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Article

Game Theoretic Analysis of Carbon Emission Abatement in Fashion Supply Chains Considering Vertical Incentives and Channel Structures

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Abstract: We study an emission-dependent dyadic fashion supply chain made up of a supplier and a manufacturer, both of which can reduce their own component/product emissions to serve the carbon-footprint sensitive consumers. With Carbon Tax regulation, we consider four scenarios resulting from two ways in form of adopting transfer price contract and/or introducing third-party emission-reduction service (TPERS) to enhance the efficiency of systematic emission reductions. We refine four models from these corresponding scenarios, which in turn constitute a decision-making framework composed of determining vertical incentives and choosing supply chain structures. By exploiting Stackelberg games in all models, we compare their emission reduction efficiencies and profitability for each pair of settings. Theoretic analysis and numerical studies show that adopting vertical transfer payment schemes can definitely benefit channel carbon footprint reduction and Pareto improvement of supply chain profitability, regardless of whether the emission-reduction service exists or not. However, whether introducing TPERS or not is heavily depending on systematic parameters when the transfer payment incentive is adopted there. We also provide insights on the sensitivity of carbon tax parameters with respect to the supply chain performance, overall carbon emission reduction, vertical incentive and TPERS adopting decision-makings.

Keywords: fashion business operations; carbon tax; emission reduction incentive; third-party emission-reduction service (TPERS); transfer payment; supply chain structure

1. Introduction

For controlling carbon emission, regulatory policies including Carbon Tax, Mandatory Cap, Cap & Trade and Carbon offset have been proposed and applied around the world (e.g., policies discussed in [1]). These policies aim to relieve global issues incurred by climate change, environmental deterioration and energy shortage worldwide. For example, more than 150 countries have signed the UN Framework Convention on Climate Change (UNFCCC) and Kyoto-Protocol [2]. Dowdey [3] addresses that Carbon Tax policy has been preferred by economists and consumers to Carbon & Trade policy due to the former's simplicity and impartiality in implementation. Compared with the complicated process of decomposing nation-level commitment of carbon caps into firm-level [4], carbon tax policy is obvious of advantage for its ease of practical manipulation. Actually, Carbon Tax has been applied in many European countries as well as in China, which has been extensively reported.

In parallel with studies on public regulatory policies, researchers have also proposed that it is possible and feasible for practitioners to confront carbon emission constraints by adjusting their operations strategies and tactics either in single firm level or supply chain level [5–7]. Moreover, carbon emission policies can have substantial impact both on operations and marketing for all parties within a supply chain.

In low carbon environment, product carbon emission is probably one of essential factors influencing its demand [8]. From the viewpoint of marketing, carbon footprint as a measure of the low-carbon degree of a unit product or service is gradually becoming one of components shaping customer value while low carbon economy evolutes and consumers' low carbon consciousness forms over time. For example, Geller *et al.* [9] mentions that some projects succeed by utilizing the economic tools (including awards and discounts) and promotion efforts (like educating and persuading to affect consumers' behaviors). In reality, many firms have adopted carbon label to increase the transparency of product carbon footprint information for better identifying low-carbon property of goods on the shelf. The input of lowering carbon emission even partially reflects firm's corporate social responsibility (CRS), which in turn affects customers' evaluation and its brands. These will naturally link to the firm's reputation and eventually impact on the firm's market popularity. Thus, many transnational companies highlight their activities and corporate social responsibility on carbon emission abatement, advocate their societal and environmental contributions and even set emission reduction target [10–12].

From the operations viewpoint, a product's overall forming and delivery processes including components fabricating, assembly manufacturing, transportation and distribution contribute emissions to the channel-side carbon footprint, as [13] identifies. Moreover, each party's engagement in carbon emission will affect other players' emission decisions as well as their interactions mutually. In this sense, for one product in low carbon setting, concentrating on the whole supply chain is more necessary and reasonable than on a single firm only. In this low-carbon economy context, there is one kind of service industry of Carbon Management Contracting (TPERS) emerged, such as the permit suppliers provisioning third party emission reduction service (TPERS) as mentioned in [4,14]. One significant function of TPERS firms is to help emission-dependent firms reduce emissions at lower cost but with higher efficiency, which creates value added for the whole supply chain. However, TPERS providers' involvement in the low-carbon oriented supply chain apparently changes the supply chain structure and further also affects interactions of each pair of chain players. Hence, vertical interactions and the chain structure configurations containing TPERS or not are two prominent aspects for supply chain operations.

In this paper, our goal is to study the impact of combinations of vertical relationship arrangement (vertical transfer price scheme by moving surcharges from one side to the other) and supply chain structures on the emission reduction efficiency and supply chain performance when the supply chain system is subject to Carbon Tax policy. As for the incentive applications like transfer payment, Jing [15] reports some supermarkets often take measures to simulate manufacturer to improve the emission reduction rate for raising the demand. Academically speaking, transfer price contract is aiming to relieve the effect of "double marginalization" the classic problem initially proposed by [16], which is extensively addressed in [17,18]. Here we utilize the transfer payment in our study to drive emission abating in low-carbon setting that is substantially different from that in existing traditional supply chain coordination literature. To learn more about transfer price contract, one is referred to a survey in [17]. In this study, whether transfer payment exists or not is one prominent dimension across all supply chain structures no matter whether TPERS involves or not.

We initially focus on a two-tier (dyadic) fashion supply chain with a single supplier providing components (or apparel parts) to a single manufacturer who do further processing and fabricating for the final apparel product, both of whom are emission-dependent, where their unit (component) product emission decrements are main decision variables of themselves, respectively. In order to concentrate on the emission reduction decision-makings in the channel, without loss of generality, we assume the supplier and the manufacturer claim fixed constant marginal profits so as to suppress the wholesale and retail pricing decisions, respectively. Therefore, we model the demand as the function of aggregate emission decrements of the channel to capture the demand sensitivity in emission reduction. Two choices of adopting or dropping transfer payment times two configurations of supply chain structures including or excluding TPERS generates four scenarios (*NE*, *HE*, *NI* and *HI*) as shown in following Table 1 (the relevant notation elaborated in Section 3). Under the each decentralized scenario, we formulate the associated problem as a Stackelberg game with the manufacturer as the leader and the supplier as the follower. The research questions we address in this study are as follows.

Table 1. Four scenarios categorized research framework.

Vertical Incentives \ **SC Structures**	**Supply Chain Excluding TPERS Provider (*E*)**	**Supply Chain Including TPERS Provider (*I*)**
No transfer payment (*N*)	Model *NE*	Model *NI*
Having transfer payment (*H*)	Model *HE*	Model *HI*

Note: For simplicity, we denote *NE*, *HE*, *NI* and *HI* sequentially as 1, 2, 3 and 4 throughout the paper.

(1) Whether there exists any transfer payment scheme to achieve Pareto improvement for the supply chain excluding or including TPERS provider, respectively?

(2) Should the manufacturer induce the TPERS provider into the system when the transfer payment scheme is devised? The same question arises in the other case when the transfer payment scheme is not adopted.
(3) What is the impact of different supply chain configuration combinations of vertical relationship (absorbing or dropping transfer payment) and supply chain structures (excluding or including TPERS provider) on the emission abatement efficiency and system-wide profitability?

Our models where transfer payment incentives choosing and third-party emission reduction provider adopting are determined by the supply chain and the leader firm, respectively, can be applicable to practice, especially to the emission dependent industries with their supply chains regulated by the Carbon Tax policy. In practice, for example, Wal-Mart sets up special zones jointly with her supplier to promote low-carbon products and advocate carbon efficient lifestyles [15]. The vertical incentives can be used to weaken emission-reduction double marginalization and incorporate the low-carbon effect on potential demand for aligning actions of the supplier and the manufacturer to enhance emission reduction and realize Pareto improvement on profits.

The paper is organized as follows. We begin by summarizing related literature. In Section 3, we present characteristics of the research problem, notation as well as assumptions applied throughout the paper. We address four scenarios and associated models in Section 4. We start by modeling first two scenarios of adopting vertical incentive or not in decentralized dyadic supply chain but excluding TPER firm's participation. We next address other two scenarios, similar problem on vertical incentive choosing and including TPERS. In Section 5, we make results analysis and conduct numerical studies to give out some managerial insights. And conclusion comes in Section 6 with some insights summarized and remarks on potential extension in the future.

2. Related Literature

Seeking for exposition conciseness, we only survey those highly relevant literatures. There exist two streams of researches related to our study: (1) single firm production optimizing with carbon emission constraints; and (2) supply chain operations in low-carbon setting. Several researchers have made comprehensive reviews on existing literatures of these two aspects both [19–21].

As an extensive study concentrating on single firm low-carbon problem, Song and Leng [7] examine the newsvendor model in four low-carbon policies (including Carbon Tax) regulated settings, respectively. They compare the optimal solution in this setting with that in the traditional newsvendor models to observe the impact of low-carbon constraints on the decision-makings. Similar studies are also conducted with stochastic demand in [22,23] and under deterministic Economic Order Quantity (EOQ) settings in [6,24]. Although these literatures have originally taken into consideration carbon emission policies, they confine their focuses only on firm-level operations resulting in solving Carbon-constrained optimization problem eventually given some policies considered. In contrast to those researches, we discuss the supply chain level problem in a similar carbon regulatory context, which embraces more complicated interactions among firms. This consideration drives our work more natural and closer to the reality.

Highly relevant literature to our study is the second stream of research. For an extensive review of low carbon supply chain operations, one is referred to [5,19]. Similar to their main points, several other researches address that properly adjusting operations strategies and tactics may be an important supplement to technological or equipment innovations for reducing carbon emission, especially for supply chain operations [25]. In this regard, the extant relevant literature can be categorized into supply chain network design optimization and game theoretic analysis. As for the former one, Hoen *et al.* [26] assert that directly implementing a constraint on freight transport emission is much more effective than other regulations like Carbon Tax and Cap and Trade policies which are proved lower efficiency on emission reduction in their study. Furthermore, Hoen *et al.* [27] derive conditions that link the total logistics cost and unit emissions to transport modes selecting. As to other studies in this aspect, readers are referred to [28–33], on supply network planning in low carbon environment. Although these papers focus on supply chain operations in presence of low carbon regulations, they have not yet analyzed channel interactions as well as mechanism design on emission abatement. Instead, they mostly tend to explore a system-wide network-optimizing solution given specific low carbon regulations, which establishes a main distinction from the first group of papers aforesaid.

There are also some researches on fashionable supply chain operations, which has a similar context to some extent related to our study. By considering the products returns in the clothing industry, seeking the optimal pricing, ordering and/or returning policies are the mainly usual topics focused in recent literature [34–37]. Similarly, Choi and Chiu [38] further include the consumers' environmental awareness into previous settings. Although they hold the research contexts similar to ours, they do not consider any carbon emission issues as we do here. Nagurney and Yu [39] and Shen [40] are representative two among the extant studies considering carbon reduction or environmental problems in fashion business operations. By focusing on a complicated fashion supply chain network subject to environmental constraints, Nagurney and Yu [39] develop optimization models to get the network equilibriums of apparel products and also examine the effect of various setting parameters on the network performance. With a different manner, Shen [40] exploits the case study method to describe in detail how the fashion firm H&M conducts her sustainable operations including carbon emission reducing efforts. However, both of them two do not touch the topics of determining emission-reduction means, such as mechanism design and supply chain structures reconstructing, which is exactly what we concentrate on.

In our study, we focus on the gaming process of vertical interacting in a supply chain. We contend to observe the mutual influences for seeking the possibility of Pareto improvement of both the upstream and the downstream. While most of previous papers suppose an existing integrator can centralize all decision-makings for trade-off to achieve a whole systematic optimum, one of our main contributions is in testifying the existence of transfer price mechanisms that realize Pareto improvement in two chain structures featured by excluding or including the third-party TPERS firm.

