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Coordination of Prefabricated Construction Supply Chain under Cap-and-Trade Policy Considering Consumer Environmental Awareness

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Abstract: The construction industry accounts for over one third of excessive CO_2 volume, so it is essential that this amount be curbed. Prefabricated construction has superior strengths in terms of both the environment and economy, but low carbon is not one such strength. Meanwhile, the increasing number of consumers with environmental awareness makes it necessary to investigate consumer preferences and behaviors. Therefore, we firstly built a prefabricated construction supply chain consisting of a prefabricated company (leader) and a manufacturer, using the Stackelberg model. To regulate and mitigate carbon emissions, this study investigated the implementation of a cap-and-trade policy. Consumer environmental consciousness was considered from preferences on improving the prefabricated rate and carbon reduction. This study provides decision-making suggestions, not only from a pricing point of view but also for green production, i.e., the prefabricated rate and carbon reduction. We find that consumer environmental consciousness and the cap-and-trade policy improve decision making. To effectively limit the manufacturer's emissions, we suggest governments set a cap below a certain threshold. However, under the policy, the prefabricated company has free-rider behaviors and gains greater profits as the leader, which results in an unfair profit distribution. Hence, for the sake of optimizing the supply chain's profits, the cost-sharing contract and the two-part tariff were discussed. Both contracts achieved Pareto improvement, while the two-part tariff contract realizes coordination and reaches the desired level under a centralized system. Numerical analysis also verified the theoretical feasibility.

Keywords: prefabricated construction; cap-and-trade policy; consumer environmental awareness; two-part tariff contract; supply chain management

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1. Introduction

The construction industry emits a large quantity of carbon dioxide, accounting for 40% of total energy consumption [1]. More seriously, it is reported that carbon emission of buildings across the world will reach 42.4 billion tons in 2035 [2]. Hence, it is imperative to reduce carbon emissions in construction.

A prefabricated construction supply chain (PCSC) is when an off-site factory manufactures the construction components, then transports them to the designated location, before a prefabricated company eventually assembles all the components on site [3]. Based on the construction characteristic, it is obvious that prefabricated construction is superior to conventional methods in terms of waste reduction [4], efficiency [5], and environmental sustainability [6]. Therefore, prefabricated buildings are vigorously promoted in countries worldwide [7,8]. Various policies have been established to promote large-scale prefabricated construction [9,10]. To sum up, prefabrication was a revolution in construction and has become the main method within in the industry. However, prefabricated construction does not significantly reduce carbon emissions, and investigations into controlling greenhouse gas and decision-making problems in PCSC are inadequate.

The Kyoto Protocol (1997) put forward four policies to reduce and regulate carbon emissions. A cap-and-trade policy, one of the policies, represents the purchasing of credits or selling redundant carbon credits within the limit of a carbon cap [11]. There are advantages, such as cost effectiveness, emission reduction reliability, and green technology incentives [12,13]. In supply chain management, the cap-and-trade policy achieves substantial emission reductions [14]. However, the influence of the policy on PCSCs is not extensively studied. Therefore, to limit and regulate the carbon emissions in prefabricated construction, we built a PCSC consisting of a manufacturer and a prefabricated company (PC), where the manufacturer was subject to the policy and traded carbon credits in the trading market.

As the environment increasingly deteriorates, consumers' environmental awareness (CEA) achieves an increasingly significant status. CEA refers to the consumer that has the awareness of protecting the environment and tends to purchase environmentally friendly products [15]. This study analyzed CEA from two aspects: carbon reduction and the prefabricated rate. First, low-carbon products attract consumers who pay attention to carbon emissions, and consumers are willing to pay a premium for enterprises' carbon reduction [16]. Second, consumers also pay attention to the improvement in the prefabricated rate. Prefabricated construction is environmentally friendly, with the aforementioned superiorities, and policies have been implemented to improve the prefabricated rate [8]. However, under the double pressures of the government and consumers, studies that simultaneously discusses CEA with regard to consumers' preferences on the prefabricated rate and carbon reduction are lacking. Generally speaking, demand will improve by reducing carbon emissions, but also by enhancing the prefabricated rate [17]. Costs of assembly and using low-carbon technology have increased, so this study explored the proper decision-making to minimize the costs. In addition, we solved another manufacturer's dilemma regarding the cost of carbon reduction and the revenues (or cost) from the trading market.

First of all, we built a PC-Stackelberg PCSC. The PC made an order to the manufacturer, and shouldered the assembly work. Next, the manufacturer produced the prefabricated components in the factory. Under the cap-and-trade policy, the manufacturer sells or buys carbon credits according to the emission volume and the cap. We solved members' decision making using centralized and decentralized systems. Finally, a cost-sharing contract and a two-part tariff contract were introduced to coordinate the PCSC. There were two essential problems that remained to be solved:

(1) When considering the two preferences and a cap-and-trade policy simultaneously, what are members' optimal decisions? How will the policy and preferences affect decisions and profits?

(2) After introducing two contracts into this PCSC, do the mechanisms achieve coordination, and what is the difference between them?

Through exploring and answering the above problems, this study could enrich the scenarios of cap-and-trade policies applied to the PCSC and could also provide enlightenments and suggestions for policymakers, who could establish market-friendly carbon allowances, and for stakeholders to make optimal pricing and production decisions in the PCSC. Finally, this study contributes to the literature through introducing two contracts, which improve collaboration and unfair profit distribution.

The remainder of this paper is organized as follows: Section 2 surveys the related literature. Section 3 presents the model formulation and assumptions. Section 4 investigates the decentralized model with the cap-and-trade policy and derives the optimal decisions and profits. In Section 5, we discuss the centralized model with the cap-and-trade policy and derive the whole supply chain's optimal decisions and profits. Section 6 examines the effect and differences after introducing the two contracts. Section 7 shows the numerical analysis based on the theoretical results. In Section 8, we present the concluding remarks, limitations, and future prospects.

2. Literature Review

Our study investigates a PCSC considering CEA under the cap-and-trade policy, so the literature reviewed here primarily relates to three research streams: (1) the operational decisions under cap-and-trade policy; (2) the operational decisions under CEA; (3) models for PCSCs.

2.1. The Operational Decisions under Cap-and-Trade Policy

The cap-and-trade policy is accepted as one of the most effective market-based mechanisms to curb carbon emissions from firms, so much of literature has been devoted to investigating operational decisions among agents in different supply chains. Under the cap-and-trade policy, Benjaafar et al. [11] developed relatively simply models to discuss operational decision-making about procurement, production, and inventory management. Xu et al. [14] investigated firms' decisions in a make-to-order supply chain, where manufacturers produced substitutes (complements).

Cao et al. [18] studied the government's policy-making problems and then explored the optimal responses under carbon subsidy and cap-and-trade policies. Wang and Han [19] considered the dual mechanisms of cap-and-trade and subsidies/penalties with stochastic returns. The realization of low-carbon supply chain not only belongs to manufacturers but also other members. Wang et al. [20] assumed that a manufacturer directly participates in carbon emission reduction, while a retailer has to invest in low-carbon promotion. Under certain conditions, a joint emission reduction model is an optimal choice for a supply chain. In the cap-and-trade mechanism, many studies are based on the linear demand function. Wang et al. [21] additionally explored the decisions on green technology innovation using a stochastic model. Qi et al. [22] considered whether decision makers have different risk preferences under cap-and-trade policy with stochastic demand. Entezaminia et al. [23] developed a new joint production and trading control policy for unreliable manufacturing systems, considering the stochastic and dynamic context. In summary, the cap-and-trade policy is an effective mechanism in reducing and regulating enterprises' emissions; thus, it will be considered to promote the green development of prefabricated construction.

2.2. The Operational Decisions under Consumer Environmental Awareness

Consumer's attitudes towards protecting the environment have significant impact on consumption [24]; evidence has shown that consumers state a preference for green products, and thus companies must consider producing environmentally friendly products [25]. Papers devoted to studying the CEA are numerous. Zhang et al. [26] confirmed that order quantity of the green products increased with CEA. Giri et al. [27] compared two models with and without consumer green preference. Hong and Guo [28] reported that retailer and manufacturer shoulder environmental responsibilities when considering CEA. Wang and Hou [29] noted that consumer green preference significantly influenced the product green level in a supply chain. Heydari and Rafiei [30] investigated the integration of environmental and social responsibilities.

One option to enable consumers to act with environmental awareness is buying low-carbon products, so consumers with CEA would purchase low-carbon products; that is, they have a preference for low carbon. Chen et al. [31] studied two rival manufacturers' optimal decisions with different market power structures, considering low-carbon preference. Ji et al. [32] discussed consumer's low-carbon preference in retail-channel and dual-channel supply chains. Improving low-carbon preference always brought an increase in carbon reduction [33] and profits [34]. Under the cap-and-trade policy, Zhang et al. [35] reached the same conclusion. Tong et al. [36] also proved this in a retailer-led supply chain. Although some scholars have considered more than one preference [37–39], most studies only consider CEA in carbon reduction. Nevertheless, enhancing the prefabricated rate is environmentally friendly. Moreover, some policies incentivize consumers to purchase high-prefabricated-rate buildings [40,41], which influences PCSC members' decision making.

We seek to address decision-making problems with CEA with regard to two preferences: the low-carbon preference and the high-prefabricated-rate preference.

2.3. Models for PCSC

Supply chain management in the construction industry improves enterprises' performance [42]. Countries all over the world have started to promote prefabrication in construction to improve buildability, quality, and efficiency as well as to reduce construction waste [43]. Supply chain management is critical to the successful delivery of prefabricated construction projects because supply chains are complex, involving multiple processes and stakeholders [44]. Therefore, the study of prefabricated construction with supply chain management resulted in the concept of PCSC.

Research topics of PCSC are classified into precast production, storage and inventory, delivery and transportation, and performance of the entire supply chain [45]. First, from the perspective of precast production, Zhai et al. [46] focused on how the production contractor prefers informing the prefab factory (PF) an earlier due date, which leads PF to compress its production process. Second, to mitigate conflicts, the production contractor requires the transportation company to store and deliver due to limited warehouse space; Zhai et al. [3] developed models with a buffer space hedging strategy in PCSC under different power structures. Further, Zhai et al. [47] extended the model into multi-period hedging. Jiang and Wu [48] proposed an algorithm to minimize total tardiness and earliness of delivery of PCSCs and achieved the optimization of precast component production. Third, from the perspective of the performance and coordination of PCSCs, Isatto et al. [49] analyzed the way commitments are demanded, bound, and fulfilled by members using a language-action perspective, which successfully coordinated PCSC.

