's environmental preference (e).

The optimal decisions and profits increase with consumer environmental preference, which means that consumer's environmental awareness affects not only demand but also profits. Thus, under the cost-sharing contract, enhancing
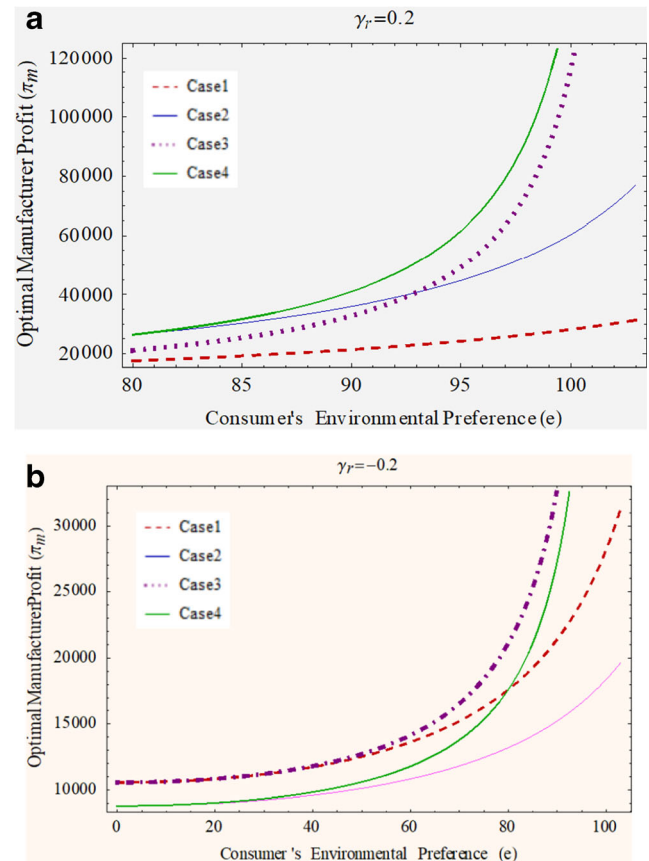

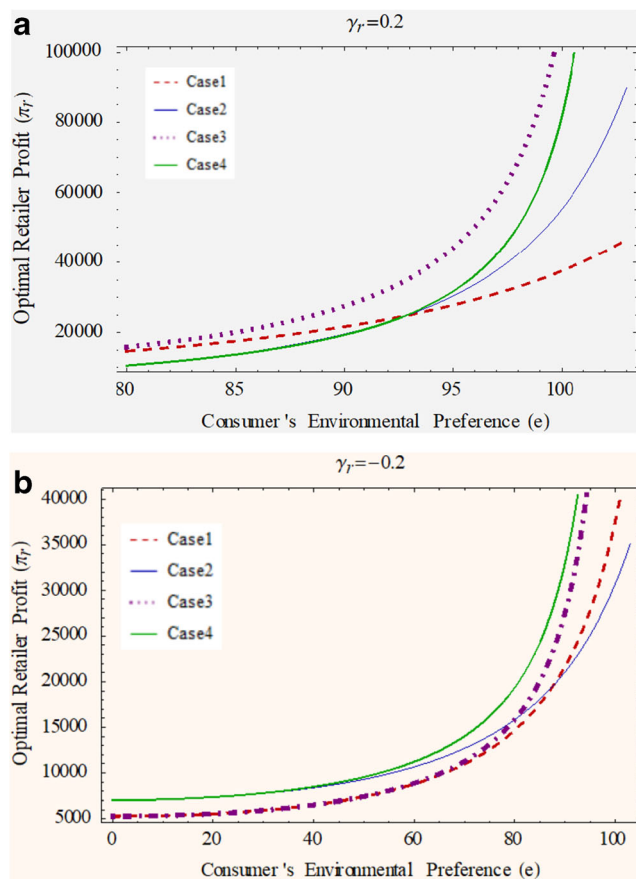**Fig. 6** Influence of e on π_m. **a** $\gamma_r = 0.2$. **b** $\gamma_r = -0.2$

Fig. 7 Influence of e on π_r. **a** $\gamma_r = 0.2$. **b** $\gamma_r = -0.2$

consumer's environmental awareness is favorable to the establishment of an energy-saving and environment-protective society.

