Research Article

Strategies on Pricing, Greenness Degree, and Carbon Emission Reduction in Supply Chains under Single and Cross Distributions of Green and Nongreen Products

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Environmental sustainability has become a critical indicator in evaluations of the success and efficiency of supply chain management. In this study, we consider a two-echelon supply chain composed of two competing manufacturers, two retailers, and one third-party logistics firm. The first manufacturer produces a green product, while the second manufacturer produces a nongreen product. Each of the two retailers can sell only a green product, only a nongreen product, or both green and nongreen products. All products are initially stored by the third-party logistics firm and delivered to the retailers. This study investigates product pricing, the degree of greenness of the first manufacturer’s product, and carbon emission reduction as carried out by the third-party logistics firm. Using a three-stage Stackelberg game framework, we present the equilibrium strategy on pricing, the degree of greenness, and carbon emission reduction for five different distribution channel structures. One of our major findings is that competition between the two manufacturers has a positive influence on the profitability of the supply chain. We also find that it is desirable for each manufacturer to choose a cross-distribution channel for its products considering the sustainability and profitability of the supply chain.

1. Introduction

During human history, there has been no rapid global warming and environmental degradation comparable to that occurring today. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [1], the Earth’s average temperature may increase from a minimum of 1.1∼2.9°C to a maximum of 2.4∼6.4°C during the twenty-first century. In addition, environmental degradation is one of the ten threats officially noted by the United Nations. The United Nations Office for Disaster Risk Reduction defines environmental degradation as the reduction of the capacity of the environment to meet social and ecological objectives and needs [2]. Rapid industrialization and economic growth have brought people material abundance and greater convenience while also causing socioenvironmental problems such as the rapid depletion of resources, unexpected natural disasters, and environmental destruction. For these reasons, environmental issues have attracted public and governmental attention around the world [3]. Environmental issues are also affecting consumer consumption patterns. Consumers are constantly changing their attitudes, behaviors, and approaches toward consumption [4]. They have become more aware of environmental degradation and of how their consumption behaviors affect the level of pollution. Thus, consumers’ purchasing patterns are becoming more environmentally friendly, and for ecologically minded consumers, protecting the environment has become the first priority when purchasing products [5].

Supply chain sustainability is a trending topic currently owing to growing consumer interest in global sustainability. Environmental damage in supply chains includes toxic waste, water and air pollution, biodiversity losses,
deforestation, long-term damage to ecosystems, and wasteful energy use. Serious awareness of global environmental issues and the shift by consumers to environmentally friendly consumption patterns are demanding sustainable supply chain management strategies for many firms in supply chains. Accordingly, more firms are willing to improve the degree of the greenness of supply chains through a variety of green innovation activities, such as using clean energy during manufacturing processes, remanufacturing end-of-life products, developing new technologies to reduce carbon emissions and pollutants, developing new green and sustainable products, and developing new green retailing and marketing techniques. One of the main aims when implementing these green innovation activities is to minimize the impact of environmental damage while enhancing operational efficiency. With consumers now leaning toward sustainable, green, and organic products, as noted above, they are searching for retail stores that operate using environmentally friendly methods and on green principles. Greening practices are now being implemented in many industry fields, such as clothing and apparel (Ecocentrik Apparel, Natural Clothing Company, and Element Eco-wear), furniture (The Old Wood, Eco Select Furniture, and Vermont Woods Studios), and household cleaning products (Wunder Budder). Due to the unprecedented popularity of eco-friendly products, large traditional retailers such as Walmart and Costco are providing consumers with green products alongside existing nongreen products. With regard to supply chain management, the logistics and transportation sector also requires green and sustainable operations. Logistics and transportation together reportedly constitute the second most prolific sources of greenhouse gas emission [6]. The main concern with respect to logistics is the impact of pollution on the air, roads, and/or water. Vehicle emissions are generally associated with fossil fuel combustion and particulate emissions from engines. In particular, considerable levels of greenhouse gas emissions are caused by trucks running empty. Because trucks are among the main sources of pollution, many studies of the environmental impact of logistics have been driven by the increase in freight traffic. In addition, today’s logistics approaches tend to speed up transportation to reduce lead times, which is also a major cause of the increased levels of carbon dioxide. Greenhouse gases produced during the transportation process are considered to be among the main causes of global warming. Therefore, many logistics and transportation companies are devising strategies to reduce their use of fossil fuels and reduce their carbon emissions by, for instance, the introduction of electric vehicles. The literature shows that logistics will be a strategic lever for reducing carbon emissions.

As such, establishing greening strategies as part of a supply chain management plan is an important task for the sustainability and profitability of supply chain members. The key research questions in this study are as follows:

(i) How is competition in the market related to the degree of greenness of the products and the strategy to reduce carbon emissions?

