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Optimal strategies for carbon emissions policies in competitive closed-loop supply chains: A comparative analysis of carbon tax and cap-and-trade policies

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ABSTRACT

This study addresses a comparative analysis of carbon emissions policies and optimal decisions in competitive closed-loop supply chains. It examines three policy scenarios: a single carbon tax, a single cap-and-trade, and a mixed policy. Competitive intensity, the degree of competition among manufacturers, and product recycling rate, a key element in closed-loop supply chains, can impact the comparative analysis of carbon policies and optimal decisions in competitive closed-loop supply chains. A supply chain system is constructed, consisting of two manufacturers and a shared retailer. We employ a decentralized decision-making approach, with a Cournot game between the manufacturers and a Stackelberg game with the retailer. The analysis considers the impacts of carbon tax, carbon trading price, and recycling rate on optimal decisions and total supply chain profit. The results demonstrate that the mixed carbon policy can yield superior economic and environmental benefits compared with the single carbon tax policy. Mixed policies are likely to be relatively less profitable in most cases than a single cap-and-trade policy. Notably, when the mixed carbon quota exceeds a certain threshold, the mixed policy surpasses the single cap-and-trade policy both economically and environmentally. This study extends previous research by examining the impacts of the recycling rate and various carbon policies on supply chain decisions and profit. The findings offer insights into optimal strategies for reducing supply chain carbon emissions, which benefits policymakers and managers. Finally, it suggests that enterprises should consider a mixed carbon policy to balance economic and environmental goals.

1. Introduction

Human life has become more comfortable with economic growth and industrial expansion, which however cause significant damage to the ecosystem. Therefore, economic expansion and energy consumption are regarded as the main causes of environmental degradation (Waheed et al., 2019).

Economic development affects carbon emissions globally, but emission levels vary by country size. Developing countries' industrial, urbanization, and transportation needs require high energy, leading to high emissions (Waheed et al., 2019; Shi et al., 2022). With growing climate change awareness, governments and businesses are recognizing the need to reduce carbon emissions. Many countries have proposed plans to control emissions and encourage businesses to focus on environmental issues (Zhou et al., 2016; Li et al., 2021). Recently, global carbon emission control policies have advanced. Carbon tax and cap-and-trade are frequently suggested as effective emission reduction measures (Sun & Yang, 2021).

Carbon tax reduces emissions through taxation (Sun & Yang, 2021; Zhang et al., 2021), while cap-and-trade is a flexible mechanism integrating government regulation and market incentives. Manufacturers can sell spare carbon quotas in the trading market if their emissions stay below the allocated quota. However, they must purchase additional permits at a trading price if they exceed it (Yang et al., 2017; Cao et al., 2019; He et al., 2022). While both policies effectively reduce emissions, selecting and setting parameters requires careful design based on specific factors and needs in different countries or regions. Moving from a focus on only a single policy to a broader mix of policies is a challenge in

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studying the role of carbon policies on corporate sustainability transitions (Edmondson et al., 2019). Zhang et al. (2022) showed that a mix of emission reduction policies can achieve the carbon emissions peak by 2030. Coordinating carbon tax and trading schemes can optimize energy consumption and curb total carbon emissions growth. Therefore, implementing suitable carbon policies for enterprises is necessary.

Under government restrictions and marketing demands, enterprises face significant challenges in production and operations. To address these issues, core supply chain enterprises employ strategies, including developing emissions reduction technologies, purchasing environmental facilities, and training employees, which lead to higher operating costs and affect supply chain performance (Mao et al., 2017). Balancing economic growth and environmental protection is a practical challenge. While traditionally seen as conflicting, it is now acknowledged that they can be mutually beneficial. Hence, thorough research and evaluation of closed-loop supply chains and carbon emission policies are necessary. These studies aid decision-makers in developing more effective strategies. It is worth studying how supply chain enterprises make decisions considering both environmental and economic benefits in a competitive environment (Zhang et al., 2022).

Carbon tax and cap-and-trade policies effectively reduce emissions and offer varying levels of environmental protection. Combining these policies may yield improved emission reductions but also introduce new challenges. Additionally, parameters such as the degree of competition for product prices, emission reductions from different manufacturers, and product recycling rates are essential factors affecting competitive closed-loop supply chains. To explore the impact of these factors on decision and the advantages of the mixed policy, as well as to enable the implementation of policies with better economic and environmental performance, this study will analyze the emissions reduction and pricing decisions of a competitive supply chain with recycling under different carbon emissions reduction policies. We try to address the three following research questions. First, what are the optimal solutions of a competitive closed-loop supply chain under three policy scenarios: the single carbon tax policy, the single cap-and-trade policy, and a mixed policy that combines the two single policies? Second, based on the characteristics of competitive closed-loop supply chains, what are the impacts of the manufacturers' competitive intensity, product recycling rates, and different carbon emissions policies on the optimal decisions and supply chain profit? Third, comparing the systems under the mixed and single policies, what conditions is the supply chain's performance better under the hybrid policy?

To answer the research questions, we construct a supply chain system with two manufacturers and a shared retailer under three scenarios: a single carbon tax, a single cap-and-trade, and a mixed carbon policy combining both. Game theory and decision-making frameworks are employed to analyze the effects of competitive intensity, recycling rate, and different carbon policy parameters on optimal decisions, profits, and the economic and environmental performance resulting from supply chain members' decisions in different carbon emission policy scenarios. The main contributions of this study are as follows.

First, previous studies have examined the impact of single policies on manufacturing enterprises (Ghosh et al., 2020a; Wang et al., 2021; Liu et al., 2021b; Lyu et al., 2022). Carbon tax aids emission reduction optimization for manufacturers (Yu et al., 2022), while cap-and-trade policy associates higher carbon prices with increased economic profits (Liu et al., 2021b). Lower carbon quotas effectively control emissions, while higher quotas enhance profitability (Wang et al., 2021). To our knowledge, there is limited research on the impacts and design guidance for diverse policy combinations. This study explores the complex relationships between carbon policies, their effects on optimal outcomes, and the synergies resulting from their joint implementation.

Second, existing works have demonstrated that implementing the cap-and-trade policy effectively mitigates carbon emissions, enhances social welfare, and bolsters manufacturers' competitiveness through carbon reduction advancements (Sun & Yang, 2021). When the carbon trading price surpasses the carbon tax, a carbon tax is advantageous with a lower carbon quota, while cap-and-trade is preferred if the carbon price falls below the carbon tax (Lyu et al., 2022). Unlike these studies, this study compares the supply chain performance under the mixed policy against two single policies. The findings suggest that the mixed policy will likely deliver superior economic and environmental benefits compared to the single carbon tax policy. Regarding profitability, the single cap-and-trade policy is generally superior, except when the mixed carbon quota exceeds a specific threshold.

Third, previous studies (Chen & Ulya, 2019; Ji et al., 2020) traditionally treated the recycling rate as a decision variable. In contrast, this study considers the impact of the recycling rate as an exogenous variable on optimal outcomes. While Zheng et al. (2016) highlighted the negative effect of the recycling rate on price and its significant contribution to profitability, our findings reveal that the influences of emissions reduction and carbon policies lead to a reversal in the relationships among the recycling rate, price, and profit.

The study is organized as follows: The related literature is reviewed and summarized in Section 2. Section 3 introduces the research problem, notation, and assumptions. Section 4 formulates and solves the models. In Section 5, we compare the mixed and single scenarios. Section 6 conducts numerical studies to gain insights from the analytical findings. Finally, Section 7 concludes the paper and suggests future research topics.

2. Literature review

This study is related to three research streams: carbon emissions policy, competition in a low-carbon supply chain, and the closed-loop supply chain. In this section, we review these research streams and discuss how this study is related to them.

2.1. Carbon emissions policy

Since many countries emphasize low-carbon economic development, many researchers have studied the issues of supply chain operations under carbon trading (Chen et al., 2021; Qi et al., 2021; Zhao et al., 2021; Li et al., 2022). Xu et al. (2018) studied the decisions and coordination of a dual-channel structure under low-carbon requirements and channel competition. It has a positive impact on guiding the low-carbon transformation of enterprises, promoting sustainable development, and expanding the field of channel competition research. Ghosh et al. (2020a) built a two-tier supply chain model under the cap-and-trade policy and consumers' environmental preferences. It helps to understand how green supply chains can be driven by policy and consumer demand. Considering varying power structures under cap-and-trade, Tang and Yang (2020) investigated a green supply chain in which the manufacturer has limited capital, and analyzed the influence of financing structure selection on the optimal decisions. Wang et al. (2021) studied production decisions and carbon emissions permit repurchase strategies (CEPRS) under financial constraints and constructed a model of the manufacturer and a supply chain model to derive the optimal solutions. Li et al. (2021) studied the cap-and-trade policy and two subsidy methods: fixed technology cost and emissions reduction. They analyzed the operational decisions of pricing and quantity, green decisions of technology investment and low-carbon marketing, and the impacts of carbon policies on the supply chain's operations. According to the operational strategy and emissions reduction effect in heterogeneous enterprises, Linghu et al. (2022) studied a hybrid model by Stackelberg and Cournot games and the impacts of the cap-and-trade policy.

In some literature based on the carbon tax policy (Yu et al., 2022; Zhang & Qin, 2022), Zhang et al. (2021) analyzed the design of a progressive carbon tax policy and the influence of production decisions in a dual-channel network. In addition, some research compares the decisions of supply chains under varied carbon emissions policies. For instance, Sun and Yang (2021) considered consumers' environmental awareness and examined the emissions reduction decisions under the carbon tax or cap-and-trade policies. It provides a basis for implementing carbon tax and cap-and-trade policies and understanding the influence of consumers' environmental awareness on emissions reduction decisions. This contributes to a deeper understanding of consumer attitudes and behaviors towards environmental issues. Lyu et al. (2022) compared the recycling decisions of manufacturers under three carbon policies and derived the manufacturer's preference under each policy.

Recently, research on the mixed carbon policy has focused on policy formulation and resource planning. However, there are few studies on mixed policies for supply chain decisions. Halat et al. (2021) analyzed a competitive network with two supply chains under three carbon policies. These studies have examined the operation and impact of supply chains under mixed carbon policies through different supply chain structures and analytical approaches. Zhao et al. (2022) considered a competitive supply chain structure under a mixed policy, and explored the complexity of dynamic supply chains.

The above studies have separately examined the effects of implementing carbon tax and cap-and-trade policies on supply chain operations. Some studies have identified the more advantageous policies for supply chain economics and environmental protection in different scenarios. However, there is limited investigation on the application of mixed carbon policies in supply chain systems. Unlike prior studies, our research emphasizes the operation of mixed carbon policies. It aims to achieve carbon neutrality while considering the economic benefits of supply chains. Therefore, we will analyze the operational mechanism of mixed carbon policies in supply chain systems and investigate scenario variations.

2.2. Low-carbon supply chain and manufacturer competition

In the related research on the low-carbon competitive supply chain, Ji et al. (2017) analyzed the emissions reduction strategies by adopting the Stackelberg game model with a dual-channel or a retail channel. Hafezalkotob (2018) investigated the competition of a green supply chain under various government interventions and obtained the best response strategy under different policies. Ghosh et al. (2020b) considered the dual-channel supply chain with manufacturers' competition and retailer competition under cost-sharing contracts, studied the effect of competition on optimal decisions, and further analyzed the cost-sharing contract of emissions reduction under different competition scenarios. Liu et al. (2021a) explored the selection of the emissions reduction mode under the cap-and-trade policy. Xia et al. (2022) constructed a competitive structure involving two supply chains. It provides insights into the strategy and decision processes in such competitive environments. Structured competition reveals the complexities and interdependencies that arise when multiple supply chains compete. Pal et al. (2023) studied a dual-channel supply chain under green innovation and promotion efforts. It reveals the challenges and opportunities of enterprises when operating through multiple channels and adopting green practices, so that a more complete picture can be gained of how green innovation and promotion efforts impact both traditional and online channels in the supply chain.

To explore manufacturers' competition in the low-carbon context, some literature considers the case of duopoly manufacturers. For manufacturers having different risk aversions, Sun et al. (2020) analyzed the optimal pricing and the issue of reducing emissions of two competing manufacturers. Sun and Yang (2021) investigated the problems of reducing carbon emissions and social welfare. Given the competitive strategies of two manufacturers, namely Cournot game and cooperation, they constructed four models considering two carbon policies, and derived the optimal decisions. Liu et al. (2021b) introduced a bi-objective nonlinear programming model to study low-carbon investment strategies. By incorporating this approach, the study considers economic and environmental objectives, highlighting their trade-offs and synergies. Considering the green preference of consumers, Wang et al. (2022) explored the pricing decisions of competing manufacturers with vertical and horizontal fairness.

Existing research has primarily examined the selection and implementation of emission reduction strategies, neglecting their impact on market competitiveness. In contrast, this study focuses on manufacturers' emissions reduction strategies and their environmental product impact. Furthermore, to accurately elucidate the dynamics of manufacturers' competition in response to low-carbon demand, this study examines the simultaneous impacts of price and emissions reduction levels on demand to understand inter-manufacturer competition in the low-carbon supply chain.

2.3. Closed-loop supply chain

Due to the importance of the circular economy and sustainable development, research on the closed-loop supply chain has received increasing attention (Golpîra & Javanmardan, 2022). This field often considers the return policy (Xu et al., 2022), the decision of the recycle mode (Zhang et al., 2022), and the quantity of recycling. Chuang et al. (2014) focused on three reverse channel structures that manufacturers choose to recycle and reprocess the used products. It can guide manufacturers to effectively design and manage their reverse logistics systems to improve sustainability performance. Gao et al. (2016) examined the decisions on the price, recycling effort, and sales effort by establishing game-theoretic models of the closed-loop supply chain, including manufacturer-led, retailer-led, and vertical Nash. Giri et al. (2017) researched a closed-loop network with the reverse dual channels recycle the used products using traditional third-party logistics and electronic media. Chen and Ulya (2019) analyzed that manufacturers seek to maximize their profits by considering the best behavior of retailers and independent third parties. Yan and Pei (2019) constructed a new online-to-offline competition model to coordinate online-to-offline distribution under the return policy, finding that the strategy benefits all supply chain members. Considering the presence of competing recyclers, Xing et al. (2020) established a model that included two competing third-party recyclers, and provided a more realistic representation of the recycling market. It investigates how different factors affect the competition between recyclers and ultimately the recycling efficiency. Zhang and Chen (2021) considered a risk-averse supplier and a capital-constrained manufacturer to analyze the production and remanufacturing decisions under different financing portfolios.

Existing literature extensively covers the selection of recycling modes and prices. Based on these studies, we will analyze the influence of recycling rates on the economic and environmental performance of businesses. This analysis will aid in understanding how recycling rates can be incorporated into production decisions. Interestingly, as we examine the mechanism underlying the recycling rate and compare it with existing research, we observe that the implementation of emissions reduction and carbon policies has the potential to significantly alter how the recycling rate influences supply chain efficiency.

2.4. Research gaps and its innovation

To summarize, there are still some research gaps in previous research.

First, previous existing studies investigated the significant impact on supply chain operations when the carbon tax and cap-and-trade are implemented independently (Xu et al., 2018; Sun et al., 2020; Zhang et al., 2021; Sun & Yang, 2021; Lyu et al., 2022). While implementing both policies can effectively reduce emissions, selecting and setting carbon policy parameters must be carefully designed according to the relevant factors and needs of different countries or regions. Moving from focusing on only a single policy to attempting a mixed one is challenging. Existing studies on the application of mixed carbon policies in supply chain systems are limited. Further research can provide valuable insights into mixed policies' design, implementation, and benefits, helping policymakers develop effective policies for low-carbon transformation in supply chains. This study explores the differences between mixed and single options in supply chain decision-making and identifies conditions for optimal implementation of mixed policies.

Second, supply chain members must consider economic benefits and environmental conservation. Intense competition among manufacturers helps reduce carbon emissions (Liu et al., 2021b). Although previous studies (Hafezalkotob, 2018; Sun & Yang, 2021; Wang et al., 2022) have addressed both firm competition and environmental considerations, there have been relatively few studies of simultaneous competition involving the two critical variables of price and emission reductions. This study examines the interaction between supply chain members regarding price and emission reduction and the impact of different competitive strategies on economic and environmental performance, bridging a gap in previous research.

Third, Chen and Ulya (2019) and Chuang et al. (2014) indicated that reward and punishment mechanisms enhance recycling rates and green efforts, influencing manufacturers' decisions and overall supply chain profitability. The recycling rate is a critical factor in closed-loop supply chains, but research on the impact of recycling rates on the system is relatively limited. This study uses the recycling rate as an exogenous variable to explore the impact of different recycling rates on emission reductions, cost-effectiveness, and supply chain performance. Such research can enhance understanding of the importance of recycling rates in achieving low-carbon emission targets and promoting effective resource recycling and reuse for businesses and policymakers.