However, research on reducing carbon emissions and cap-and-trade policy in PCSCs is limited. As one of three major sources of carbon emissions, it is significant to reduce global greenhouse gases in the construction industry [50]. Yu et al. [51] discussed a construction manufacturer's carbon reduction decision. Reducing carbon emissions in PCSCs plays an important role in the realization of low-carbon construction. In addition, it is beneficial to accelerate the development of prefabricated construction. Jiang et al. [48] proposed a joint carbon reduction model in a PCSC under the cap-and-trade policy. To optimize operational strategies and enrich the research context in prefabricated construction, this study will investigate PCSC decision making and coordination under cap-and-trade policy and CEA.

3. Model Description and Assumptions

This study investigates a two-echelon PCSC composed of a manufacturer and a PC. The manufacturer is in charge of producing the prefabricated components, and the PC takes the responsibility of assembly. In reality, the relationship between the PC and the manufacturer is a make-to-order relationship [14]; thus, in the Stackelberg model, we assume that the PC is the leader and the manufacture is the follower, which is practical in real cases. The two members will work under the following procedures: the manufacturer receives the company's order Q and manufactures using low-carbon technology. The manufacturer can produce revenue or expense through the carbon trading market according to the cap E. Then, the PC relays the prefabricated components to the manufacturer with the wholesale price w. Finally, the assembled product sells to the public as the sale price p. Because of the increasing number of consumers with CEA, this study considers two preferences from consumers: (1) low-carbon manufacturing, where the manufacture achieves the carbon reduction V by low-carbon investment, and a greater reduction will attract consumers with CEA; (2) high-prefabricated-rate buildings, where the prefabricated rate r is decided by PC, and the assembly cost is related to the rate. The higher rate also attracts consumers with CEA.

Parameters and variables are specified in Table 1.

Table 1. Parameters and variables.

Parameters			
a	potential market demand	b	consumer's sensitive coefficient to price
h	consumer's sensitive coefficient to prefabricated rate	d	consumer's sensitive coefficient to carbon reduction
C	unit cost of production for manufacturer	k	green technology investment cost coefficient of manufacturer
ε	the cost coefficient of assembling prefabricated components	E	initial carbon allowance set by the government
e	enterprise's initial carbon emissions	P_e	unit price of carbon credits (carbon trading price)
K	a fixed fee	π_j^i	profit function for supply chain member i in model j
Decision variables			
v	total carbon reduction $v \geq 0$	w	wholesale price, unit price of prefabricated components $p < w < C$
β	margin revenue	r	prefabricated rate $0 \leq r \leq 1$
p	unit product price set by prefabricated company	φ	cost allocation coefficient $0 < \varphi < 1$

The subscript $i \in \{PC,\ M,\ SC\}$ represents the PC, manufacturer, and supply chain, respectively. The $*$ in the superscript represents the optimal solution. Superscript $j \in \{N,\ GO,\ CS,\ TT\}$ represents the following four scenarios: decentralized system, global (centralized) optimal supply chain system, cost-sharing contract, and the two-part tariff contract.

For the convenience of calculation and practice in reality, the following assumptions are proposed, and symbols are defined as follows:

(1) Both subjects in the PCSC are rational with symmetrical information, so both of them will maximize their own profits.

(2) Based on the market linear demand function proposed by Ferguson and Toktay [52], additionally, with consumer's preferences [53], the equation is as follows:

$$Q(p, r, v) = a - bp + hr + dv \tag{1}$$

where a denotes the potential market demand, which is sufficiently large, p denotes the sale price, r denotes the prefabricated rate, and v is carbon reduction. The quantity Q increases with r and v, and the preference coefficients are h, d; Q decreases with p, and the price sensitivity is b.

(3) p can be expressed as

$$p = \beta + w \tag{2}$$

Equation (2) shows that if w (set by manufacturer) increases, p will be increased accordingly [36,54]. Therefore, PC will determine a final sale price by determining an optimal marginal revenue β. In addition, $p > w > C > 0$, ensuring a positive marginal profit.

(4) $C_v = \frac{kv^2}{2}, C_r = \frac{\varepsilon r^2}{2}$. The first function denotes the cost of emission reduction for the manufacturer, and the second denotes the cost of assembly for the PC. If enterprises improve the prefabricated rate and carbon reduction, the costs are higher accordingly [31,55].

(5) $P_e[E - (e - v)]$ denotes the profit and loss function for manufacture under the cap-and-trade policy, where E denotes the initial carbon allowance set by the government and e denotes the initial carbon emission discharged by manufacturer. After introducing low-carbon technologies, the carbon reduction is achieved. If the emission is still more than E, they can only purchase carbon credits in the carbon trading market for a unit price P_e or they can sell their extra carbon credits as profits.

(6) $b > d$, $b > h$, $k > d$, $\varepsilon > h$. The first and second assumptions represent price sensitivity having a greater influence on demand, which is common in reality. The last two

assumptions are reasonable, denoting that the cost coefficient is greater than the sensitivity. Thus, $bk > d^2$, then $2bk - d^2 > bk > hk$, so $\varepsilon(2bk - d^2) > h^2k$ and $2\varepsilon(2bk - d^2) > h^2k$, and the sharing rate should satisfy $0 < \varphi < 1 - \frac{d^2\varepsilon}{2bk\varepsilon - h^2k}$.

4. The Decentralized Model with Cap-and-Trade Policy

The profit function of the manufacturer can be expressed as

$$\pi_M^N(w, v) = (w - C)Q + [E - (e - v)]P_e - k\frac{v^2}{2} \tag{3}$$

The first term denotes that the revenue of prefabricated components sold to PC where $w > C$ guarantees the manufacturer's profit. The second term represents the revenue (or cost) received from carbon trading market. This study will discuss the cap for government. The third term is the cost of technology for reducing carbon emissions. The manufacturer will make decisions through $\underset{(w,v)}{max}\ \pi_M^N(w, v)$.

The profit function of the prefabricated company can be expressed as

$$\pi_{PC}^N(p, r) = (p - w)Q - \varepsilon\frac{r^2}{2} \tag{4}$$

The first term represents the revenue from selling products, where $p > w$, and the second term is the cost of assembling prefabricated components. The PC will make decisions through $\underset{(p,r)}{max}\ \pi_{PC}^N(p, r)$.

Through the decentralized Stackelberg model, two members' optimal decisions are expressed in Proposition 1.

Proposition 1. *(1)* $p^{N*} = \frac{\varepsilon X}{N} + \frac{\varepsilon X(2bk - d^2)}{bkN} + C$, $r^{N*} = \frac{hX}{N}$; *(2)* $w^{N*} = \frac{\varepsilon X}{N} + C$, $v^{N*} = \frac{d\varepsilon X + P_e N}{kN}$.

The proof is provided in Appendix A. Where $X = ak - bkC + P_e d > 0$ and $N = 2\varepsilon(2bk - d^2) - h^2k > 0$.

From Proposition 1, in the case of the decentralized model, there exists optimal decisions for the manufacturer. Proposition 1 shows that the initial carbon emission has no impact on members' decisions, because the initial carbon emission only affects the carbon trading quantity for the manufacturer, and the cap-and-trade policy influences members' decisions through the trading price.

The optimal profits under a decentralized system can be derived with the above optimal solutions, which are expressed as Equations (5)–(7):

$$\pi_{PC}^{N*}\left(p^{N*}, r^{N*}\right) = \frac{\varepsilon X^2}{2kN} \tag{5}$$

$$\pi_M^{N*}\left(w^{N*}, v^{N*}\right) = \frac{(P_e N)^2 + (2bk - d^2)\varepsilon^2 X^2}{2kN^2} + P_e(E - e) \tag{6}$$

$$\pi_{SC}^{N*} = \pi_{PC}^{N*} + \pi_M^{N*} = \frac{(P_e N)^2 + \varepsilon X^2\left[\varepsilon(2bk - d^2) + N\right]}{2kN^2} + P_e(E - e) \tag{7}$$

Results indicate that the initial emission allowance affects only the manufacturer's profits.

Regarding the PC's optimal prefabricated rate and sale price (denoted by r^{N*}, p^{N*}), we explore how the cap-and-trade policy, cost coefficient, and preference of carbon reduction influence the PC's decisions, and we obtain the following proposition:

Proposition 2. *(1)* $\frac{\partial r^{N*}}{\partial P_e} > 0$, $\frac{\partial r^{N*}}{\partial d} > 0$, $\frac{\partial r^{N*}}{\partial k} < 0$; *(2)* $\frac{\partial p^{N*}}{\partial P_e} > 0$, $\frac{\partial p^{N*}}{\partial d} > 0$, $\frac{\partial p^{N*}}{\partial h} > 0$, $\frac{\partial p^{N*}}{\partial k} < 0$, $\frac{\partial p^{N*}}{\partial \varepsilon} < 0$.

The proof is provided in Appendix A.

Based on Proposition 2, when the trading price increases, the PC will increase the prefabricated rate, as an increase of P_e motivates the manufacturer to further reduce to avoid the trading cost, which makes demand increase; thus, PC has the motivation to increase the rate and sale price. Hence, the introduction and implementation of a cap-and-trade policy is beneficial to improve the prefabricated rate. However, if the manufacturer spends more on low-carbon technology, then the PC has a lower marginal revenue, leading a decrease in the sale price; then, the PC will decrease the prefabricated rate to lower the investment on assembly technology. Hence, if the two preferences are enhanced, the PC should enhance the sale price and prefabricated rate, and thus the construction industry should increase the publicity of prefabricated buildings. Higher CEA is beneficial to decision making, which is beneficial to the economy and the environment.

Regarding the manufacturer's optimal carbon reduction and wholesale price (denoted by v^{N*}, w^{N*}), we explore how the PC's cost coefficiency and preferences will influence the manufacturer's decisions; thus, we obtain the following proposition:

Proposition 3. *(1)* $\frac{\partial v^{N*}}{\partial P_e} > 0, \frac{\partial v^{N*}}{\partial h} > 0$, $\frac{\partial v^{N*}}{\partial \varepsilon} < 0$; *(2)* $\frac{\partial w^{N*}}{\partial P_e} > 0$, $\frac{\partial w^{N*}}{\partial h} > 0$, $\frac{\partial w^{N*}}{\partial \varepsilon} < 0$, $\frac{\partial w^{N*}}{\partial k} < 0$.