(ii) How are the structures of distribution channels of green and nongreen products related to the profitability of the supply chain?

(iii) Are consumer preferences for green products related to profits in the supply chain?

(iv) Do efforts to reduce carbon emissions affect the profitability of a supply chain?

The aim of this study is to find the answers to the above questions using a game-theoretical framework. The main contributions of this research with respect to the literature are threefold. First, we develop the various game models under various distribution channel structures and suggest the equilibrium strategy of each game model. Second, we investigate the effects of different parameters on the supply chain’s profitability and sustainability. Finally, through the numerical experiments, we support main findings.

The remainder of this paper is organized as follows. In Section 2, we present a review of the relevant literature, after which we introduce the five different distribution channel structures discussed in the paper. In Section 3, we review the notations used and the assumptions. Section 4 deals with the equilibrium strategies for each of the five distribution channel structures. Parametric analyses and various numerical experiments are conducted and described in Sections 5 and 6 to investigate the impacts of certain parameters on the equilibrium decisions. The last section provides a summary of the paper, presents the conclusion, and provides some directions for future research.

2. Literature Review

In this section, we review the relevant literature considering three different streams of research in this area: green supply chains, distribution channel strategies, and third-party logistics.

2.1. Green Supply Chains. The supply chain is an important branch of operations management, and it has a considerable impact on the environment through emissions and pollution, which affect the health of a community. Companies in various industries are now attempting to minimize their environmental effects by integrating environmental concerns into their supply chain operations. Applying environmental issues to supply chain management is referred to as “green supply chain management” [7–11]. Zhang and Liu [12] studied the coordination mechanism in a three-level green supply chain in which product demand correlates with the degree of greenness of the product. Under various game models, profits reach their maximal level under cooperative decision-making, while the equilibrium results are far from satisfactory in a noncooperative game. Zhang et al. [13] considered cooperation and noncooperation games with a green supply chain in which green and nongreen products coexist and substitute for each other. Zhang et al. [13] revealed that profitability in the cooperation game is always greater than that in a noncooperation game. Huang and Wang [14] surveyed the coordination of a multilevel green
supply chain through pricing and remanufacturing decisions and investigated the effects of power and distribution channel structures on pricing, remanufacturing decisions, and profits. Madani and Rasti-Barzoki [15] extended the green supply chain to the context of government intervention. In their model, the role of a government is to drive supply chains to produce green and sustainable products. A numerical experiment conducted by Madani and Rasti-Barzoki [15] showed that increases in governmental subsidies lead to increases in the demand for the degree of greenness of a product as well as the profits of all supply chain members and the government and decreases in the pollution costs borne by the government. Zhu and He [16] investigated green product design issues in supply chains under several competition scenarios and asserted that increasing greenness competition hurts the equilibrium greenness of a product while increasing price competition can be the driving force to increase the greenness of a product. Song and Gao [17] applied the concept of revenue sharing to a green supply chain to promote the cooperation of upstream and downstream firms and ultimately realize high performance of the green supply chain. Song and Gao [17] proved that a revenue-sharing contract enhances the greening levels of products. Jamali and Rasti-Barzoki [18] explored the chain-to-chain competition of a dual-channel supply chain in which green products are distributed through one chain and nongreen products are distributed through the other. They asserted that in order to encourage consumers to purchase more green products, public awareness of green products should be increased in the market. Heydari et al. [19] studied three types (open-triad, closed-triad, and transitional-triad) of decision problems in relation to pricing and greening in a three-echelon dual-channel supply chain and suggested that both the total profit of the supply chain and the green level of the product in the closed-triad decision structure are the highest among these three decision problems. Rahmani and Yavari [20] examined pricing and greening decisions for a dual-channel green supply chain when the level of market demand is disrupted. They found that an increased market scale caused by a disruption and lower greening costs are not only beneficial for the entire supply chain but also increase the greening level of green products. Hong and Guo [21] examined several cooperation contracts within a green supply chain and investigated their environmental performance outcomes, showing that a two-part tariff contract results in the highest greenness degree of products and the highest level of cooperation among supply chain members.