Much closer to our work is the literature with game theoretic analysis of low carbon supply chain operations, say, Du *et al.* [4], Liu *et al.* [41] and Du *et al.* [14]. Considering a supply chain consisting of one emission permit supplier and one manufacturer with permit pricing and production quantity, respectively, Du *et al.* [4] state that drawing on strict regulations policies government can improve environment significantly at low price of reasonably less economic growth. Moreover, the permit supplier is more likely to lower her permit price for stimulating larger production scale in downstream as the demand uncertainty goes up. Subsequently, by setting emission cap a changeable parameter and adding fairness preference and social total welfare in the same supply chain, Du *et al.* [14] study the impact of carbon policies on emission permit supplier and manufacturer. However, neither of these two papers consider designing an incentive mechanism to improve the performances of both participants, so is it in [41]. They exploit three two-tier Stackelberg game modes as well as different supply chain structures to demonstrate the impact of consumers' environmental awareness, tier competition intensity and eco-friendliness engagement level on profitability of chain players as well as those factors' cross effects. While they change their chain structures by endogenously increasing a functionally homogeneous firm, we do it by exogenously adding a functionally heterogeneous firm. This makes our study distinct from theirs completely. In addition, our study distinguishes from previous papers by providing firms strategic level decision-making framework of determining configuration of the vertical incentive designs and supply chain structures in Carbon Tax regulation.

3. Notation, Assumptions and Problem Characteristics

We initially consider a dyadic fashion supply chain in low carbon environment where a supplier provides one kind of apparel component to the downstream apparel manufacturer before it is finally processed into final apparel product by the latter. There are carbon dioxides generated in two stages, both of which are to be charged carbon tax according to their emission amount of making the components/products, respectively. Hence, the supplier and the manufacturer separately make efforts to reduce their own carbon emission as well as associated cost incurred by carbon tax, respectively. Consequently, the footprint of final product is determined by the aggregate emission decrements through the supply chain. We assume the deterministic demand is sensitive to the selling price and overall emission decrements, which reflects consumers' low-carbon awareness.

We model their interactions as two-stage Stackelberg games. For simplicity but without loss of generality, we assume a manufacturer-dominated supply chain with manufacturer the leader and supplier the follower. To raise each party's profitability, on one hand, manufacturer may stimulate the supplier's emission reduction to overcome the efficiency resulting from double marginalization. On the other hand, manufacturer may also introduce the third-party emission reduction service or technology provider to cut down emission-reduction relevant cost. Therefore, manufacturer has four main strategies (with corresponding models denoted in Table 1) for emission abating:

(1) Upstream and downstream sides reduce emission separately (denoted Model *NE*);
(2) Only stimulate supplier to reduce emission (denoted Model *HE*);
(3) Only introduce a TPERS provider to reduce emission without stimulating supplier (denoted Model *NI*);
(4) Introduce a TPERS provider and simultaneously simulate supplier to reduce emission (denoted Model *HI*). Subscripts *m*, *s*, *t* denote the manufacturer, the supplier and third-party emission reduction service (TPERS) provider, respectively.

The notation we use throughout the paper is set as follows:

3.1. Parameters

λ_i : Initial emission rate for firm *i*, $i = m, s$;
r : Demand sensitivity coefficient on emission, $r > 0$;

σ_i: Government carbon emission allowance that is provided in the form of duty-free emission quota for each unit product, $i = m, s$ $0 \le \sigma_i < \lambda_i$;

p_c: Carbon emission tax rate for $0 \le e_i \le \lambda_i - \sigma_i$ or the tax-rebate rate for $\lambda_i - \sigma_i < e_i \le \lambda_i$, $p_c > 0$;

ρ_i: Unit product profit of manufacturer or supplier (cost of emission reduction not counted), $\rho_i > 0$;

u_i: Emission reduction relevant fixed cost coefficient for firm *i*, $i = m, s, t$ where $0 < u_t < u_m$;

a': Intrinsic demand without considering the influence of emission reduction, $a' > 0$;

a: Intrinsic demand equaling $a' - b(c_m + c_s + \rho_m + \rho_s) - r(\lambda_m + \lambda_s)$ after accounting for variable costs, emission reductions, initial emission rates and fixed margin profits;

c_i: Unit production cost of firm *i*, $i = m, s$.

$D(e_s, e_m, e_t)$: Deterministic market demand of product generated by aggregate emission decrements under our assumptions;

Π_i: Profit of firm *i*, $i = m, s, t$;

Π: Total profit of the supply chain.

3.2. Decision Variables

e_i: Emission decrement per unit product for firm *i*, $0 \le e_i < \lambda$, $i = m, s, t$;

v: Transfer payment coefficient provided by the manufacturer to the supplier, $v \ge 0$;

θ: Unit emission reduction amount compensation coefficient provided by manufacturer to third-party, $\theta \ge 0$;

We set *assumptions* as follows:

A1. Only one kind of product is considered and shortage is not permitted;

A2. Both supplier and manufacturer maintain fixed margin profits, respectively, namely, ρ_m and ρ_r are constants;

A3. The deterministic demand function $D(e_s, e_m, e_t) = a + r(e_m + e_s)$ is linear in the supplier's and the manufacturer's emission decrements with same coefficient;

A4. The manufacturer is as a dominant leader to move first, while the supplier as a follower;

A5. All information of parameters is common knowledge to supplier and manufacturer.

To facilitate calculations and center our focus on carbon emission reduction, we establish assumption A2 as a similar way as in [42,43], aiming to suppress the influence of wholesale and retail pricing decisions. We set the deterministic demand function $D(p, C_e) = a' - bp - rC_e$ to capture its sensitivity on selling price and total emission decrement, where the selling price expression $p = c_m + c_s + \rho_m + \rho_s$ can be induced by wholesale price $w = c_s + \rho_s$ and formula $p = w + c_m + \rho_m$ under assumption A2. a' is the original intrinsic demand without considering any influences $C_e = \lambda_m + \lambda_s - (e_m + e_s)$ is the emission amount per unit product. Denoting $a = a' - b(c_m + c_s + \rho_m + \rho_s) - r(\lambda_m + \lambda_s)$ that coincides with corresponding parameter description and substituting it into $D(p, C_e)$ yields a concise form of the demand function:

$$D(e_s, e_m) = a + r(e_m + e_s) \tag{1}$$

For the emission reduction, it is relatively easy to carry out in small reduction amount with low cost and much higher cost as reduction goes up [44]. Thus, the reduction cost $c(e)$ holds conditions $c'(e) > 0$ and $c''(e) > 0$, and is a convex function of emission reductions. For convenience, assume the emission-reduction relevant fixed costs for the manufacturer and the supplier both have quadratic modes $\frac{1}{2}u_m e_m^2$ and $\frac{1}{2}u_s e_s^2$, respectively. The quadratic form here means the diminishing marginal return on this kind of expenditure. Furthermore, without loss of generality, we also suppose there exist government provided allowances in the form of duty-free carbon emission quotas that varies over industries, *i.e.*, $\sigma_s \geq 0$ and $\sigma_m \geq 0$ for the supplier and manufacturer, respectively [45]. Considering the initial emissions per product λ_i, the emission tax charged per unit component/product for firm *i* is $p_c(\lambda_i - \sigma_i - e_i)$ when $0 \leq e_i \leq \lambda_i - \sigma_i$ holds; otherwise, the firm can obtain revenue $p_c(e_i + \sigma_i - \lambda_i)$ when we have $\lambda_i - \sigma_i < e_i \leq \lambda_i$, where $i = s, m$.

4. The Models

In this section, we start to study a dyadic fashion supply chain consisting of an apparel manufacturer (he) and an apparel supplier (she), indexed by *m* and *s*, respectively. The focal manufacturer holds emission-dependent production process and provisions differentiated products to emission-sensitive consumers. Therefore, he has apparent motivation to reduce the unit product carbon emission. Moreover, He has the option to encourage the supplier to reduce emission and/or to outsource emission reduction to a third-party emission reduction service (TPERS) supplier besides he also reduces in-house. The transfer payment incentive and TPERS adding to the initial dyadic chain structure or not determine four supply chain configurations. We analyze those aforementioned four scenarios *NE*, *HE*, *NI* and *HI* sequentially by modeling them as Stackelberg games with solving processes and interpretations. For better understanding the gaming process in each scenario, here we explain Stackelberg game formally but simply. A Stackelberg game can be derived from a given strategic-form game *G* by letting the players in a certain order for strategy selecting. Actually, as an extensive-form game, it defines each player choose a move from his/her strategies after observing all other players' moves preceding theirs in the order provided. Accordingly, the player moving first in the order is called the Stackelberg leader, otherwise the follower. For details of the above definition and interpretation of the Stackelberg game, one may refer to [46–48].

4.1. The Setting neither with Transfer Payment nor TPERS (Model NE)

In this subsection, we consider the initial simplest setting where manufacturer and supplier conduct carbon emissions independently neither with emission-reducing relevant transfer payment incentive nor third-party emission reduction service involved. The move sequence in the process of the corresponding Stackelberg game can be described like this: (1) we assume the manufacturer as a game leader to move first to determine his emission reduction amount e_m per unit product; (2) the supplier as a follower to decide his emission reduction rate e_s after she observes the manufacturer's decision. The dominance for the focal firm manufacturer is to some extent interpreted as he has more power over supplier. The supply chain configuration in Model *NE* is shown in Figure 1.

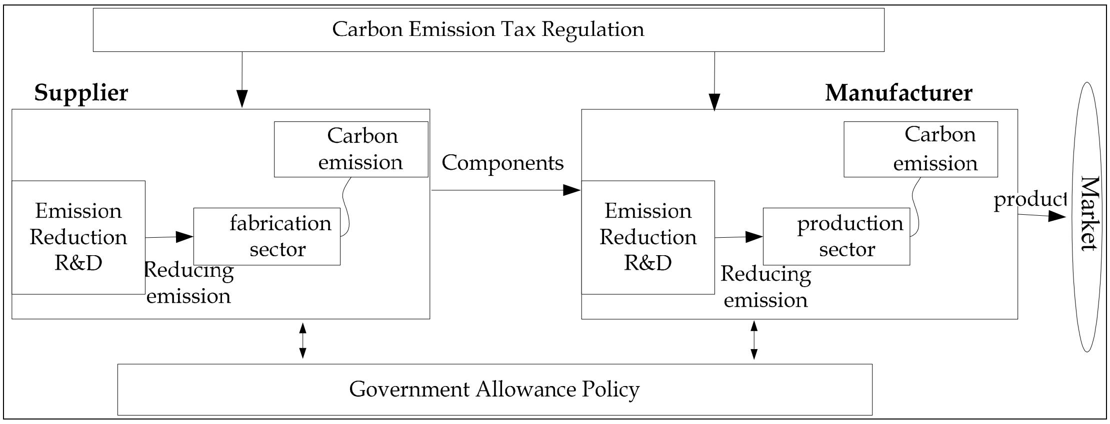


Figure 1. Schematic diagram of setting *NE*.

4.1.1. The Supplier's Emission-Reduction Decision

We apply backward induction to solve the gaming process for the subgame-perfect equilibrium. Hence, we firstly look into supplier's problem by getting her objective function as follows:

$$\max_{0 \le e_s < \lambda_s} \Pi_s(e_s, e_m) = \rho_s[a + r(e_m + e_s)] - p_c(\lambda_s - \sigma_s - e_s)[a + r(e_m + e_s)] - \frac{1}{2}u_s e_s^{\,2} \tag{2}$$

where the first term in right hand side (RHS) is the gross profit realized by the emission-reduction-sensitive demand and the second term emission tax fee if $\sigma_s < \lambda_s - e_s$ or extra revenue if $\sigma_s \ge \lambda_s - e_s$. The supplier's problem is to choose a suitable emission reduction rate e_s to maximize her profit. Differentiating the profit function $\Pi_s(e_s, e_m)$ with respect to e_s yields:

$$\frac{\partial \Pi_s}{\partial e_s} = r\rho_s + p_c(a + re_m) + rp_c(\sigma_s - \lambda_s) + (2rp_c - u_s)e_s \tag{3}$$

where we premise $\frac{\partial^2 \Pi_s}{\partial e_s^{\,2}} = 2rp_c - u_s < 0$ to ensure the concavity of the function $\Pi_s(e_s, e_m)$, namely, we need following conditions Equations (4) and (5) holds:

$$\frac{rp_c}{u_s} < \frac{\lambda_s}{2\lambda_s + \lambda_m} \tag{4}$$

$$\lambda_s \ge \frac{\rho_s}{p_c} + \frac{a}{r} \tag{5}$$

Letting $\frac{\partial \Pi_s}{\partial e_s} = 0$ in Function (3) generates the supplier's best response function given manufacturer's emission reduction rate e_m:

$$e_{s1}(e_m) = \frac{r\rho_s + p_c(a + re_m) + rp_c(\sigma_s - \lambda_s)}{u_s - 2rp_c} \tag{6}$$

As neither the manufacturer nor the supplier could be able to reduce its emission level to zero, namely, $0 \le e_s < \lambda_s$ and $0 \le e_m < \lambda_m$, we need the following Inequalities (7) hold since the function $e_{s1}(e_m)$ is increasing as e_m increases.

$$0 \le e_{s1}|_{e_m=0} < e_{s1}(e_m) < e_{s1}|_{e_m=\lambda_m} < \lambda_s \tag{7}$$

The above inequalities transformed to $0 \le r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s) < (u_s - 2rp_c)\lambda_s - rp_c\lambda_m$ are equivalent to the conditions as follows:

$$\frac{rp_c\lambda_s - (r\rho_s + ap_c)}{rp_c} \le \sigma_s < \frac{(u_s - rp_c)\lambda_s - (r\rho_s + ap_c + rp_c\lambda_m)}{rp_c} \tag{8}$$

which can be proved to hold and ensured by Condition (4). This condition means the government carbon emission allowance σ_s should be restrained in some reasonable interval so that the game process can make sense well.