The proof is provided in Appendix A.

Proposition 3 is similar to Proposition 2. First, when the preference increases, the demand increases, so the PC orders more and increases the sale price, and the manufacturer has the motivation to reduce carbon emissions. At the same time, the manufacturer enhances the wholesale price to ensure profits. However, when the assembly cost improves, the PC's marginal revenue decreases, which influences the PC's order quantity from the manufacturer; thus, the manufacturer cuts the wholesale price to ensure the order. Accordingly, the manufacturer lowers carbon reduction to decrease the cost. In all, it is intuitive that the cost of the technology investment should be controlled, and members should improve independent research and the efficiency of the technology. Implementing cap-and trade policy and improving CEA are effective to improve the level of green production and pricing decisions, which is economically and environmentally friendly.

We obtain the optimal member's decentralized decisions, then analyze the factors influencing decisions. Next, we will explore members' profits using the following proposition:

Proposition 4. *(1)* $\frac{\partial \pi_{PC}^{N*}}{\partial P_e} > 0$, $\frac{\partial \pi_{PC}^{N*}}{\partial k} < 0$; *(2)* $\frac{\partial \pi_{M}^{N*}}{\partial P_e} = \frac{P_e N^2 + 2bdk\varepsilon^2 X}{kN^2} + E - e$, $\frac{\partial \pi_{M}^{N*}}{\partial \varepsilon} < 0$.

The proof is provided in Appendix A.

From Proposition 4, it is intuitive and easily understood that when firms increase the costs of assembly or low-carbon technology, the PC and manufacturer simultaneously have lower revenues. However, there is a difference between the PC and manufacturer for carbon trading price P_e. The initial carbon cap only influences the manufacturer's integrated cost. If the government enhances the trading price to regulate the carbon emissions, the PC will achieve higher profits without expenditure because the manufacturer is motivated to spend on green technology, which is a "free-rider" behavior. However, the manufacturer has three cases, including the situation in which the profits decrease. This implies that the policy is more beneficial to the PC because of the 'free-rider' behavior.

From the government's point of view, we suggest the government set the carbon cap $E < e - \frac{P_e N^2 + 2bdk\varepsilon^2 X}{kN^2}$. Only in this way, when the government increases the intensity of punishment will it have an impact on manufacturers, because $\frac{\partial \pi_{M}^{N*}}{\partial P_e} < 0$, and manufacturers will take green measures to minimize costs and to ensure profits. The volume of carbon emission reduction should be at least $\frac{P_e N^2 + 2bdk\varepsilon^2 X}{kN^2}$.

5. The Centralized Model with Cap-and-Trade Policy

In a centralized system, the PCSC is regarded as a whole entity, so the PC and the manufacturer changes the goal to maximization of the global profit instead of personal interest. Based on this, w will be internalized for the whole supply chain, so it is not necessary to make a decision on w. Instead, we should solve optimal v, p and r.

The total profit can be expressed as below:

$$\pi_{GO}^{N}(p,r,v) = (p-C)Q + [E-(e-v)]P_e - k\frac{v^2}{2} - \varepsilon\frac{r^2}{2} \tag{8}$$

Two members are chasing a global optimal system, so the whole PCSC makes decisions based on $\underset{(p,r,v)}{max}\ \pi_{GO}^{N}(p,r,v)$.

Proposition 5. *(1)* $r_{G0}^{N*} = \frac{hX}{Z}$, $p_{GO}^{N*} = \frac{\varepsilon X}{Z} + C$; *(2)* $v_{G0}^{N*} = \frac{Xd\varepsilon}{kZ} + \frac{P_e}{k}$.

where $Z = \varepsilon\left(2bk - d^2\right) - h^2k$ and $Z > 0$. The proof is provided in Appendix A.

Taking optimal solutions into (1) and (8), we obtain global optimal profit under a centralized system:

$$\pi_{GO}^{N*}\left(p_{GO}^{N*}, r_{GO}^{N*}, v_{GO}^{N*}\right) = \frac{\varepsilon X^2}{2kZ} + \frac{{P_e}^2}{2k} + P_e(E-e) \tag{9}$$

Members' optimal solutions under different model systems have different results, so we compare and analyze the two results, and we obtain the following proposition:

Proposition 6. *(1)* $v_{GO}^{N*} > v^{N*}$, $r_{GO}^{N*} > r^{N*}$; *(2) if* $\varepsilon > \frac{h^2k}{bk-d^2}$, $p_{GO}^{N*} \le p^{N*}$; *if* $\frac{h^2k}{2bk-d^2} < \varepsilon < \frac{h^2k}{bk-d^2}$, $p_{GO}^{N*} > p^{N*}$; *(3)* $\pi_{GO}^{N*} > \pi_{SC}^{N*}$.

The proof is provided in Appendix A.

In Proposition 6, comparing decisions under the two systems, the profit under the centralized model is more beneficial, so it is important to integrate supply chain members as a whole from the economic perspective. However, it is surprising that although green production decisions perform better in a centralized system, the centralized system is better for the environment because the PC decreases the sale price.

The global optimal profit of the PCSC is denoted as π_{GO}^{N*} under a centralized system, and we denote π_{SC}^{N*} as the PCSC's profits under decentralized system ($\pi_{SC}^{N*} = \pi_{PC}^{N*} + \pi_{M}^{N*}$). Although we know $\pi_{GO}^{N*} > \pi_{SC}^{N*}$, we will explore the differences between the two systems faced with the cap-and-trade mechanism; thus, the proposition is as follows:

Proposition 7. $\frac{\partial \pi_{GO}^{N*}}{\partial P_e} = E - e + \frac{P_e\left(2b\varepsilon - h^2\right) + d\varepsilon(a-Cb)}{Z}$, $\frac{\partial \pi_{SC}^{N*}}{\partial P_e} = E - e + \frac{N(d\varepsilon X + P_eN) + 2bdk\varepsilon^2 X}{kN^2}$; $e_{GO} - E_{GO} < e_{SC} - E_{SC}$.

The proof is provided in Appendix A. From the supply chain's perspective, we denote two thresholds when $\frac{\partial \pi_{SC}}{\partial P_e} = 0$: $e_{GO} - E_{GO}$ under a centralized system and $e_{SC} - E_{SC}$ under decentralized system, which represent the maximum emissions for the supply chain.

Proposition 7 suggests the government set the cap $E < e - \frac{P_e\left(2b\varepsilon - h^2\right) + d\varepsilon(a-bC)}{2bk\varepsilon - d^2\varepsilon - h^2k}$; that is to say, if the government raises the trading price, the cap will serve as a punishment mechanism because the manufacturer's profit will decrease when the trading price raises. Furthermore, $e - E$ represents the carbon emission in excess of quota E. Furthermore, the thresholds of the two systems have $e_{GO} - E_{GO} < e_{SC} - E_{SC}$, implying that the government execute a more stringent and rigorous cap under the centralized model. However, this exerts greater pressures on the manufacturer, as only the manufacturer shoulders the responsibility of reduction. It is difficult to reach a steady supply chain and to achieve centralized system.

First, when two enterprises make decisions independently, the manufacturer undertakes the whole burden of carbon emission reduction, and the PC acts as a leader that derives greater profits, resulting in an unfair profit distribution, which makes the PCSC unstable. Second, regarding the supply chain as a whole leads to better response and profits; thus, it is necessary to promote collaboration in the PCSC. These two problems will be addressed in the following section by introducing coordination contracts into the PCSC.

6. The Coordination Contracts

In this section, we investigate two contracts: (1) a cost-sharing contract; (2) a two-part tariff contract [28]. For each contract, there are mainly three decision stages. In the first stage, one of the members designs a contract and determines the optimal contract parameters. The other member decides to accept or reject the offer. If accepting, in the second stage, the PC decides on their decision variables, considering the reaction function of the manufacturer. In the third stage, the follower decides on their decision variables, finally the market outcomes are realized.

6.1. The Cost-Sharing Contract

Under a cost-sharing contract, the PC shares part of the cost of emission reduction $\varphi\frac{kv^2}{2}$; thus, the remainder of the cost for manufacturer is $(1-\varphi)\frac{kv^2}{2}$. Similarly, we solve this problem using a Stackelberg model and backward induction. Under the cost-sharing contract, the PC is a leader, and the manufacturer is a follower. PC decides the p, r, φ, and the manufacturer decides v and w. Hence, objective functions under the cost-sharing contract are $\underset{(p,r,\varphi)}{max}\ \pi_{PC}^{CS}(p,r,\varphi)$ and $\underset{(w,v)}{max}\ \pi_{M}^{CS}(w,v)$, which can be expressed as below:

$$\pi_{PC}^{CS}(p,r,\varphi) = (p-w)Q - \varepsilon\frac{r^2}{2} - \varphi\frac{kv^2}{2} \tag{10}$$

$$\pi_{M}^{CS}(w,v) = (w-C)Q + [E-(e-v)]P_e - (1-\varphi)\frac{kv^2}{2} \tag{11}$$

Proposition 8. *(1)* $r^{CS*} = \frac{h(4X-P_e d)}{4N-d^2\varepsilon}$, $p^{CS*} = \frac{12b\varepsilon X+P_e dh^2-7P_e bd\varepsilon-3d^2\varepsilon(a-bC)}{b(4N-d^2\varepsilon)} + C$, $\varphi^* = \frac{d\varepsilon X-P_e N}{d\varepsilon(3X-P_e d)+P_e N}$*; (2)* $v^{CS*} = \frac{2P_e}{k} + \frac{6(d\varepsilon X-P_e N)}{k(4N-d^2\varepsilon)}$, $w^{CS*} = \frac{\varepsilon(4X-P_e d)}{4N-d^2\varepsilon} + C$.

The proof is provided in Appendix A.