2.2. Distribution Channel Strategy. A variety of distribution channel structures are common in supply chains. Many studies have proven that the profitability of a supply chain is generally influenced by its distribution structure. McGuire and Staelin [22] found that a decentralized channel can ease market competition. They also found that in a state of equilibrium, vertically integrated channels always arise, whereas decentralized channels only occur with highly substitutable products. Choi [23] discussed a distribution channel structure consisting of two independent manufacturers and two common retailers and considered price competition with differentiation of the products and stores for various decentralized channel structures. Choi [23] found that product differentiation helps manufacturers, whereas it hurts retailers. Conversely, while store differentiation helps retailers, it hurts manufacturers. Moner-Colonques et al. [24] examined an asymmetric noncooperative game between two manufacturers who decide the number of retailers and suggested that when product differentiation is strong and brand asymmetry is moderate, the two manufacturers prefer a cross-distribution channel in equilibrium. Wu and Mallik [25] extended the work of Choi [23], assuming that channel configurations are determined endogenously by the Nash equilibrium between the manufacturer and the retailers. They found that manufacturers should strategically use a cross-distribution channel to maximize their profits. Bian et al. [26] dealt with equilibrium channel strategies with a public firm competing with a private firm and found that the equilibrium strategy for the distribution channel structure in question depends on the market competition mode (Bertrand or Cournot competition), the form of vertical contract, and the degree of product substitutability. Bian et al. [27] studied manufacturers’ distribution channel strategies under environmental taxation and suggested that a monopolistic manufacturer can benefit from a decentralized distribution channel when its technology is sufficiently polluting and that two competing manufacturers are more likely to decentralize the distribution channel when their technologies are more environmentally damaging. Nie et al. [28] investigated the effects of a cross online-and-offline channel (OOC) on two competing retailers’ distribution channel strategies and showed that such retailers may abandon the OOC strategy when the cross-channel effect is significantly negative. Bian et al. [29] analyzed the dynamic interactions between manufacturers’ distribution channel strategies and incentives for collusion. They suggested that a single distribution channel does not always facilitate collusion between manufacturers and held that the selection of the distribution channel mainly depends on the discount factor and on the degree of product differentiation. This paper is related to the literature on distribution channel conflicts and coordination. Readers may refer to Tsay and Agrawal [30] to review this stream of work.

2.3. Third-Party Logistics. Third-party logistics (3PL) in relation to supply chain management refers to an organization’s use of third-party businesses to outsource elements of its distribution, warehousing, and fulfillment services. To focus on core business development and operations, large firms delegate their logistical and transportation tasks to specialized 3PL firms to drive operational efficiency. Many studies have proved that a transportation outsourcing service is beneficial to economies of scale, leading to savings in capital investments and reductions of financial risk [31–36]. However, environmental problems become more serious in the field of logistics management because logistics and
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transportation are the second most common causes of the emission of greenhouse gases such as carbon monoxide and carbon dioxide. Thus, many researchers have examined environmental problems and their links to 3PL. Suzuki [37] developed a truck-scheduling solution which minimizes fuel consumption and pollutant emissions, showing that considerable savings in fuel consumption can be realized if the distance a truck travels with heavy payloads can be minimized, which can further increase energy efficiency and reduce pollutant emissions. De Giovanni and Zaccour [38] studied a two-echelon closed-loop supply chain in which 3PL is responsible for collecting used products. They revealed that unless 3PL performs better than the retailer, the manufacturer never selects 3PL as a means by which to outsource in reverse logistics. Zhu et al. [39] established a maximum-capacity model and developed a vehicle-routing procedure that allows a particular vehicle to use the maximum-capacity route with a set fuel consumption level. Bazan et al. [40] investigated different models of greenhouse gas emissions from the production and transportation operations in a supply chain under a multilevel emission-taxing scheme. They found that energy usage is the main cost component in their research models, implying that reducing energy usage should be prioritized. Maiti and Giri [41] surveyed a closed-loop supply chain consisting of a retailer, a 3PL firm, and a manufacturer who operates hybrid manufacturing and a remanufacturing system. Their numerical study showed that the 3PL-led decision game performs worst. Li et al. [42] addressed the transportation outsourcing problems of a supply chain under various carbon tax policies and found that a strict carbon tax policy and increasing energy prices can force a manufacturer to outsource more transportation services to a professional 3PL firm. Jamali and Rasti-Barzoki [43] investigated the effects of reduced carbon emissions by a 3PL firm on the profitability of a three-echelon supply chain and asserted that in order to reduce greenhouse gas emissions, 3PL firms should deliver products to retailers using green transportation means. Consequently, the reduction in carbon emissions by the 3PL firm increases the demand for green as well as nongreen products.

2.4. Research Gaps. As discussed above, in-depth research on green supply chains, distribution channel structures, and third-party logistics has been conducted over the past few decades. Moreover, the distribution channel structure plays a very important role in determining the profitability of the supply chain. In addition, a manufacturer’s interest in green products and a 3PL firm’s carbon emission reduction efforts are important factors when evaluating the success and efficiency of a supply chain for sustainable growth. However, to the best of the author’s knowledge, no research has dealt with all of these issues simultaneously. Also to the best of the author’s knowledge, the only paper dealing with the greenness design of a product and 3PL firms’ efforts to reduce carbon emissions is that by Jamali and Rasti-Barzoki [43]. Therefore, this study focuses on how the ecofriendliness of a manufacturer and efforts to reduce carbon emissions by a 3PL firm affect the profits of supply chain members under various distribution channel structures.