4.1.2. The Manufacturer's Emission-Reduction Decision

The supplier's best response Function $e_{s1}(e_m)$ is then used in manufacturer's objective function as follows:

$$\max_{0 \le e_m < \lambda_m} \Pi_m(e_{s1}(e_m), e_m) = \rho_m[a + r(e_m + e_s)] - p_c(\lambda_m - \sigma_m - e_m)[a + r(e_m + e_s)] - \frac{1}{2}u_m e_m^{\ 2} \tag{9}$$

Substituting Equation (6) into $\Pi_m(e_s, e_m)$ and differentiating it yields the first derivative:

$$\frac{\partial \Pi_m}{\partial e_m} = [\rho_m + p_c(\sigma_m - \lambda_m)]r(1 + \frac{rp_c}{u_s - 2rp_c}) + p_c[a + r\frac{r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s)}{u_s - 2rp_c}]$$
$$+ (rp_c\frac{2u_s - 2rp_c}{u_s - 2rp_c} - u_m)e_m$$

To ensure the concavity of function $\Pi_m(e_{s1}(e_m), e_m)$ with respect to e_m, we need the condition $\frac{\partial^2 \Pi_m}{\partial e_m^{\ 2}} = rp_c\frac{2u_s - 2rp_c}{u_s - 2rp_c} - u_m < 0$ holds, namely,

$$\frac{rp_c}{u_m} < \frac{u_s - 2rp_c}{2(u_s - rp_c)} \tag{10}$$

To ensure $0 \le e_m < \lambda_m$ for the existence of the optimizer located in the interval $(0, \lambda_m)$ due to the concavity structure of function $\Pi_m(e_{s1}(e_m), e_m)$, we need the conditions $\frac{\partial \Pi_m}{\partial e_m}\big|_{e_m = 0} > 0$ and $\frac{\partial \Pi_m}{\partial e_m}\big|_{e_m = \lambda_m} < 0$, which is equivalent to the following inequalities:

$$\frac{1}{rp_c}(u_s - rp_c)(rp_c\lambda_m - r\rho_m - ap_c) + r(p_c\lambda_s - \rho_s) < (u_s - rp_c)\sigma_m + rp_c\sigma_s <$$
$$\frac{1}{rp_c}(u_s - rp_c)[(u_m - rp_c)\lambda_m - r\rho_m - ap_c] + [r(p_c\lambda_s - \rho_s) - u_m\lambda_m] \tag{11}$$

with the following prerequisite:

$$p_c < \frac{1}{2r}[u_s + u_m - \sqrt{u_s^{\ 2} + u_m^{\ 2}}] \tag{12}$$

By letting $\frac{\partial \Pi_m}{\partial e_m} = 0$, we find manufacturer's optimal emission reduction amount:

$$e_{m1} = \frac{(u_s - rp_c)[r\rho_m + ap_c + rp_c(\sigma_m - \lambda_m)] + r^2 p_c[\rho_s + p_c(\sigma_s - \lambda_s)]}{u_m(u_s - 2rp_c) - 2rp_c(u_s - rp_c)} \tag{13}$$

Substituting e_{m1} into Equation (6), and we obtain the supplier's optimal emission decrement:

$$e_{s1} = \frac{rp_c}{u_s - 2rp_c} \frac{(u_s - rp_c)[r\rho_m + ap_c + rp_c(\sigma_m - \lambda_m)] + r^2 p_c[\rho_s + p_c(\sigma_s - \lambda_s)]}{u_m(u_s - 2rp_c) - 2rp_c(u_s - rp_c)} + \frac{r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s)}{u_s - 2rp_c} \tag{14}$$

So the (e_{s1}, e_{m1}) are the emission-reduction decision equilibrium in the setting without transfer payment incentive scheme or third-party emission reduction service. In the following sections, we will compare this equilibrium with those obtained in other settings.

4.2. The Setting with Transfer Payment Incentive Only (Model HE)

In this section, we employ transfer payment incentive to generate vertical incentive for the channel emission reduction. The reason for considering transfer payment in our study is due to double marginalization mentioned and researched frequently by supply chain contracts as well as industrial organization literatures. Although we study the carbon emission problem, its essence can be applied to this kind of solving double marginalization. We presume the manufacturer will provide supplier some transfer payment to enhance the latter's emission reduction while the final product carbon footprint includes the carbon emissions of both supplier and the manufacturer. The behavior of any one party will affect the interests of the other. From the system-side perspective, we tend to optimize the overall emission reduction of the supply chain and at the same time achieve the Pareto improvement of profits. And supply chain structure in Model *HE* is shown in Figure 2.

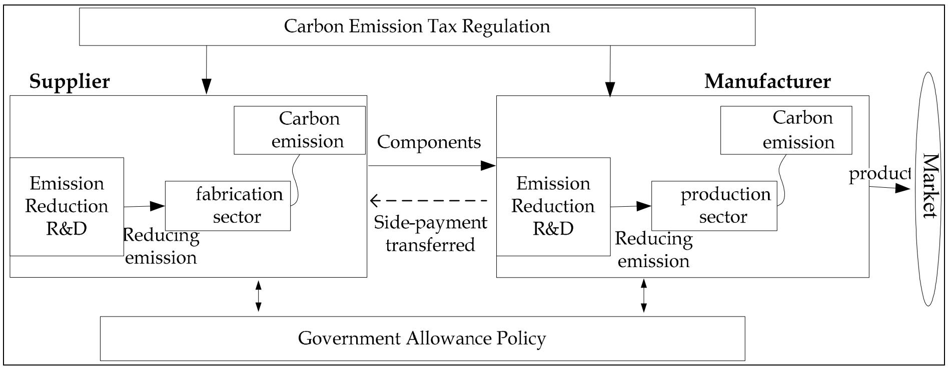


Figure 2. Schematic diagram of setting *HE.*

For simplicity but without loss of generality, assume that the transfer payment is linearly increasing in the supplier's emission reduction per unit product, *i.e.*, ve_s. In this case, both sides still execute Stackelberg Game where manufacturer declares its reduction e_m and transfer payment coefficient v first, and then supplier decides its emission reduction e_s. The objective functions of both sides are as follows, respectively

$$\max_{0 \le e_s < \lambda_s} \Pi_s(e_s, e_m) = \rho_s[a + r(e_m + e_s)] + p_c(\sigma_s + e_s - \lambda_s)[a + r(e_m + e_s)] - \frac{1}{2}u_s e_s^2 + ve_s \tag{15}$$

and

$$\max_{0 \le e_m < \lambda_m} \Pi_m(e_s, e_m) = \rho_m[a + r(e_m + e_s)] + p_c(\sigma_m + e_m - \lambda_m)[a + r(e_m + e_s)] - \frac{1}{2}u_m e_m^2 - ve_s \tag{16}$$

4.2.1. The Supplier's Emission-Reduction Decision

Drawing on the backward induction, we still start with supplier's problem. According to function and condition in Equation (4), we can get $\frac{\partial^2\Pi_s(e_s,e_m)}{\partial {e_s}^2}=2rp_c-u_s<0$ to ensure $\Pi_s(e_s,e_m)$ concave in e_s provided e_m is given. Here we need two conditions hold

$$rp_c<\frac{\lambda_s u_s-u_m}{2\lambda_s+\lambda_m} \tag{17}$$

$$\lambda_s\geq\frac{\rho_s}{p_c}+\frac{a}{r} \tag{18}$$

Letting $\frac{\partial\Pi_s(e_s,e_m)}{\partial e_s}=r\rho_s+p_c[a+r(e_m+e_s)]+rp_c(\sigma_s+e_s-\lambda_s)-u_s e_s+v=0$ yields the best reaction function of supplier's emission decrement decision e_s with respect to manufacturer's decision e_m;

$$e_{s2}(e_m)=\frac{r\rho_s+p_c(a+re_m)+rp_c(\sigma_s-\lambda_s)+v}{u_s-2rp_c} \tag{19}$$

For the manufacturer, he encourages the supplier to reduce emission by transfer payment ve_s only if his marginal emission reduction cost is higher than v in other words $0\leq v<u_m$.

Regarding the linearly increasing structure of function $e_{s2}(e_m)$ in e_m and v, we just need, we need conditions $e_{s2}\,|_{e_m=0,v=0}\geq 0$ and $e_{s2}\,|_{e_m=\lambda_m,v=u_m}<\lambda_s$ hold to satisfy $0\leq e_s<\lambda_s$ and $0\leq e_m<\lambda_m$, which is equivalent to the inequalities $0\leq r\rho_s+ap_c+rp_c(\sigma_s-\lambda_s)<\lambda_s(u_s-2rp_c)-rp_c\lambda_m-u_m$, which can be guaranteed by Inequalities (8).

4.2.2. The Manufacturer's Emission-Reduction Decision

Substituting $e_{s2}(e_m)$ into Equation (15) and differentiating it, we know $\frac{\partial^2\Pi_m}{\partial e_m\partial v}=0$, $\frac{\partial^2\Pi_m}{\partial v\partial e_m}=0$, $\frac{\partial^2\Pi_m}{\partial v^2}=-\frac{2}{u_s-2rp_c}$, $\frac{\partial^2\Pi_m}{\partial {e_m}^2}=2rp_c(1+\frac{rp_c}{u_s-2rp_c})-u_m$. We need conditions $\frac{rp_c}{u_m}<\frac{u_s-2rp_c}{2(u_s-rp_c)}$ and $\frac{rp_c}{u_s}<\frac{1}{2}$ to ensure $\Pi_m(e_m,v)$'s Hess matrix negative definite for guaranteeing the concavity of $\Pi_s(e_s,e_m)$. To ensure $0\leq e_m<\lambda_m$, we need the conditions $\partial\Pi_m/\partial e_m\big|e_m=0>0$ and $\partial\Pi_m/\partial e_m\big|e_m=\lambda_m<0$ hold, which is ensured by Condition (11) and its prerequisite.