Addressing the research gaps in mixed policies and the impact of recycling rates is necessary for advancing the field by deepening our understanding of policy effectiveness, improving sustainable supply chain management practices, driving technological innovation, and promoting overall environmental sustainability. Therefore, this study aims to contribute to research on low-carbon supply chains by investigating these factors. Table 1 compares the related research and distinguishes this study.

3. Problem definition, notation, and assumptions

This study considers a closed-loop supply chain model with two manufacturers and a shared retailer. Each manufacturer produces one low-carbon product for the relatively high cost of emissions reduction (Ji et al., 2017). Then, the retailer sells the two homogeneous and substitutable products to consumers. Under decentralized decision-making, there is a Cournot game between the two manufacturers and a Stackelberg game between the manufacturers and the retailer. As shown in Fig. 1, the manufacturers, as leaders, simultaneously decide the wholesale prices and emissions reduction levels for their products, and then the retailer sets the retail price. After sales, each manufacturer recycles and remanufactures the used product at a specific rate.

There are three scenarios under three carbon emissions policies.

Scenario 1: Single carbon tax policy. According to its actual carbon emissions in production, each manufacturer pays a specific carbon tax.

Scenario 2: Single cap-and-trade policy. The administration initially allocates a fixed quota to the manufacturers. If the actual emissions exceed the quota, the manufacturer needs to acquire emission permits from the carbon trading market. Otherwise, the remaining quota can be sold for additional revenues. Chen et al. (2021) distinguished between two types of cap-and-trade policies: benchmarking and grandfathering. Benchmarking sets unit carbon quotas to limit emissions per unit while grandfathering sets a total carbon emissions quota based on past production (Chen et al., 2021). This study focuses on the grandfathering regulation, specifically a total carbon emissions quota.

Scenario 3: Mixed policy. The mixed policy combines the carbon tax and cap-and-trade policies (Shen et al., 2022). In practice, mixed carbon policy refers to the simultaneous adoption of multiple carbon emission policies. This study considers explicitly a mixed carbon policy consisting of a carbon tax and cap-and-trade. Both policies can influence enterprise carbon emission behavior from different perspectives. A carbon tax directly regulates the cost of carbon emissions, while cap-and-trade encourages enterprises to actively reduce carbon emissions by setting limits on total carbon emissions. Therefore, under **Scenario 3**, these two policies can complement each other to form a more effective policy framework.

Our objective is to determine the optimal emissions reduction level, wholesale prices of the manufacturers, and retail prices of the retailers to maximize the profits of supply chain members. Additionally, we analyze the effects of competitive intensity, recycling rate, and carbon policies on optimal decisions and profits. The assumptions are as follows.

Assumption 1. The demand for each product is a linear function of the retail price and emission reductions level (Sun et al., 2020; Wang et al., 2022), $d_i = a - p_i + \beta p_j + \tau(e_i - \beta e_j), i = 1,2, j = 3 - i$, where a ($a > 0$) is the basis market demand, β is the intensity of competition between the two manufacturers ($0 < \beta < 1$), p_i is the retail price of product i, τ is the low-carbon preference coefficient that reflects consumers' environmental awareness ($0 < \tau < 1$), and e_i is the emissions reduction level of manufacturer i (Ji et al., 2017), consumers can be informed of the emission reduction level through product information, e.g., green labeling and certification.

Assumption 2. A common retailer promotes two kinds of products from the two low-carbon manufacturers. The quality of the remanufactured product is identical to that of the standard product, and both have the same acceptance in the market (Zheng et al., 2016). To simplify the calculation, we assume that both the remanufactured and standard products have the same production cost c. Manufacturer i wholesales its product to the retailer at a unit price of w_i and the retail price of the product is p_i ($c < w_i < p_i$).

Table 1
Comparisons between related literature and this study.

Related Literature	Carbon Emission Policy			Competitive Manufacturers	Loop		Decision Mode	
	Carbon Tax	Cap-and-trade	Mixed Policy		Open	Closed	Pricing	Order
Xu et al. (2018)		√			√		√	
Sun et al. (2020)		√		√	√		√	
Ghosh et al. (2020a)		√				√	√	√
Wang et al. (2021)		√			√			√
Zhang et al. (2021)	√				√		√	√
Sun and Yang (2021)	√	√		√	√			
Lyu et al. (2022)	√	√		√	√	√		
Shen et al. (2022)	√	√	√				√	
Chen and Ulya (2019)						√	√	
Ghosh et al. (2020b)				√	√		√	
Wang et al. (2022)				√	√		√	
This study	√	√	√	√		√	√	

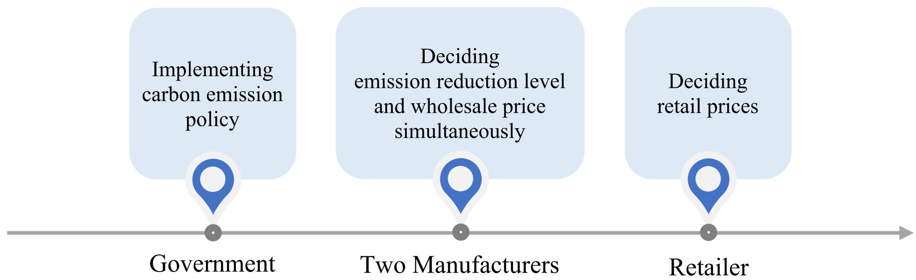

Fig. 1. Decision sequence.

Assumption 3. Manufacturers must invest in carbon reduction technologies to reduce emissions. The cost of emissions reduction is a quadratic function of the emissions reduction level (Raz et al., 2013; Taleizadeh et al., 2018; Sharma & Venkataraman, 2022; Zhang et al., 2023), $C(e_i) = \frac{1}{2}he_i^2$, where h is the cost coefficient of carbon emissions reduction of the manufacturers ($h > 0$). Assuming that the investment in carbon reduction technologies is a one-time investment (Peng et al., 2018; Sun & Yang, 2021), we consider h has more significant value (Ji et al., 2017). As a critical metric to assess the environmental performance of the supply chain, the total carbon emissions of manufacturer i is $E_i = (e_0 - e_i)d_i$, where e_0 is the initial carbon emissions per unit of product ($0 < e_i < e_0$) (Sun & Yang, 2021).

Assumption 4. Regarding economies of scale, we assume that the cost function of recycling is $C(\varphi_i) = \frac{1}{2}h_r\varphi_i{}^2 + \varphi_i d_i f$(Savaskan et al., 2004; Atasu et al., 2013; Chuang et al., 2014; Chen & Ulya, 2019; Wang & Wu, 2020), where h_r is the cost coefficient of recycling ($h_r > 0$), f is the unit recycle cost of the manufacturers ($f > 0$), and φ_i is the recycling rate of manufacturer i ($0 < \varphi_i < 1$). The recycling cost is affected by the recycling rate of manufacturers, and the quantity of products recycled by manufacturer i is $\varphi_i d_i$, the per unit recycling cost is decreasing in the total amount of the recycling products based on $\frac{C(\varphi_i)}{\varphi_i d_i} = f + \frac{h_r\varphi_i{}^2}{2\varphi_i d_i}$ (Chuang et al., 2014). Chuang et al. (2014), and Zhang and Yu (2022) supposed that the recycling rate is enforced by the recycling laws, requiring firms to be responsible for product recycling. A higher mandatory recycling rate compels manufacturers to increase recycling efforts, leading to improved environmental benefits. Consequently, manufacturers may adjust pricing and production cost strategies to address recycling cost pressures. This can affect their decisions on product pricing and supply chain operations. In addition, differences in legal requirements across jurisdictions may impact the model's applicability and outcomes, necessitating manufacturers to devise strategies for different markets. In this study, we consider the case of direct recycling by manufacturers and regard the recycling rate as an exogenous variable.

Assumption 5. We consider three scenarios representing different carbon emission policies. In each scenario, manufacturers are obligated to bear the associated costs of the carbon policy according to their actual production emissions. **Scenario 1** is the single carbon tax policy with the cost function, $CEP1 = m_sE_i$, where m_s expresses the tax per unit of carbon emissions ($m_s > 0$). **Scenario 2** is the single cap-and-trade policy with the cost function, $CEP2 = p_s(E_i - \overline{E}_s)$, where $\overline{E}_s$ is the carbon quota allocated by the government ($\overline{E}_s > 0$) and p_s is carbon trading price ($p_s > 0$). If $E_i < \overline{E}_s$, the remaining quota can be sold for the revenue $+p_s(\overline{E}_s - E_i)$. Otherwise, the manufacturer must purchase carbon emission permits at the purchase cost $-p_s(E_i - \overline{E}_s)$. **Scenario 3** is a mixed carbon policy including carbon tax and cap-and-trade, $CEP3 = p_c(E_i - \overline{E}_c) + m_cE_i$, where the expenditure or revenue of cap-and-trade is $p_c(E_i - \overline{E}_c)$ and the carbon tax is m_cE_i ($m_c > 0$, $p_c > 0$, and $\overline{E}_c > 0$).

Assumption 6. All the parameters in the model are shared information (Wang et al., 2022). Table 2 shows the notation used throughout the paper.

Table 2
Notation.

Notation	Description
Parameter	
a	Basic market demand
β	The intensity of competition between two manufacturers
τ	Consumer's low-carbon preference
c	Unit production cost
φ_i	Recycling rate of products made by manufacturer i
h_r	Cost coefficient of recycling
f	Unit recycling cost
h	Cost coefficient of carbon emission reduction
e_0	Initial carbon emissions per unit of product
m_s	Unit carbon tax under a single carbon tax policy
m_c	Unit carbon tax under the mixed policy
p_s	Carbon trading price under single cap-and-trade policy
p_c	Carbon trading price under mixed policy
$\overline{E}_s$	Carbon quota from the government under single cap-and-trade policy
$\overline{E}_c$	Carbon quota from government under mixed policy
Decision variable	
e_i	Emission reduction level of manufacturer i
w_i	Wholesale price of manufacturer i
p_i	Retail price of product i
Function	
E_i	Total carbon emission of manufacturer i
d_i	Demand of product i
$CEP1$	Cost of single carbon tax policy,$CEP1 = m_sE_i$
$CEP2$	Cost of single cap-and-trade policy,$CEP2 = p_s(E_i - \overline{E}_s)$
$CEP3$	Cost of mixed policy,$CEP3 = m_cE_i + p_c(E_i - \overline{E}_c)$
π_{Mi}	The profit of manufacturer i
π_R	The profit of the retailer
π	The total profit of the supply chain
Other	
Superscript TA, CT, CO	Represent policy scenarios, i.e. **Model TA**, **Model CT**, and **Model CO**
Subscript d, c	Represent decentralized and centralized

4. Model construction and solution

Based on manufacturer competition, we construct three competitive supply chain models with reverse channels under three carbon policies. We derive the optimal decisions and profits under the three models corresponding to the three policy scenarios discussed above and analyze the effects of competitive intensity, recycling rate, and policy parameters on the optimal outcomes.

4.1. Scenario 1: Single carbon tax policy (Model TA)

In **Model TA,** the supply chain operates under the single carbon tax policy. As shown in Fig. 2, the two manufacturers must pay taxes based on their actual carbon emissions in manufacturing. The profits of the manufacturer i and retailer in **Model TA** are as follows:

$$\pi_{Mid}^{TA} = (w_i - c)d_i - \frac{1}{2}he_i^2 - (\frac{1}{2}h_r\varphi_i{}^2 + \varphi_i d_i f) - m_sE_i, i = 1, 2, j = 3 - i \quad (1)$$

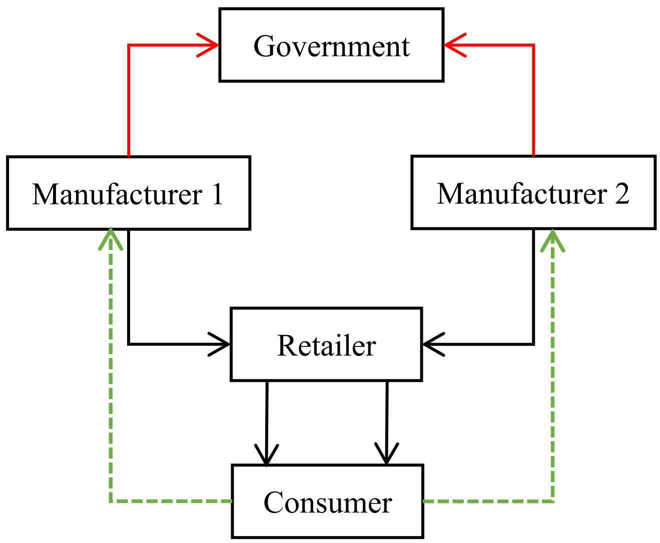

Fig. 2. Supply chain diagram of **Model TA**.

$$\pi_{Rd}^{TA} = \sum_{i=1}^{2}(p_i - w_i)d_i, i = 1,2, j = 3-i \tag{2}$$

Theorem 1. *In* ***Model TA****, the optimal outcome (decentralized) is as follows:*

$$e_{id}^{TA^*} = \frac{(\tau+m_s)\left[A\cdot C1 + f(\varphi_i\cdot D - 2\beta\varphi_j h)\right]}{B}$$

$$w_{id}^{TA^*} = \frac{A\cdot\{a[2h - m_s(\tau+m_s)] + (c+e_0m_s)[2h+\tau(\beta-1)(\tau+m_s)]\}}{B} + \frac{f\{\varphi_i\cdot F2 - 2\beta\varphi_j h[2h - m_s(\tau+m_s)]\}}{B}$$

$$p_{id}^{TA^*} = \frac{A\cdot\{a\cdot F1 + (\beta-1)(c+e_0m_s)[h+\tau(\beta-1)(\tau+m_s)]\}}{(\beta-1)\cdot B} - \frac{f\left[\varphi_i\cdot F3 + \beta\varphi_j h(2h+\tau^2 - {m_s}^2)\right]}{B}$$

$$\pi_{Mid}^{TA^*} = \frac{h\cdot\left[4h-(\tau+m_s)^2\right]\left[A\cdot C1 + f(\varphi_i\cdot D - 2\beta\varphi_j h)\right]^2}{2\cdot B^2} - \frac{{\varphi_i}^2 h_r}{2}$$

$$\pi_{Rd}^{TA^*} = -\frac{h^2\left[2f(\varphi_i+\varphi_j)\cdot A^2\cdot C1 + f^2({\varphi_1}^2+{\varphi_2}^2)\cdot F4 + 2\beta\varphi_i\varphi_j f^2\cdot F5\right]}{B^2} - \frac{2h^2\cdot A^2\cdot C1^2}{(\beta-1)\cdot B^2}, \quad i = 1,2, j = 3-i$$

Proof: See Appendix A1.

Given the constraints on the optimal decisions $0 < e_i < e_0$ and $c < w_i < p_i$, we derive $a_{1i}^{TA} < a < a_{2i}^{TA}$ or $a_{0i}^{TA} < a < a_{2i}^{TA}$. In the following sections, we adopt this assumption. From Theorem 1, we derive the following two propositions.

Proposition 1. *When the intensity of competition is in an appropriate range, there are positive correlations between $e_{id}^{TA^*}$, $w_{id}^{TA^*}$, $p_{id}^{TA^*}$, $\pi_{Mid}^{TA^*}$, and $\pi_{Rd}^{TA^*}$, and the intensity of competition (take* ***Model TA*** *for example).*

Proof: See Appendix A2.

Proposition 1. explores how the intensity of competition affects the optimal emissions reduction level, wholesale prices, retail prices, and the profits of manufacturers and retailers. It is found that within a specific range of competitive intensity ($0 < \beta < \frac{2h-(\tau+m_s)^2}{(\tau+m_s)^2}$), the optimal outcome will increase with increasing competitive intensity.

This suggests that competition plays a crucial role in incentivizing firms to pursue significant emissions reduction efforts. From an economic standpoint, this result can be attributed to several factors. Heightened competition results in more firms operating in the market, creating a greater incentive for differentiation. In the context of emissions reduction, this can involve adopting sustainable production processes, cleaner technologies, and eco-friendly practices. As firms strive to differentiate themselves in a competitive market, they are more likely to invest in emissions reduction efforts that align with consumer preferences and societal concerns for the environment. This increased investment can translate into a higher optimal emissions reduction level. Moreover, firms may also pass on a portion of their costs associated with emissions reduction to wholesale and retail prices, resulting in price increases.