3. Model Description and Assumptions

3.1. Notations. In this paper, we use the notations presented in Table 1.

3.2. Investigated Supply Chain. We consider a green supply chain composed of two manufacturers, two retailers, and one third-party logistics firm. In this supply chain, the manufacturers provide consumers with substitutable products. The first manufacturer (M1) produces a green (ecofriendly) product, while the second manufacturer (M2) produces a nongreen product. All products produced by the two manufacturers are delivered to and stored by the 3PL firm. When shipping the products to the 3PL firm, each manufacturer pays per unit product. The two retailers (R1 and R2) the green and nongreen products from the 3PL firm. For retailers, the unit shipping cost is assumed to be equal to . Each manufacturer can choose to distribute their goods through either one retailer or both retailers.

There is a three-stage game involved in the green supply chain. In the first stage of the game, M1 determines its wholesale price and the greenness degree of its green product. At the same time, M2 sets its wholesale price . By specifying the values of , , and , in the second stage, 3PL determines its carbon emission reduction . Finally, based on all information of other members, R1 and R2 determine the selling quantities of the manufacturers’ products and . In order to establish a game-theoretical model, the following basic assumptions are made.

Assumption 1. Each manufacturer can distribute its products through a single retailer or through both retailers. If a manufacturer chooses to distribute through a single retailer, the channel structure is called a single distribution channel. A cross-distribution channel represents the channel structure by which a manufacturer distributes its product through both retailers. Therefore, the following four different distribution channel structures can be defined: the single-single structure (SS), cross-cross structure (CC), cross-single structure (CS), and single-cross structure (SC). One more possible structure is the case where both retailers cooperate with each other (CO). In this study, we deal with these five different distribution channel structures (see Figure 1).

Assumption 2. The demands for the green and nongreen products are sensitive to price, the degree of greenness, and the amount of carbon emission reduction. It is assumed that the green and nongreen products show no significant difference in terms of function but vary in terms of price and environmental value. The greenness degree of the product has a positive (negative) impact on M1’s (M2’s) demand because M1 only produces green products. Hence, the demand function of each manufacturer can be expressed as follows:
Impact of a competitive price on the selling quantity
Impact of carbon emission reduction by 3PL on the selling quantity
Impact of the greenness degree of a product on the selling quantity
Retail price of manufacturer $i$’s product
Retailer $i$’s profit
Retailers’ total profit ($\pi_{r} = \pi_{r1} + \pi_{r2}$)
3PL’s profit
Supply chain profit ($\pi_{sc} = \pi_{m1} + \pi_{m2} + \pi_{r1} + \pi_{r2} + \pi_{3}$)

Figure 1: Five distribution channel structures. (a) SS structure. (b) CC structure. (c) CS structure. (d) SC structure. (e) CO structure.

\[
q_1 = \alpha_1 - p_1 + \beta p_2 + \lambda_1 g + \mu e, \\
q_2 = \alpha_2 - p_2 + \beta p_1 - \lambda_2 g + \mu e.
\]

In equation (1), we assume that $\lambda_1 > \lambda_2$. The ratio of people interested in buying the green (nongreen) product is $\lambda_1 / (\lambda_1 - \lambda_2)$. If the green products are not available in the market, consumers are then willing to switch to buying the nongreen products. Therefore, the difference $\lambda_1 - \lambda_2$ determines the number of consumers who give up buying the nongreen product. A similar assumption can be found in earlier studies [15, 18, 43].

Assumption 3. Cournot competition is an economic model which describes an industry structure in which firms compete on the selling quantity, with decisions made independently of each other and at the same time. In this paper, we assume that the two manufacturers compete on selling quantity rather than wholesale price. From equation (1), the following retail price functions are derived:

\[
p_1(q_1, q_2) = \frac{\alpha_1 - q_1 + \lambda_1 g + \beta (\alpha_2 - q_2 - \lambda_2 g) + \mu e (1 + \beta)}{1 - \beta^2},
\]

\[
p_2(q_2, q_1) = \frac{\alpha_2 - q_2 - \lambda_2 g + \beta (\alpha_1 - q_1 + \lambda_1 g) + \mu e (1 + \beta)}{1 - \beta^2}.
\]

Because each manufacturer can distribute its product through different retailers, we have $q_i = q_{i1} + q_{i2}$ and $q_i = q_{ij} + q_{ij}$, where $q_{ij}$ is manufacturer $i$’s selling quantity distributed through retailer $j$.