Proposition 8 shows that there are optimal decisions under the cost-sharing contract. The PC should cover less than half of the cost as the sharing rate is $\varphi < \frac{1}{2}$. Bringing these optimal solutions into Equations (10) and (11), we have the maximum profits for the PC and manufacturer under the cost-sharing contract.

$$\pi_{PC}^{CS*}\left(p^{CS*}, r^{CS*}, \varphi^*\right) = \frac{4(\alpha-bC)\varepsilon X + 2P_e d\varepsilon(a-bC) + {P_e}^2\left(4b\varepsilon - h^2\right)}{2(4N-d^2\varepsilon)} \tag{12}$$

$$\pi_{M}^{CS*}\left(w^{CS*}, v^{CS*}\right) = \frac{[d\varepsilon(dP_e-2X)-2P_e N]^2 + \varepsilon^2\left(bk-d^2\right)[4k(a-bC)+3P_e d]^2}{k(4N-d^2\varepsilon)^2} + P_e(E-e) \tag{13}$$

After introducing the cost-sharing contract, members of the PCSC obtain optimal decisions. When we compare decisions under the two systems (with and without a cost-sharing contract), we obtain the following proposition:

Proposition 9. *(1)* $r_{GO}^{N*} > r^{CS*} > r^{N*}$*; (2)* $w^{CS*} > w^{N*}$, $v_{GO}^{N*} > v^{CS*} > v^{N*}$*; (3)* $Q_{GO}^{N*} > Q^{CS*} > Q^{N*}$.

The proof is provided in Appendix A.

Proposition 9 illustrates that, compared with the decentralized model, the manufacturer has lower carbon emissions and has higher wholesale prices under the contract. The PC improves the prefabricated rate under this contract. In addition, a greater demand is also achieved. Therefore, the introduction of this cost-sharing contract is beneficial to pricing and production. However, compared with the centralized model, we find the cost-sharing contract is no longer more beneficial, and optimization should be further proposed and studied, as the cost-sharing contract does not reach the level of the centralized model.

With greater v and r, the cost of carbon reduction and assembly will be increased. The profits of the PC, manufacturer and PCSC under the cost-sharing contract are denoted as $\pi_{PC}^{CS*}, \pi_{M}^{CS*}, \pi_{SC}^{CS*}$, respectively. Whether the cost-sharing contract achieves Pareto improvement is related to whether the profits under the cost-sharing contract are greater than under the decentralized system. We obtain the following proposition:

Proposition 10. *(1)* $\pi_{PC}^{CS*} > \pi_{PC}^{N*}$; *(2) if* $P_e \geq \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-d^2\varepsilon(\Theta+1)}$, $\pi_{M}^{CS*} \geq \pi_{M}^{N*}$; *if* $P_e < \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-d^2\varepsilon(\Theta+1)}$, $\pi_{M}^{CS*} < \pi_{M}^{N*}$; *(3)* $\pi_{SC}^{CS*} > \pi_{SC}^{N*}$.

The proof is provided in Appendix A. Where $\Theta = d\varepsilon\left[\frac{d}{2N} + \frac{8N}{2d\varepsilon^2(2bk-d^2)}\right] - 4 > 0$.

Proposition 10 illustrates that with this cost-sharing contract, both the PC and manufacturer are willing to cooperate with each other to achieve greater profits when $P_e \geq \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-(\Theta+1)d^2\varepsilon}$; thus, an improved and stable PCSC is realized. However, when $P_e \geq \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-(\Theta+1)d^2\varepsilon}$, the trading price is too high if emissions exceed the cap. Hence, the manufacturer must spend more on the low-carbon investment to avoid buying credits with a high trading price. At the moment, the cost-sharing contract is beneficial to the manufacturer, because the PC shares some of the cost of the carbon reduction technology.

When $P_e < \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-(\Theta+1)d^2\varepsilon}$, the trading price is rational, and the manufacturer can undertake the cost. Furthermore, the greater investment in the technology promotes increased carbon reduction, and the manufacturer can gain revenues from the trading market and does not need the cost-sharing contract. The above results also suggest that when there is a cost-sharing contract, the policymaker should make the trading price satisfy $P_e \geq \frac{(a-bC)\Theta kd\varepsilon}{N(\Theta+4)-(\Theta+1)d^2\varepsilon}$.

Certain key lessons can be derived from this. Leaders are often concerned about the loss of profit owing to the introduction of a cost-sharing contract. However, we prove that the contract not only not decreases the pricing and production, but also increases the profit. Finally, a better performance is achieved than in the decentralized model.

The cost-sharing improves the performance of members; however, it does not reach the level of the centralized system. Hence, we will investigate another coordination mechanism, called the two-part tariff contract.

6.2. The Two-Part Tariff Contract

The cost-sharing contract achieves Pareto improvement but does not optimize the PCSC. We use a linear two-part tariff contract to optimize the decentralized supply chain [39,56]. In a linear two-part tariff contract, the PC commits to pay a fixed fee to the manufacturer, because the objective of the contract is to incentivize the manufacturer to reduce the wholesale price. We assume that the PC offers a lump-sum payment K to the manufacturer as compensation for the lower values of wholesale price; thus, the profit functions for the PC and manufacturer are $\underset{(p,r,K)}{max}\ \pi_{PC}^{TT}(p,r,K)$ and $\underset{(w,v)}{max}\ \pi_{M}^{TT}(w,v)$. Again, the PC is dominant in the model. The Equations are as follows:

$$\pi_{PC}^{TT}(p,r,K) = (p-w)Q - \varepsilon\frac{r^2}{2} - K \tag{14}$$

$$\pi_M^{TT}(w, v) = (w - C)Q + [E - (e - v)]P_e - k\frac{v^2}{2} + K \tag{15}$$

In order to achieve the level under the centralized model and ensure collaboration of the two members, we obtain the following proposition:

Proposition 11. $K_l < K < K_u$, $K_l = \frac{X^2\varepsilon^2\left[2bh^4k^3 - 2h^2k\varepsilon\left(4b^2k^2 - d^4\right) + \varepsilon^2\left(2bk - d^2\right)^2\left(3d^2 + 2bk\right)\right]}{2k(ZN)^2}$, $K_u = \frac{X^2\varepsilon^2\left[2bk^2\left(2b\varepsilon - h^2\right) - d^4\varepsilon\right]}{2kNZ^2}$, $w^{TT} = C$, $r^{TT} = r_{GO}^{N*}$, $p^{TT} = p_{GO}^{N*}$, $v^{TT} = v_{GO}^{N*}$.

The proof is provided in Appendix A.

From Proposition 11, the two-part tariff contract achieves coordination and optimization. Surprisingly, the wholesale price has been slashed, but the two-part contract still exists, as it guarantees $\pi_M^{TT} > \pi_M^{N*}$ and $\pi_{PC}^{CS*} > \pi_{PC}^{N*}$. The premise of a feasible coordination is that profits are higher than in the decentralized system. Under the contract, the sum of members' profits is optimal and equal to that under the centralized model, which is $\pi_{PC}^{TT*} + \pi_M^{TT*} = \pi_{GO}^{N*}$; thus, the contract only changes the profit distribution between them. However, in reality, the applicability of the two-part tariff contract is a challenge, because the manufacturer may not be willing to cut the wholesale price to the production cost, and it requires the PC's bargaining ability. Compared with the cost-sharing contract, the two-part tariff performs better because it fully coordinates the channel when $K_l < K < K_u$, while the cost-sharing contract does not.

7. Numerical Analysis

In this section, we present the numerical analysis to illustrate the theoretic results obtained above and the impact of carbon trading price and cap on the operational decisions of stakeholders. We assume $a = 1000$, $b = 8$, $C = 40$, $h = 6$, $d = 0.8$, $k = 1$, $\varepsilon = 300$, $e = 80$. Similar numerical studies are widely used in the literature, such as Xu et al. [14] and Kuiti et al. [39].

7.1. Carbon Reduction Level and Prefabricated Rate

Figures 1–3 show that carbon reduction level, prefabricated rate, and optimal sale price all increase with the trading price, which has been theoretically proven in Propositions 2 and 3. Our observations suggest that a higher trading price incentivizes the manufacturer to emit less carbon, as it can benefit from a surplus in the trading market, and the PC is motivated to enhance the prefabricated rate and sale price. Therefore, the cap-and-trade policy is beneficial to the members' operational decisions. Moreover, from the comparisons, we find that prefabricated rate and carbon reduction under a centralized model (two-part tariff contract model) are greater. Although the cost-sharing contract achieves greater values in all decisions than the decentralized model, the cost-sharing contract in our study does not perfectly coordinate the PCSC, as the values cannot reach the level of the centralized model. From Figure 3, the sale price is the lowest in the centralized model. This can be explained as follows: as a dominant leader, the PC decides the sale price in order to obtain greater profits in decentralized system; however, when it comes to centralized system, the PC has to lower price to maximize the profits of the whole PCSC instead of just itself, which has been shown in Proposition 9.

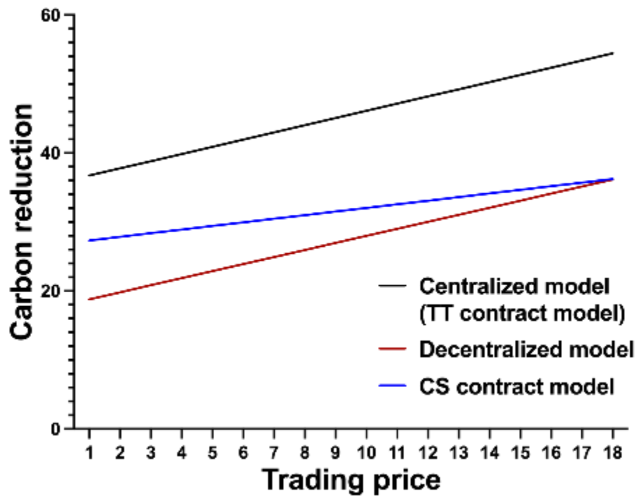

Figure 1. Impact of trading price on emission abatement level.

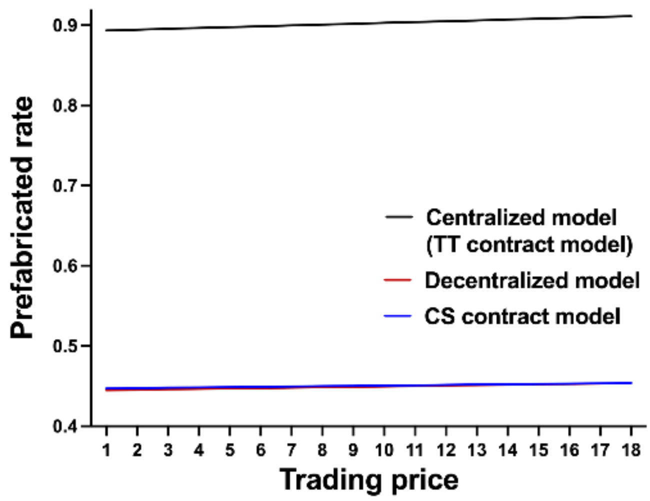

Figure 2. Impact of trading price on prefabricated rate.