While Wang et al. (2022) have similar findings to ours regarding the positive impact of competition on product greenness, wholesale prices, retail prices, and retailers' profits, they argue that competition is detrimental to manufacturers. This disparity may arise from differences in the parameters considered in their model compared to ours. However, we cannot dismiss the findings of Wang et al. (2022); in practice, the effect of competition intensity on manufacturers may vary depending on factors such as industry, market conditions, and policy environment.

Proposition 2. *The recycling rate of the manufacturer i has the following features (take* ***Model TA*** *for example):*

(1) $e_{jd}^{TA^*}$, $w_{id}^{TA^*}$, $w_{jd}^{TA^*}$, $p_{id}^{TA^*}$, $p_{jd}^{TA^*}$, *and* $\pi_{Mjd}^{TA^*}$ *are positively correlated to* φ_i; $e_{id}^{TA^*}$, $\pi_{Mid}^{TA^*}$, *and* $\pi_{Rd}^{TA^*}$ *are negatively correlated to* φ_i.

(2) *When* $\varphi_i < \varphi_j$, *the optimal outcomes are such that* $e_{id}^{TA^*} > e_{jd}^{TA^*}$, $w_{id}^{TA^*} < w_{jd}^{TA^*}$, $p_{id}^{TA^*} < p_{jd}^{TA^*}$, *and* $\pi_{Mid}^{TA^*} > \pi_{Mjd}^{TA^*}$.

Proof: See Appendix A3.

Proposition 2. analyzes how the recycling rates of the manufacturers in Model TA affect the optimal decision variables, as well as the profits of supply chain members.

Zheng et al. (2016) showed that retail prices decrease as the recycling rate increases. At the same time, higher recycling rates increase manufacturers' profits while decreasing competitors' profits. However, in Proposition 2(1), we found that the recycling cost increases with an increase in the recycling rate, which may lead to a decrease in its profit. To balance earnings, manufacturers may need to increase the wholesale gross profit or reduce other costs (e.g., emission reduction costs or carbon policy costs). However, reducing the emissions reductions level may lead to a reduction in demand for the product, which may result in a loss of profit for the retailer. Thus, the retailer may increase the retail price of both products.

Due to the homogeneity and substitutability of the two products, a decrease in demand for one item can potentially result in an increase in demand for the other. Competitors may adjust carbon emissions and wholesale prices to sustain profits and gain a competitive edge. However, such actions can lead to market instability, with different competitors engaging in price wars or other competitive behaviors.

Proposition 2(2). proves that the emissions reduction level of a manufacturer is higher when its recycling rate is lower. This is because lower recycling costs allow manufacturers to allocate more capital towards improving carbon emissions, resulting in increased demand. Conversely, a higher recycling rate necessitates raising wholesale and retail prices to offset the elevated recycling costs. As a result, the relatively lower emissions reduction level fails to meet consumer expectations, leading to decreased demand and reduced profits for manufacturers.

As the profit of the supply chain is the sum of the two manufacturers and retailer, by **Eqs (1) and (2)**, the profit of the supply chain in **Model TA** is as follows:

$$\pi_c^{TA} = \sum_{i=1}^{2}[(p_i - c)d_i - \frac{1}{2}he_i^2 - m_sE_i - (\frac{1}{2}h_r\varphi_i^{\ 2} + \varphi_i d_i f)], i = 1,2, j = 3 - i \tag{3}$$

Theorem 2. *In **Model TA**, the optimal outcomes (centralized) are as follows:*

$$e_{ic}^{TA*} = \frac{(\tau + m_s)\left[A1\cdot C1 + f\left(\varphi_i\cdot D1 - 2\beta\varphi_j h\right)\right]}{B1}$$

$$p_{ic}^{TA*} = \frac{A1\cdot\left\{\left[h + \tau(\beta-1)(\tau+m_s)\right]\cdot C1 - a\left[2h - (\beta-1)(\tau+m_s)^2\right]\right\}}{(\beta-1)\cdot B1} + \frac{f\left[\varphi_i\cdot G1 - \beta\varphi_j h(\tau^2 - m_s^{\ 2})\right]}{B1}$$

$$\pi_c^{TA*} = -\frac{\left[(\varphi_i^{\ 2}+\varphi_j^{\ 2})h_r\cdot B1 + (\varphi_i^{\ 2}+\varphi_j^{\ 2})f^2h\cdot D1 + 2fh(\varphi_i+\varphi_j)\cdot A1\cdot C1 - 4\beta\varphi_i\varphi_j f^2h^2\right]}{2\cdot B1} - \frac{h\cdot A1\cdot C1^2}{(\beta-1)\cdot B1}, \quad i = 1,2, j = 3-i$$

Proof: See Appendix A4.

Given the constraints on the optimal decisions $0 < e_i < e_0$ and $c < p_i$, we derive $a_{3i}^{TA} < a < a_{4i}^{TA}$. From Theorem 2, we derive the following proposition.

Proposition 3. *In **Model TA**, the single carbon tax has the following features:*

(1) *When $a_{6i}^{TA} < a < a_{4i}^{TA}$, e_{ic}^{TA*} is positively related to m_s; when $a_{3i}^{TA} < a < a_{6i}^{TA}$, e_{ic}^{TA*} is negatively related to m_s.*

(2) *When $a_{3i}^{TA} < a < a_{7i}^{TA}$, p_{ic}^{TA*} is positively related to m_s; when $a_{7i}^{TA} < a < a_{4i}^{TA}$, p_{ic}^{TA*} is negatively related to m_s.*

(3) *π_c^{TA*} is negatively related to m_s.*

Proof: See Appendix A5.

As we know, the actual carbon emissions and the tax on unit products are lower when there is a higher emissions reduction level. Therefore, many studies have shown a positive relationship between the carbon tax and emission reduction levels (Sarkar et al., 2022; Shen et al., 2022). Proposition 3(1) reveals a positive correlation between the carbon tax and emissions reduction level when $a_{6i}^{TA} < a < a_{4i}^{TA}$, due to manufacturers' emission abatement. But differently, when the basis market demand is in a small range ($a_{3i}^{TA} < a < a_{6i}^{TA}$), the emissions reduction level decreases with the carbon tax. This phenomenon may occur for several reasons. When the basis market demand is low, the manufacturers may prioritize cost control over high levels of emission reduction. An increase in carbon tax can raise carbon policy cost leading producers to balance benefits by reducing emissions. This highlights the relationship between a carbon tax and the emission reduction level, emphasizing the need to consider different market environments and manufacturers' behaviors when formulating relevant policies.

In Proposition 3(2), when $a_{3i}^{TA} < a < a_{7i}^{TA}$, there is a positive correlation between the carbon tax and retail price, However, when $a_{7i}^{TA} < a < a_{4i}^{TA}$, the influence trend is opposite with slight fluctuation. This inverse relationship may stem from different market conditions and business strategies. When carbon taxes increase, some enterprises might increase product prices to sustain profits instead of lowering retail prices. In addition, some of them may prioritize market share and sales volume over profit maximization and thus may choose to sacrifice some profits to maintain sales volume with increasing carbon tax.

Moreover, the total profit of the system shows an obvious decreasing trend as the carbon tax increases (as Proposition 3(3)). When the carbon tax increases, the manufacturers decrease the policy cost by reducing carbon emissions. Therefore, the carbon tax policy can effectively lead manufacturers to increase investment in emissions control and realize a low-carbon economy (Shen et al., 2022).

In search of higher profits than manufacturers and retailers under decentralization, we propose Proposition 4, which introduces a wholesale price contract to coordinate the supply chain.

Proposition 4. *Wholesale price contracts effectively coordinate the supply chain, resulting in higher profits for supply chain members.*

Proof. The implementation of wholesale price contracts requires the manufacturer i to negotiate with the retailer to determine wholesale prices w_i^{wp}.

In Theorem 2, we have derived the optimal decision result under centralization, where the total supply chain profit is maximized. To obtain a negotiated range of wholesale prices when all decision variables and profits are maximized, we consider fixing the optimal emission reduction level e_{ic}^* and retail price p_{ic}^* so that the sum of coordinated profits of supply chain members is maximized along with their respective profits. With the implementation of wholesale price contract coordination throughout the supply chain system, the manufacturer i can be allocated $\lambda_i(0 < \lambda_i < 1)$ of the total supply chain profit, and the retailer is assigned the remaining $1 - \sum_{i=1}^{2}\lambda_i$. Then, the coordinated manufacturer's and retailer's profits are expressed as $\pi_{Mi}^{wp*}(w_i^{wp}) = \lambda_i\pi_c^*$ and $\pi_R^{wp*}(w_i^{wp}) = (1 - \sum_{i=1}^{2}\lambda_i)\pi_c^*$.

According to the optimal profits of manufacturers and retailers under decentralization in Theorem 1, the contract is efficiently coordinated under the condition that coordinated profits are higher than uncoordinated decentralized profits, for instance, $\pi_{Mi}^{wp*} \geq \pi_{Mid}^*$ and $\pi_R^{wp*} \geq \pi_{Rd}^*$. Derive w_i^{wp} and λ_i from these conditions.

We refer to the relevant literature (Wang et al., 2022; Zhang & Qin, 2022) for values to select the values of the parameters within a specific range: $a = 100, \beta = 0.6, c = 50, e_0 = 10, \tau = 0.5, h = 20, h_r = 5, \varphi_1 = \varphi_2 = 0.1, f = 20$, and $m_s = 2$. Based on the coordination conditions, the range of w_i^{wp} and λ_i are derived as $w_i^{wp} = 68.44 + 178.00\lambda_i$, $0.19 < \lambda_i < 0.48 - \lambda_j (i = 1, 2, j = 3 - i)$. In other words, when the wholesale prices are in this range, the contract effectively coordinates the supply chain, resulting in higher profits for each supply chain member.

Table 3 lists the profits of supply chain members at different portfolios of wholesale prices. In these portfolios, wholesale price contracts can effectively coordinate the supply chain so that each member can

Table 3
Profits under wholesale price contracts.

(λ_i, λ_j)	(w_i^{wp}, w_j^{wp})	π_{Mi}^{wp*}	π_{Mid}^{*}	π_{Mj}^{wp*}	π_{Mjd}^{*}	π_{R}^{wp*}	π_{Rd}^{*}	π_{c}^{*}
(0.20, 0.20)	(104.04, 104.04)	1351.84	1306.19	1351.84	1306.19	4055.52	3542.28	6759.20
(0.20, 0.22)	(104.04, 107.60)	1351.84		1487.02		3920.34		
(0.20, 0.24)	(104.04, 111.16)	1351.84		1622.21		3785.15		
(0.20, 0.26)	(104.04, 114.72)	1351.84		1757.39		3649.97		
(0.22, 0.22)	(107.60, 107.60)	1487.02		1487.02		3785.15		
(0.22, 0.24)	(107.60, 111.16)	1487.02		1622.21		3649.97		

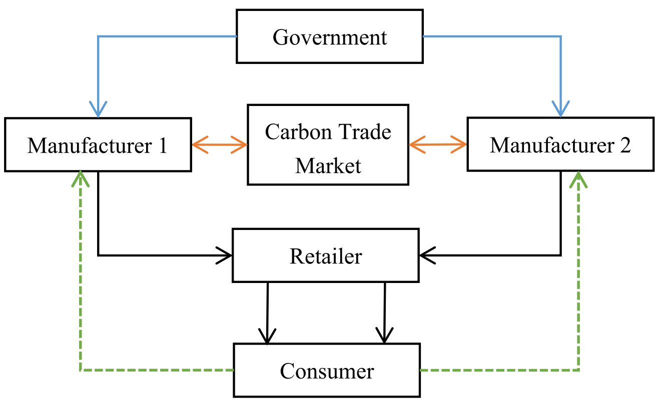

Fig. 3. Supply chain diagram of **Model CT**.

achieve greater profitability.

In the latter two scenarios, this approach can also be used to coordinate.

4.2. Scenario 2: Single cap-and-trade policy (Model CT)

Scenario 2 is **Model CT**, which implements the single cap-and-trade policy. As shown in Fig. 3, we suppose that the government allocates an equal carbon quota to each manufacturer, which they can trade on the carbon market based on their actual carbon emissions during production. The profit of the supply chain in **Model CT** is as follows:

$$\pi_{Mid}^{CT} = (w_i - c)d_i - \frac{1}{2}he_i^2 - \left(\frac{1}{2}h_r{\varphi_i}^2 + \varphi_i d_i f\right) - p_s(E_i - \overline{E}_s), i = 1, 2, j = 3 - i \tag{4}$$

$$\pi_{Rd}^{CT} = \sum_{i=1}^{2}(p_i - w_i)d_i, i = 1, 2, j = 3 - i \tag{5}$$

$$\pi_c^{CT} = \sum_{i=1}^{2}[(p_i - c)d_i - \frac{1}{2}he_i^2 - (\frac{1}{2}h_r{\varphi_i}^2 + \varphi_i d_i f) - p_s(E_i - \overline{E}_s)], i = 1, 2, j = 3 - i \tag{6}$$

Theorem 3. *In **Model CT**, the optimal outcomes (centralized) are as follows:*

$$e_{ic}^{CT*} = \frac{(\tau + p_s)\left[A2{\cdot}C2 + f\left(\varphi_i{\cdot}D2 - 2\beta\varphi_j h\right)\right]}{B2}$$

$$p_{ic}^{CT*} = \frac{A2{\cdot}\left\{[h + \tau(\beta - 1)(\tau + p_s)]{\cdot}C2 - a\left[2h - (\beta - 1)(\tau + p_s)^2\right]\right\}}{(\beta - 1){\cdot}B2} + \frac{f\left[\varphi_i{\cdot}G2 - \beta\varphi_j h(\tau^2 - {p_s}^2)\right]}{B2}$$

$$\pi_c^{CT*} = 2\overline{E}_s p_s - \frac{h{\cdot}A2{\cdot}C2^2}{(\beta - 1){\cdot}B2} - \frac{\left[\left({\varphi_i}^2 + {\varphi_j}^2\right)\left(h_r{\cdot}B2 + hf^2{\cdot}D2\right) + 2fh\left(\varphi_i + \varphi_j\right){\cdot}A2{\cdot}C2 - 4\beta\varphi_i\varphi_j f^2h^2\right]}{2{\cdot}B2}, \quad i = 1, 2, j = 3 - i$$

Proof: See Appendix B1.

As previously known, the constraints on the optimal decision variables are $0 < e_i < e_0$ and $c < p_i$, we derive that $a_{1i}^{CT} < a < a_{2i}^{CT}$. We conduct the analyses in the following sections based on these assumptions. From Theorem 3, we derive the following proposition.

Proposition 5. *In **Model CT**, the single carbon trading price and carbon quota have the following features:*

1. *When $a_{3i}^{CT} < a < a_{2i}^{CT}$, e_{ic}^{CT*} is positively related to p_s; when $a_{1i}^{CT} < a < a_{3i}^{CT}$, e_{ic}^{CT*} is negatively related to p_s.*
2. *When $a_{1i}^{CT} < a < a_{4i}^{CT}$, p_{ic}^{CT*} is positively related to p_s; when $a_{4i}^{CT} < a < a_{2i}^{CT}$, p_{ic}^{CT*} is negatively related to p_s.*
3. *When $\overline{E}_s > \overline{E}_{s1}$, π_c^{CT*} is positively related to p_s; otherwise ($0 < \overline{E}_s < \overline{E}_{s1}$), π_c^{CT*} is negatively related to p_s. There is a positive correlation between π_c^{CT*} and $\overline{E}_s$.*

Proof: See Appendix B2.

Proposition 5. analyzes the impacts of the carbon trading price and carbon quota in **Model CT** on optimal outcomes and the profit of the supply chain.

In Proposition 5(1), when the basis market demand is at a low level (lower than the threshold a_{3i}^{CT}), a higher carbon trading price leads to a lower emissions reduction level. When the basis market demand is higher ($a_{3i}^{CT} < a < a_{2i}^{CT}$), their relationship is the opposite. These results are similar to Proposition 3(1), where $a_{1i}^{CT} < a < a_{3i}^{CT}$, the growth of the carbon trading price causes a more significant policy cost, meanwhile the manufacturer needs to control the emissions reduction cost by reducing the emissions reduction levels. When a is higher than the threshold a_{3i}^{CT}, the trend is similar to the existing research (Sun et al., 2020). A high carbon trading price encourages firms to limit carbon emissions, increasing their emission reduction levels.

Similarly, the relationship between the carbon trading price and retail prices in Proposition 5(2) is also positive when $a_{1i}^{CT} < a < a_{4i}^{CT}$, and the trend is opposite when the primary market demand a is high ($a_{4i}^{CT} < a < a_{2i}^{CT}$).