Assumption 4. We assume that the investment in greening the product is an increasing and convex function of the greenness degree of M1’s product. Hence, the greenness cost can be expressed as $(c_m g^2 / 2)$. We also assume that the investment in reducing carbon emissions is an increasing and convex function of 3PL’s carbon emission reduction. Thus, the carbon abatement investment cost can be given by
4.1. SS Structure: Both M1 and M2 Adopt Single Distribution Channel. First, we discuss the SS structure in which M1’s (M2’s) product is exclusively distributed through R1 (R2) (Figure 1(a)). The profit function of each member in the green supply chain is given as

\[
\pi_{i1} = (w_1 - t_m)q_1 - \frac{c_m g^2}{2},
\]

\[
\pi_{i2} = (w_2 - t_m)q_2,
\]

\[
\pi_i = (p_i - w_i - t_r)q_i, \quad i = 1, 2
\]

Proposition 1. Let \(q_i^*, e^*, g^*, \) and \(w_i^*\) denote the selling quantity, the carbon emission reduction, the greenness degree, and the wholesale price of product \(i\) in the SS distribution channel structure, respectively. If the condition \(4c_m(1 - \beta^2)(4 - \beta^2) > A_3^2\) is met, the optimal decisions can be determined as follows:

\[
q_1^* = A_1 + a^* A_3 + \frac{(1 - \beta^2)((\beta w_1^* - 2w_1^*) + \mu e^*(2 + \beta - \beta^2))}{4 - \beta^2},
\]

\[
q_2^* = A_2 + a^* A_4 + \frac{(1 - \beta^2)((\beta w_2^* - 2w_2^*) + \mu e^*(2 + \beta - \beta^2))}{4 - \beta^2},
\]

\[
e^* = \frac{2\mu (1 + \beta)(t_m + t_r)}{c_3(2 + \beta)}.
\]

The values of \(A_1\) to \(A_7\) are given in Appendix.

Proof. The decision sequence in the case of the SS structure is as follows:

\[
\max_{w_1^*} \pi_{i1} \quad \rightarrow \quad \max_{w_2^*} \pi_i \quad \rightarrow \quad \max_{e^*} \pi_i \quad \rightarrow \quad \max_{g^*} \pi_i.
\]

To solve the decision problem in equation (5), we use backward induction. Given the values of other members’ decision variables, we initially maximize the retailers’ profits. From the fact that \((\partial^2 \pi_{i2}/\partial q_i^2) = -(2/(1 - \beta^2)) < 0\), for \(i = 1, 2\), the profit function of each retailer is strictly concave w.r.t. its own selling quantity. Thus, solving the first-order conditions (FOCs) of the retailers yields equations (4a) and (4b). Substituting them into the 3PL’s profit function, the second-order condition (SOC) of the 3PL’s problem is given by \((\partial^2 \pi_{i3}/\partial e^2) = -c_3 < 0\). From the 3PL’s FOC, we have equation (4c). Integrating equations (4a)-(4c) into the profit functions of the manufacturers, we can obtain M1’s Hessian matrix as follows:

\[
H_{m1}^{SS} = \begin{bmatrix}
\frac{\partial^2 \pi_{i1}}{\partial w_1^* \partial w_1^*} & \frac{\partial^2 \pi_{i1}}{\partial w_1^* \partial g} \\
\frac{\partial^2 \pi_{i1}}{\partial g \partial w_1^*} & \frac{\partial^2 \pi_{i1}}{\partial g^2}
\end{bmatrix} = \begin{bmatrix}
\frac{4(1 - \beta^2)}{4 - \beta^2} & A_3 \\
\frac{A_1}{4 - \beta^2} & -c_m
\end{bmatrix}.
\]

We define \(A_3^*\) as the leading principal minor of order \(k\) in \(H_{m1}^{SS}\). We then find that \(A_3^* < 0\). If we assume that \(4c_m(1 - \beta^2)(4 - \beta^2) > A_3^2, A_3^* > 0\), implying that M1’s profit function is strictly concave w.r.t. \(w_1\) and \(g\). M2’s profit function is also strictly concave w.r.t. \(w_2\) because \((\partial^2 \pi_{i3}/\partial w_2^2) = -(4((1 - \beta^2)/(4 - \beta^2)) < 0\). By solving the FOCs of manufacturers’ problem, all members in the green supply chain can find their own equilibrium strategies in equations (4a)-(4f). This completes the proof.

4.2. CC Structure: Both M1 and M2 Adopt Cross-Distribution Channel. Next, we analyze the CC structure in which each manufacturer distributes via both retailers (Figure 1(b)). Recall that, in the case of the CC structure, \(q_i = q_i + q_i\), for \(i = 1, 2\), and because each manufacturer can distribute its product through different retailers. Thus, the profit function of each member in the green supply chain is given as
\[
\begin{align*}
\pi_{m_1} &= (w_1 - t_m)(q_{11} + q_{12}) - \frac{c_m g^2}{2}, \\
\pi_{m_2} &= (w_2 - t_m)(q_{21} + q_{22}), \\
\pi_{r_1} &= (p_1 - w_1 - t_r)q_{11} + (p_2 - w_2 - t_r)q_{21}, \\
\pi_{r_2} &= (p_1 - w_1 - t_r)q_{12} + (p_2 - w_2 - t_r)q_{22}, \\
\pi_3 &= (t_m + t_r)(q_{11} + q_{12} + q_{21} + q_{22}) - \frac{c_2 e^2}{2}.
\end{align*}
\]