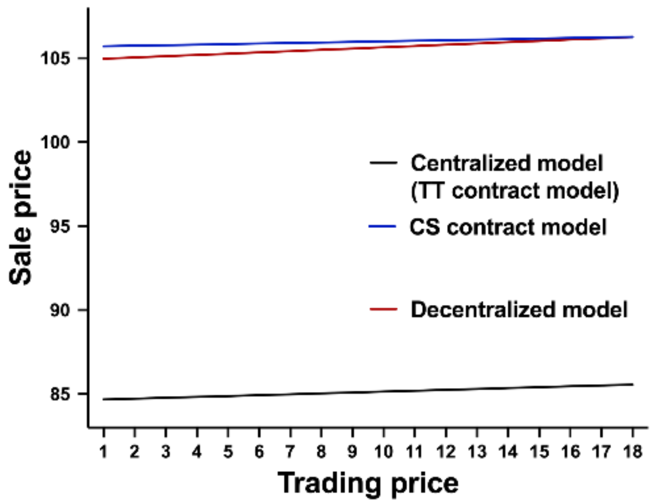

Figure 3. Impact of trading price on sale price.

7.2. Decentralized and Centralized Model Comparisons

Figure 4 presents the impact of trading price on the PC's profits, which increase with the trading price. However, the PC's profits are independent of the cap, showing the same conclusion as Proposition 4. Moreover, the manufacturer's profit initially decreases and then increases after the trading price reaches a certain threshold value when the cap is at a low level. However, when the trading price is at a high level, it will motivate the manufacturer to reduce emissions to avoid cost, so profits will gradually increase. Furthermore, Figure 4 also illustrates that the manufacturer's profits increase with cap, as more surplus could result in revenues. Compared to the manufacturer, the PC gains greater profits as the leader, but when the cap is extremely high, the direct revenues of the manufacturer from the external trading market are extremely high, and thus the profit of the PC is no longer greater.

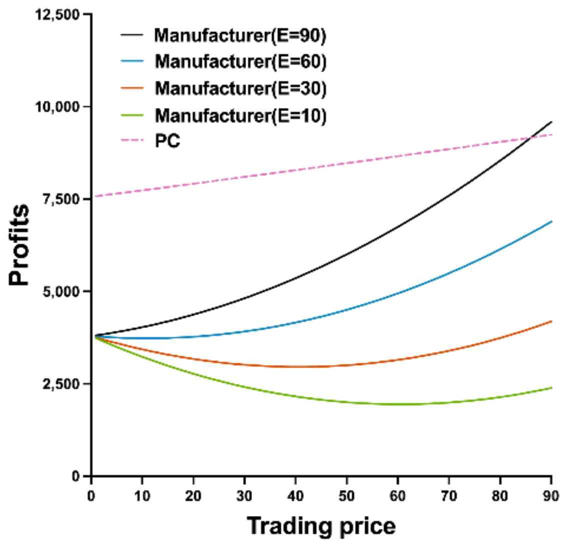

Figure 4. Impact of trading price and cap on two members' profits.

Figure 5 illustrates that the PCSC's profits have similar trends as the manufacturer, because the cap *E* is not in the PC's profit function; this is a "free-rider" behavior, as proven in Propositions 6 and 7. The centralized model performs better, as shown in Figure 5.

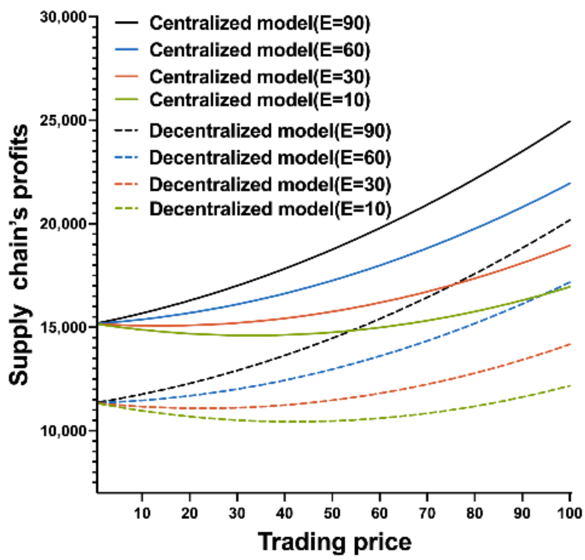

Figure 5. Impact of trading price and cap on PCSC's profits.

7.3. The Cost-Sharing Contract's Profit Analysis

Figure 6 shows that the cost-sharing contract is preferable for the PC. Although the PC takes on part of the cost of carbon reduction, the profit still increases. However, in Figure 7, for the manufacturer, when the trading price is over a certain threshold, the cost-sharing contract performs better than the decentralized model, which implies that the cost-sharing contract cannot perfectly coordinate the PCSC. Similarly, the PC as the leader obtains greater profits more obviously, and the line trend of profits is similar to 7.2. Figure 8 shows that the cost-sharing contract achieves Pareto improvement, because the supply chain's profits are greater than decentralized model, but the improvement is not significant.

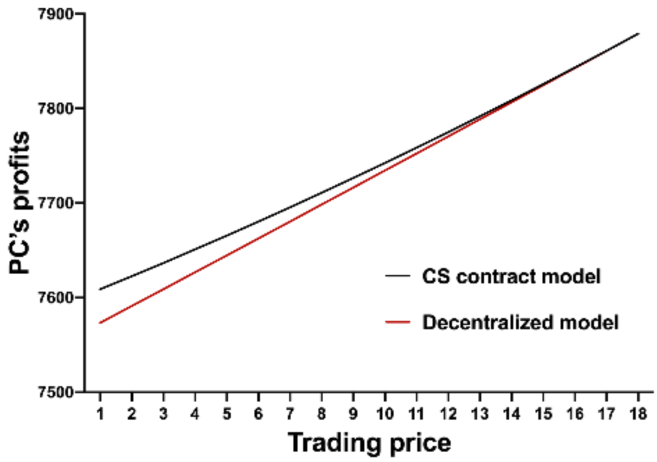

Figure 6. Impact of trading price between cost-sharing contract.

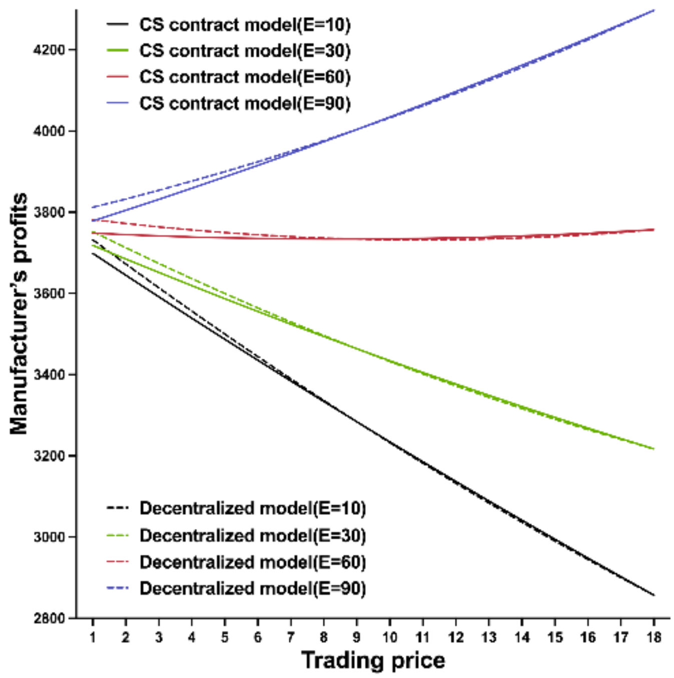

Figure 7. Impact of trading price and cap on manufacturer's profits.

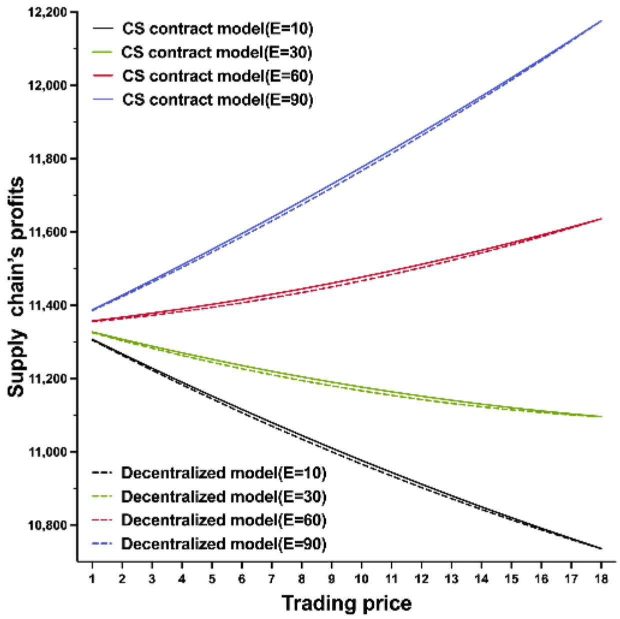

Figure 8. Impact of trading price and cap on the PCSC's profits.

7.4. The Two-Part Tariff Contract's Profit Analysis

Figure 9 presents the PC's profits with the upper bound (K_u) and lower bound (K_l) of the fixed fee, varying with the carbon trading price. With the upper bound, the PC shares the greatest fixed fee, and the PC's profits are equal to those under the decentralized model; thus, the manufacturer achieves the greatest profits with K_u. With the lower bound, the PC achieves the greatest revenues, so the manufacturer wins the minimum fixed fee. Therefore, the fixed fee varies from K_l to K_u. In addition, Figure 10 also shows that the trading price is not always beneficial to the manufacturer, and under a low carbon cap, the manufacturer's profits decrease with the trading price. Moreover, operational decisions in the two-part tariff contract reach the level of centralized approach; thus, the supply chain's profits are equal to the centralized model, which optimizes the supply chain's profits. Comparing the two-part tariff contract to the cost-sharing contract, we can conclude that members win more profits under the two-part tariff contract, and the PCSC achieves coordination optimization; however, profit allocation between the two members depends on the leader.