By Proposition 5(3), the carbon trading price's impact on the supply chain's profit depends on the carbon quota. When $\overline{E}_s > \overline{E}_{s1}$, the total profit has a positive relationship with the carbon trading price. When $0 < \overline{E}_s < \overline{E}_{s1}$, the trend of the supply chain's profit is the opposite. Furthermore, at a fixed carbon trading price, the supply chain's profit increases with the carbon quota. These results reflect the advantages of the cap-and-trade policy. When the actual carbon emissions exceed the quota, a carbon emissions permit needs to be obtained from the carbon trading market. Apart from the actual carbon emissions, the rest of the carbon quota can be used to get additional benefits. Therefore, a larger carbon quota is beneficial for the supply chain members.

4.3. Scenario 3: Mixed policy (Model CO)

Scenario 3 is **Model CO,** which implements the mixed policy. As shown in Fig. 4, like **Model CT**, we suppose that each manufacturer is allocated the same carbon quota. According to its carbon emissions in production, each manufacturer pays a carbon tax for its transactions in the carbon trading market. The profit of the supply chain in **Model CO** is as follows:

$$\pi_{Mid}^{CO} = (w_i - c)d_i - \frac{1}{2}he_i^2 - \left(\frac{1}{2}h_r{\varphi_i}^2 + \varphi_i d_i f\right) - [m_c E_i + p_c(E_i - \overline{E}_c)], i = 1, 2, j = 3 - i \quad (7)$$

$$\pi_{Rd}^{CO} = \sum_{i=1}^{2}(p_i - w_i)d_i, i = 1, 2, j = 3 - i \quad (8)$$

$$\pi_c^{CO} = \sum_{i=1}^{2}\{(p_i - c)d_i - \frac{1}{2}he_i^2 - [m_c E_i + p_c(E_i - \overline{E}_c)] - (\frac{1}{2}h_r{\varphi_i}^2 + \varphi_i d_i f)\}, i = 1, 2, j = 3 - i \quad (9)$$

Theorem 4. *In **Model CO**, the optimal outcomes (centralized) are as follows:*

$$e_{ic}^{CO*} = \frac{(\tau + m_c + p_c)\left[A3\cdot C3 + f\left(\varphi_i\cdot D3 - 2\beta\varphi_j h\right)\right]}{B3}$$

$$p_{ic}^{CO*} = \frac{A3\cdot\left\{[h + \tau(\beta - 1)(\tau + m_c + p_c)]\cdot C3 - a\left[2h - (\beta - 1)(\tau + m_c + p_c)^2\right]\right\}}{(\beta - 1)\cdot B3} + \frac{f\left\{\varphi_i\cdot G3 - \left[\tau^2 - (m_c + p_c)^2\right]\beta\varphi_j h\right\}}{B3}$$

$$\pi_c^{CO*} = 2\overline{E}_c p_c - \frac{h\cdot A3\cdot C3^2}{(\beta - 1)\cdot B3} - \frac{\left[\left({\varphi_i}^2 + {\varphi_j}^2\right)\left(h_r\cdot B3 + f^2 h\cdot D3\right) + 2fh\left(\varphi_i + \varphi_j\right)\cdot A3\cdot C3 - 4\beta\varphi_i\varphi_j f^2 h^2\right]}{2\cdot B3},$$
$$i = 1, 2, j = 3 - i$$

Proof: See Appendix C1.

As previously known, the constraints on the optimal decision variables are $0 < e_i < e_0$ and $c < p_i$, and we derive that $a_{1i}^{CO} < a < a_{2i}^{CO}$. We conduct the analyses in the following sections based on these assumptions. From Theorem 4, we derive the following proposition.

Proposition 6. *In **Model CO**, the mixed carbon tax and carbon trading price, as well as the carbon quota, have the following features:*

(1) *When $a_{3i}^{CO} < a < a_{2i}^{CO}$, e_{ic}^{CO*} is positively related to m_c and p_c; when $a_{1i}^{CO} < a < a_{3i}^{CO}$, e_{ic}^{CO*} is negatively related to m_c and p_c. .*

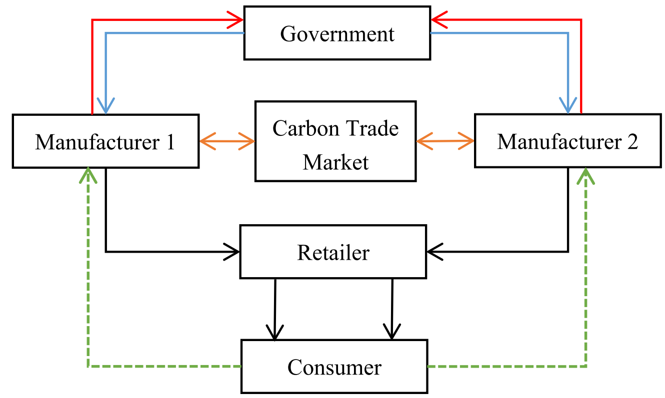

Fig. 4. Supply chain diagram of **Model CO**.

(2) *When $a_{1i}^{CO} < a < a_{4i}^{CO}$, p_{ic}^{CO*} is positively related to m_c and p_c; when $a_{4i}^{CO} < a < a_{2i}^{CO}$, p_{ic}^{CO*} is negatively related to m_c and p_c.*

(3) *When $\overline{E}_c > \overline{E}_{c1}$, π_c^{CO*} is positively related to p_c; otherwise ($0 < \overline{E}_c < \overline{E}_{c1}$), π_c^{CO*} is negatively related to p_c. There is a positive correlation between π_c^{CO*} and $\overline{E}_c$, and a negative correlation between π_c^{CO*} and m_c.*

Proof: See Appendix C2.

Proposition 6. investigates the impacts of the carbon tax, carbon trading price, and carbon quota in **Model CO** on optimal outcomes. The trends of these parameters' influence on optimal outcomes under the mixed policy align with those under the two single policies. Still, the thresholds for these changes differ. The differences between these thresholds depend on the ranges of the policy variables (m_s, p_s, $\overline{E}_s$, m_c, p_c and $\overline{E}_c$).

In lower basis market demand, carbon taxes and carbon trading prices have a slight negative effect on the emissions reduction level and a positive impact on retail prices due to relatively low consumer purchasing power and environmental awareness. Despite weak incentives from carbon emission policies, retail prices increase to maintain profits. Enterprises may invest part of their profits in low-carbon technologies to improve environmental performance and market competitiveness. However, while raising retail prices can maintain short-term profits, excessively high prices may decrease consumer willingness, affecting market share and long-term growth. Therefore, enterprises must balance pricing with market competition and consumer demand to avoid market shrinkage.

When the market demand is above the medium level, carbon tax and trading price positively impact on the emission reduction level, and enterprises may adopt more environmentally friendly production methods to meet market demand. As a result, the cost of the carbon policy decreases, eliminating the need for supply chain members to raise retail prices to maintain revenue. In this scenario, appropriately lowering retail prices becomes crucial for enterprises to attract more consumers and maintain competitiveness in the market.

Additionally, there are significant differences in the impacts of

Table 4
Comparison of supply chain profits in **Model CO** and **Model TA**.

Carbon tax	Carbon trading price	Carbon quota	Profit of supply chain
$m_s \le m_c$	$p_c > 0$	$\overline{E}_c > \overline{E}_1$	$\pi_c^{CO^*} > \pi_c^{TA^*}$
		$0 < \overline{E}_c < \overline{E}_1$	$\pi_c^{CO^*} < \pi_c^{TA^*}$
$m_s > m_c$	$0 < p_c \le m_s - m_c$	$\overline{E}_c > 0$	$\pi_c^{CO^*} > \pi_c^{TA^*}$
	$p_c > m_s - m_c$	$\overline{E}_c > \overline{E}_1$	$\pi_c^{CO^*} > \pi_c^{TA^*}$
		$0 < \overline{E}_c < \overline{E}_1$	$\pi_c^{CO^*} < \pi_c^{TA^*}$

carbon tax and cap-and-trade policies on supply chain profits. Carbon taxes, as a direct economic instrument, primarily affect supply chain profits through taxation. However, in some cases, an increase in carbon tax can instead increase manufacturers' profits. If the manufacturers can improve carbon emissions below the carbon quota level, an increase in the carbon tax can incentivize them to take more measures to reduce emissions, thereby increasing their profits. On the other hand, a cap-and-trade policy affects supply chain profits by limiting total carbon emissions and allocating carbon credits. It effectively controls the total carbon emissions to protect the environment but can be challenging to implement.

In summary, mixed carbon policies combine carbon tax and cap-and-trade mechanisms to achieve emission reduction targets while preserving supply chain profits. However, implementing such policies also faces challenges in terms of regulation, technology, and market acceptance, requiring policymakers to carefully consider and formulate appropriate policy measures.

5. Comparative analysis

This section compares the economic and environmental benefits of the supply chain under two single policies and mixed policies. Each subsection explores the optimal profit and the emission of the supply chain at maximum profit.

5.1. Model TA vs Model CO

This subsection compares the optimal profits of the supply chain and the actual carbon emissions in **Model TA** and **Model CO**. Table 4 shows the total profits for two scenarios based on several conditions of carbon parameters. Proposition 7 is derived by exploring the range of carbon quotas under different conditions.

Proposition 7. *Comparing the mixed policy and single carbon tax policy:*

(1) *The condition that the supply chain's profit in **Model CO** is higher than that in **Model TA** ($\pi_c^{CO^*} > \pi_c^{TA^*}$):*

a. $m_s \le m_c, \overline{E}_c > \overline{E}_1$

b. $m_s > m_c$,

(i) $0 < p_c \le m_s - m_c, \overline{E}_c > 0$

(ii) $p_c > m_s - m_c, \overline{E}_c > \overline{E}_1$

(2) *When $m_s < m_c + p_c$, the environmental benefits in **Model CO** are better than those in **Model TA** ($E^{TA^*} > E^{CO^*}$).*

As Proposition 7(1)a, when $m_s \le m_c$, no matter how the carbon trading price ($p_c > 0$) changes, if there is a higher carbon quota ($\overline{E}_c > \overline{E}_1$), the profit of supply chain under mixed policy is better than that under single policy. In addition to a carbon tax, there is a rule of cap-and-trade in **Model CO**. When the carbon quota is higher; the rest of the emission permits should be promoted to acquire more income, excluding the carbon emissions in the production process. While the carbon quota is low (below the threshold $\overline{E}_1$), once the carbon emission exceeds the quota allocated by the government, the enterprises must purchase carbon emission permits from the carbon trading market at the price of p_c, thus generating more costs of carbon emission.

As Proposition 7(1)b that the single carbon tax is higher ($m_s > m_c$), the range of carbon trading price needs to be discussed in two situations: (i) When $0 < p_c \le m_s - m_c$, the performance of **Model CO** will obviously be better than **Model TA** regardless of any carbon quota. (ii) When $p_c > m_s - m_c$, the **Model CO** has better profit in the case of carbon quota above the threshold $\overline{E}_1$.

The expressions of threshold $\overline{E}_1$ is shown in Appendix D1.

Different from a single carbon tax policy, the cap-and-trade mechanism in the mixed policy offers two possibilities to the supply chain members: One is that carbon emissions exceed the carbon quota, leading to the cost of purchasing emission permits. The other is to obtain the proceeds for selling the remaining quota when the carbon emission limit is not reached. This flexible rule incentivizes manufacturers to reduce emissions, while the single carbon tax only forces them to pay the penalty costs.

In addition, we assess the environmental performance of the supply chain by using the manufacturer's total carbon emissions as a key additional metric to make more comprehensive decisions. We obtained the optimal total carbon emissions through the model calculations while maximizing profits. As Proposition 7(2), in the case of $m_s < m_c + p_c$, the model constrained by mixed policy has better environmental benefits.

Similar to Sarkar et al. (2022), the combination of carbon policy is more economically and environmentally effective than a single carbon tax policy. However, since the different parameters in carbon policy, the mixed policy is not always better than the single carbon tax policy. Therefore, how to set parameters of carbon policy needs to be discussed. The analysis in this study found that in the case of $m_c + p_c \le m_s$, regardless of the carbon limit value, the economic benefits of **Model CO** are better, but the effect of emission reduction in **Model CO** is not good simultaneously. In the case of $m_c + p_c > m_s$ and the carbon quota is set above the threshold $\overline{E}_1$, the economic and environmental benefits in **Model CO** can be better than that in **Model TA**.

5.2. Model CT vs Model CO

This subsection compares the profits and the actual carbon emissions when maximizing profit in **Model CT** and **Model CO**. Table 5 shows the total profits for two scenarios based on several conditions of carbon parameters. Proposition 8 is derived by analyzing the range of carbon quota under vary conditions.

Proposition 8. *Comparing the mixed policy and the single cap-and-trade policy:*

(1) *The condition that the supply chain's profit in **Model CO** is better than that in **Model CT** ($\pi_c^{CO^*} > \pi_c^{CT^*}$):*

a. $p_s \le p_c, \overline{E}_c > \overline{E}_2$

b. $p_s > p_c, m_c \ge p_s - p_c, \overline{E}_c > \overline{E}_2$

c. $p_s > p_c, 0 < m_c < p_s - p_c$,

(i) $0 < \overline{E}_s < \overline{E}_3$

Table 5
Comparison of supply chain profits in **Model CO** and **Model CT**.

Carbon trading price	Carbon tax	Carbon quota	Profit of supply chain
$p_s \le p_c$	$m_c > 0$	$\overline{E}_c > \overline{E}_2$	$\pi_c^{CO^*} > \pi_c^{CT^*}$
		$0 < \overline{E}_c < \overline{E}_2$	$\pi_c^{CO^*} < \pi_c^{CT^*}$
$p_s > p_c$	$0 < m_c < p_s - p_c$	$0 < \overline{E}_s < \overline{E}_3$	$\pi_c^{CO^*} > \pi_c^{CT^*}$
		$\overline{E}_s > \overline{E}_3 \& \overline{E}_c > \overline{E}_2$	
		$\overline{E}_s > \overline{E}_3 \& 0 < \overline{E}_c < \overline{E}_2$	$\pi_c^{CO^*} < \pi_c^{CT^*}$
	$m_c \ge p_s - p_c$	$\overline{E}_c > \overline{E}_2$	$\pi_c^{CO^*} > \pi_c^{CT^*}$
		$0 < \overline{E}_c < \overline{E}_2$	$\pi_c^{CO^*} < \pi_c^{CT^*}$

(ii) $\overline{E}_s > \overline{E}_3 \& \overline{E}_c > \overline{E}_2$

(2) *When $p_s < m_c + p_c$, the environmental benefits in **Model CO** are better than those in **Model CT** ($E^{CT^*} > E^{CO^*}$).*

According to Proposition 8(1)a, when $p_s \le p_c$, only when the mixed carbon quota is higher than the threshold $\overline{E}_2$, the profit of the supply chain in **Model CO** can be higher than that in **Model CT**. Since the carbon tax mechanism in **Model CO**, no matter whether the cap-and-trade makes it gain revenue or pay for the carbon emission permits, the cost of carbon tax exists if there are carbon emissions.

As Proposition 8(1)b, in the case of lower single carbon trading price, no matter what the range of the single carbon quota, if the mixed carbon quota is over the threshold $\overline{E}_2$, the supply chain in **Model CO** is more advantageous.

As Proposition 8(1)c that the single carbon trading price is relatively high ($p_s > m_c + p_c$), if the single carbon quota is below the threshold $\overline{E}_4$ ($0 < \overline{E}_s < \overline{E}_3$), **Model CO** has a higher profit than **Model CT** no matter what the range of the mixed carbon quota. Otherwise, if $\overline{E}_s > \overline{E}_3$, only when $\overline{E}_c > \overline{E}_2$, the **Model CO** has a higher profit.

The expressions of threshold $\overline{E}_2$ and $\overline{E}_3$ are shown in Appendix D2.

From the above, the increase in carbon quotas is more helpful for the supply chain under the restraint of cap-and-trade. Unlike a single policy, a mixed emission reduction mechanism has greater constraints on carbon emissions.

Proposition 8(2). compares the carbon emissions of the two models under the optimal profits. When $p_s < m_c + p_c$, the total carbon emissions of two manufacturers under the mixed policy are below that under a single scenario, indicating that the mixed function of the carbon tax and carbon price has a great effect on reducing carbon emissions.

To sum up, there are few conditions for **Model CO** to be economically and environmentally better than **Model CT**. In the case of $m_c + p_c < p_s$, the economic benefit of **Model CO** is obviously better, but it has a higher carbon emission. Otherwise ($m_c + p_c > p_s$), when the mixed carbon quota is above the threshold $\overline{E}_2$ makes **Model CO** more economical and eco-friendlier.