Proposition 2. Let \(q_{i,j}^{CC}\), \(e^{CC}\), and \(w_i^{CC}\) correspondingly denote the selling quantity of product i via retailer j, the carbon emission reduction, the greenness degree, and the wholesale price of product i in the CC distribution channel structure. If the condition \(3c_m > \lambda_1^2\) is met, the optimal decisions can be determined as follows:

\[
\begin{align*}
q_{11}^{CC} &= q_{12}^{CC} = \frac{B_1 + \lambda_1 g^{CC} - \mu w_2^{CC} + \mu e^{CC}}{3}, \\
q_{21}^{CC} &= q_{22}^{CC} = \frac{B_2 - \lambda_2 g^{CC} + \mu w_2^{CC} + \mu e^{CC}}{3}, \\
e^{CC} &= \frac{4\mu(t_m + t_r)}{3c_3}, \\
g^{CC} &= \frac{2\lambda_1(2B_1 + \beta B_2 - (2 + \beta)(t_m(1 - \beta) - \mu e^{CC}))}{3c_m(4 - \beta^2) - 2\lambda_1(2\lambda_1 - \beta\lambda_2)}, \\
w_1^{CC} &= t_m + \frac{3c_m g^{CC}}{2\lambda_1}, \\
w_2^{CC} &= \frac{\beta w_1^{CC} - \lambda_2 g^{CC} + \mu e^{CC} + t_m + B_2}{2}.
\end{align*}
\]

The values of \(B_1\) and \(B_2\) are given in Appendix.

\begin{proof}
\end{proof}

Note that from equations (7), (8a), and (8b), we have \(\pi_{r_1} = \pi_{r_2}\) in the CC structure.

4.3. CS Structure: M1 Adopts Cross-Distribution Channel while M2 Adopts Single Distribution Channel. In the case of the CS structure, M1 distributes its green products through both R1 and R2 while M2 distributes its nongreen products only through R2 (Figure 1(c)). Because green products are distributed through both retailers, we have \(q_1 = q_{11} + q_{12}\). Thus, the profit function of each member in the green supply chain is given as

\[
\begin{align*}
\pi_{m_1} &= (w_1 - t_m)(q_{11} + q_{12}) - \frac{c_m g^2}{2}, \\
\pi_{m_2} &= (w_2 - t_m)q_{2}, \\
\pi_{r_1} &= (p_1 - w_1 - t_r)q_{11}, \\
\pi_{r_2} &= (p_1 - w_1 - t_r)q_{12} + (p_2 - w_2 - t_r)q_{2}, \\
\pi_3 &= (t_m + t_r)(q_{11} + q_{12} + q_{2}) - \frac{c_2 e^2}{2}.
\end{align*}
\]

Proposition 3. Let \(q_{i,j}^{CS}\), \(e^{CS}\), \(g^{CS}\), and \(w_i^{CS}\) correspondingly denote the selling quantity of product i via retailer j, the carbon emission reduction, the greenness degree, and the wholesale price of product i in the CS distribution channel structure. If the condition \(12c_m(4 - \beta^2) > (4\lambda_1 - \beta\lambda_2)^2\) is met, the optimal decisions are can be determined as follows:

\[
H_{m_1}^{CC} = \begin{bmatrix}
\frac{\partial^2 \pi_{r_1}}{\partial q_{11}^2} & \frac{\partial^2 \pi_{r_1}}{\partial q_{11} \partial q_{12}} \\
\frac{\partial^2 \pi_{r_1}}{\partial q_{11} \partial q_{21}} & \frac{\partial^2 \pi_{r_1}}{\partial q_{12}^2}
\end{bmatrix} = \begin{bmatrix}
\frac{2}{1 - \beta^2} & \frac{2\beta}{1 - \beta^2} \\
\frac{2\beta}{1 - \beta^2} & \frac{2}{1 - \beta^2}
\end{bmatrix}.
\]

\[
H_{m_1}^{CS} = \begin{bmatrix}
\frac{\partial^2 \pi_{r_1}}{\partial q_{11}^2} & \frac{\partial^2 \pi_{r_1}}{\partial q_{11} \partial q_{12}} \\
\frac{\partial^2 \pi_{r_1}}{\partial q_{11} \partial q_{21}} & \frac{\partial^2 \pi_{r_1}}{\partial q_{12}^2}
\end{bmatrix} = \begin{bmatrix}
\frac{2}{1 - \beta^2} & \frac{2\beta}{1 - \beta^2} \\
\frac{2\beta}{1 - \beta^2} & \frac{2}{1 - \beta^2}
\end{bmatrix}.
\]
The values of $C_1$ and $C_2$ are given in Appendix.