Drawing on the above conditions to ensuring the concavity of the manufacturer's profit function in decision variables pair (e_m,v) and equating their first-order derivatives zero:

$$\begin{cases}\frac{\partial\Pi_m}{\partial v}=\frac{r\rho_m+rp_c(\sigma_m+e_m-\lambda_m)-r\rho_s-p_c(a+re_m)-rp_c(\sigma_s-\lambda_s)-2v}{u_s-2rp_c}=0\\ \frac{\partial\Pi_m}{\partial e_m}=\frac{[r\rho_m+ap_c+rp_c(\sigma_m-\lambda_m)](u_s-rp_c)+r^2p_c[\rho_s+p_c(\sigma_s-\lambda_s)]}{u_s-2rp_c}+\\ \qquad\qquad\frac{2rp_c(u_s-rp_c)-u_m(u_s-2rp_c)}{u_s-2rp_c}e_m=0\end{cases}$$

We can obtain the manufacturer's optimal emission reduction e_{m2} and transfer payment coefficient v_2 as follows:

$$v_2 = \frac{1}{2}[r(\rho_m + \rho_s) - ap_c - rp_c(\sigma_s - \lambda_s) + rp_c(\sigma_m - \lambda_m)] \tag{20}$$

$$e_{m2} = \frac{[r\rho_m + ap_c + rp_c(\sigma_m - \lambda_m)](u_s - rp_c) + r^2 p_c[\rho_s + p_c(\sigma_s - \lambda_s)]}{u_m(u_s - 2rp_c) - 2rp_c(u_s - rp_c)} \tag{21}$$

Substituting Equations (20) and (21) into Function (19) yields the supplier's optimal emission reduction equilibriums:

$$e_{s2} = \frac{r\rho_s + rp_c(\sigma_s - \lambda_s) + ap_c + r\rho_m + rp_c(\sigma_m - \lambda_m)}{2(u_s - 2rp_c)} + \frac{rp_c}{u_s - 2rp_c}\frac{[r\rho_m + ap_c + rp_c(\sigma_m - \lambda_m)](u_s - rp_c) + r^2 p_c[\rho_s + p_c(\sigma_s - \lambda_s)]}{u_m(u_s - 2rp_c) - 2rp_c(u_s - rp_c)} \tag{22}$$

4.3. The Setting with Only TPERS Involved (Model NI)

In parallel with the way of inspiring supplier on emission reduction, the manufacturer can also choose to outsource their emission reduction management to a professional third-party emission reduction service providers (TPERS), such as Carbon Management Company. Relying heavily on the professional service providers' lower cost of emission reduction, the manufacturer not only benefits from cost cutting down, but can also concentrate on his major business. In this case, the third-party service provider decides the unit product emission reductions of manufacturer e_m, while the manufacturer decides the reduction compensation coefficient θ for the third-party. Meanwhile, the manufacturer pays the TPERS provider θe_m for emission reduction. The supply chain structure in this setting is sketched in Figure 3.

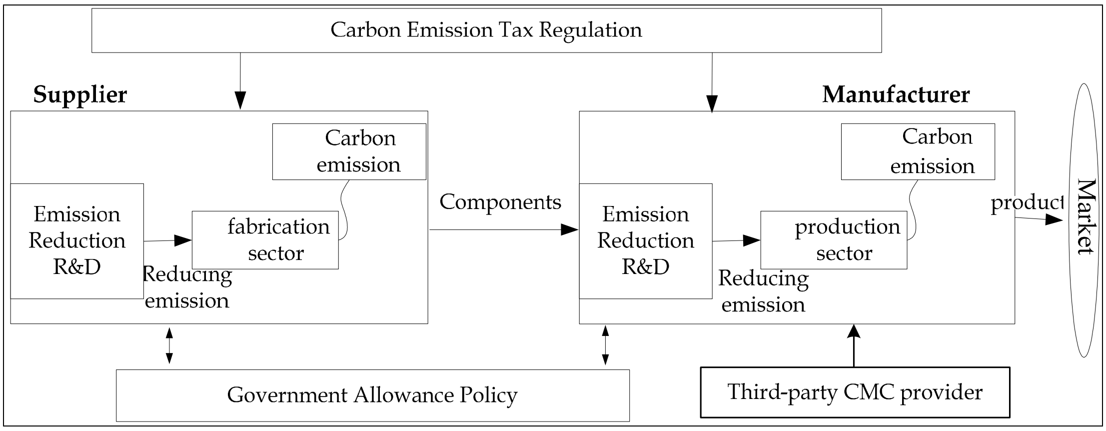


Figure 3. Schematic diagram of setting *NI*.

The move sequence in this setting is described as follows: the manufacturer firstly announces the reduction compensation coefficient θ for the TPERS provider, the third-party next decides e_m the emission reduction per unit product, and then the supplier chooses e_s her own emission reduction per product. The objective functions for manufacturer, TPERS provider and supplier are as follows, respectively:

$$\max_{\theta} \Pi_m(e_m, e_s) = \rho_m[a + r(e_m + e_s)] + p_c(\sigma_m + e_m - \lambda_m)[a + r(e_m + e_s)] - \theta e_m \tag{23}$$

$$\max_{0 \le e_m \le \lambda_m} \Pi_t(e_m) = \theta e_m - \frac{1}{2} u_t e_m^{\ 2} \tag{24}$$

$$\max_{0 \le e_s \le \lambda_s} \Pi_s(e_m,\ e_s) = \rho_s[a + r(e_m + e_s)] + p_c(\sigma_s + e_s - \lambda_s)[a + r(e_m + e_s)] - \frac{1}{2} u_s e_s^{\ 2} \tag{25}$$

By using backward induction, we start with supplier's problem. According to conditions in Section 4.1, we can get $\frac{\partial^2 \Pi_s}{\partial e_s^{\ 2}} = 2rp_c - u_s < 0$ and accordingly $\Pi_s(e_m,\ e_s)$ is concave in e_s for given e_m.

Let $\frac{\partial \Pi_s}{\partial e_s} = r\rho_s + p_c[a + r(e_m + e_s)] + rp_c(\sigma_s + e_s - \lambda_s) - u_s e_s$, thus, we get her best reaction function of the supplier as follows:

$$e_{s3}(e_m) = \frac{r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s)}{u_s - 2rp_c} + \frac{rp_c e_m}{u_s - 2rp_c} \tag{26}$$

Apparently, we can find that the function $e_{s3}(e_m)$ is linearly increasing in e_m. By considering the constraints $0 \le e_s < \lambda_s$ and $0 \le e_m < \lambda_m$, we need conditions $e_{s3}|_{e_m=0} \ge 0$ and $e_{s3}|_{e_m=\lambda_m} < \lambda_s$ hold, *i.e.*, $0 \le r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s) < \lambda_s(u_s - 2rp_c) - rp_c\lambda_m$, which can be ensured by aforementioned Conditions (4), (5) and (8).

Then we turn to TPERS provider's problem to optimize his profit function by determining the suitable emission reduction offered to the manufacturer. According to Function (24), we know $\frac{\partial^2 \Pi_t}{\partial e_m^{\ 2}} = -u_t < 0$ implying that $\Pi_t(e_m,\ e_s)$ is concave in e_m. We can get the optimal emission reduction provided to manufacturer through $\frac{\partial \Pi_t}{\partial e_m} = \theta - u_t e_m = 0$, namely:

$$e_{m3} = \frac{\theta}{u_t} \tag{27}$$

It is possible for the manufacturer to reduce its emission with the TPERS provider only if $0 \le \theta < u_m$ To ensure $0 \le e_m < \lambda_m$, we need the conditions $\frac{\partial \Pi_t}{\partial e_m}|_{e_m = \lambda_m, \theta = u_m} < 0$ hold, *i.e.*,:

$$\frac{u_m}{u_t} < \lambda_m \tag{28}$$

Utilizing Equations (26) and (27) simplifies manufacturer's objective function and we ensure $\Pi_m(e_m,\ e_s)$ concave in e_m for given e_s by assuming $\frac{rp_c}{u_t} < \frac{u_s - 2rp_c}{u_s - rp_c}$ so as to let $\frac{\partial^2 \Pi_m}{\partial \theta^2} = \frac{2}{u_t}[\frac{rp_c(u_s - rp_c)}{u_t(u_s - 2rp_c)} - 1] < 0$.

By solving $\frac{\partial \Pi_m}{\partial \theta} = \frac{p_c}{u_t}[a + r(e_m + e_s)] + [r\rho_m + rp_c(\sigma_m + e_m - \lambda_m)]\frac{u_s - rp_c}{u_t(u_s - 2rp_c)} - \frac{2\theta}{u_t} = 0$, we obtain the optimal emission reduction compensation coefficient provided to TPERS provider as follows:

$$\theta_3 = u_t \frac{[r\rho_m + rp_c(\sigma_m - \lambda_m) + ap_c](u_s - rp_c) + r^2 p_c[\rho_s + p_c(\sigma_s - \lambda_s)]}{2u_t(u_s - 2rp_c) - 2rp_c(u_s - rp_c)]} \tag{29}$$

Accordingly, the optimal emission reductions of manufacturer and supplier are as follows respectively:

$$e_{m3}=\frac{[r\rho_m+rp_c(\sigma_m-\lambda_m)+ap_c](u_s-rp_c)+r^2p_c[\rho_s+p_c(\sigma_s-\lambda_s)]}{2u_t(u_s-2rp_c)-2rp_c(u_s-rp_c)]} \quad (30)$$

$$e_{s3}=\frac{r\rho_s+ap_c+rp_c(\sigma_s-\lambda_s)}{u_s-2rp_c}+\frac{rp_c}{u_s-2rp_c}\frac{[r\rho_m+rp_c(\sigma_m-\lambda_m)+ap_c](u_s-rp_c)+r^2p_c[\rho_s+p_c(\sigma_s-\lambda_s)]}{2u_t(u_s-2rp_c)-2rp_c(u_s-rp_c)]} \quad (31)$$

Consequently, the combination $(e_{m3},\ e_{s3},\ \theta_3)$ valuated in Equations (29)–(31) is the sub-game perfect Nash equilibrium in this setting.

4.4. The Setting with Emission-Reducing Incentive and TPERS Simultaneously (Model HI)

In this section, we consider the situation where supply chain employ the TPERS and devise the transfer payment schemes simultaneously. Even though the manufacturer entrusts the third-party to provide emission reduction technology and management service, it can still stimulate the supplier to enhance their emissions reductions by providing the associated transfer payment. The supply chain structure in this setting is shown in Figure 4.

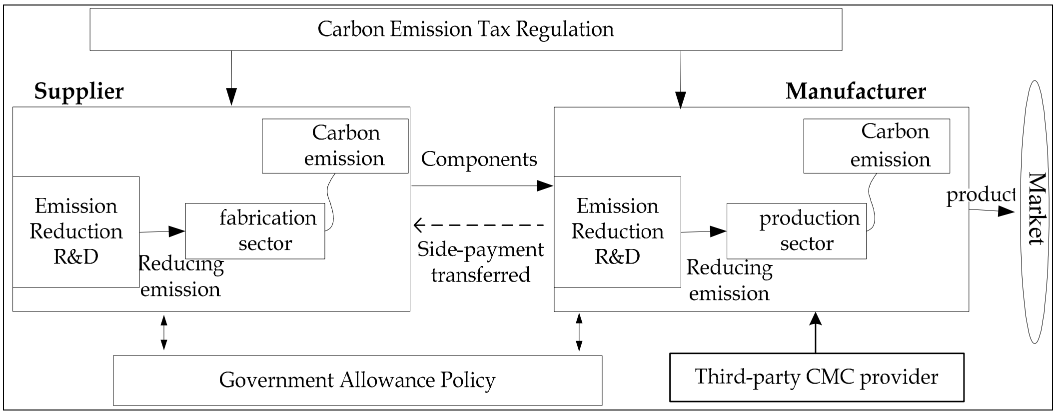


Figure 4. Schematic diagram of setting *HI*.