Proposition 9 The optimal cost-sharing ratio (ϕ^{YS*}) and retailer's profit (π_r^{YS*}) decrease with the retailer's reciprocal preference parameter (γ_r); the optimal wholesale price (w^{YS*}) and the manufacturer's profit (π_m^{YS*}) increase with the retailer's reciprocal preference parameter (γ_r).

Proposition 9 implies that the manufacturer will improve wholesale price if the cooperator (the retailer) treats him/her more kinder or less mean. Higher wholesale price can bring the manufacturer more profit. Interestingly, the cost-sharing ratio (ϕ^{YS*}) decreases with retailer's reciprocal preference parameter (γ_r). This indicates the retailer shares less cost of emission abatement if retailer has stronger reciprocal preference. More interestingly, the retail price, emission abatement level, and GSC's profit are equal in case 3 and case 4, that is: $\pi_{sc}^{NS*} = \pi_{sc}^{YS*}$, $\theta^{YS*} = \theta^{NS*}$ and $p^{YS*} = p^{NS*}$. The retailer's reciprocal preference (γ_r) affects the wholesale price and cost-sharing ratio. Signing the cost-sharing contract contributes to achieve redistribution of the supply chain profit between the manufacturer and retailer.

Proposition 10 Within the reasonable range of retailer's reciprocity (Ω_r^{YS}), the optimal decision variables and profits in case 4 are greater than those in case 2, that is: $\theta^{YS*} > \theta^{Y*}$, $w^{YS*} > w^{Y*}$, $p^{YS*} > p^{Y*}$, $\pi_m^{YS*} > \pi_m^{Y*}$, $\pi_r^{YS*} > \pi_r^{Y*}$, $\pi_{sc}^{YS*} > \pi_{sc}^{Y*}$.

Proposition 10 indicates that within a reasonable range (Ω_r^{YS}), both the retailer and the manufacturer make more profits in case 4 than those in case 2. Interestingly, the emission abatement level is also greater in case 4, which implies that the cost-sharing contract is conducive to realizing Pareto improvement of channel profits and improving the manufacturer's environmental protection efforts. The above results will contribute to the coordination theory of the GSC with reciprocity preference.

Numerical analysis

In this section, we comprehensively analyze the equilibrium in "The models" section by several numerical examples. We mainly concentrate on the influences of the retailer's reciprocal preference and consumer environmental preference on the optimal decisions and profits.
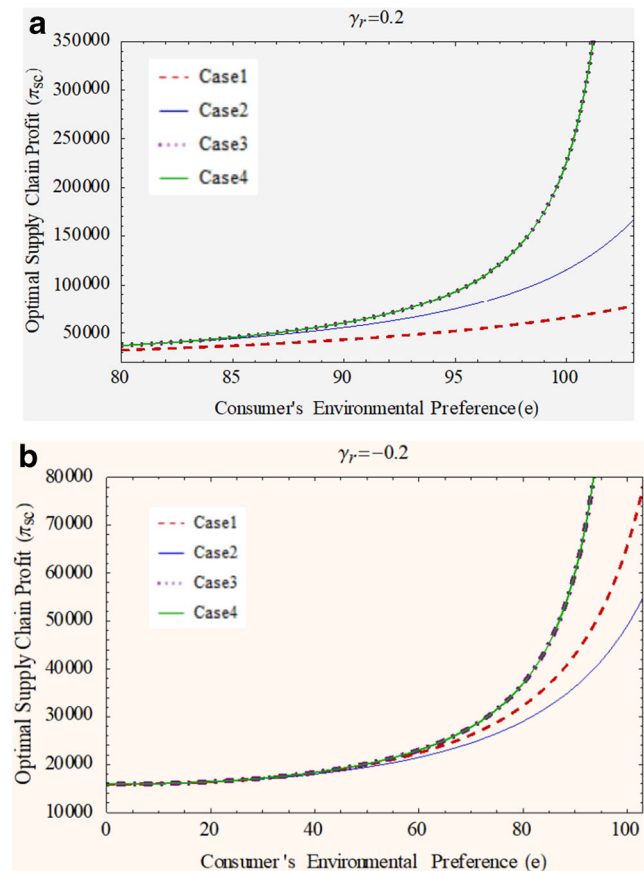