**Proof.** The decision sequence in the case of the CS structure is as follows:
\[
\max_{q_{11}, q_{12}} \pi_{m1} \rightarrow \max_{\omega_1} e \rightarrow \max_{\omega_2} \pi_{r1} \rightarrow \max_{q_{21}, q_{22}} \pi_{r2}.
\] (14)

Given the values of other members’ decision variables, we maximize the retailers’ profits first. The SOC of retailer 1’s problem is expressed as $(\partial^2 \pi_{r1}/\partial q_{11}^2) = -(2/(1 - \beta^2)) < 0$; therefore, the profit function of retailer 1 is strictly concave w.r.t. its own selling quantity. Let $H_{CS}^{12}$ denote the Hessian matrix of retailer 2’s profit maximization problem. Then, we have
\[
H_{CS}^{12} = \begin{bmatrix}
\frac{\partial^2 \pi_{r2}}{\partial q_{11}\partial q_{12}} & \frac{\partial^2 \pi_{r2}}{\partial q_{12}\partial q_{11}} \\
\frac{\partial^2 \pi_{r2}}{\partial q_{11}\partial \omega_2} & \frac{\partial^2 \pi_{r2}}{\partial \omega_2\partial q_{11}}
\end{bmatrix} = \begin{bmatrix}
-\frac{2}{1 - \beta^2} & \frac{-2\beta}{1 - \beta^2} \\
\frac{2}{1 - \beta^2} & -\frac{2}{1 - \beta^2}
\end{bmatrix}.
\] (15)

Because $H_{CS}^{12} = H_{r2}^{CC}$, the profit function of retailer 2 is strictly concave w.r.t. its own selling quantities. Accordingly, solving the FOCs of the retailers’ problems yields equations (13a) to (13c). Substituting them into the 3PL’s profit function, the SOC of the 3PL’s problem is given by $(\partial^2 \pi_{0}/\partial e^2) = -c_3 < 0$. From the 3PL’s FOC, we have (13d). Integrating equations (13a)–(13d) into the profit functions of the manufacturers, we can obtain M1’s Hessian matrix as follows:
\[
H_{m1}^{CS} = \begin{bmatrix}
\frac{\partial^2 \pi_{m1}}{\partial \omega_1^2} & \frac{\partial^2 \pi_{m1}}{\partial \omega_1\partial \omega_2} & \frac{\partial^2 \pi_{m1}}{\partial \omega_2^2} \\
\frac{\partial^2 \pi_{m1}}{\partial g^2} & \frac{\partial^2 \pi_{m1}}{\partial g\partial \omega_1} & \frac{\partial^2 \pi_{m1}}{\partial g^2}
\end{bmatrix} = \begin{bmatrix}
\frac{4 - \beta^2}{3} & -\frac{4\lambda_1 - \beta\lambda_2}{6} \\
\frac{4\lambda_1 - \beta\lambda_2}{6} & -c_m
\end{bmatrix}.
\] (16)

We define $\Delta_k^{CS}$ as the leading principal minor of order $k$ in $H_{m1}^{CS}$. We then find that $\Delta_1^{CS} < 0$. Assuming that $12c_m (4 - \beta^2)^2 > (4\lambda_1 - \beta\lambda_2)^2$, we have $\Delta_2^{CS} > 0$, implying that M1’s profit function is strictly concave w.r.t. $w_1$ and $g$. M2’s profit function is also strictly concave w.r.t. $w_2$ because the SOC of M2’s problem is given by $(\partial^2 \pi_{m2}/\partial w_2^2) = -1 < 0$. By solving the FOCs of the manufacturers’ problem, all members in the green supply chain can find their own equilibrium strategies using equations (13a)–(13g). This completes the proof. □

4.4. SC Structure: M1 Adopts Single Distribution Channel while M2 Adopts Cross-Distribution Channel. In the SC structure as opposed to the CS structure, M1 distributes its green products only through R1 while M2 distributes its non-green products through both R1 and R2 (Figure 1(d)). Because nongreen products are distributed through both retailers, we have $q_2 = q_{21} + q_{22}$. Thus, the profit function of each member in the green supply chain is given as
\[
\begin{align*}
\pi_{m1} &= (w_1 - t_m)q_1 - \frac{c_m g^2}{2}, \\
\pi_{m2} &= (w_2 - t_m)(q_{21} + q_{22}), \\
\pi_{r1} &= (p_1 - w_1 - t_r)q_{21} + (p_2 - w_2 - t_r)q_{21}, \\
\pi_{r2} &= (p_2 - w_2 - t_r)q_{22}, \\
\pi_3 &= (t_m + t_r)(q_{21} + q_{22}) - \frac{c_3 g^2}{2}.
\end{align*}
\]

**Proposition 4.** Let $q_{ij}^{SC}$, $e^{SC}$, $g^{SC}$, and $w_i^{SC}$ correspondingly denote the selling quantity of product $i$ via retailer $j$, the carbon emission reduction, the greenness degree, and the
Proposition 3. Hence, we omit the proof here. □

Proof. The proof of Proposition 4 is quite similar to that of Proposition 3; hence, we omit the proof here.