In this case, the manufacturer firstly announces the reduction compensation coefficient θ for the TPERS provider and the transfer payment coefficient v for supplier; and then CMC provider decides emission reduction per product for manufacturer; finally the supplier decides her emission reduction. We can write down objective functions of manufacturer, TPERS provider and supplier as follows, respectively:

$$\max_{v\geq 0,\ \theta\geq 0}\ \Pi_m(e_m,\ e_s)=\rho_m[a+r(e_m+e_s)]+p_c(\sigma_m+e_m-\lambda_m)[a+r(e_m+e_s)]-\theta e_m-ve_s \quad (32)$$

$$\max_{0\leq e_m\leq\lambda_m}\ \Pi_t(e_m,\ e_s)=\theta e_m-\frac{1}{2}u_te_m{}^2 \quad (33)$$

$$\max_{0\leq e_s\leq\lambda_s}\ \Pi_s(e_m,\ e_s)=\rho_s[a+r(e_m+e_s)]+p_c(\sigma_s+e_s-\lambda_s)[a+r(e_m+e_s)]-\frac{1}{2}u_se_s{}^2+ve_s \quad (34)$$

By using backward induction for starting with supplier's problem and according to Function (23), we get $\dfrac{\partial^2\Pi_s}{\partial e_s{}^2}=2rp_c-u_s$. Still again with $2rp_c-u_s\leq 0$ holding for ensuring the concavity of objective function. Considering $\frac{\partial \Pi_s}{\partial e_s} = r\rho_s + p_c(a + re_m) + rp_c(\sigma_s - \lambda_s) + (2rp_c - u_s)e_s + v = 0$, we have the optimal solution:

$$e_{s4}(e_m) = \frac{r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s)}{u_s - 2rp_c} + \frac{rp_c e_m + v}{u_s - 2rp_c} \tag{35}$$

Similar to in the Model *HE,* the manufacturer encourages the supplier to reduce emission by transfer payment ve_s only if $0 \le v < u_m$. For the constraints $0 \le e_s < \lambda_s$ and $0 \le e_m < \lambda_m$ existing, we need conditions $e_{s4}|_{e_m=0, v=0} \ge 0$ and $e_{s4}|_{e_m=\lambda_m, v=u_m} < \lambda_s$ hold, which is $0 \le r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s) < \lambda_s(u_s - 2rp_c) - rp_c\lambda_m - u_m$ ensured by:

$$\frac{rp_c\lambda_s - r\rho_s - ap_c}{rp_c} \le \sigma_s < \frac{\lambda_s(u_s - rp_c) - (r\rho_s + ap_c + rp_c\lambda_m + u_m)}{rp_c} \tag{36}$$

According to Function (33) with $\frac{\partial^2 \Pi_t}{\partial e_m^{\ 2}} = -u_t < 0$, so $\Pi_t(e_m, e_s)$ is concave in e_m for given e_s. By letting $\frac{\partial \Pi_t}{\partial e_m} = \theta - u_t e_m = 0$, we obtain the optimum choice for e_m in the following:

$$e_{m4} = \frac{\theta}{u_t} \tag{37}$$

Just like in the Model *NI*, the prerequisite for the manufacturer to source his emission reduction amount from the TPERS provider if and only if $0 \le \theta < u_m$. To ensure $0 \le e_m < \lambda_m$, we need the condition $\frac{\partial \Pi_t}{\partial e_m}|_{e_m = \lambda_m, \theta = u_m} < 0$ hold, *i.e.*, $\frac{u_m}{u_t} < \lambda_m$. By substituting e_{m4} and e_{s4} into Equation (32), we can obtain $\frac{\partial^2 \Pi_m}{\partial v^2} = -\frac{2}{u_s - 2rp_c}$, $\frac{\partial^2 \Pi_m}{\partial v \partial \theta} = 0$, $\frac{\partial^2 \Pi_m}{\partial \theta \partial v} = 0$ and $\frac{\partial^2 \Pi_m}{\partial \theta^2} = \frac{2}{u_t}\left[\frac{rp_c(u_s - rp_c)}{u_t(u_s - 2rp_c)} - 1\right]$. Hence, We need conditions $\frac{rp_c(u_s - rp_c)}{u_t(u_s - 2rp_c)} - 1 \le 0$ and $2rp_c - u_s < 0$ to ensure $\Pi_m(e_m, v)$'s Hessen matrix negatively definite to guarantee its concavity. Subsequently, solving the following equation system simultaneously:

$$\begin{cases} \frac{\partial \Pi_m}{\partial \theta} = \frac{ap_c(u_s - rp_c) + rp_c[r\rho_s + rp_c(\sigma_s - \lambda_s)] + (u_s - rp_c)[r\rho_m + rp_c(\sigma_m - \lambda_m)]}{u_t(u_s - 2rp_c)} + [\frac{rp_c(u_s - rp_c)}{u_t(u_s - 2rp_c)} - 1]\frac{2\theta}{u_t} = 0 \\ \frac{\partial \Pi_m}{\partial v} = \frac{r\rho_m + rp_c(\sigma_m - \lambda_m)}{u_s - 2rp_c} - \frac{r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s)}{u_s - 2rp_c} - \frac{2v}{u_s - 2rp_c} = 0 \end{cases}$$

yields the optimal emission-reduction compensation factor and transfer payment coefficient to TPERS and supplier, respectively, as follows:

$$\theta_4 = \frac{r^2 p_c[\rho_s + p_c(\sigma_s - \lambda_s)] + (u_s - rp_c)[ap_c + r\rho_m + rp_c(\sigma_m - \lambda_m)]}{2u_t(u_s - 2rp_c) - 2rp_c(u_s - rp_c)} u_t \tag{38}$$

$$v_4 = \frac{r\rho_m - r\rho_s + rp_c(\sigma_m - \lambda_m) - rp_c(\sigma_s - \lambda_s) - ap_c}{2} \tag{39}$$

Accordingly, the optimal emission reductions per product for the manufacturer and the supplier are as follows, respectively:

$$e_{m4} = \frac{r^2 p_c[\rho_s + p_c(\sigma_s - \lambda_s)] + (u_s - rp_c)[ap_c + r\rho_m + rp_c(\sigma_m - \lambda_m)]}{2u_t(u_s - 2rp_c) - 2rp_c(u_s - rp_c)} \quad (40)$$

$$e_{s4} = \frac{r\rho_m + r\rho_s + ap_c + rp_c(\sigma_m - \lambda_m + \sigma_s - \lambda_s)}{2(u_s - 2rp_c)} + \frac{rp_c}{u_s - 2rp_c}\frac{r^2 p_c[\rho_s + p_c(\sigma_s - \lambda_s)] + (u_s - rp_c)[ap_c + r\rho_m + rp_c(\sigma_m - \lambda_m)]}{2u_t(u_s - 2rp_c) - 2rp_c(u_s - rp_c)} \quad (41)$$

Therefore, $(e_{m4}, e_{s4}, \theta_4, v_4)$ valuated in Equations (38)–(41) is the sub-game perfect Nash equilibrium in this setting.

5. Discussion and Numerical Studies

The studies conducted in this paper have explored to determine the impact of supply chain configurations consisting of two dimensions, executing vertical incentives and/or outsourcing third-party emission-reduction service (TPERS) on the carbon emission efficiency and supply chain performances. In this section, we comprehensively analyze the results addressed in Section 4. We present a series of propositions to respond the questions listed the introduction.

5.1. Results Analysis

In this section, we intend to make a thorough comparison and analysis on results in four scenarios aforementioned in Section 4.

Proposition 1. As for the transfer payment design as vertical incentive to enhance the emission reduction efficiency, we can obtain

(1) No matter whether the TPERS provider is engaged or not in the supply chain carbon emission reduction, we can always find a transfer pricing contract to realize the Pareto improvement of the supply chain performance.
(2) The coefficients design for transfer payment contracts keeps the same in those two settings of including or excluding TPERS provider, *i.e.*, $v_2 = v_4 = v$ in our study. Furthermore, the coefficient v is increasing in ρ_m, $\lambda_s - \sigma_s$, and r, decreasing in ρ_s and $\lambda_m - \sigma_m$, and independent of u_m and u_s.

The proof for Proposition 1 is obvious. Comparing Equations (20) and (39) implies us $v_2 = v_4 = v$ .Since the transfer payment provided to the supplier is only related to e_s and independent of manufacturer's unit production emission-reduction e_m, the transfer coefficient is not relevant to the *TPERS provider*. The coefficient design $v = \frac{1}{2}\{r(\rho_m - \rho_s) - ap_c + rp_c[(\lambda_s - \sigma_s) - (\lambda_m - \sigma_m)]\}$ indicates that v is also independent of u_m and u_s. Furthermore, the optimal transfer payment coefficient v increases in $\rho_m, \lambda_s - \sigma_s$ and r, and decreases in ρ_s and $\lambda_m - \sigma_m$ since the conditions $v \geq 0$, $\partial v / \partial r > 0$, $\partial v / \partial(\lambda_s - \sigma_s) > 0$, $\partial v / \partial \rho_s < 0$, $\partial v / \partial(\lambda_m - \sigma_m) < 0$ and $\partial v / \partial \rho_m > 0$ hold. These results also reveal that the functions of manufacturer's transfer payment and profit and realized demand are increasing as manufacturer's marginal profit constant increases. Regarding supplier's marginal profit constant ρ_s, her profit increment is increasing as ρ_s increases while the manufacturer has lower motivation to provide transfer payment to the upstream. Moreover, we can conclude that the transfer payment has the linearly increasing structure with respect to the comparable value of the marginal profits, $\rho_m - \rho_s$. That's to say, the transfer payment acts on shrinking the profit difference between the downstream and the upstream and its magnitude is in proportion to this difference. Similarly, as the potential emission reduction space, the difference between initial emission level and government allowance on carbon emission, $\lambda_s - \sigma_s$ and $\lambda_m - \sigma_m$ has positive and negative effects on the transfer payment coefficient design, respectively. Actually, the comparable value of supplier's and manufacturer's emission-reduction spaces will finally influence the coefficient design. That means the willingness of manufacturer's provisioning vertical incentive is rising as the supplier's emission-reduction advantage over the manufacturer's increases.

Proposition 2. Comparing the situations before and after the TPERS provider is engaged in the supply chain, we can get:

(1) The supplier's emission-reduction level under transfer payment is not lower than that without transfer payment, and it is an increasing function of the transfer payment coefficient v .But the manufacturer's optimal emission-reduction level is irrespective of the transfer payment;
(2) After the transfer payment contract performs, the increment of the supplier's emission reduction level $\Delta e_s = e_{4s} - e_{3s}$ increases with the transfer payment coefficient v, supplier's potential emission-reduction space $\lambda_s - \sigma_s$, emission tax p_c and demand responsiveness r, but decreases with manufacturer's potential emission-reduction space $\lambda_m - \sigma_m$, supplier's emission-reduction relevant fixed cost coefficient u_s and independent of u_m of manufacturer's, respectively.

The above proposition implies that the manufacturer can encourage the supplier to increase its emission reduction level effectively by enlarging the transfer payment coefficient when the former provides the latter vertical incentives. Considering the results $e_{m1} = e_{m2}$, $e_{m4} = e_{m3}$, $e_{s2} - e_{s1} \geq 0$ and $e_{s4} - e_{s3} \geq 0$, it is essentially an optimized re-allocation of emission reduction resource within the whole supply chain with manufacturer's emission-reduction level maintained and supplier's increased after implementing the transfer payment scheme.

Proposition 3. Given the TPERS adopted in the supply chain, no matter whether the transfer payment contract is implemented or not, we can conclude following properties:

(1) The manufacturer's optimal reduction level increases with emission-reduction compensation coefficient θ and decreases with TPERS provider's emission-reduction fixed cost factor u_t;
(2) Emission reduction compensation coefficients are independent of the existence of transfer payment, *i.e.*, $\theta_4 = \theta_3$; and they decrease with u_t, $\lambda_m - \sigma_m$ and $\lambda_s - \sigma_s$, but increase with and ρ_s.

As shown in Equations (29) and (38), the emission-reduction levels offered by TPERS provider increases with θ and decreases with u_t while he aims to maximize his profits. Referring to the associated representations of compensation coefficients design θ_3 and θ_4, one may be directed to the conclusion (2) in above proposition.

Proposition 4. Provided the initial dyadic supply chain adopting the transfer payment to generate the vertical incentive for emission reduction, whether outsourcing emission reduction from TPERS has certain advantages over reducing emission in-house is heavily dependent on the value of TPERS provider's fixed cost coefficient, namely,

(1) Outsourcing is more beneficial to emission reduction than doing it in-house, *i.e.*, $e_{m2} \geq e_{m4}$ and $e_{s2} \geq e_{s4}$ when inequalities $\frac{1}{2}u_m \leq u_t < u_m$ holds;

(2) On the contrary, outsourcing is less beneficial to emission reduction than doing it in-house, *i.e.*, $e_{m2} \geq e_{m4}$ and $e_{s2} \geq e_{s4}$ when inequalities $0 < u_t < \frac{1}{2}u_m$ holds.

For the proof of Proposition 4, one can refer to Appendix A. The Proposition 4 implies that transfer payment contract can be certainly effective in reducing the carbon footprint of the product, while adopting the TPERS may conditionally lead to the positive effect on emission reduction.

Proposition 5. No matter whether the TPERS provider is engaged or not in the supply chain, the transfer payment contract between the manufacturer and supplier can realize the Pareto improvement of supply chain profit, that is $\Pi_2 \geq \Pi_1$, $\Pi_2 \geq \Pi_1$, $\Pi_{m2} \geq \Pi_{m1}$ and $\Pi_4 \geq \Pi_3$, $\Pi_{s4} \geq \Pi_{s3}$, $\Pi_{m4} \geq \Pi_{m3}$.