Fig. 8 Influence of e on π_{sc}. **a** $\gamma_r = 0.2$. **b** $\gamma_r = -0.2$

Table 5 Numerical example of parameters in the "Influence of consumer environmental preference" section

Parameter	Values	Values
Retailer's reciprocal preference	$\gamma_r = 0.2$	$\gamma_r = -0.2$
The total market potential	$a = 1500$	$a = 1500$
Price elasticity of demand	$b = 20$	$b = 20$
Manufacturer's variable cost of production	$c = 10$	$c = 10$
Consumer's environmental preference	$80 < e < 103$	$0 < e < 103$
The investment coefficient of emission abatement	$\beta = 100$	$\beta = 100$

Influence of retailer's reciprocal preference

According to the related conditions and literature, we provide some parameter values related to the current study, as shown in Table 3.

We can derive the reasonable range of retailer's reciprocity: $\{\gamma_r | -1 \leq \gamma_r < 0, 0 < \gamma_r < 0.2\}$. The equilibrium solutions and profits in different cases are obtained and shown in Table 4.

Based on our theoretical results in "The models" section and the numerical results in Table 4, we draw the following insights: (1) compared with other decentralized models, both emission abatement level and GSC's profit are the highest, while the retail price is the lowest in the centralized model, which illustrates that the centralized decision-making is able to improve the GSC's efficiency; (2) in case 2 and case 4, the profit of retailer decreases with γ_r, the profit of manufacturer and wholesale price decrease with γ_r. This can be explained by the fact that with a greater γ_r, the retailer is more kind to the manufacturer and prefers to sacrifice self-profit to realize the growth of GSC's profit. Meanwhile, increasing the wholesale price can result in a higher manufacturer profit, indicating that the Pareto improvement of channel profit can be realized through cost-sharing contract. However, in case 4, γ_r has no significant effect on the emission abatement level, GSC's profit, and retail price, which shows that the cost-sharing contract can realize profits Pareto only by affecting wholesale price and cost-sharing ratio; (3) in case 4, the manufacturer's profit shows an increasing trend when the retailer is kinder to the manufacturer. Interestingly, the profit of the GSC is constant. This is because reciprocal preferences only work between enterprises within the GSC, and the change of the retailer's reciprocity preference value does not affect the GSC's profit when the supply chain is a system; (4) the cost-sharing contract plays an active role in improving the environmental and economic performance in the GSC. For each value of retailer's reciprocal preference, the players' profits and the emission abatement level in the models of using cost-sharing contract (in case 3 and case 4) are higher than those of the models without using cost-sharing contract (in case 1 and case 2), which means that the contract is able to realize the profit's Pareto improvement, as well as environmental protection and economic growth of the whole society.

Influence of consumer environmental preference

In this part, we focus on interpreting the impacts of consumer environmental preference on optimal decisions and profits. Similar to the "Influence of retailer's reciprocal preference" section, the parameters are set to $a = 1500$, $b = 20$, $c = 10$, and $\beta = 100$. Importantly, we derive the value range of consumer's environmental level (e) from the conditions: $\gamma_r < e^2/16b\beta$ and $3e^2 - 16b\beta < 0$. According to the above conditions, we find that the value range of e is related to the value of γ_r. Therefore, we illustrate the influence of the consumer environmental preference in the cases of positive retailer's reciprocal preference (i.e., $\gamma_r = 0.2$) and negative retailer's reciprocal preference (i.e., $\gamma_r = -0.2$) respectively. The changes of the optimal decisions and profits are shown in Figs. 3, 4, 5, 6, 7, and 8 (by Matlab 2010). Here, the value of e approximately varies from 80 to 103 if $\gamma_r = 0.2$, while the value of e almost varies from 0 to 103 when $\gamma_r = -0.2$. The numerical example of parameters is shown in the Table 5.