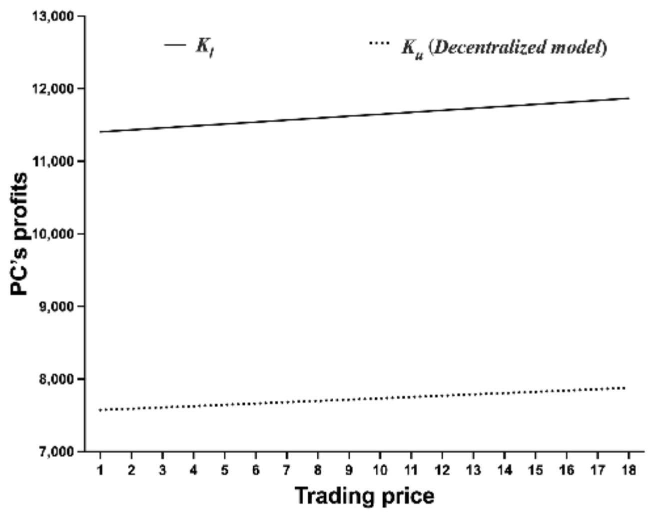

Figure 9. Impacts of trading price on two-part tariff contract.

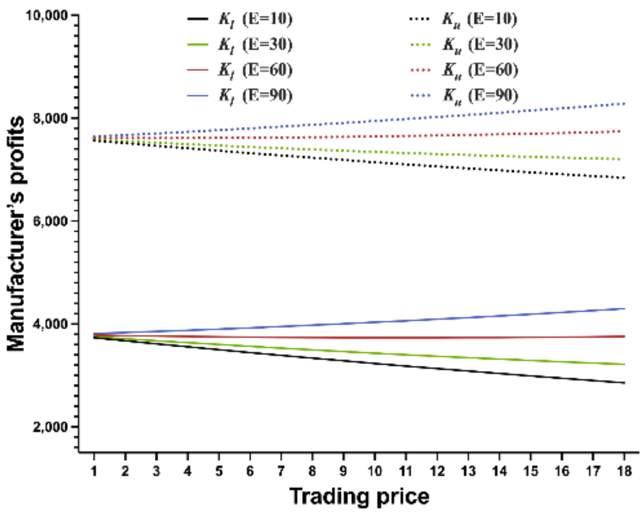

Figure 10. Impacts of trading price and cap on two-part tariff contract.

8. Conclusions

In this paper, we build a PCSC consisting of a manufacturer and a PC. This study is aimed at solving issues regarding decision making and coordination of the PCSC using the Stackelberg model and backward induction under different systems, where the PC is the leader. The cap-and-trade policy is implemented to limit emissions in prefabricated component manufacturing. In addition, with the increasing CEA, we consider the consumer's preferences in terms of prefabricated rate and carbon reduction. Furthermore, sensitivity analysis is carried out to analyze mutual influences. Finally, we take a cost-sharing contract and a two-part tariff contract to coordinate the PCSC. Managerial findings are obtained as follows:

(1) In the PCSC, we determine the members' optimal decisions. The trading price promotes carbon reduction, prefabricated rate, and pricing decisions. Therefore, the cap-and-trade policy has a positive effect on the PCSC from economic and environmental perspectives, and the policy is beneficial to the development of prefabricated construction. Moreover, enhancing consumer preferences promotes pricing and green production, and thus it is beneficial to guide consumers to improve the CEA to protect the environment. Additionally, the publicity of prefabricated buildings should be strengthened.

(2) In the Stackelberg model, the PC is dominant, so it gains more profits than the manufacturer. For two members, the PC's profits increase with the trading price; however, this is essentially a 'free-rider' behavior, because the cap-and-trade policy only affects the manufacturer. Profits of the manufacturer are complicated, which relates to the cap. The government policymaker should set the cap below a threshold, so the policy works as a punishment mechanism that regulates the manufacturer's emissions. The centralized models perform better, achieving greater profits and environmental benefits.

(3) To coordinate the PCSC, this study designs and compares two contracts (the cost-sharing contract and two-part tariff contract). First, all decisions under the cost-sharing contract are improved over the decentralized system, but it does not achieve the same level as under the centralized system, indicating that the contract only achieves Pareto improvement. Moreover, when the cap is high, the manufacturer will prefer the decentralized system to obtain revenues in the trading market, while the cost-sharing contract is redundant. Next, we investigate the two-part tariff contract: members also win more profits than in the decentralized system. Furthermore, decisions reach the level of the centralized system, and the contract only changes the profit distribution; thus, the contract achieves coordination and optimization. Nevertheless, it is worth noting that the manufacturer's wholesale price is slashed under the two-part tariff contract, so it give the PC (leader) high bargaining power.

This study has several limitations, and opportunities exist to extend this research in the future. First, the model in our study considers one prefabricated company and one manufacturer, but multiple manufacturers are more realistic in the construction industry, so the investigation should consider the lateral competition. Second, this study assumes a deterministic demand, so another extension is to use the stochastic model to analyze the effect of cap-and-trade policy and preferences on the PCSC. Finally, the process of assembling prefabricated parts also emits greenhouse gas. Therefore, the PC shoulders the responsibility of emission reduction; a new profit function of PC could be adopted in the future research.

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Conflicts of Interest: All authors declare that they have no conflict of interest.

Appendix A

Proof of Proposition 1. Through backward induction, the manufacturer first determines the optimal emission reduction amounts v and w. The Hessian matrix $\begin{vmatrix} -k & d \\ d & -2b \end{vmatrix}$, only when $2bk - d^2 > 0$, is a negative definite matrix; in this case, there are optimal solutions for the manufacturer: $w^N = \frac{k(Cb+a-b\beta+hr)-d(Cd-P_e)}{2bk-d^2}$, $v^N = \frac{d(Cb+a-b\beta+hr)-2b(Cd-P_e)}{2bk-d^2}$. As derivatives of β, r in $\pi_{PC}^N\left(v^N,\ w^N\right)$, we obtain a Hessian Matrix $\begin{vmatrix} -\frac{2b^2k}{2bk-d^2} & \frac{bhk}{2bk-d^2} \\ \frac{bhk}{2bk-d^2} & -\varepsilon \end{vmatrix}$. $N > 0$, hence, there are optimal solutions of β and r, and we get $\begin{cases} r^N = \frac{bhk\beta}{\varepsilon*(2bk-d^2)} \\ \beta^N = \frac{-Cbk+P_ed+k(a+hr)}{2bk} \end{cases}$. The optimal β, r under the decentralized system are: $r^{N*} = \frac{hX}{N}$, $\beta^{N*} = \frac{\varepsilon X\left(2bk-d^2\right)}{bkN}$. Substituting r^{N*}, β^{N*} to other variables, the optimal solutions of w^{N*}, V^{N*}, p^{N*}, Q^{N*} are

$$w^{N*} = \frac{\varepsilon X}{N} + C, v^{N*} = \frac{Xd\varepsilon + P_eN}{kN},\ p^{N*} = \frac{\varepsilon X}{N} + \frac{\varepsilon\left(2bk-d^2\right)X}{bkN} + C,\ Q^{N*}\frac{b\varepsilon X}{N}.$$

□

Proof of Proposition 2. As $N = 2\varepsilon\left(2bk - d^2\right) - h^2k > 0$, $2bk - d^2 > 0$, $r^{N*} = \frac{hX}{N}$ with $r^{N*} \in (0,1]$, we get $X > 0$. Therefore, $\frac{\partial r^{N*}}{\partial P_e} = \frac{hd}{N} > 0$; $\frac{\partial r^{N*}}{\partial d} = \frac{P_eN+4d\varepsilon X}{N^2} > 0$; $\frac{\partial r^{N*}}{\partial k} = \frac{-h*\left(P_edN+2d^2\varepsilon X\right)}{kN^2} < 0$. Because $3bk - d^2 > 2bk - d^2 > 0$, then $\frac{\partial p^{N*}}{\partial P_e} = \frac{d\varepsilon\left(3bk-d^2\right)}{bkN} > 0$; $\frac{\partial p^{N*}}{\partial h} = \frac{2h\varepsilon X\left(3bk-d^2\right)}{bN^2} > 0$; $\frac{\partial p^{N*}}{\partial d} = \frac{\varepsilon\left[2h^2kdX+4bdk\varepsilon X+P_eN\left(3bk-d^2\right)\right]}{bkN^2} > 0$; $\frac{\partial p^{N*}}{\partial \varepsilon} = \frac{-h^2X\left(3bk-d^2\right)}{bN^2} < 0$; $\frac{\partial p^{N*}}{\partial k} = \frac{-d\varepsilon\left[h^2kdX+2bkd\varepsilon X+P_eN\left(3bk-d^2\right)\right]}{bk^2N^2} < 0$. □

Proof of Proposition 3. $\frac{\partial v^{N*}}{\partial P_e} = \frac{1}{k} + \frac{d^2\varepsilon}{kN} > 0$; $\frac{\partial v^{N*}}{\partial h} = \frac{2hd\varepsilon X}{N^2} > 0$; $\frac{\partial v^{N*}}{\partial \varepsilon} = -\frac{dh^2X}{N^2} < 0$; $\frac{\partial w^{N*}}{\partial P_e} = \frac{d\varepsilon}{N} > 0$;$\frac{\partial w^{N*}}{\partial h} = \frac{2hk\varepsilon X}{N^2} > 0$; $\frac{\partial w^{N*}}{\partial \varepsilon} = \frac{-h^2kX}{N^2} < 0$; $\frac{\partial w^{N*}}{\partial k} = \frac{-d\varepsilon\left[2d\varepsilon*(a-bC)+P_e\left(4b\varepsilon-h^2\right)\right]}{N^2}$

First, $a - bC > a - bp > 0$ with $p > w > C$. Second, $2\varepsilon\left(2bk - d^2\right) - h^2k > 0 \Leftrightarrow k\left(4b\varepsilon - h^2\right) - 2d^2\varepsilon > 0 \Leftrightarrow 4b\varepsilon - h^2 > \frac{2d^2\varepsilon}{k} > 0$; we get $4b\varepsilon - h^2 > 0$; then, $2d\varepsilon(a - bC) + P_e\left(4b\varepsilon - h^2\right) > 0$, so $\frac{\partial w^{N*}}{\partial k} < 0$. □