The proof of Proposition 5 is directed to Appendix B. It implies that the transfer payment contract can realize the Pareto improvement of the supply chain profits for all parties.

Proposition 6. Provided the transfer payment contract is adopted between the manufacturer and the supplier, we can obtain some observations on the comparison of the supply chain parties' profits in the settings NI and HI as follows:

(1) $\Pi_{m4} \leq \Pi_{m2}$ if $ap_c - \frac{u_m(e_{m2}+e_{m4})}{2} - \frac{rp_c v_4}{u_s - 2rp_c} \geq 0$ and $u_m \geq u_t \geq \frac{1}{2}u_m$; on the contrary, $\Pi_{m4} > \Pi_{m2}$ if $ap_c - u_t(e_{m2}+e_{m4}) - \frac{rp_c v_4}{u_s - 2rp_c} \geq 0$ and $0 < u_t < \frac{1}{2}u_m$;

(2) $\Pi_{s4} \leq \Pi_{s2}$ if $u_m \geq u_t \geq \frac{1}{2}u_m$ and $\frac{1}{2}(e_{s2}+e_{s4})u_s - v_4 \leq 0$; otherwise, $\Pi_{s4} > \Pi_{s2}$ if $0 < u_t < \frac{1}{2}u_m$ and $\frac{1}{2}(e_{s2}+e_{s4})u_s - v_4 < 0$.

Proposition 6 is proved in Appendix C. Conclusions 1 to 6 show that the transfer payment contract can realize the Pareto improvement of supply chain profits effectively, and at the same time reduce product carbon footprint through the overall supply chain. However, Outsourcing emission-reduction to TPERS providers is not always to achieve the same positive effect as adopting transfer payment scheme. That is because the emission-reduction efficiency and effect by executing TPERS is highly relying on systematic parameters. In this sense, the propositions in the current section give out a achieving path or selecting framework on the supply chain configurations consisting of transfer payment and/or third-party emission-reduction service.

5.2. Numerical Experiments

In this section, we conduct a variety of numerical experiments to examine the previous theoretic analyses and conclusions. We analyze and compare the carbon footprint and profits of system and its players in different supply chain configurations so as to study how emission-reduction patterns and various parameters like u_m, u_s, u_t and p_c impact on the decision variables. To ensure the existence of the optimal solution in all settings in present study, values of all parameters satisfy all requirements and assumptions proposed in previous sections. The evaluations for all numerical studies are described in Table 2. The results of numerical analysis are shown in from Figures 5–10.

Table 2. The numerical evaluation of parameters.

a	ρ_m	ρ_s	σ_m	σ_s	λ_m	λ_s	r	u_m	u_s	u_t	p_c
100	70	50	4	10	6	20	15	500–1500	400	450	4
100	70	50	4	10	6	20	15	1500	400–1400	1450	4
100	70	50	4	10	6	20	15	1500	400	450–1400	4
100	70	50	4	10	6	20	15	800	400	700	0–4

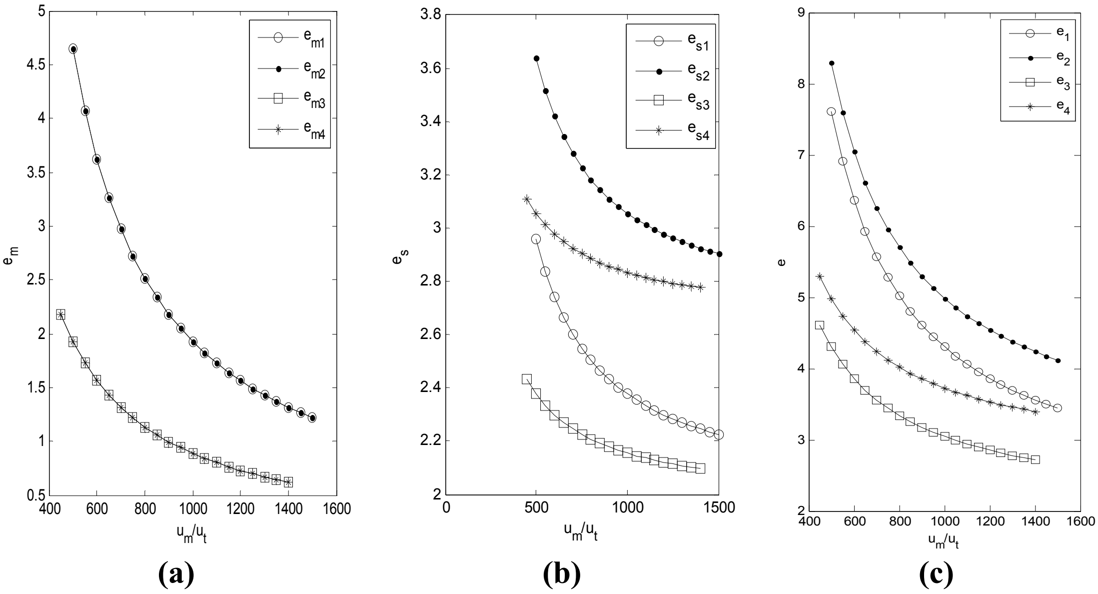


Figure 5. The impact of co-efficient of emission-reduction relevant fixed cost u_m or u_t on the emission-reduction amount per unit product. (**a**) The impact of u_m and u_t on e_m, (**b**) The impact of u_m and u_t on e_s, (**c**) The impact of u_m and u_t on e.

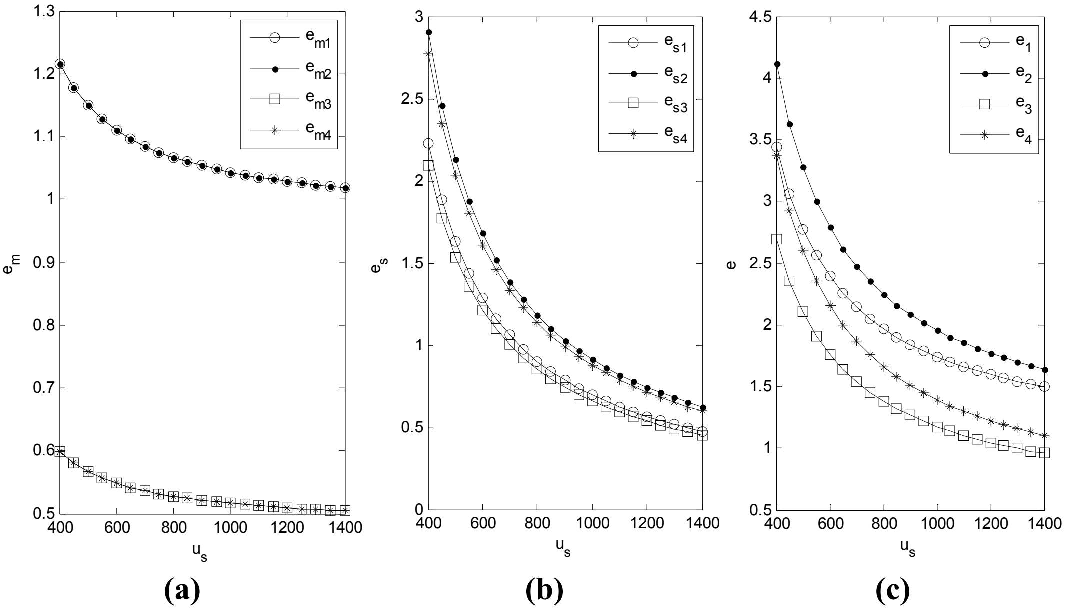


Figure 6. The impact of coefficient of emission-reduction relevant fixed cost u_s on emission reduction amount per unit product. (**a**) The impact of u_s on e_m, (**b**) The impact of u_s on e_s, (**c**) The impact of u_s on e.

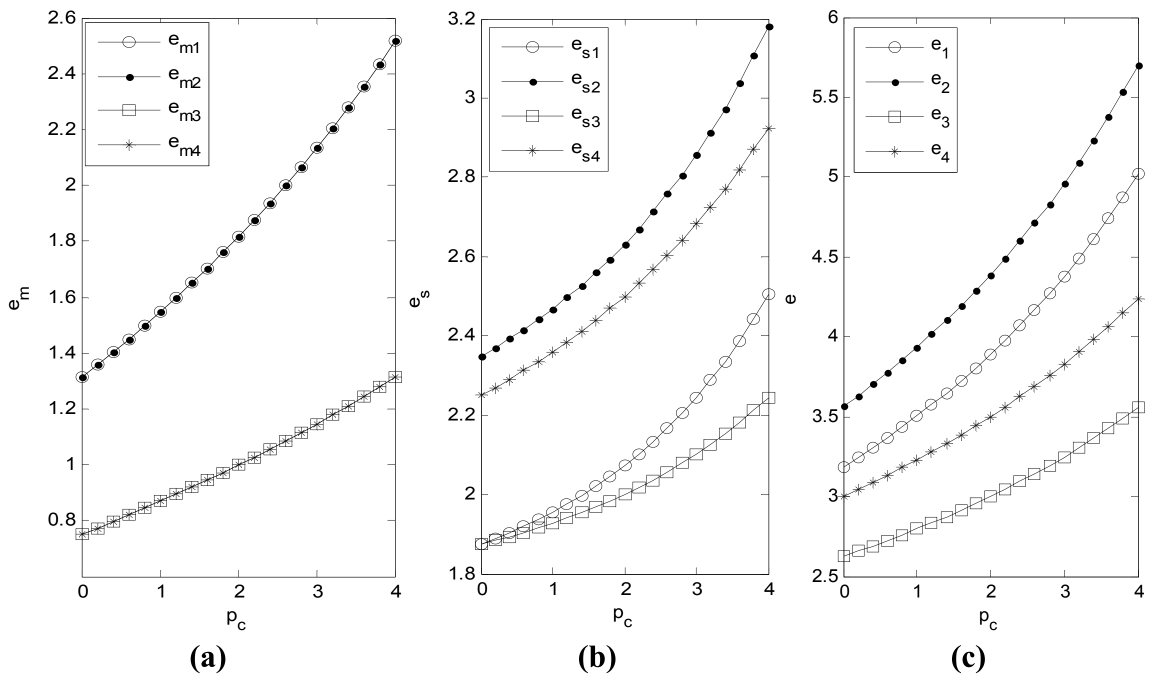


Figure 7. The impact of carbon emission tax rate p_c on emission reduction. (**a**) The impact of p_c on e_m, (**b**) The impact of p_c on e_s, (**c**) The impact of p_c on e.