As shown in Figs. 3, 4, 5, 6, 7, and 8, consumer's environmental preference (e) positively impacts optimal decisions and profits regardless of whether the retailer's positive or negative reciprocal preference is considered. The higher the e, the more likely consumers are to buy green products. Then the manufacturer increases emission-reduction efforts to produce consumer-oriented products (refer to Fig. 5), which means greater costs of investing carbon emission abatement. To make up for the loss of profit caused by the increase in environmental cost, the manufacturer raises the wholesale price (refer to Fig. 4), and the retailer accordingly increases the retail price (refer to Fig. 3).

In addition, we find that the members' profits and GSC's profit are increased with e (refer to Figs. 6, 7, and 8). Therefore, the manufacturer and environmental regulators should devote themselves to improve consumers' low-carbon concerns to ensure that the players' in the GSC make more profits. Interestingly, the curves of the optimal retail price, emission abatement level, and GSC's profit in case 3 and case 4 coincide completely. This means that the retail price, emission abatement level, and GSC's profit are out of the effect of retailer's reciprocal preference parameter (γ_r). The retailer's reciprocal preference (γ_r) affects the wholesale

price and cost-sharing ratio. Signing the cost-sharing contract contributes to achieve redistribution of the supply chain profit between the manufacturer and retailer.

Conclusions

Reciprocal preference has a profound influence on the policymakers and managers. In this paper, we attempt to integrate the consumers' environmental preference in the channel members' decision-making with and without the retailer's reciprocal preference. We present a centralized model to characterize pricing and emission-reduction decisions, as well as four decentralized cases in which retailer's reciprocal preference and cost-sharing contract are selectively considered.

The key conclusions and management implications of this paper are highlighted as follows: (1) The higher consumers' environmental awareness makes them prefer to pay for low-carbon products. The emission abatement level, channel profits, and GSC's profit tend to increase with consumer's environmental preference. Green products provide more value-add for the GSC system. Therefore, improving consumer environmental awareness is favorable to the construction of resource-saving society. The government should strengthen civic awareness of protecting environment. Meanwhile, the enterprises need to enhance the propaganda of low-carbon products. (2) In this paper, reciprocal behavior is further divided into two types: reciprocation for a friendly act (positive reciprocity) and revenge for a hostile one (negative reciprocity). When the retailer shows positive reciprocal concern to the cooperator, he/she is willing to sacrifice his/her own interest to improve the manufacturer's and the GSC's interest. Thus, the retailer with reciprocal preference is trying to ensure that the cooperator (the manufacturer) can make profit. In addition, within the reasonable range of retailer's reciprocal preference, higher value of the retailer's reciprocal preference is conducive to the better realization of environmental protection and the improvement of the economic welfare of the whole society. (3) Regardless of whether the retailer's reciprocal preference is considered, the channel profits can realize Pareto improvement under certain conditions using the cost-sharing contract. Thus, the cost-sharing contract plays an active role in improving the environmental and economic performance in the GSC. These conclusions provide a theoretical basis on cooperation contract for companies committed to reducing carbon emissions in the GSC when the retailer has a reciprocal preference.

Although this research provides useful insights, there are some limitations to this study. Firstly, only a two-stage supply chain structure without competitive relationship is considered. However, the actual supply chain structure is more complicated; it is necessary to develop models among competing retailers or manufacturers. Secondly, the current research is based on the assumption that each member has symmetrical information. Given that players' information is usually asymmetric in practice, it would be of value to investigate the GSC with incomplete asymmetric information for getting more convincing results. Furthermore, we will be looking at perfecting our research by introducing random demand that has wider applicability.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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