5.3. Discussion

In **Subsections 5.1** and **5.2**, by comparing the mixed policies with two single policies respectively, we find that higher carbon quotas or a specific range of carbon taxes and carbon trading prices can yield better results when implementing mixed policies. The combination of carbon parameters significantly affects enterprise carbon emission behavior. First, higher carbon quotas or a specific range of carbon tax and carbon trading prices incentivize manufacturers to take more measures to reduce carbon emissions. The manufacturers facing upward cost pressures will intensify efforts to identify and adopt measures for carbon emission reduction and cost savings. Secondly, enterprises are encouraged to innovate and develop technology, and invest more resources in finding lower-cost and more efficient solutions.

In addition, by analyzing the expressions for these thresholds, a complex relationship between them and other parameters is revealed. Factors such as the basis market demand and emission reduction costs significantly impact the threshold of the carbon quota. When the carbon quota exceeds a certain threshold, enterprises can obtain higher profits by reducing carbon emissions. With increasing market demand, enterprises may need to adopt more radical measures, such as investing in low-carbon technologies or altering production processes, to maintain higher profits. Overall, through the market mechanism and carbon emission limits, enterprises can be incentivized to adopt more environmentally friendly production methods, promoting sustainable development. Emission reduction costs are also crucial; industries or regions with higher costs must implement stricter measures, while those with lower costs may adopt more lenient approaches. Therefore, formulating an effective and feasible carbon policy requires considering the combined effects of various factors.

In summary, the comparative analysis findings offer valuable

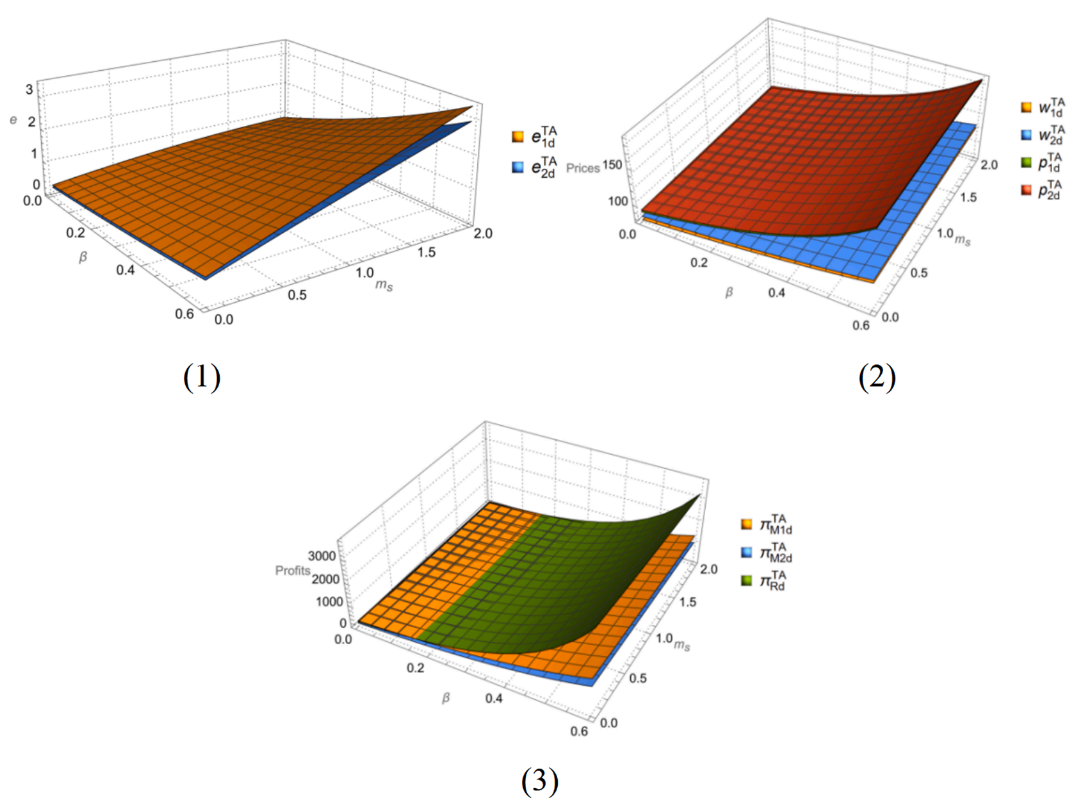

Fig. 5. Effect of β on the optimal outcomes.

insights for policy design, specifically for mixed policies and regulatory adjustments based on market conditions. Mixed policies, combining carbon taxes and cap-and-trade mechanisms, offer better economic incentives for carbon emissions reduction than single policies. The cap-and-trade mechanism allows flexibility in emissions reductions and the potential for additional income from selling emission permits. Higher carbon quotas, specific carbon tax, and trading price ranges can optimize mixed policies. However, the effectiveness of mixed policies is contingent on parameters such as carbon quotas, taxes, and trading prices, which are influenced by factors such as market demand and emission reduction costs. Policymakers should carefully consider these factors to design effective and feasible policies that promote economic growth and address environmental challenges.

6. Numerical studies

In this section, we verify the above propositions using numerical studies. We refer to the relevant literature (Wang et al., 2022; Zhang & Qin, 2022) to set the values of the following parameters in a specific range of values: $c = 50$, $e_0 = 10$, $\tau = 0.5$, $h = 20$, $h_r = 5$, and $f = 20$.

6.1. Effect of β on the optimal outcomes

This subsection takes the **Model TA** as an example, let $a = 100$, $\varphi_1 = 0.1$, $\varphi_2 = 0.3$. The following analyzes the change of the optimal outcome when the competitive intensity of manufacturers β is among 0 to 0.6, and the carbon tax is among 0 to 2.

As illustrated in Fig. 5, the influence trend of competitive intensity on optimal outcomes is similar to that in Proposition 1. The optimal outcomes and profits increase with the competitive intensity.

As shown in Fig. 5(1), the extent of the impact of a carbon tax as an environmental tax policy instrument on emission reduction is characterized by different levels of competition intensity. At low market competition intensity, the implementation effect of the carbon tax may be weakened to a certain extent, as enterprises may choose to reduce investment or shift production to reduce the tax burden. In contrast, a carbon tax can produce more significant environmental benefits at higher levels of market competition. In this case, a carbon tax can effectively encourage enterprises to take action to reduce emissions, thus achieving the goal of reducing carbon emissions. Therefore, the design and implementation of carbon tax policies need to take into full consideration the important factor of the intensity of market competition to ensure the policies' effectiveness and sustainability.

As shown in Fig. 5(2) and (3), there is little difference in the extent to which the carbon tax affects prices and profits at different levels of competitive intensity, with smaller increases in wholesale prices and manufacturers' profits and more significant increases in retail prices and retailers' profits. While increased competitive intensity may lead to higher profits, there are also some risks and challenges. For example, enterprises must continuously adapt to changes in the market and the competitive environment to maintain their competitive advantage. Manufacturers will have to invest more in low-carbon technologies to meet consumer demands and thus increase wholesale and retail prices.

6.2. Effect of φ on the optimal outcomes

This subsection also takes the **Model TA** as an example. We set $a = 100$, $m_s = 3$, $\varphi_j = 0.3$, and $\beta = 0.6$. The following analyzes the change in the optimal outcome when the recycling rate φ_i varies between 0 and 1.

As shown in Fig. 6(1), the emission reduction levels for both products decrease as their respective recycling rates increase, contrary to the trend of their rivals. When the recycling rate of one product is higher than that of its competitor ($\varphi_i > \varphi_j$), its emission reduction level is lower than that of the other, and the gap between them will grow wider.

According to Fig. 6(2), an increase in the recycling rate of either product will increase the wholesale and retail prices of both products but will result in a relatively small increase in competitor's prices.

As shown in Fig. 6(3), as the product recycling rate increases, the total carbon emissions of the manufacturer decrease significantly and increase the total carbon emissions of the other manufacturer.

As shown in Fig. 6(4), with the recycling rate increases, both its manufacturer and retailer lose profit while the other gains more. When it rises to a very high level, the profit of its manufacturer gradually falls to 0.

In summary, many benefits can be derived from increased recycling

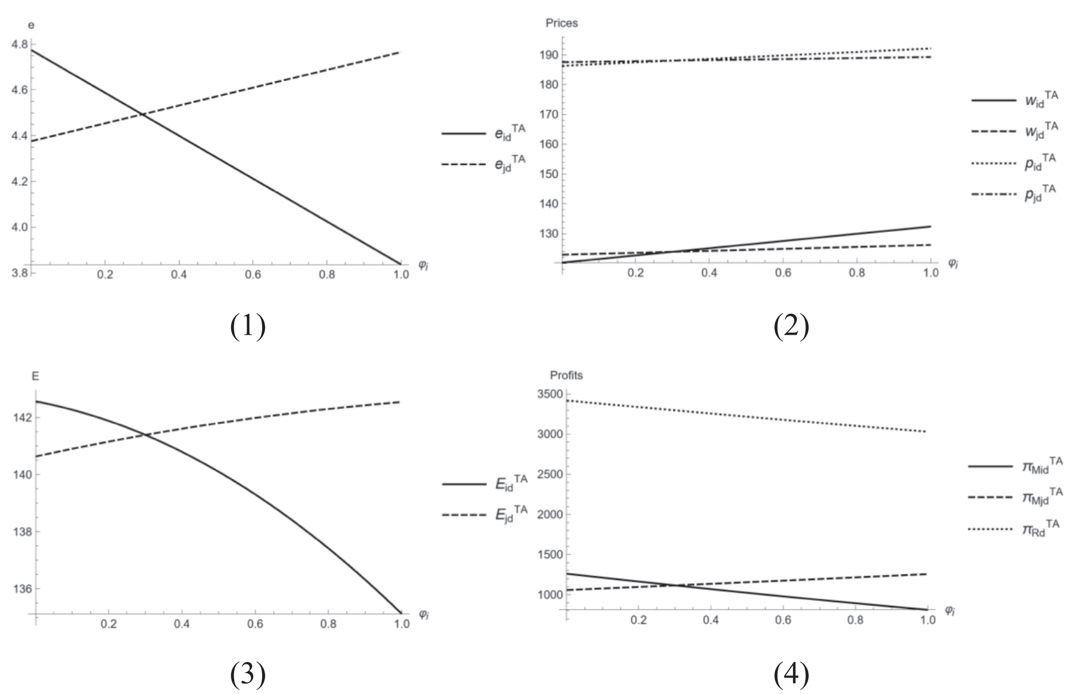

Fig. 6. Effect of φ_i on the optimal outcomes.

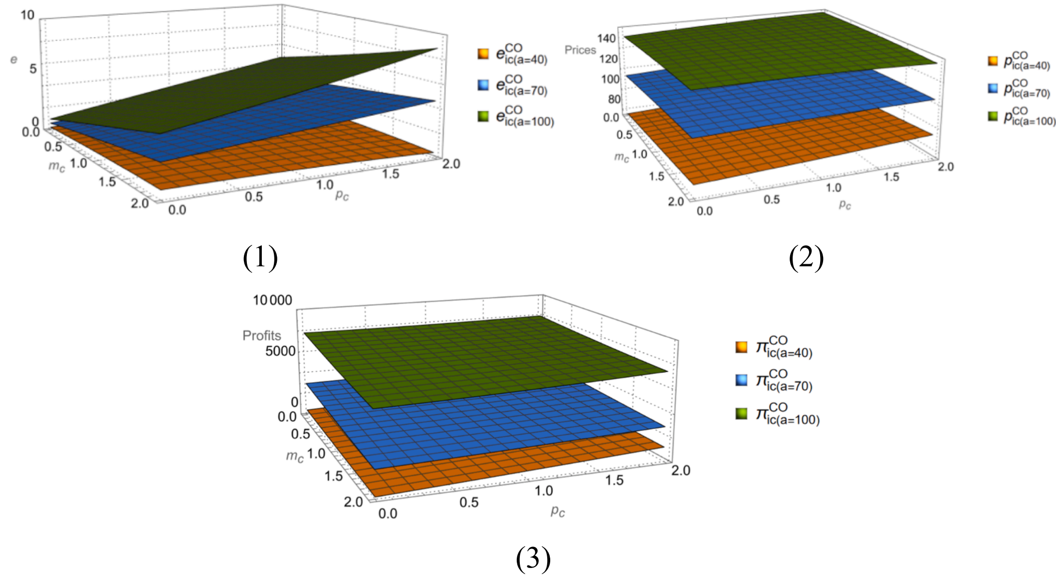

Fig. 7. Effect of m_c and p_c on the optimal outcome.

rates. However, problems such as rising costs and diminishing returns may also arise. Therefore, these factors need to be weighed and considered in developing a recycling system. On the economic side, the increasing cost of recycling operations leads to diminishing returns. On the environmental side, an increase in the recycling rate reduces total carbon emissions but increases problems such as the difficulty of disposing of waste, and the emission reduction level of products is relatively declined. Therefore, these issues also need to be fully considered and addressed in the process of increasing recycling rates.

6.3. Effects of m_c and p_c on the optimal outcomes

In this section, we examine the effects of mixed carbon parameters on the optimal outcome in the **Model CO**. Let $\beta = 0.6, \varphi_1 = \varphi_2 = 0.1$. According to **Propositions 3, 5, and 6**, we see that the trend of the optimal result will be different when the primary market demand changes; thus, there are three basic market demands ($a = 40, 70, 100$). The following investigates the change of optimal outcome when m_c and p_c vary between 0 and 2; we set the carbon quota $\overline{E}_c = 500$.

As illustrated in Fig. 7(1) and (2), when the primary market demand is low ($a = 40$), with the carbon tax and carbon trading price increasing, the emissions reduction level only slightly decreases, while the retail price rises. To reduce the losses from the rising costs of the carbon policies, the retail prices of the products will be increased by supply chain members, and the other costs may also be reduced. Suppose the emissions reduction cost is relatively high. In that case, the manufacturers will reduce the emissions reduction levels to control the prices. When the primary market demand is relatively high (a $= 70, 100$), it is evident that the retail price is almost unchanged as the carbon tax and carbon price increase. The emissions reduction levels of the manufacturers are significantly increased. Manufacturers reduce carbon emissions by increasing their emissions reduction levels when the cost of

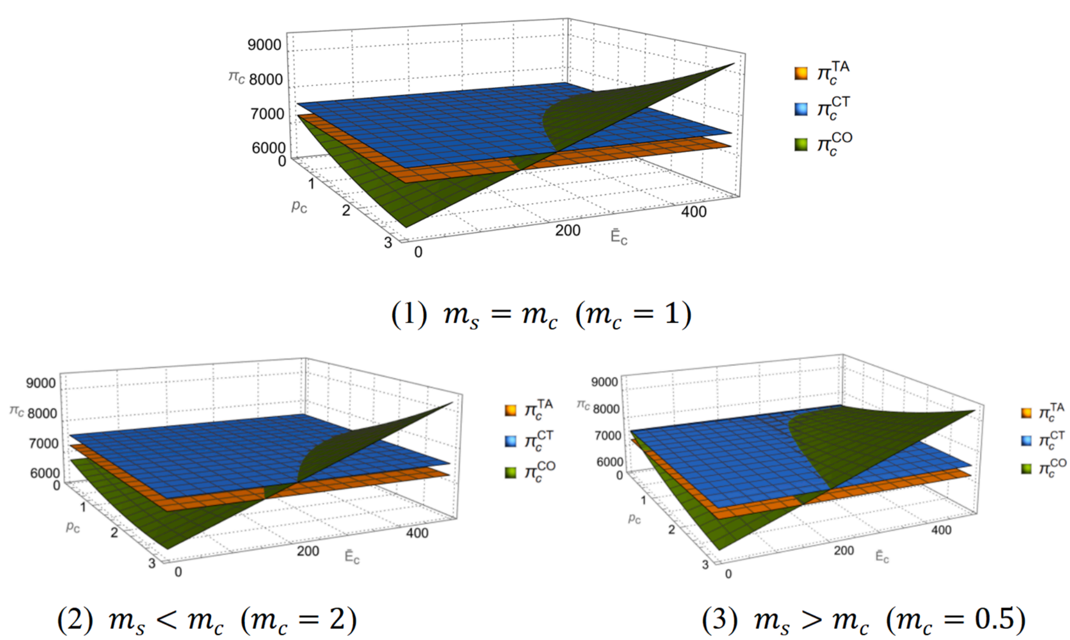

Fig. 8. Comparison of supply chain profits under three scenarios.

carbon emissions rises to reach the goal of restricting carbon policy costs.

As shown in Fig. 7(3), variations of the supply chain's profit are also roughly the same as before. The higher the carbon tax is, the more the profit. While the carbon price rises at a higher carbon quota, the supply chain's profit will go up accordingly. Moreover, the increase in the supply chain's profit is more significant at lower primary market demand than that at more considerable basic market demand. This may be due to the tiny fluctuations in retail prices, which, in this case, result in a stable profit.