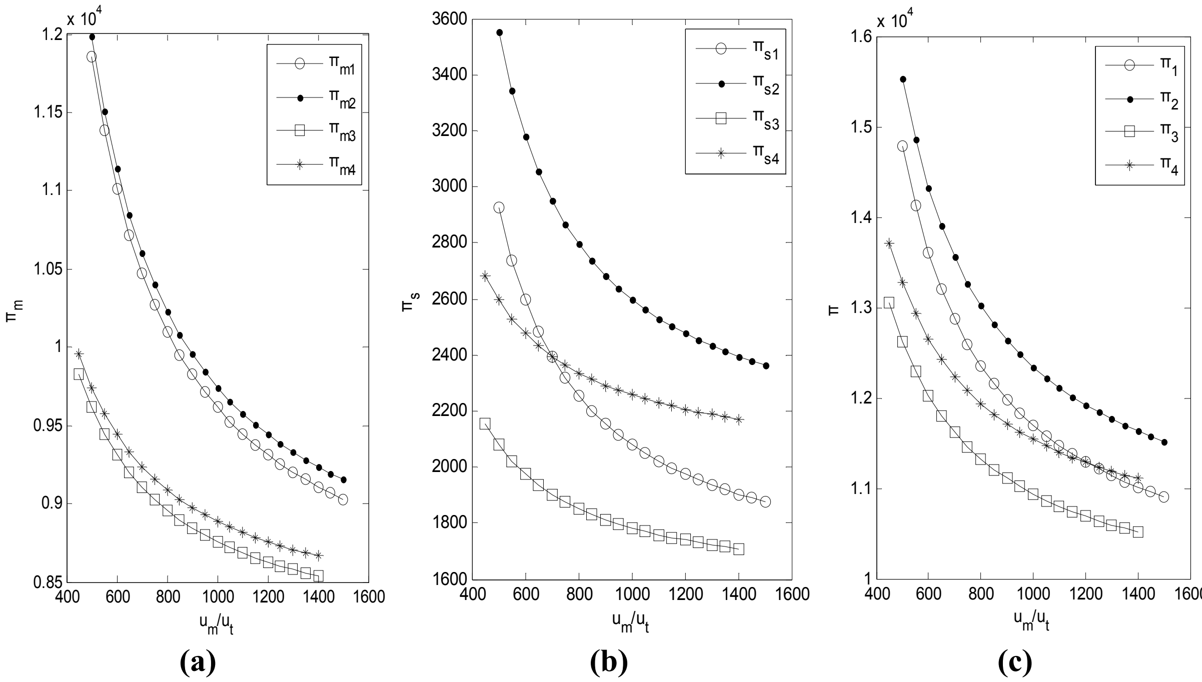
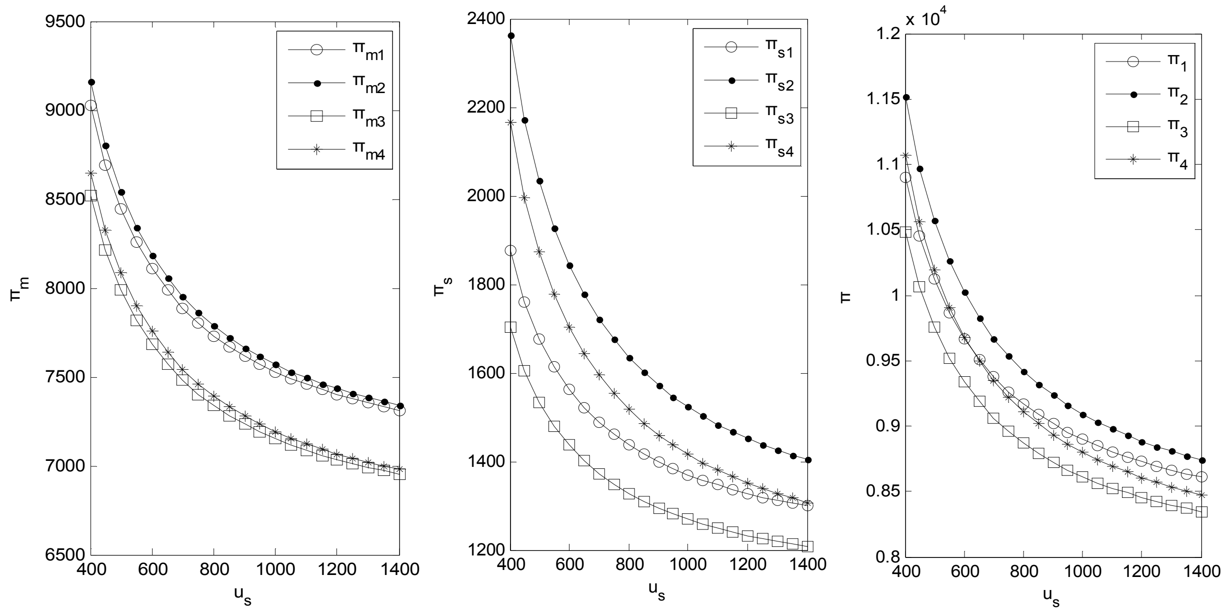
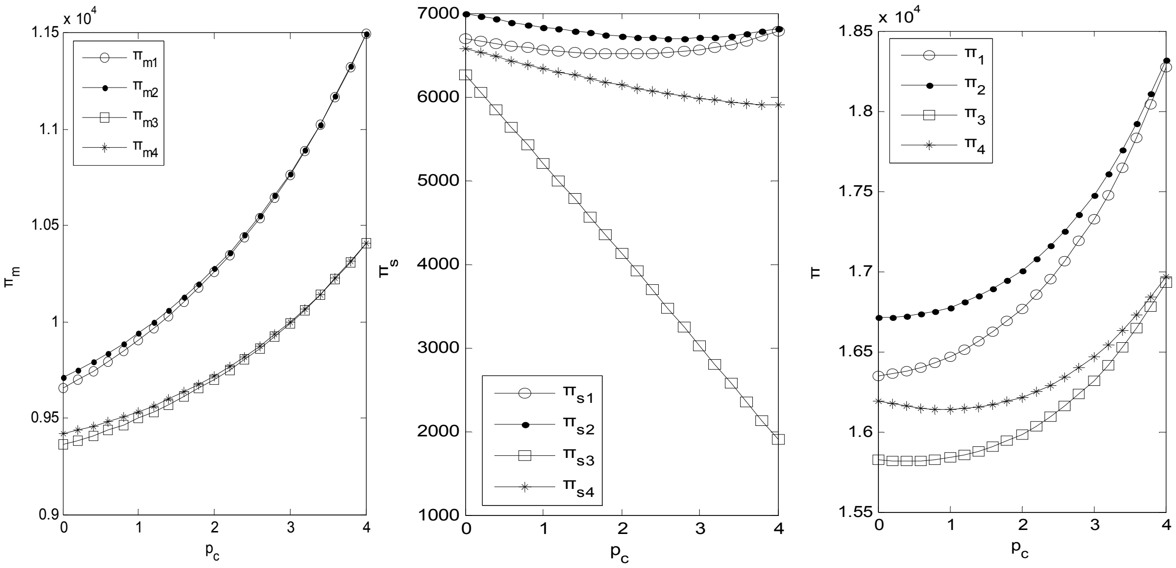


Figure 8. The impact of u_m or u_t on profits of supply chain parties. (**a**) The impact of u_m or u_t on e_m, (**b**) The impact of u_m or u_t on e_s, (**c**) The impact of u_m or u_t on e.



(a) **(b)** **(c)**

Figure 9. The impact of emission-reduction relevant fixed cost coefficient u_s on profits of supply chain parties. (**a**) The impact of *us* on π_m, (**b**) The impact of *us* on π_s, (**c**) The impact of *us* on π.



(a) **(b)** **(c)**

Figure 10. The impact of carbon tax rate p_c on profits of supply chain parties. (**a**) The impact of *pc* on π_m, (**b**) The impact of *pc* on π_s, (**c**) The impact of *pc* on π.

One should note that the u_m and u_t refers to reducing emission in-house and through outsourcing, respectively. So we can have only one of them exist over all settings afterwards. Hence, u_m / u_s means u_m or u_s.

The numerical experiments testify the aforementioned conclusions and show some managerial insights as follows:

As shown in Figures 5–7, the optimal emission-reduction amounts for the manufacturer, the supplier and the system all decrease with u_m, u_t and u_s, and increase with carbon emission tax rate p_c. The results are in accord with our intuition. The emission-reduction relevant fixed cost will have negative effect on emission reducing while the carbon tax works for positive influence.

As shown in Figures 8 and 9, in any case, the equilibrium profits of manufacturer, supplier and the supply chain system decrease with emission-reduction rates u_m (or u_t) and u_s. This implies the necessity of improving the emission reducing fixed cost for raising the profits. Figure 8a depicts, before the TPERS provider is introduced, the profit increment of manufacturer resulted from adopting transfer payment contract has nothing to do with u_m. Similarly, after the TPERS provider is introduced, the profit increment of manufacturer results from adopting transfer payment contract has nothing to do with u_t, and the two profits increment are equal. Figure 8b depicts that the profit increment of the supplier resulted from adopting transfer payment contract decreases with u_m in case of the TPERS provider is not engaged in the supply chain, and the profit increment of the supplier resulted from adopting transfer payment contract increases with u_t in case of the TPERS provider disengaged the supply chain. As can be seen from Figure 8c, the profit increment of the supply chain system resulted from adopting transfer payment contract decreases with $u_m\,(u_t)$ no matter whether the TPERS provider is engaged or not in the supply chain.

From Figure 9a we can learn that, providing the transfer payment contract adopted, the manufacturer's profit increments attained before and after the TPERS provider is introduced both decrease with u_s, and those two increments are almost the same. Figure 9b,c show both of the profit increments of the supplier and the supply chain system decrease with u_s no matter whether the TPERS provider is introduced or not.

Figure 10 depicts the sensitivity of profits of manufacturer, supplier and system with respect to carbon tax p_c, respectively. The results show that manufacturer's equilibrium profit increases with p_c, which is counter intuitive since we usually think the tax will hinder the ripe of profits. However, supplier's profits decreases with p_c firstly, and then increases before and decreases after the TPERS provider's involvement.

Figure 10 also illustrates that TPERS provider's involvement heavily matter the change trends of all parties' profit increments, provided the transfer payment scheme exists. Before the TPERS provider is introduced, all of the profit increments of the manufacturer, the supplier and the system decrease with p_c. In contrast, after the TPERS provider is introduced, the profit increments of the manufacturer and the system decreases with p_c, but the related profit increment of the supplier increases with p_c.

6. Concluding Remarks

We studied a fashion supply chain made up of an apparel components supplier and an apparel downstream manufacturer, both of whom generate carbon emission during their fabricating or manufacturing processes. The supply chain provided one kind of product to environmental awareness concerned consumers who are sensitive to the product footprint, which motivated the supply chain parties to reduce their carbon emissions, respectively.

In order to relieve the inefficiency of decentralized carbon emission reduction, we proposed two representative modes for carbon emission reduction, namely, vertical transfer payment contract and third-party carbon emission reduction service provider. We recognized and categorized four models incurred by solely using one or combining these two modes together, which formed a strategic decision-making framework for the supply chain. We analyzed the corresponding Stackelberg game for each model and compared emission reduction effectiveness; individual and system-side profits resulted from four models, respectively.

In our work, we get key findings as follows:

(1) No matter whether the manufacturer employed the third-party emission-reduction service provider or not, such as Carbon Management Contracting, the transfer payment incentive scheme between the supplier and the manufacturer can increase the channel carbon reduction amount and realize the Pareto improvement of the supply chain profits.
(2) The optimal coefficient parameters design are the same when the supply chain adopted a transfer payment scheme between the upstream and the downstream without respect to the manufacturer consigned the emission reduction to third-party emission-reduction provider or not.
(3) When the transfer payment contract was executed, introducing a third-party emission-reduction provider can incur higher emission decrement per product only if the coefficient of emission reduction relevant fixed cost for emission-reduction provider is lower than the half of that of the manufacturer's. The comparison outcomes of the individual as well as supply chain profits depending on a variety of parameters, such as emission-reduction relevant fixed cost coefficients and carbon tax regulatory parameters.

Of course there exist some limitations in our studies. For example, we only consider the transfer payment incentive schemes to achieve the Pareto improvement. We also only focus on the deterministic demand mode. Hence, there is still room for improvement and extension in the future research. One can study the centralized decision and investigate the existence of coordination contract. Taking stochastic demand and the retail pricing incorporated into the research will be also a potential tentative, while it will complicate the problem much more.

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Author Contributions

Longfei He contributed to design, conduct this research and write and revise the whole paper. Daozhi Zhao contributed to join the research and discussion and give valuable suggestions. Liangjie Xia contributed to jointly conduct the research and solve some of models and is responsible for doing the numerical studies and he can be viewed as a co-first author of this paper.

Appendix A

This is proof for Proposition 4.

From Equations (21) and (40), we know the emission reduction level of the manufacturer in setting HE and setting HI, e_{m2} and e_{m4}, respectively, and $\frac{e_{m2}}{e_{m4}} = \frac{2u_t(u_s - 2rp_c) - 2rp_c(u_s - rp_c)}{u_m(u_s - 2rp_c) - 2rp_c(u_s - rp_c)}$. Since $\frac{rp_c}{u_m} < \frac{u_s - 2rp_c}{2(u_s - rp_c)}$, then $u_m(u_s - 2rp_c) > 2rp_c(u_s - rp_c)$.

If $\frac{1}{2}u_m \le u_t < u_m$, then $2u_t(u_s - 2rp_c) \ge u_m(u_s - 2rp_c)$ holds and the following inequality can be obtained: $2u_t(u_s - 2rp_c) - 2rp_c(u_s - rp_c) \ge u_m(u_s - 2rp_c) - 2rp_c(u_s - rp_c)$.Thus, $\frac{e_{m2}}{e_{m4}} \ge 1$, *i.e.*, $e_{m2} \ge e_{m4}$. In other words, the manufacturer's emission cutting level in setting HE is higher than which in setting HI if $\frac{1}{2}u_m \le u_t < u_m$ holds.