Proof of Proposition 4. $\frac{\partial \pi_{PC}^{N*}}{\partial P_e} = \frac{d\varepsilon X}{kN} > 0$; $\frac{\partial \pi_{PC}^{N*}}{\partial k} = -\frac{d\varepsilon X\left[d\varepsilon X+P_ek\left(4b\varepsilon-h^2\right)\right]}{(kN)^2}$; Proposition 3 proved $4b\varepsilon - h^2 > 0$; thus, $\frac{\partial \pi_{PC}}{\partial k} < 0$, $\frac{\partial \pi_M^{N*}}{\partial \varepsilon} = \frac{-h^2\varepsilon\left(2bk-d^2\right)X^2}{N^3} < 0$;

$\frac{\partial \pi_M^{N*}}{\partial P_e} = \frac{P_eN^2+2bdk\varepsilon^2X}{kN^2} + E - e$; then, the sign of $\frac{\partial \pi_M^{N*}}{\partial P_e}$ depends on the values between $\frac{P_eN^2+2bdk\varepsilon^2X}{kN^2}$ and $E - e$. There are three conditions: (1) if $e - E > \frac{P_eN^2+2bdk\varepsilon^2X}{kN^2}$, then $\frac{\partial \pi_M}{\partial P_e} < 0$; (2) if $e - E < \frac{P_eN^2+2bdk\varepsilon^2X}{kN^2}$, then $\frac{\partial \pi_M}{\partial P_e} > 0$; (3) if $e - E - \frac{P_eN^2+2bdk\varepsilon^2X}{kN^2}$, P_e and r are irrelevant. □

Proof of Proposition 5. In the decentralized model, $N = 2\varepsilon\left(2bk - d^2\right) - h^2k > 0$, which can be transformed to $\varepsilon > \frac{h^2k}{2(2bk-d^2)}$, so $\varepsilon > \frac{h^2k}{(2bk-d^2)} > \frac{h^2k}{2(2bk-d^2)}$. The second derivative of v is $\frac{\partial^2 \pi_{GO}^N}{\partial v^2} = -k < 0$, so when $\frac{\partial \pi_{GO}^N}{\partial v} = 0$, the optimal solution is: $v_{GO}^N = \frac{dp-Cd+P_e}{k}$.

The Hessian Matrix of p and r is $\begin{vmatrix} \frac{-2b+d^2}{k} & h \\ h & -\varepsilon \end{vmatrix}$ with $Z = \varepsilon\left(2bk - d^2\right) - h^2k > 0$ as the evidence that there are optimal solutions for p and r; then, we get $\begin{cases} p_{GO}^N = \frac{Cbk-Cd^2+P_ed+ak+hkr}{2bk-d^2} \\ r_{GO}^N = \frac{h*(p-C)}{\varepsilon} \end{cases}$, so we have: $r_{G0}^{N*} = \frac{hX}{Z}$; $p_{GO}^{N*} = \frac{\varepsilon X+CZ}{Z} = \frac{\varepsilon X}{Z} + C$; $Q_{GO}^{N*} = \frac{b\varepsilon X}{Z}$.

Bringing the p^{GO*}, r^{GO*} into v^{G0}, we get $v_{GO}^{N*} = \frac{Xd\varepsilon+P_eZ}{kZ} = \frac{Xd\varepsilon}{kZ} + \frac{P_e}{k}$. □

Proof of Proposition 6. $N - Z = \varepsilon\left(2bk - d^2\right) - h^2k$ with $2bk - d^2 > 0$, then $N > Z$. r, v have the same numerator but different denominators under the two models, so $v_{GO}^{N*} > v^{N*}$; $r_{GO}^{N*} > r^{N*}$.

p_{GO}^{N*} and p^{N*}: $p_{GO}^{N*} - p^{N*} = -\frac{\varepsilon X\left(2bk-d^2\right)\left[\varepsilon\left(bk-d^2\right)-h^2k\right]}{bkZN}$. The value of $\varepsilon\left(bk - d^2\right) - h^2k$ is unknown, so $p_{GO}^{N*} - p^{N*}$ has three possibilities: (1) if $\varepsilon\left(bk - d^2\right) < h^2k < \varepsilon\left(2bk - d^2\right)$, then $\frac{h^2k}{2bk-d^2} < \varepsilon < \frac{h^2k}{bk-d^2}$, $p_{GO}^{N*} > p^{N*}$; (2) if $\varepsilon\left(bk - d^2\right) - h^2k > 0$, then $\varepsilon > \frac{h^2k}{bk-d^2}$, $p_{GO}^{N*} < p^{N*}$; (3) $\varepsilon\left(bk - d^2\right) - h^2k = 0$, $p_{GO}^{N*} = p^{N*}$. However, order quantity and profit are: $Q_{GO}^{N*} > Q^{N*}$. $\pi^{N*} - \pi_{GO}^{N*} = -\frac{\varepsilon^3X^2\left(2bk-d^2\right)^2}{2kN^2Z} < 0$, so $\pi_{GO}^{N*} > \pi^{N*}$. □

Proof of Proposition 7. $\frac{\partial \pi_{GO}^{N*}}{\partial P_e} = E - e + \frac{P_e}{k} + \frac{d\varepsilon X}{kZ}$. When $\frac{\partial \pi_{GO}^{N*}}{\partial P_e} < 0$, $e^{GO} - E^{GO} > \frac{P_e\left(2b\varepsilon-h^2\right)+d\varepsilon(a-Cb)}{2bk\varepsilon-d^2\varepsilon-h^2k} > 0$, when $\frac{\partial \pi_{GO}^{N*}}{\partial P_e} \geq 0$, $e^{GO} - E^{GO} \leq \frac{P_e\left(2b\varepsilon-h^2\right)+d\varepsilon(a-Cb)}{2bk\varepsilon-d^2\varepsilon-h^2k} \leq 0$. Decentralized system: $\frac{\partial(\pi_M^{N*}+\pi_{PC}^{N*})}{\partial P_e} < 0$, let $e^{SC*} - E^{SC*}$, $e^{GO*} - E^{GO*}$ as decentralized and centralized thresholds, the difference of two thresholds is $e^{GO*} - E^{GO*} - (e^{SC*} - E^{SC*}) = \frac{d\varepsilon X}{k}\left(\frac{1}{Z} - \frac{1}{N} - \frac{2bk\varepsilon}{N^2}\right) = -\frac{d\varepsilon^2X}{kZN^2} * \left[d^2Z + \varepsilon\left(d^2 - 2bk\right)^2\right] < 0$. □

Proof of Proposition 8. From assumptions, $\varphi < 1 - \frac{d^2\varepsilon}{2bk\varepsilon-h^2k}$, and $\frac{2bk-d^2}{2bk} - \left(1 - \frac{d^2\varepsilon}{2bk\varepsilon-h^2k}\right) = \frac{h^2d^2k}{2bk(2bk\varepsilon-h^2k)} > 0$, so $Y = 2bk(1 - \varphi) - d^2 > 0 \Leftrightarrow \varphi < \frac{2bk-d^2}{2bk} < \frac{1}{2}$. Taking (1) and (2) into (7), the manufacturer first determines the optimal V and w under the cost-sharing contract. The Hessian matrix is $\begin{vmatrix} -k(1-\varphi) & d \\ d & -2b \end{vmatrix}$ and $2bk(1 - \varphi) - d^2 > 0$, so there are optimal w and v under the cost-sharing contract when $\frac{\partial \pi_M^{CS}}{\partial v} = 0$, $\frac{\partial \pi_M^{CS}}{\partial w} = 0$, and the solutions are: $v^{CS} = \frac{2b(Cd-P_e)-d(Cb+a-b\beta+hr)}{-Y}$, $w^{CS} = \frac{d(Cd-P_e)+k(\varphi-1)(Cb+a-b\beta+hr)}{-Y}$. Substituting w^{CS}, v^{CS} into (7), we find β and r's partial derivatives, and we can obtain the Hessian matrix: $\begin{vmatrix} -\frac{b^2k[d^2\varphi+2Y(1-\varphi)]}{Y^2} & \frac{h[bd^2k\varphi+bk*(1-\varphi)Y]}{Y^2} \\ \frac{h[bd^2k\varphi+bk*(1-\varphi)Y]}{Y^2} & -d^2h^2k\frac{\varphi}{Y^2}-\varepsilon \end{vmatrix}$. If $\frac{(b^2d^2h^2k^2\frac{\varphi}{Y^2}+b^2k\varepsilon)[d^2\varphi+2Y*(1-\varphi)]}{Y^2} - (hbk)^2\left[\frac{d^2\varphi+(1-\varphi)*Y}{Y^2}\right]^2 > 0$, then optimal decisions for the PC exist.

Obviously $\frac{d^2\varphi+2Y(1-\varphi)}{Y^2} > \frac{d^2\varphi+Y(1-\varphi)}{Y^2}$ with $Y > 0$ and $\varphi \in [0,1]$, so we compare $b^2d^2h^2k^2\frac{\varphi}{Y^2} + b^2k\varepsilon$ with $(hbk)^2\frac{d^2\varphi+(1-\varphi)*Y}{Y^2}$: $\left(b^2d^2h^2k^2\frac{\varphi}{Y^2} + b^2k\varepsilon\right) - (hbk)^2 * \frac{d^2\varphi+(1-\varphi)*Y}{Y^2} = \frac{b^2kY[\varepsilon Y-h^2k(1-\varphi)]}{Y^2}$, $\varphi < 1 - \frac{d^2\varepsilon}{2bk\varepsilon-h^2k}$, thus $\varepsilon Y - h^2k(1-\varphi) > 0$; then, the revenue of the PC is a concave function, so there is optimal β and r. With v^{CS}, w^{CS}, we can obtain $\beta(v^{CS}, w^{CS})$ and $r^{CS}(v^{CS}, w^{CS})$. Substituting the above variables into (7), the PC determines the optimal φ^*. Similarly, we get $\varphi_1 = \frac{d\varepsilon X-P_eN}{d\varepsilon(3X-P_ed)+P_eN}$, $\varphi_2 = \frac{-Cbdk\varepsilon+4P_ebk\varepsilon-P_ed^2\varepsilon-P_eh^2k+adk\varepsilon}{-Cbdk\varepsilon+4P_ebk\varepsilon-P_eh^2k+adk\varepsilon}$. Substituting φ_2 into $w^{CS}(\beta^{CS}, r^{CS})$ and $v^{CS}(\beta^{CS}, r^{CS})$, we find $w = C - \frac{P_e}{d} < C$ and $v = 0$; manufacturer has no motive to produce and cooperate, so only φ_1 exists.