This subsection verifies the above findings, showing that the carbon tax and carbon trading price have similar effects on the emissions reduction level and retail price, but different effects on the supply chain's profit.

6.4. Comparison of supply chain profits under a mixed policy and two single policies

This subsection explores the advantages of the mixed carbon policy versus the two single policies. We set $a = 100$, $\beta = 0.6$, and $\varphi_1 = \varphi_2 = 0.1$. The following explores the difference in total profit among **Model TA**, **Model CT**, and **Model CO**, where p_c varies between 0 and 3, and $\overline{E}_c$ varies between 0 and 500.

Under the fixed carbon tax, carbon trading price and carbon quota of single policy ($m_s = 1$, $p_s = 2$, $\overline{E}_s = 200$), as shown in Fig. 8, it is found that the lower the carbon tax in **Model CO**, the larger the portion of **Model CO**'s profits above the single policies (The green part in Fig. 8 is higher than the area of the orange and blue planes). Due to the negative effect of carbon tax on supply chain profits, the higher the carbon tax rate in the mixed scenario, the stronger the restriction on carbon emissions and the better the effect of emission reduction can be achieved, but at the same time, the total profits of the supply chain will be harmed.

As mentioned above (**Propositions 7 and 8**), when a mixed policy is implemented, supply chain members can earn higher profits when the set carbon quota is above a certain threshold than when a single policy is implemented. In Fig. 8, the images of the mixed policy intersect the curves, i.e., the thresholds, of the two single models respectively, and these thresholds can be expressed as a function on the carbon trading price (As shown in Table 6).

6.5. Discussion on the practical feasibility

Adjusting parameters in real-world policy settings, such as carbon quotas, taxes, and trading prices, can pose practical challenges and may have unintended consequences.

A practical challenge is determining appropriate levels for these parameters. Setting carbon quotas requires accurate, resource-intensive measurement and monitoring systems. Reliable emissions data is crucial for setting realistic targets. Determining optimal carbon taxes and trading prices involves balancing economic incentives for emission reductions against burdens on industries and consumers. Policymakers must consider factors like industry competitiveness, economic impacts, and social considerations when setting these parameters.

Adjusting these parameters may also result in unintended consequences and market distortions. For instance, if carbon quotas are too high, it may lead to an oversupply of emission permits, reducing their price and undermining emissions reduction incentives. Conversely, low quotas can lead to scarcity, resulting in higher permit prices that may disproportionately burden certain industries or regions. Additionally, rapidly increasing carbon taxes or trading prices can place financial burdens on businesses, impacting competitiveness and potentially causing job losses. It could also incentivize polluting industries to relocate to less regulated regions, leading to potential emissions leakage.

Compliance challenges can also arise when adjusting these parameters. Industries, especially those with complex supply chains, may struggle to accurately measure and report emissions. Compliance costs might increase as businesses invest in emission reduction measures or purchase additional permits. Ensuring compliance and enforcing penalties for non-compliance necessitates effective monitoring, reporting, verification, and enforcement mechanisms.

To address these challenges, policymakers need to carefully assess the feasibility of adjusting parameters in real-world policy settings. Monitoring and evaluating policy effectiveness can enable timely adjustments and corrections to minimize market distortions and address compliance challenges.

Table 6
Thresholds for different situations.

	Threshold of $\pi_c^{CO^*} > \pi_c^{TA^*}$	Threshold of $\pi_c^{CO^*} > \pi_c^{CT^*}$
$m_s = m_c$	$\dfrac{4615.75(p_c - 5.80)}{p_c^2 + 3p_c - 97.75}$	$\dfrac{4779.63(p_c^2 - 5.49p_c - 3.35)}{p_c(p_c^2 + 3p_c - 97.75)}$
$m_s < m_c$	$\dfrac{4615.75(p_c^2 - 3.80p_c - 4.80)}{p_c(p_c^2 + 5p_c - 93.75)}$	$\dfrac{4779.63(p_c^2 - 3.49p_c - 7.85)}{p_c(p_c^2 + 5p_c - 93.75)}$
$m_s > m_c$	$\dfrac{4615.75(p_c^2 - 6.80p_c + 3.15)}{p_c(p_c^2 + 2p_c - 99)}$	$\dfrac{4779.63(p_c^2 - 6.49p_c - 0.35)}{p_c(p_c^2 + 2p_c - 99)}$

7. Conclusions and managerial implications

7.1. Conclusions

This study examines optimal carbon emissions strategies in competitive closed-loop supply chains, focusing on three policy scenarios: single carbon tax, single cap-and-trade, and mixed policies. We consider factors like competitive intensity, recycling rates, and carbon policies, aiming to balance environmental and economic benefits. Our analysis involves a supply chain with two manufacturers and a shared retailer, studying the impact of carbon quota, trading price, recycling rate, and other elements on optimal decisions and total profit. The main findings are as follows:

First, carbon tax and cap-and-trade policies similarly impact carbon emissions and pricing, but affect supply chain profits differently. These policies effectively limit emissions when market demand is high, encouraging manufacturers to invest in reducing emissions. However, in weak markets, these policies have minimal impact on emissions reduction, offering insufficient incentives for investment. Small-scale market volatility can also deter investment in carbon reduction. Carbon tax increases operational costs, potentially reducing profits and affecting supply chain stability. Conversely, cap-and-trade policies can increase profitability by incentivizing emissions reduction and lowering carbon permit costs through technology and production optimization. Yet, if emissions aren't reduced or carbon permit prices are high, this policy can add burdens.

Second, the government and supply chain members can develop low-carbon strategies with greater flexibility, as demonstrated in Sarkar et al. (2022). While the mixed policy isn't always advantageous, it can yield better economic and environmental results when the quota exceeds a certain threshold. This policy optimizes benefits by combining carbon tax, price, and quota, encouraging businesses to decrease emissions through volume limits and cost penalties, and providing more carbon trading opportunities for additional economic benefits.

Third, the study found that within a certain competition intensity range, manufacturers are encouraged to invest in low-carbon technologies, increasing supply chain profitability. This supports Wang et al. (2022) and Liu et al. (2021b) findings that moderate competition in a highly competitive market environment has a positive impact on carbon emissions. Intense competition pushes manufacturers to improve emissions control, meeting high environmental standards and attracting eco-conscious consumers.

Finally, manufacturers with lower recycling rates can gain a competitive edge by investing in environmental protection and improving production processes. Even with lower prices, high emissions reduction in low-carbon products can boost revenues. This contradicts Zheng et al.'s (2016) finding that while the recycling rate negatively affects price, it contributes to profitability. Including carbon reduction costs and policy into the profit function shows their significant impact on profits, changing the recovery rate's effects on price and profit.

7.2. Managerial implications

The conclusions of this study can provide the following managerial insights for governments and enterprises. The government should enforce varied mixed policies for carbon-emitting businesses based on their production, scale, and suitable parameters to limit emissions and boost profitability. Developing a differentiated mixed policy presents challenges like setting appropriate thresholds based on industries' carbon emissions, energy efficiency, and product carbon footprints. Fairness must also be ensured, avoiding overly high standards that could cause unfair competition or market distortion. Policymakers should consider businesses' realities and capabilities, and plan suitable transition periods and support measures.

For enterprises, it is essential to strictly adhere to carbon policies when making production and sales decisions to meet low-carbon demand. They should increase investment in emission-reduction technologies and take responsibility for recycling and treating used products while pursuing economic benefits. Managing the supply chain's carbon footprint through monitoring and evaluating emissions is vital for sustainable production. Active participation in the carbon market and utilizing flexible trading mechanisms can optimize economic benefits and carbon costs. While certain technologies can be advantageous in this context, there may also be obstacles to their implementation.

1) Energy-efficient technologies: Adopting energy-efficient machinery and equipment, optimizing production processes, and improving energy management systems can help enterprises lower their energy consumption and operational costs while reducing their carbon footprint.
2) Renewable energy sources: Investing in renewable energy sources, such as solar panels or wind turbines, can promote cleaner energy, reduce fossil fuel dependence and minimize emissions.
3) Carbon capture and storage (CCS): CCS technologies capture and store industrial carbon dioxide emissions underground to prevent atmospheric release. Despite being in its nascent stages and encountering obstacles, it holds considerable potential to substantially decrease industrial carbon emissions.
4) Waste management and recycling technologies: Efficient waste management and recycling technologies can reduce waste generation, promote material reuse, and minimize landfill emissions.

However, there are potential barriers to adopting these technologies. For instance, high upfront costs, technological uncertainty, regulatory and policy challenges, and lack of awareness and technical expertise. Overcoming these requires collaboration between governments, businesses, and research institutions. Public-private partnerships can aid technology development, knowledge exchange, and cost-sharing. Financial mechanisms like grants or subsidies can support low-carbon technology adoption, and international collaborations can provide specialized expertise and resources.

Future research can explore two potential issues as follows.

1) Production costs of remanufactured vs. newly manufactured products: The current study focuses on product recycling and remanufacturing without explicitly distinguishing between the production costs of these products. Future research could delve into the costs associated with remanufactured products versus newly manufactured ones. By considering the production costs, researchers can identify the cost-effectiveness of remanufacturing and its potential impact on the decision-making process.
2) Dynamic impact of emissions reduction costs: The study acknowledges that the impact of emissions reduction costs on supply chain decision-making might not be constant. Understanding the dynamics of these costs and their influence on decision-making is a critical area for future research. By incorporating technological advancements, economies of scale, and environmental regulations, researchers can explore how emissions reduction costs vary over time. This analysis can provide insights into the long-term implications of adopting low-carbon practices and help optimize decision-making strategies in the supply chain.
3) Multiple factors affecting demand: Assuming demand is only influenced by price competition and emission reductions may simplify the real market environment. Consumer demand is affected by factors like brand loyalty and product differentiation. Future research would consider multiple factors for better market relevance.
4) Implications of dynamic market conditions for carbon policies and supply chain strategies: Demand fluctuations can impact production and carbon emissions, with peaks increasing and troughs reducing emissions. Enterprises should monitor market dynamics, including demand changes and technological advancements, when developing their carbon policies and supply chain strategies, to maintain a sustainable low-carbon competitive advantage.

Addressing these limitations can offer a thorough evaluation of remanufacturing's economic feasibility, its supply chain impact, and a detailed insight into decision-making, potential hurdles, and opportunities for embracing low-carbon practices.

CRediT authorship contribution statement

Yuxin Huang: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Pengfei He:** Investigation, Formal analysis, Data curation. **T.C.E. Cheng:** Writing – review & editing, Supervision, Methodology, Investigation. **Senyu Xu:** Validation, Methodology, Investigation, Formal analysis. **Chuan Pang:** Supervision, Project administration, Methodology, Investigation. **Huajun Tang:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Appendix A. Model TA

A1. Proof of Theorem 1

Under decentralized decision-making, there exists a Stackelberg game between manufacturers and retailer dominated by manufacturers. This part is analyzed using backward induction.

First, from the profit function of retailer Eq. (2), the Hessian matrix of the retailer in **Model TA** is

$$H_R = \begin{vmatrix} \dfrac{\partial^2 \pi_R}{\partial^2 p_1} & \dfrac{\partial^2 \pi_R}{\partial p_1 p_2} \\ \dfrac{\partial^2 \pi_R}{\partial p_2 p_1} & \dfrac{\partial^2 \pi_R}{\partial^2 p_2} \end{vmatrix} = \begin{vmatrix} -2 & 2\beta \\ 2\beta & -2 \end{vmatrix} = 4 - 4\beta^2$$

Based on the assumption that $0 < \beta < 1$, it can be derived that the second principal minor $4 - 4\beta^2 > 0$, H_R is a negative definite. Therefore, π_R is concave in p_1 and p_1.

Let $\frac{\partial \pi_R}{\partial p_1} = 0$ and $\frac{\partial \pi_R}{\partial p_2} = 0$, then we get $p_1{}' = \frac{a+(1-\beta)\tau e_1+(1-\beta)w_1}{2(1-\beta)}$ and $p_2{}' = \frac{a+(1-\beta)\tau e_2+(1-\beta)w_2}{2(1-\beta)}$.

Substituting $p_1{}'$ and $p_2{}'$ into Eq. (1), the Hessian matrix of manufacturers in **Model TA** is

$$H_{Mi} = \begin{vmatrix} \dfrac{\partial^2 \pi_{Mi}}{\partial^2 e_i} & \dfrac{\partial^2 \pi_{Mi}}{\partial e_i w_i} \\ \dfrac{\partial^2 \pi_{Mi}}{\partial w_i e_i} & \dfrac{\partial^2 \pi_{Mi}}{\partial^2 w_i} \end{vmatrix} = \begin{vmatrix} \tau m_s - h & \dfrac{1}{2}(\tau - m_s) \\ \dfrac{1}{2}(\tau - m_s) & -1 \end{vmatrix} = \frac{1}{4}\left[4h - (\tau + m_s)^2\right]$$

Based on the assumption that $0 < \tau < 1$, and h is considered as a more significant value, it can be derived that the second principal minor $\frac{1}{4}[4h - (\tau + m_s)^2] > 0$, H_{Mi} is a negative definite. Therefore, π_{Mi} is concave in e_i and w_i.

Let $\frac{\partial \pi_{M1}}{\partial e_1} = 0$, $\frac{\partial \pi_{M2}}{\partial e_2} = 0$, $\frac{\partial \pi_{M1}}{\partial w_1} = 0$, and $\frac{\partial \pi_{M2}}{\partial w_2} = 0$, we get

$e_{id}^{TA*} = \frac{(\tau+m_s)\left[A\cdot C1 + f\left(\varphi_i \cdot D - 2\beta\varphi_j h\right)\right]}{B}$, and

$$w_{id}^{TA*} = \frac{A\cdot\{a[2h - m_s(\tau + m_s)] + (c + e_0 m_s)[2h + \tau(\beta - 1)(\tau + m_s)]\} + f\{\varphi_i \cdot F2 - 2\beta\varphi_j h[2h - m_s(\tau + m_s)]\}}{B} (i = 1, 2, j = 3 - i)$$

Substituting e_{id}^{TA*} and w_{id}^{TA*} into $p_i{}'$, we get

$$p_{id}^{TA*} = \frac{A\cdot\{a\cdot F1 + (\beta - 1)(c + e_0 m_s)[h + \tau(\beta - 1)(\tau + m_s)]\} - (\beta - 1)f\left[\varphi_i \cdot F3 + \beta\varphi_j h(2h + \tau^2 - m_s{}^2)\right]}{(\beta - 1)\cdot B}.$$

At last, we obtain the optimal profit:

$\pi_{Mid}^{TA*} = \frac{h\cdot\left[4h-(\tau+m_s)^2\right]\left[A\cdot C1 + f\left(\varphi_i \cdot D - 2\beta\varphi_j h\right)\right]^2 - \varphi_i{}^2 h_r \cdot B^2}{2\cdot B^2}$, and

$$\pi_{Rd}^{TA*} = \frac{-2h^2\cdot A^2\cdot C1^2 - (\beta - 1)h^2\left[2f\left(\varphi_i + \varphi_j\right)\cdot A^2\cdot C1 + f^2(\varphi_1{}^2 + \varphi_2{}^2)\cdot F4 + 2\beta\varphi_i\varphi_j f^2\cdot F5\right]}{(\beta - 1)\cdot B^2} (i = 1, 2, j = 3 - i)$$

where $A = (\beta + 1)(\tau + m_s)^2 - 2h(\beta + 2)$, $B = (\beta^2 - 1)(\tau + m_s)^4 - 4h(\beta^2 - 2)(\tau + m_s)^2 + 4h^2(\beta^2 - 4)$, $C1 = a + (\beta - 1)(c + e_0 m_s)$, $D = (\beta^2 - 1)(\tau + m_s)^2 - 2h(\beta^2 - 2)$, $F1 = h(2\beta - 3) - m_s(\beta - 1)(\tau + m_s)$, $F2 = \tau(\beta^2 - 1)(\tau + m_s)^3 + 2h(\tau + m_s)(m_s + 3\tau - \beta^2\tau) - 8h^2$, $F3 = 4h^2 - \tau(\beta^2 - 1)(\tau + m_s)^3 - h(\tau + m_s)(5\tau + m_s - 2\beta^2\tau)$, $F4 = 4h^2(3\beta^2 - 4) - 8h(\beta^2 - 1)(\tau + m_s)^2 + (\beta^2 - 1)(\tau + m_s)^4$, $F5 = 4\beta^2 h^2 - 4h(\beta^2 - 1)(\tau + m_s)^2 + (\beta^2 - 1)(\tau + m_s)^4$.