On the contrary, if $0 < u_t < \frac{1}{2}u_m$, the inequality $2u_t(u_s - 2rp_c) < u_m(u_s - 2rp_c)$ is yield , then the inequality $2u_t(u_s - 2rp_c) - 2rp_c(u_s - rp_c) < u_m(u_s - 2rp_c) - 2rp_c(u_s - rp_c)$ holds. Thus, the manufacturer's emission cutting level in setting HE is lower than which in setting HI, *i.e.*, $e_{m2} < e_{m4}$.

From Equations (22) and (41), we know the emission reduction level of the supplier in setting HE, e_{s2}, and which in setting HI, e_{m4}, respectively. Then the function $e_{s4} - e_{s2} = \frac{rp_c}{u_s - 2rp_c}(e_{m4} - e_{m2})$ yields. Since $\frac{rp_c}{u_s - 2rp_c} > 0$, if $\frac{1}{2}u_m \le u_t < u_m$ holds, then $e_{m2} \ge e_{m4}$. Thus, $e_{s2} \ge e_{s4}$. On the contrary, if $0 < u_t < \frac{1}{2}u_m$, then $e_{m2} < e_{m4}$ and $e_{s2} < e_{s4}$.

In other words, both of the emission reduction levels of the supplier and the manufacturer in setting HE is higher than which in setting HI if $\frac{1}{2}u_m \le u_t < u_m$ holds, and the adverse conclusion yields if $0 < u_t < \frac{1}{2}u_m$ holds.

Proposition 4 is proved.

Appendix B

This is the proof for Proposition 5.

(1) Before the TPERS provider is introduced

Substituting Equations (13) and (14) into Equation (9) yields the manufacturer's optimal profit in setting NE, Π_{m1}. Substituting Equations (21) and (22) into Equation (16) yields the manufacturer's optimal profit in setting HE, Π_{m2}. Then, $\Pi_{m2} - \Pi_{m1} = r[\rho_m + p_c(\sigma_m + e_{m2} - \lambda_m)](e_{s2} - e_{s1})] + \frac{1}{2}u_m e_{m1}{}^2 - \frac{1}{2}u_m e_{m2}{}^2 - v_2 e_{s2} = \frac{v_2{}^2}{u_s - 2rp_c}$.

Since $u_s - 2rp_c > 0$ and $v_2^2 \geq 0$, then $\Pi_{m2} - \Pi_{m1} \geq 0$. Thus, the manufacturer's optimal profit in setting HE is no less than which in setting NE. In other words, the transfer payment contract is helpful for improving the profit of the manufacturer. Similarly, the following inequality

$$\begin{aligned}\Pi_{s2} - \Pi_{s1} &= [r\rho_s + ap_c + rp_c(\sigma_s - \lambda_s) + rp_c e_{m2}](e_{s2} - e_{s1}) + rp_c {e_{s2}}^2 - \frac{1}{2}u_s {e_{s2}}^2 - rp_c {e_{s1}}^2 + \frac{1}{2}u_s {e_{s1}}^2 + v_2 e_{s2} \\ &= \frac{1}{2}v_2(e_{s1} + e_{s2}) > 0\end{aligned}$$

since $v_2 \geq 0, e_{s1} \geq 0$ and $e_{s2} \geq 0$. Thus, the supplier's optimal profit in setting HE is noless than which in setting NE. In other words, the transfer payment contract is helpful for improving the profit of the supplier.

Obviously, the profit of the supply chain in setting HE is no less than which in setting NE, *i.e.*, $\Pi_2 = \Pi_{m2} + \Pi_{s2} \geq \Pi_1 = \Pi_{m1} + \Pi_{s1}$.

(2) After the TPERS provider is introduced

Similar to the situation before the TPERS provider is introduced, $\Pi_{m4} - \Pi_{m3} = \frac{{v_4}^2}{u_s - 2rp_c}$ and $\Pi_{s4} - \Pi_{s3} = \frac{v_4(e_{s3} + e_{s4})}{2}$ with $\theta_4 = \theta_3$ and $v_2 = v_4$. Since $u_s - 2rp_c > 0$, $v_4 \geq 0$ and $e_{s3} + e_{s4} \geq 0$, $\Pi_{s4} - \Pi_{s3} \geq 0$ and $\Pi_{m4} - \Pi_{m3} \geq 0$ hold. In other words, after the TPERS provider is introduced, the transfer payment contract is helpful for improving the optimal profits of the supplier and the manufacturer. Since $\theta_4 = \theta_3$, $e_{m4} = e_{m3}$, $v_2 = v_4$ and $\Pi_t(e_m) = \theta e_m - \frac{1}{2}u_t {e_m}^2$, the TPERS provider gains the same optimal profit no matter whether a transfer pricing contract is adopted, *i.e.*, $\Pi_{t3} = \Pi_{t4}$. Thus, after the TPERS provider is introduced, the supply chain can get a Pareto improvement with a transfer price contract, *i.e.*, $\Pi_4 \geq \Pi_3$.

Proposition 5 is proved.

Appendix C

This is the proof for Proposition 6.

(1) For the manufacturer

The following function yields from Equations (15) and (32):

$$\begin{aligned}\Pi_{m4} - \Pi_{m2} = {} & [r\rho_m + rp_c(\sigma_m - \lambda_m) + rp_c e_{m4}](e_{m4} + e_{s4}) - [r\rho_m + rp_c(\sigma_m - \lambda_m) + rp_c e_{m2}](e_{m2} + e_{s2}) + \\ & ap_c e_{m4} - ap_c e_{m2} + \frac{1}{2}u_m {e_{m2}}^2 - \frac{1}{2}u_t {e_{m4}}^2 + v_2 e_{s2} - v_4 e_{s4}\end{aligned}$$

If $\frac{1}{2}u_m \leq u_t < u_m$, since $e_{m2} \geq e_{m4}$ and $e_{s2} \geq e_{s4}$, which have been proved in Appendix A

$$\begin{aligned}\Pi_{m4} - \Pi_{m2} \leq {} & [r\rho_m + rp_c(\sigma_m - \lambda_m) + rp_c e_{m2}](e_{m2} + e_{s2}) - [r\rho_m + rp_c(\sigma_m - \lambda_m) + rp_c e_{m2}](e_{m2} + e_{s2}) + \\ & ap_c e_{m4} - ap_c e_{m2} + \frac{1}{2}u_m {e_{m2}}^2 - \frac{1}{2}u_m {e_{m4}}^2 - v_4 \frac{rp_c}{u_s - 2rp_c}(e_{m4} - e_{m2}) \\ = {} & [ap_c - \frac{u_m}{2}(e_{m2} + e_{m4}) - v_4 \frac{rp_c}{u_s - 2rp_c}](e_{m4} - e_{m2})\end{aligned}$$

Thus, if $\Delta = ap_c - \frac{u_m}{2}(e_{m2}+e_{m4}) - v_4\frac{rp_c}{u_s - 2rp_c} \geq 0$, $\Pi_{m4} - \Pi_{m2} \leq 0$.

In other words, the manufacturer's optimal profit in setting HI is no more than which in setting HE if $\frac{1}{2}u_m \leq u_t < u_m$ and $\Delta = ap_c - \frac{u_m}{2}(e_{m2}+e_{m4}) - v_4\frac{rp_c}{u_s - 2rp_c} \geq 0$ hold.

Similarly, if $0 < u_t < \frac{1}{2}u_m$, since $e_{m2} < e_{m4}$ and $e_{s2} < e_{s4}$ have been proved in Appendix A, then

$$\Pi_{m4} - \Pi_{m2} > [r\rho_m + rp_c(\sigma_m - \lambda_m) + rp_c e_{m4}](e_{m4}+e_{s4}) - [r\rho_m + rp_c(\sigma_m - \lambda_m) + rp_c e_{m4}](e_{m4}+e_{s4}) + ap_c e_{m4} - ap_c e_{m2} + u_t e_{m2}{}^2 - u_t e_{m4}{}^2 - v_4\frac{rp_c}{u_s - 2rp_c}(e_{m4} - e_{m2})$$

$$= [ap_c - u_t(e_{m2}+e_{m4}) - v_4\frac{rp_c}{u_s - 2rp_c}](e_{m4} - e_{m2})$$

Thus, if $\Delta = ap_c - u_t(e_{m2}+e_{m4}) - v_4\frac{rp_c}{u_s - 2rp_c} \geq 0$, $\Pi_{m4} - \Pi_{m2} > 0$.

In other words, the manufacturer's optimal profit in setting HI is no less than which in setting HE if $0 < u_t < \frac{1}{2}u_m$ and $\Delta = ap_c - u_t(e_{m2}+e_{m4}) - v_4\frac{rp_c}{u_s - 2rp_c} \geq 0$ hold.

(2) For the supplier

The following function yields from Equations (16) and (34):

$$\Pi_{s4} - \Pi_{s2} = \rho_s[a + r(e_{m4}+e_{s4})] + p_c(\sigma_s + e_{s4} - \lambda_s)[a + r(e_{m4}+e_{s4})] - \frac{1}{2}u_s e_{s4}{}^2 + v_4 e_{s4} - \rho_s[a + r(e_{m2}+e_{s2})] - p_c(\sigma_s + e_{s2} - \lambda_s)[a + r(e_{m2}+e_{s2})] + \frac{1}{2}u_s e_{s2}{}^2 - v_2 e_{s2}$$

If $\frac{1}{2}u_m \leq u_t < u_m$, since $e_{m2} \geq e_{m4}$ and $e_{s2} \geq e_{s4}$ have been proved in Appendix A, then, the following inequality yields,

$$\Pi_{s4} - \Pi_{s2} \leq \rho_s[a + r(e_{m4}+e_{s4})] + p_c(\sigma_s + e_{s4} - \lambda_s)[a + r(e_{m4}+e_{s4})] - \rho_s[a + r(e_{m4}+e_{s4})] - p_c(\sigma_s + e_{s4} - \lambda_s)[a + r(e_{m4}+e_{s4})] + \frac{1}{2}u_s e_{s2}{}^2 - v_2 e_{s2} - \frac{1}{2}u_s e_{s4}{}^2 + v_4 e_{s4}$$

$$= (e_{s2} - e_{s4})[\frac{1}{2}(e_{s2}+e_{s4})u_s - v_4]$$

Thus, if $\frac{1}{2}(e_{s2}+e_{s4})u_s - v_4 \leq 0$, then $\Pi_{s4} - \Pi_{s2} \leq 0$. In other words, the supplier's optimal profit in setting HI is no more than which in setting HE if $\frac{1}{2}u_m \leq u_t < u_m$ and $\frac{1}{2}(e_{s2}+e_{s4})u_s - v_4 \leq 0$ hold.

Similarly, if $0 < u_t < \frac{1}{2}u_m$, $e_{m2} < e_{m4}$ and $e_{s2} < e_{s4}$ have been proved in Appendix A, then, the following inequality yields,

$$\Pi_{s4} - \Pi_{s2} > \rho_s[a + r(e_{m4}+e_{s4})] + p_c(\sigma_s + e_{s4} - \lambda_s)[a + r(e_{m4}+e_{s4})] - \rho_s[a + r(e_{m4}+e_{s4})] - p_c(\sigma_s + e_{s4} - \lambda_s)[a + r(e_{m4}+e_{s4})] + \frac{1}{2}u_s e_{s2}{}^2 - v_2 e_{s2} - \frac{1}{2}u_s e_{s4}{}^2 + v_4 e_{s4}$$

$$= (e_{s2} - e_{s4})[\frac{1}{2}(e_{s2}+e_{s4})u_s - v_4]$$

Thus, if $\frac{1}{2}(e_{s2}+e_{s4})u_s - v_4 < 0$, then $\Pi_{s4}-\Pi_{s2} > 0$. In other words, the supplier's optimal profit in setting HI is no less than which in setting HE if if $0 < u_t < \frac{1}{2}u_m$ and $\frac{1}{2}(e_{s2}+e_{s4})u_s - v_4 < 0$ hold. Proposition 6 is proved.

Conflicts of Interest

The authors declare no conflict of interest.

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