Then, we have: $\varphi^* < \frac{Z}{2bk\varepsilon-h^2k}$, that is, $P_e > \frac{(a-bC)d\varepsilon(-2h^2k-3d^2\varepsilon+4bk\varepsilon)}{-2h^4k+4h^2(3bk-d^2)\varepsilon+2b(8bk-5d^2)\varepsilon^2}$, $\beta^{CS*} = \frac{\varepsilon(3X-P_ed)(2bk-d^2)+2bk\varepsilon X-P_edN}{bk(4N-d^2\varepsilon)}$; $r^{CS*} = \frac{h(4X-P_ed)}{4N-d^2\varepsilon}$; $w^{CS*} = \frac{4\varepsilon X-P_ed\varepsilon}{(4N-d^2\varepsilon)} + C$; $v^{CS*} = \frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)}$; $p^{CS*} = \frac{12b\varepsilon X+dh^2P_e-7P_ebd\varepsilon-3d^2\varepsilon(a-bC)}{b(4N-d^2\varepsilon)} + C$; $Q^{CS*} = \frac{b\varepsilon(4X-P_ed)}{4N-d^2\varepsilon}$. □

Proof of Proposition 9. (1) Comparisons with decentralized model:

The denominator of φ^* is $d\varepsilon(3X-P_ed)+P_eN = 3dk\varepsilon(a-Cb)+P_e(4bk\varepsilon-h^2k)$, as we have proven $a-bC > 0$, $4bk\varepsilon - h^2k > 0$; that is, $d\varepsilon(3X-P_ed)+P_eN > 0$. $\varphi^* \in (0,1)$, then, $d\varepsilon X > P_eN > 0$ and $2d\varepsilon X + 2P_eN - P_ed^2\varepsilon > 0$. In addition, $d\varepsilon(3X-P_ed)+P_eN = d\varepsilon(4X-P_ed)+(P_eN-d\varepsilon X) > 0$, then $d\varepsilon(4X-P_ed) > d\varepsilon X - P_eN > 0$, which means $4X - P_ed > 0$. As $Q^{CS*} = \frac{b\varepsilon(4X-P_ed)}{4N-d^2\varepsilon} > 0$, and then $4N - d^2\varepsilon > 0$.

$\beta^{CS*} - \beta^{N*} = \frac{\varepsilon d(2bk-d^2)(d\varepsilon X-P_eN)+Nd(d\varepsilon X-P_eN)}{bkN(4N-d^2\varepsilon)} > 0$, $w^{CS*} - w^{N*} = \frac{d\varepsilon(d\varepsilon X-P_eN)}{N(4N-d^2\varepsilon)} > 0$. Therefore, $p^{CS*} > p^{N*}$, $r^{CS*} - r^{N*} = \frac{hd*(d\varepsilon X-P_eN)}{N(4N-d^2\varepsilon)} > 0$, $v^{CS} - v^{N} = \frac{2N(d\varepsilon X-P_eN)+d^2\varepsilon(d\varepsilon X-P_eN)}{kN(4N-d^2\varepsilon)} > 0$, $Q^{CS*} - Q^{N*} = \frac{b\varepsilon d(d\varepsilon X-P_eN)}{N(4N-d^2\varepsilon)} > 0$.

(2) Comparisons with centralized model: $r^{cs*} = \frac{h(4X-P_ed)}{4N-d^2\varepsilon} < \frac{4hX}{4N-d^2\varepsilon}$ and $N - d^2\varepsilon - Z > 0$ in proof of Proposition 10; thus, $4N - d^2\varepsilon - 4Z > 0$, so $\frac{4hX}{4N-d^2\varepsilon} = \frac{4hX}{4N-d^2\varepsilon} < \frac{4hX}{4Z} = \frac{hX}{Z} = r_{GO}^{N*}$, that is $r^{cs*} < r_{GO}^{N*}$. Similarly, $w^{CS*} < w_{GO}^{N*}$, which leads to $p^{CS*} < p_{GO}^{N*}$, $Q^{CS*} < Q_{GO}^{N*}$. While for the carbon reduction, $v_{GO}^{N*} = \frac{Xd\varepsilon}{kZ} + \frac{P_e}{k} > \frac{Xd\varepsilon}{kN} + \frac{P_e}{k}$ because $N > Z$, so we compare $\frac{Xd\varepsilon}{kN} + \frac{P_e}{k}$ with $v^{cs*} = \frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)}$. $\frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)} - \frac{Xd\varepsilon}{kN} + \frac{P_e}{k} = \frac{-(d\varepsilon X-PN)(2N-d^2\varepsilon)}{kN(4N-d^2\varepsilon)}$, $2N - d^2\varepsilon > N - d^2\varepsilon > 0$ as $N > 0$, thus $\frac{2P_e}{k} + \frac{6(d\varepsilon X-P_eN)}{k(4N-d^2\varepsilon)} - \frac{Xd\varepsilon}{kN} + \frac{P_e}{k} < 0$, so $v^{CS*} < \frac{Xd\varepsilon}{kN} + \frac{P_e}{k} < v_{GO}^{N*}$. □

Proof of Proposition 10. $\pi_{PC}^{CS*} - \pi_{PC}^{N*} = \frac{(Xd\varepsilon-P_eN)^2}{2kN*(4N-d^2\varepsilon)} > 0$, so $\pi_{PC}^{CS*} > \pi_{PC}^{N*}$. $\Theta = \left[\frac{d}{2N} + \frac{8N}{(2bk-d^2)*2\varepsilon^2d}\right]d\varepsilon - 4 > \frac{8Nd\varepsilon}{(2bk-d^2)2\varepsilon^2d} - 4 = \frac{8Z}{2\varepsilon(2bk-d^2)} > 0$.

$\Delta M = \pi_M^{CS*} - \pi_M^{N*} = \frac{2N^2(2d\varepsilon X+2P_eN-d^2\varepsilon P_e)^2+N^2\varepsilon^2(2bk-d^2)(4X-P_ed)^2-N^2d^2\varepsilon^2(4X-P_ed)^2}{2k(4N-d^2\varepsilon)^2N^2} - \frac{[\varepsilon^2X^2(2bk-d^2)+N^2P_e{}^2]*(4N-d^2\varepsilon)^2}{2kN^2(4N-d^2\varepsilon)^2}$. Through the squared difference, we achieve the following simplification: $\Delta M = \frac{(d\varepsilon X-P_eN)*\{2\varepsilon^2dN(2bk-d^2)(4X-P_ed)-(d\varepsilon X-P_eN)[(2bk-d^2)d^2\varepsilon^2+8N^2]\}}{2k(4N-d^2\varepsilon)^2N^2}$. As $d\varepsilon X - P_eN > 0$ and $2k(4N-d^2\varepsilon)^2N^2 > 0$, the sign of ΔM depends on $H = 2\varepsilon^2dN(2bk-d^2)(4X-P_ed) - (d\varepsilon X-P_eN)[(2bk-d^2)d^2\varepsilon^2+8N^2]$. When $H > 0$, the contract achieves Pareto improvement, and members in the PCSC are willing to accept the cost-sharing contract.

As Proposition 9 has proven, $d\varepsilon X - P_e N > 0, 4X - P_e d > 0$, then $H > 0 \Leftrightarrow \frac{4X - P_e d}{d\varepsilon X - P_e N} \geq \frac{d}{2N} + \frac{8N}{(2bk - d^2) * 2\varepsilon^2 d} \Leftrightarrow \left\{3d + \left(N - d^2\varepsilon\right) * \left[\frac{d}{2N} + \frac{8N}{(2bk - d^2) * 2\varepsilon^2 d}\right]\right\} P_e \geq (ak - Cbk)\Theta$, with $\Theta > 0$; thus, the right-hand side of the inequality sign is greater than 0. As and $Z > 0$ and $\varepsilon - Z = 2\varepsilon\left(bk - d^2\right) > 0$, that is, $N - d^2\varepsilon > 0$, then $3d + \left(N - d^2\varepsilon\right)\left[\frac{d}{2N} + \frac{8N}{(2bk - d^2) * 2\varepsilon^2 d}\right] > 0$, $P_e \geq \frac{(a - bC)\Theta k d\varepsilon}{N(\Theta + 4) - (\Theta + 1)d^2\varepsilon}$. With $P_e \geq \frac{(a - bC)d\varepsilon\left(-2h^2 k - 3d^2\varepsilon + 4bk\varepsilon\right)}{-2h^4 k + 4h^2(3bk - d^2)\varepsilon + 2b(8bk - 5d^2)\varepsilon^2}$ in the proof of Proposition 8, $P_e \geq \frac{(a - bC)\Theta k d\varepsilon}{N(\Theta + 4) - (\Theta + 1)d^2\varepsilon}$, which means $\Delta M \geq 0$, so $\pi_M^{CS*} \geq \pi_M^{N*}$. □

Proof of Proposition 11. The first order proposition is given by $\frac{\partial \pi_{PC}^{TT}}{\partial p} = a - bp_{GO}^{N*} + dv_{GO}^{N*} - b\left(p_{GO}^{N*} - w^{TT}\right) + hr_{GO}^{N*} = 0$. $\frac{\partial \pi_{PC}^{TT}}{\partial r} = h\left(p_{GO}^{N*} - w\right) - r_{GO}^{N*}\varepsilon = 0$. We use the r_{GO}^{N*}, p_{GO}^{N*}, v_{GO}^{N*} equal to the solutions to solve the w^{TT}, so we have $w^{TT} = C\pi_M^{TT} > \pi_M^{N*}$; then, we obtain the lower bound:

$K_l = \frac{X^2\varepsilon^2\left[2bh^4k^3 - 2h^2k\varepsilon\left(4b^2k^2 - d^4\right) + \left(d^2 - 2bk\right)^2\left(3d^2 + 2bk\right)\varepsilon^2\right]}{2k(ZN)^2} > 0$, $\pi_{PC}^{TT} > \pi_{PC}^{N*}$; and we obtain the upper bound: $K_u = \frac{X^2\varepsilon^2\left[2bk^2\left(2b\varepsilon - h^2\right) - d^4\varepsilon\right]}{2kNZ^2} > 0$. $K_u - K_l = \frac{\left(2bk - d^2\right)^2 X^2\varepsilon^3}{2kZN^2} > 0$. Hence, $K_l < K < K_u$. □

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