Based on $0 < e_i < e_0$ and $c < w_i < p_i$, we derived the range of basis market demand a as $a_{1i}^{TA} < a < a_{2i}^{TA}$ and $a > a_{0i}^{TA}$.

Where $a_{1i}^{TA} = (1 - \beta)(c + e_0 m_s) - \frac{f\left(\varphi_i \cdot D - 2\beta\varphi_j h\right)}{A}$,

$a_{2i}^{TA} = (1 - \beta)(c - \tau e_0) - \frac{f\left(\varphi_i \cdot D - 2\beta\varphi_j h\right)}{A} + \frac{2e_0 h(2-\beta)}{\tau + m_s}$, and

$$a_{0i}^{TA} = (1 - \beta)(c + e_0 m_s) - \frac{(1 - \beta)f\{\varphi_i[4h - (\tau + m_s)^2] + \beta\varphi_j[2h - (\tau + m_s)^2]\}}{A}$$

When $\varphi_1 \geq \varphi_2$, $a_{0i}^{TA} \leq a_{1i}^{TA}$, the range of basis market demand is expressed as $a_{1i}^{TA} < a < a_{2i}^{TA}$. When $\varphi_1 < \varphi_2$, $a_{0i}^{TA} > a_{1i}^{TA}$, we take $a_{0i}^{TA} < a < a_{2i}^{TA}$.

A2. Proof of Proposition 1

Taking **Model TA** for example, we judge the first-order partial derivation of the optimal outcome on competitive intensity under decentralization. Investing in green technology will consume a large input, so we derived the lower bounds of the cost coefficient of carbon emission reduction ($h > \frac{1}{2}(\tau + m_s)^2$).

When $0 < \beta < \frac{2h-(\tau+m_s)^2}{(\tau+m_s)^2}$, we found that $\frac{\partial e_{id}^{TA*}}{\partial \beta} > 0$, $\frac{\partial w_{id}^{TA*}}{\partial \beta} > 0$, $\frac{\partial p_{id}^{TA*}}{\partial \beta} > 0$, $\frac{\partial \pi_{Mid}^{TA*}}{\partial \beta} > 0$, $\frac{\partial \pi_{Rd}^{TA*}}{\partial \beta} > 0$.

When $\frac{1}{2}(\tau + m_s)^2 < h < (\tau + m_s)^2$, $\frac{2h-(\tau+m_s)^2}{(\tau+m_s)^2} < 1$, so we take $\frac{2h-(\tau+m_s)^2}{(\tau+m_s)^2}$ as the upper bound of β. When $h \geq (\tau + m_s)^2$, $\frac{2h-(\tau+m_s)^2}{(\tau+m_s)^2} \geq 1$, in this case, we take the assumed range before ($0 < \beta < 1$).

A3. Proof of Proposition 2

(1) Taking **Model TA** for example, the first-order partial derivation of the optimal outcome on recycle rate by decentralization is analyzed.

We derived the lower bounds of the cost coefficient of carbon emission reduction ($h > \frac{1}{2}(\tau + m_s)^2$) because of the large expense of investing in low-carbon technology, and obtained that $\frac{\partial e_{id}^{TA*}}{\partial \varphi_i} < 0$, $\frac{\partial e_{jd}^{TA*}}{\partial \varphi_i} > 0$, $\frac{\partial w_{id}^{TA*}}{\partial \varphi_i} > 0$, $\frac{\partial w_{jd}^{TA*}}{\partial \varphi_i} > 0$, $\frac{\partial p_{id}^{TA*}}{\partial \varphi_i} > 0$, $\frac{\partial p_{jd}^{TA*}}{\partial \varphi_i} > 0$, $\frac{\partial \pi_{Mid}^{TA*}}{\partial \varphi_i} < 0$, $\frac{\partial \pi_{Mjd}^{TA*}}{\partial \varphi_i} > 0$, and $\frac{\partial \pi_{Rd}^{TA*}}{\partial \varphi_i} < 0$.

(2) The optimal outcomes of two competitive channels with different product recycle rates are compared:

$e_{id}^{TA*} - e_{jd}^{TA*} = \frac{f(\beta+1)(\tau+m_s)(\varphi_i-\varphi_j)}{(\beta+1)(\tau+m_s)^2-2h(\beta+2)}$. Since $f(\beta+1)(\tau+m_s) > 0$ and $(\beta+1)(\tau+m_s)^2 - 2h(\beta+2) < 0$, when $\varphi_i < \varphi_j$, $\varphi_i - \varphi_j < 0$, hence, $e_{id}^{TA*} > e_{jd}^{TA*}$.

$w_{id}^{TA*} - w_{jd}^{TA*} = \frac{f[\tau(\beta+1)(\tau+m_s)-2h](\varphi_i-\varphi_j)}{(\beta+1)(\tau+m_s)^2-2h(\beta+2)}$. Since $f[\tau(\beta+1)(\tau+m_s) - 2h] < 0$ and $(\beta+1)(\tau+m_s)^2 - 2h(\beta+2) < 0$, when $\varphi_i < \varphi_j$, $\varphi_i - \varphi_j < 0$, hence, $w_{id}^{TA*} < w_{jd}^{TA*}$.

$p_{id}^{TA*} - p_{jd}^{TA*} = \frac{f[\tau(\beta+1)(\tau+m_s)-h](\varphi_i-\varphi_j)}{(\beta+1)(\tau+m_s)^2-2h(\beta+2)}$. Since $f[\tau(\beta+1)(\tau+m_s) - h] < 0$ and $(\beta+1)(\tau+m_s)^2 - 2h(\beta+2) < 0$, when $\varphi_i < \varphi_j$, $\varphi_i - \varphi_j < 0$, hence, $p_{id}^{TA*} < p_{jd}^{TA*}$.

$\pi_{Mid}^{TA*} - \pi_{Mjd}^{TA*} = \frac{\{h_r \cdot B + hf^2(\beta^2-1)[4h-(\tau+m_s)^2]\}(\varphi_i^2-\varphi_j^2) - 2fh(\beta+1)[4h-(\tau+m_s)^2] \cdot C1(\varphi_i-\varphi_j)}{2 \cdot B}$. When $\varphi_i < \varphi_j$ and at a certain base market size, $\pi_{Mid}^{TA*} > \pi_{Mjd}^{TA*}$.

A4. Proof of Theorem 2

The supply chain members make decisions simultaneously, according to the profit function of retailer Eq. (3), the Hessian matrix of the supply chain in **Model TA** is

$$H_c = \begin{vmatrix} \frac{\partial^2 \pi_c}{\partial^2 p_1} & \frac{\partial^2 \pi_c}{\partial p_1 p_2} & \frac{\partial^2 \pi_c}{\partial p_1 e_1} & \frac{\partial^2 \pi_c}{\partial p_1 e_2} \\ \frac{\partial^2 \pi_c}{\partial p_2 p_1} & \frac{\partial^2 \pi_c}{\partial^2 p_2} & \frac{\partial^2 \pi_c}{\partial p_2 e_1} & \frac{\partial^2 \pi_c}{\partial p_2 e_2} \\ \frac{\partial^2 \pi_c}{\partial e_1 p_1} & \frac{\partial^2 \pi_c}{\partial e_1 p_2} & \frac{\partial^2 \pi_c}{\partial^2 e_1} & \frac{\partial^2 \pi_c}{\partial e_1 e_2} \\ \frac{\partial^2 \pi_c}{\partial e_2 p_1} & \frac{\partial^2 \pi_c}{\partial e_2 p_2} & \frac{\partial^2 \pi_c}{\partial e_2 e_1} & \frac{\partial^2 \pi_c}{\partial^2 e_2} \end{vmatrix}$$

$$= \begin{vmatrix} -2 & 2\beta & \tau - m_s & \beta(m_s - \tau) \\ 2\beta & -2 & \beta(m_s - \tau) & \tau - m_s \\ \tau - m_s & \beta(m_s - \tau) & 2\tau m_s - h & -2\beta\tau m_s \\ \beta(m_s - \tau) & \tau - m_s & -2\beta\tau m_s & 2\tau m_s - h \end{vmatrix}$$

$$= (\beta^2 - 1)[4h(\tau + m_s)^2 - 4h^2 + (\beta^2 - 1)(\tau + m_s)^4]$$

Based on the assumption that $0 < \beta < 1$, $0 < \tau < 1$, and h is considered as a larger value, it can be derived that the second principal minor $H_{c2} = 4 - 4\beta^2 > 0$, the third principal minor $H_{c3} = 2(\beta^2 - 1)[2h - (\tau + m_s)^2] < 0$, and $H_c = (\beta^2 - 1)[4h(\tau + m_s)^2 - 4h^2 + (\beta^2 - 1)(\tau + m_s)^4] > 0$, therefore, π_c is concave in e_1, e_2, p_1, and p_2.

Let $\frac{\partial \pi_c}{\partial e_1} = 0$, $\frac{\partial \pi_c}{\partial e_2} = 0$, $\frac{\partial \pi_c}{\partial p_1} = 0$, and $\frac{\partial \pi_c}{\partial p_2} = 0$, we get.

$e_{ic}^{TA*} = \frac{(\tau+m_s)[A1 \cdot C1 + f(\varphi_i \cdot D1 - 2\beta\varphi_j h)]}{B1}$, and

$$p_{ic}^{TA*} = \frac{A1 \cdot \left\{[h + \tau(\beta - 1)(\tau + m_s)] \cdot C1 - a\left[2h - (\beta - 1)(\tau + m_s)^2\right]\right\} + (\beta - 1)f\left[\varphi_i \cdot G1 - \beta\varphi_j h(\tau^2 - m_s^2)\right]}{(\beta - 1) \cdot B1} (i = 1, 2, j = 3 - i)$$

Substituting e_{ic}^{TA*} and p_{ic}^{TA*} into **Eq. (3)**, the total profit of the entire system expresses as

$$\pi_c^{TA*} = \frac{-2h \cdot A1 \cdot C1^2 - (\beta - 1)\left[(\varphi_i^2 + \varphi_j^2)h_r \cdot B1 + (\varphi_i^2 + \varphi_j^2)f^2 h \cdot D1 + 2fh(\varphi_i + \varphi_j) \cdot A1 \cdot C1 - 4\beta\varphi_i\varphi_j f^2 h^2\right]}{2(\beta - 1) \cdot B1} (i = 1, 2, j = 3 - i)$$

where $A1 = (\beta + 1)(\tau + m_s)^2 - 2h$, $B1 = (\beta^2 - 1)(\tau + m_s)^4 + 4h(\tau + m_s)^2 - 4h^2$, $C1 = a + (\beta - 1)(c + e_0 m_s)$, $D1 = (\beta^2 - 1)(\tau + m_s)^2 + 2h$, $G1 = \tau(\beta^2 - 1)(\tau + m_s)^3 + h(\tau + m_s)(3\tau + m_s) - 2h^2$.

Based on $0 < e_i < e_0$ and $c < p_i$, we derived the range of basis market demand a as $a_{3i}^{TA} < a < a_{4i}^{TA}$ and $a > a_{5i}^{TA}$.

Where $a_{3i}^{TA} = (1 - \beta)(c + e_0 m_s) - \frac{f(\varphi_i \cdot D1 - 2\beta\varphi_j h)}{A1}$,

$$a_{4i}^{TA} = (1 - \beta)(c - \tau e_0) + \frac{2e_0 h(2 - \beta)}{\tau + m_s} - \frac{f(\varphi_i \cdot D1 - 2\beta\varphi_j h)}{A1}$$

$$a_{5i}^{TA} = (1-\beta)(c+e_0m_s) - \frac{(1-\beta)f\left\{\varphi_i\left[4h-(\tau+m_s)^2\right]+\beta\varphi_j\left[2h-(\tau+m_s)^2\right]\right\}}{A1}$$

When $\varphi_i = \varphi_j$, $a_{3i}^{TA} = a_{5i}^{TA}$, the range of basis market demand is expressed as $a_{3i}^{TA} < a < a_{4i}^{TA}$.

A5. Proof of Proposition 3

Based on the assumptions before, the range of a and h are regarded as $a_{3i}^{TA} < a < a_{4i}^{TA}$ and $h > \frac{1}{2}(\tau+m_s)^2$. In this range, the first-order partial derivation of the optimal outcome on m_s by centralization is determined:

(1) When $a_{6i}^{TA} < a < a_{4i}^{TA}$, $\frac{\partial e_{ic}^{TA*}}{\partial m_s} > 0$. When $a_{3i}^{TA} < a < a_{6i}^{TA}$, $\frac{\partial e_{ic}^{TA*}}{\partial m_s} < 0$.

$$a_{6i}^{TA} = (1-\beta)(c-\tau e_0+\varphi f)+\frac{4e_0h(1-\beta)(\tau+m_s)}{2h-(\beta-1)(\tau+m_s)^2}$$

(2) When $a_{3i}^{TA} < a < a_{7i}^{TA}$, $\frac{\partial p_{ic}^{TA*}}{\partial m_s} > 0$. When $a_{7i}^{TA} < a < a_{4i}^{TA}$, $\frac{\partial p_{ic}^{TA*}}{\partial m_s} < 0$.

$$a_{7i}^{TA} = (1-\beta)(c-\tau e_0+\varphi f)+\frac{e_0h[2h-(\beta-1)(m_s-3\tau)(\tau+m_s)]}{2hm_s+\tau(\beta-1)(\tau+m_s)^2}$$

In the whole range, $\frac{\partial \pi_c^{TA*}}{\partial m_s} < 0$.

Appendix B. Model CT

B1. Proof of Theorem 3

The process of optimal solutions for **Model CT** is similar to Theorem 2 (Appendix A4).

According to the profit function of retailer Eq. (6), the Hessian matrix of the supply chain in **Model CT** is

$$H_c = \begin{vmatrix} \frac{\partial^2\pi_c}{\partial^2 p_1} & \frac{\partial^2\pi_c}{\partial p_1 p_2} & \frac{\partial^2\pi_c}{\partial p_1 e_1} & \frac{\partial^2\pi_c}{\partial p_1 e_2} \\ \frac{\partial^2\pi_c}{\partial p_2 p_1} & \frac{\partial^2\pi_c}{\partial^2 p_2} & \frac{\partial^2\pi_c}{\partial p_2 e_1} & \frac{\partial^2\pi_c}{\partial p_2 e_2} \\ \frac{\partial^2\pi_c}{\partial e_1 p_1} & \frac{\partial^2\pi_c}{\partial e_1 p_2} & \frac{\partial^2\pi_c}{\partial^2 e_1} & \frac{\partial^2\pi_c}{\partial e_1 e_2} \\ \frac{\partial^2\pi_c}{\partial e_2 p_1} & \frac{\partial^2\pi_c}{\partial e_2 p_2} & \frac{\partial^2\pi_c}{\partial e_2 e_1} & \frac{\partial^2\pi_c}{\partial^2 e_2} \end{vmatrix}$$

$$= \begin{vmatrix} -2 & 2\beta & \tau-p_s & \beta(p_s-\tau) \\ 2\beta & -2 & \beta(p_s-\tau) & \tau-p_s \\ \tau-p_s & \beta(p_s-\tau) & 2\tau p_s-h & -2\beta\tau p_s \\ \beta(p_s-\tau) & \tau-p_s & -2\beta\tau p_s & 2\tau p_s-h \end{vmatrix}$$

$$= (\beta^2-1)[4h(\tau+p_s)^2-4h^2+(\beta^2-1)(\tau+p_s)^4]$$

Based on the assumption that $0 < \beta < 1$, $0 < \tau < 1$, and h is considered as a larger value, it can be derived that the second principal minor $H_{c2} = 4-4\beta^2 > 0$, the third principal minor $H_{c3} = 2(\beta^2-1)[2h-(\tau+p_s)^2] < 0$, and $H_c = (\beta^2-1)[4h(\tau+p_s)^2-4h^2+(\beta^2-1)(\tau+p_s)^4] > 0$, therefore, π_c is concave in e_1, e_2, p_1, and p_2.

Let $\frac{\partial\pi_c}{\partial e_1} = 0$, $\frac{\partial\pi_c}{\partial e_2} = 0$, $\frac{\partial\pi_c}{\partial p_1} = 0$, and $\frac{\partial\pi_c}{\partial p_2} = 0$, we get

$e_{ic}^{CT*} = \frac{(\tau+p_s)\left[A2\cdot C2+f\left(\varphi_i\cdot D2-2\beta\varphi_j h\right)\right]}{B2}$, and

$$p_{ic}^{CT*} = \frac{A2\cdot\left\{[h+\tau(\beta-1)(\tau+p_s)]\cdot C2-a\left[2h-(\beta-1)(\tau+p_s)^2\right]\right\}+f(\beta-1)\left[\varphi_i\cdot G2-\beta\varphi_j h(\tau^2-p_s^2)\right]}{(\beta-1)\cdot B2}(i=1,2,j=3-i)$$

Substituting e_{ic}^{CT*} and p_{ic}^{CT*} into **Eq.(6)**, the total profit of entire system expresses as $\pi_c^{CT*} = \frac{4\overline{E}p_s(\beta-1)\cdot B2-2h\cdot A2\cdot C2^2-(\beta-1)\left[\left(\varphi_i^2+\varphi_j^2\right)\left(h_r\cdot B2+hf^2\cdot D2\right)+2fh\left(\varphi_i+\varphi_j\right)\cdot A2\cdot C2-4\beta\varphi_i\varphi_j f^2h^2\right]}{2(\beta-1)\cdot B2}(i = 1,\ 2,\ j = 3-i)$where $A2 = (\beta+1)(\tau+p_s)^2-2h$, $B2 = (\beta^2-1)(\tau+p_s)^4+4h(\tau+p_s)^2-4h^2$, $C2 = a+(\beta-1)(c+e_0p_s)$, $D2 = (\beta^2-1)(\tau+p_s)^2+2h$, $G2 = \tau(\beta^2-1)(\tau+p_s)^3+h(\tau+p_s)(3\tau+p_s)-2h^2$.

Based on $0 < e_i < e_0$ and $c < p_i$, we derived the range of basis market demand a as $a_{1i}^{CT} < a < a_{2i}^{CT}$ and $a > a_{3i}^{CT}$.Where $a_{1i}^{CT} = (1-\beta)(c + e_0 p_s) - \frac{f(\varphi_i \cdot D2 - 2\beta\varphi_j h)}{A2}$,

$$a_{2i}^{CT} = (1-\beta)(c - \tau e_0) + \frac{2e_0 h(2-\beta)}{\tau + p_s} - \frac{f(\varphi_i \cdot D2 - 2\beta\varphi_j h)}{A2}$$

$$a_{3i}^{CT} = (1-\beta)(c + e_0 p_s) - \frac{(1-\beta)f\left\{\varphi_i\left[4h - (\tau + p_s)^2\right] + \beta\varphi_j\left[2h - (\tau + p_s)^2\right]\right\}}{A2}$$

When $\varphi_i = \varphi_j$, $a_{1i}^{CT} = a_{3i}^{CT}$, the range of basis market demand is expressed as $a_{1i}^{CT} < a < a_{2i}^{CT}$.

B2. Proof of Proposition 5

Based on the assumptions before, the range of a and h are regarded as $a_{3i}^{CT} < a < a_{4i}^{CT}$ and $h > \frac{1}{2}(\tau + p_s)^2$. In this range, the first-order partial derivation of the optimal outcome on p_s is determined:

(1) When $a_{3i}^{CT} < a < a_{2i}^{CT}$, $\frac{\partial e_{ic}^{CT^*}}{\partial p_s} > 0$. When $a_{1i}^{CT} < a < a_{3i}^{CT}$, $\frac{\partial e_{ic}^{CT^*}}{\partial p_s} < 0$.

$$a_{3i}^{CT} = (1-\beta)(c - \tau e_0 + \varphi f) + \frac{4e_0 h(1-\beta)(\tau + p_s)}{2h - (\beta - 1)(\tau + p_s)^2}$$

(2) When $a_{1i}^{CT} < a < a_{4i}^{CT}$, $\frac{\partial p_{ic}^{CT^*}}{\partial p_s} > 0$. When $a_{4i}^{CT} < a < a_{2i}^{CT}$, $\frac{\partial p_{ic}^{CT^*}}{\partial p_s} < 0$.

$$a_{4i}^{CT} = (1-\beta)(c - \tau e_0 + \varphi f) + \frac{e_0 h[2h - (\beta - 1)(p_s - 3\tau)(\tau + p_s)]}{2hp_s + \tau(\beta - 1)(\tau + p_s)^2}$$

(3) When $\overline{E}_s > \overline{E}_{s1}$, $\frac{\partial \pi_c^{CT^*}}{\partial p_s} > 0$. When $0 < \overline{E}_s < \overline{E}_{s1}$, $\frac{\partial \pi_c^{CT^*}}{\partial p_s} < 0$.

$$\overline{E}_{s1} = \frac{h[a + (\beta - 1)(c + e_0 p_s + \varphi f)][(1-\beta)(c - \tau e_0 + \varphi f)(\tau + p_s) + 2e_0 h - a(\tau + p_s)]}{\left[2h + (\beta - 1)(\tau + p_s)^2\right]^2}.$$

$\frac{\partial \pi_c^{CT^*}}{\partial \overline{E}_s} > 0$ expresses that there is a positive correlation between $\pi_c^{CT^*}$ and $\overline{E}_s$.

Appendix C. Model CO

C1. Proof of Theorem 4

The process of optimal decision variables for **Model CO** is similar to Theorem 2 (Appendix A4).

According to the profit function of retailer Eq. (9), the Hessian matrix of the supply chain in **Model CO** is

$$H_c = \begin{vmatrix} \frac{\partial^2 \pi_c}{\partial^2 p_1} & \frac{\partial^2 \pi_c}{\partial p_1 p_2} & \frac{\partial^2 \pi_c}{\partial p_1 e_1} & \frac{\partial^2 \pi_c}{\partial p_1 e_2} \\ \frac{\partial^2 \pi_c}{\partial p_2 p_1} & \frac{\partial^2 \pi_c}{\partial^2 p_2} & \frac{\partial^2 \pi_c}{\partial p_2 e_1} & \frac{\partial^2 \pi_c}{\partial p_2 e_2} \\ \frac{\partial^2 \pi_c}{\partial e_1 p_1} & \frac{\partial^2 \pi_c}{\partial e_1 p_2} & \frac{\partial^2 \pi_c}{\partial^2 e_1} & \frac{\partial^2 \pi_c}{\partial e_1 e_2} \\ \frac{\partial^2 \pi_c}{\partial e_2 p_1} & \frac{\partial^2 \pi_c}{\partial e_2 p_2} & \frac{\partial^2 \pi_c}{\partial e_2 e_1} & \frac{\partial^2 \pi_c}{\partial^2 e_2} \end{vmatrix}$$

$$= \begin{vmatrix} -2 & 2\beta & \tau - (m_c + p_c) & \beta(m_c + p_c - \tau) \\ 2\beta & -2 & \beta(m_c + p_c - \tau) & \tau - (m_c + p_c) \\ \tau - (m_c + p_c) & \beta(m_c + p_c - \tau) & 2\tau(m_c + p_c) - h & -2\beta\tau(m_c + p_c) \\ \beta(m_c + p_c - \tau) & \tau - (m_c + p_c) & -2\beta\tau(m_c + p_c) & 2\tau(m_c + p_c) - h \end{vmatrix}$$

$$= (\beta^2 - 1)[4h(\tau + m_c + p_c)^2 - 4h^2 + (\beta^2 - 1)(\tau + m_c + p_c)^4]$$

Based on the assumption that $0 < \beta < 1$, $0 < \tau < 1$, and h is considered as a larger value, it can be derived that the second principal minor $H_{c2} = 4 - 4\beta^2 > 0$, the third principal minor $H_{c3} = 2(\beta^2 - 1)[2h - (\tau + m_c + p_c)^2] < 0$, and $H_c = (\beta^2 - 1)[4h(\tau + m_c + p_c)^2 - 4h^2 + (\beta^2 - 1)(\tau + m_c + p_c)^4] > 0$, therefore, π_c is concave in e_1, e_2, p_1, and p_2.

Let $\frac{\partial \pi_c}{\partial e_1} = 0$, $\frac{\partial \pi_c}{\partial e_2} = 0$, $\frac{\partial \pi_c}{\partial p_1} = 0$, and $\frac{\partial \pi_c}{\partial p_2} = 0$, we get.

$e_{ic}^{CO*} = \frac{(\tau+m_c+p_c)\left[A3\cdot C3+f\left(\varphi_i\cdot D3-2\beta\varphi_j h\right)\right]}{B3}$, and

$$p_{ic}^{CO*} = \frac{A3\cdot\left\{[h+\tau(\beta-1)(\tau+m_c+p_c)]\cdot C3 - a\left[2h-(\beta-1)(\tau+m_c+p_c)^2\right]\right\} + f(\beta-1)\left\{\varphi_i\cdot G3 - \left[\tau^2-(m_c+p_c)^2\right]\beta\varphi_j h\right\}}{(\beta-1)\cdot B3}(i=1,2,j=3-i)$$

Substituting e_{ic}^{CO*} and p_{ic}^{CO*} into **Eq.** (9), the total profit of entire system expresses as $\pi_c^{CO*} = \frac{4\overline{E}_c p_c(\beta-1)\cdot B3 - 2h\cdot A3\cdot C3^2 - (\beta-1)\left[\left(\varphi_i{}^2+\varphi_j{}^2\right)\left(h_r\cdot B3+f^2h\cdot D3\right)+2fh\left(\varphi_i+\varphi_j\right)\cdot A3\cdot C3 - 4\beta\varphi_i\varphi_j f^2h^2\right]}{2(\beta-1)\cdot B3}(i = 1, 2, j = 3-i)$where $A3 = (\beta+1)(\tau+m_c+p_c)^2-2h$, $B3 = (\beta^2-1)(\tau+m_c+p_c)^4 + 4h(\tau+m_c+p_c)^2-4h^2$, $C3 = a+(\beta-1)[c+e_0(m_c+p_c)]$, $D3 = (\beta^2-1)(\tau+m_c+p_c)^2+2h$, $G3 = \tau(\beta^2-1)(\tau+m_c+p_c)^3 + h(\tau+m_c+p_c)(3\tau+m_c+p_c)-2h^2$.

Based on $0 < e_i < e_0$ and $c < p_i$, we derived the range of basis market demand a as $a_{1i}^{CO} < a < a_{2i}^{CO}$ and $a > a_{3i}^{CO}$.

Where $a_{1i}^{CO} = (1-\beta)[c+e_0(m_c+p_c)] - \frac{f\left(\varphi_i\cdot D3-2\beta\varphi_j h\right)}{A3}$, $a_{2i}^{CO} = (1-\beta)(c-\tau e_0) + \frac{2e_0h(2-\beta)}{\tau+m_c+p_c} - \frac{f\left(\varphi_i\cdot D3-2\beta\varphi_j h\right)}{A3}$, $a_{3i}^{CO} = (1-\beta)[c+e_0(m_c+p_c)] - \frac{(1-\beta)f\left\{\varphi_i\left[4h-(\tau+m_c+p_c)^2\right]+\beta\varphi_j\left[2h-(\tau+m_c+p_c)^2\right]\right\}}{A3}$.

When $\varphi_i = \varphi_j$, $a_{1i}^{CO} = a_{3i}^{CO}$, the range of basis market demand is expressed as $a_{1i}^{CO} < a < a_{2i}^{CO}$.

C2. Proof of Proposition 6

Based on the assumptions before, the range of a and h are regarded as $a_{3i}^{CO} < a < a_{4i}^{CO}$ and $h > \frac{1}{2}(\tau+m_c+p_c)^2$. In this range, the first-order partial derivation of the optimal outcome on m_c, p_c, and $\overline{E}_c$ are determined:

(1) When $a_{3i}^{CO} < a < a_{2i}^{CO}$, $\frac{\partial e_{ic}^{CO*}}{\partial m_c} > 0$ and $\frac{\partial e_{ic}^{CO*}}{\partial p_c} > 0$. When $a_{1i}^{CO} < a < a_{3i}^{CO}$, $\frac{\partial e_{ic}^{CO*}}{\partial m_c} < 0$ and $\frac{\partial e_{ic}^{CO*}}{\partial p_c} < 0$.
where $a_{3i}^{CO} = (1-\beta)(c-\tau e_0+\varphi f) + \frac{4e_0h(1-\beta)(\tau+m_c+p_c)}{2h-(\beta-1)(\tau+m_c+p_c)^2}$.

(2) When $a_{1i}^{CO} < a < a_{4i}^{CO}$, $\frac{\partial p_{ic}^{CO*}}{\partial m_c} > 0$ and $\frac{\partial p_{ic}^{CO*}}{\partial p_c} > 0$. When $a_{4i}^{CO} < a < a_{2i}^{CO}$, $\frac{\partial p_{ic}^{CO*}}{\partial m_c} < 0$ and $\frac{\partial p_{ic}^{CO*}}{\partial p_c} < 0$.
where $a_{4i}^{CO} = (1-\beta)(c-\tau e_0+\varphi f) + \frac{e_0h[2h-(\beta-1)(m_c+p_c-3\tau)(\tau+m_c+p_c)]}{2h(m_c+p_c)+\tau(\beta-1)(\tau+m_c+p_c)^2}$.

(3) When $\overline{E}_c > \overline{E}_{c1}$, $\frac{\partial \pi_c^{CO*}}{\partial p_c} > 0$. When $0 < \overline{E}_c < \overline{E}_{c1}$, $\frac{\partial \pi_c^{CO*}}{\partial p_c} < 0$.
where $\overline{E}_{c1} = \frac{h\{a+(\beta-1)[c+e_0(m_c+p_c)+\varphi f]\}[(1-\beta)(c-\tau e_0+\varphi f)(\tau+m_c+p_c)+2e_0h-a(\tau+m_c+p_c)]}{[2h+(\beta-1)(\tau+m_c+p_c)^2]^2}$.

$\frac{\partial \pi_c^{CT*}}{\partial \overline{E}_s} > 0$ expresses that there is a positive correlation between π_c^{CT*} and $\overline{E}_s$.

In addition, $\frac{\partial \pi_c^{CO*}}{\partial m_c} < 0$ and $\frac{\partial \pi_c^{CO*}}{\partial \overline{E}_c} > 0$ in the whole range.

Appendix D. Comparative analysis

D1. Threshold expressions of Proposition 7

Expressions for thresholds $\overline{E}_1$:

$$\overline{E}_1 = \frac{h(m_s-m_c-p_c)\cdot A1\cdot A3}{2p_c\cdot B1\cdot B3}\cdot\left\{T^2(2\tau+m_s+m_c+p_c)+2e_0(\beta-1)\left[m_s(m_c+p_c)-\tau^2\right]\cdot T - 4e_0h\cdot T - e_0{}^2(\beta-1)[2h(m_s+m_c+p_c)+\tau(\beta-1)(2m_sm_c + 2m_sp_c+\tau m_s+\tau m_c+\tau p_c)]\right\}.$$

where $T = a+(\beta-1)(c+\varphi f)$, $A1 = (\beta+1)(\tau+m_s)^2-2h$, $B1 = (\beta^2-1)(\tau+m_s)^4+4h(\tau+m_s)^2-4h^2$, $A3 = (\beta+1)(\tau+m_c+p_c)^2-2h$, $B3 = (\beta^2-1)(\tau+m_c+p_c)^4+4h(\tau+m_c+p_c)^2-4h^2$.

D2. Threshold expressions of Proposition 8

Expressions for thresholds $\overline{E}_2$ and $\overline{E}_3$:

$$\overline{E}_2 = \frac{A2\cdot A3}{2p_c\cdot B2\cdot B3}\cdot\left\{e_0{}^2h(\beta-1)(m_c+p_c-p_s)[2h(m_c+p_c+p_s)+\tau(\beta-1)(2p_sm_c+2p_sp_c+\tau p_s+\tau m_c+\tau p_c)] + 2e_0h(m_c+p_c-p_s)\left[2h-(\beta-1)\left(p_sm_c+p_sp_c - \tau^2\right)\right]\cdot T - h(m_c+p_c-p_s)(2\tau+m_c+p_c+p_s)\cdot T^2\right\} + \frac{\overline{E}_s p_s}{p_c}.$$

$$\overline{E}_3 = \frac{h(m_c+p_c-p_s)\cdot A2\cdot A3}{2p_s\cdot B2\cdot B3}\cdot\left\{T^2(2\tau+m_c+p_c+p_s)+2e_0(\beta-1)\left[p_s(m_c+p_c)-\tau^2\right]\cdot T - 4e_0h\cdot T - e_0{}^2(\beta-1)[2h(p_s+m_c+p_c)+\tau(\beta-1)(2p_sm_c+2p_sp_c + \tau p_s+\tau m_c+\tau p_c)]\right\},$$

Where $T = a+(\beta-1)(c+\varphi f)$, $A2 = (\beta+1)(\tau+p_s)^2-2h$, $B2 = (\beta^2-1)(\tau+p_s)^4+4h(\tau+p_s)^2-4h^2$, $A3 = (\beta+1)(\tau+m_c+p_c)^2-2h$, $B3 = (\beta^2-1)(\tau+m_c+p_c)^4+4h(\tau+m_c+p_c)^2-4h^2$.

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