4.5. CO Structure: R1 and R2 Cooperate When Determining Their Selling Quantities. In the case of the CO structure, R1 and R2 cooperate with each other to set the selling quantities. More specifically, the cooperation behavior is similar to the case in which the two retailers recognize their interdependence and agree to act in union in order to maximize their total profit (Figure 1(e)). Thus, the profit function of each member in the green supply chain is given as

\[
\begin{align*}
\pi_{m1} &= (w_1 - t_m)q_1 - \frac{c_m g^2}{2}, \\
\pi_{m2} &= (w_2 - t_m)q_2, \\
\pi_1 &= (p_1 - w_1 - t_r)q_1 + (p_2 - w_2 - t_r)q_2, \\
\pi_3 &= (t_m + t_r)\left(q_1 + q_2\right) - \frac{c_g e^2}{2}.
\end{align*}
\]

Proposition 5. Let \(q^CO_1\), \(e^CO\), \(g^CO\), and \(w^CO_i\) correspondingly denote the selling quantity of product \(i\), the carbon emission reduction, the greenness degree, and the wholesale price of product \(i\) in the CO distribution channel structure. If the condition \(4c_m > \lambda^2\) is met, the optimal decisions are can be determined as follows:

\[
\begin{align*}
q^CO_1 &= \frac{B_1 + \lambda_1 g^CO - w^CO_1 + \beta w^CO_2 + \mu e^CO}{2}, \\
q^CO_2 &= \frac{B_2 - \lambda_2 g^CO + \beta w^CO_1 - w^CO_2 + \mu e^CO}{2}, \\
e^CO &= \frac{\mu(t_m + t_r)}{c_3}, \\
g^CO &= \frac{\lambda_1 (2B_1 + \beta B_2 - (2 + \beta)(t_m (1 - \beta) - \mu e^CO))}{2c_m (4 - \beta^2) - \lambda_1 (2\lambda_1 - \beta \lambda_2)}, \\
w^CO_1 &= \frac{t_m + \frac{2c_m g^CO}{\lambda_1}}{1}, \\
w^CO_2 &= \frac{\beta w^CO_1 - \lambda_3 g^CO + \mu e^CO + t_m + B_3}{2}.
\end{align*}
\]

Proof. The decision sequence in the case of the CO structure is as follows:

\[
\begin{align*}
\max \pi_{m1} \\
\max \pi_{m2} \\
\max \pi_3 \\
\max \pi_{rt}.
\end{align*}
\]
Given the values of other members’ decision variables, we initially maximize the retailers’ total profit. Let $H^{CO}_{rt}$ denote the profit function of the retailers’ profit maximization problem. Then, we have

$$H^{CO}_{rt} = \begin{bmatrix} \frac{\partial^2 \pi_m}{\partial q_1^2} & \frac{\partial^2 \pi_m}{\partial q_1 \partial q_2} \\ \frac{\partial^2 \pi_m}{\partial q_2^2} & \frac{\partial^2 \pi_m}{\partial q_2^2} \end{bmatrix} = \begin{bmatrix} 2 & -2 \beta \\ -1 - \beta^2 & -1 - \beta^2 \\ 2 \beta & 2 \end{bmatrix}. \quad (22)$$

Since $H^{CO}_{rt} = H^{CC}_{rt}$, the profit function of retailers’ problem is strictly concave w.r.t. its own selling quantities. Accordingly, solving the FOCs of the retailers’ problem yields equations (20a) and (20b). Substituting them into the 3PL’s profit function, the SOC of the 3PL’s problem is given by $\frac{\partial^2 \pi_f}{\partial z^2} = -c_m < 0$. From the 3PL’s FOC, we have equation (20c). Integrating equations (20a) to (20c), we have the equilibrium strategies via equations (20a)–(20f). IK_his completes the proof.

5. Discussion

This section provides some parametric analyses. First, we investigate the impact of potential market demand on the green supply chain of M1’s product. Second, the analysis of the strategies by the 3PL to reduce their carbon emissions is conducted.

5.1 Effects of $\alpha_i$ and $\alpha_2$ on M1’s Greenerness Strategy. The parameter $\alpha_i$ in the demand function $q_i$ indicates the potential market demand for manufacturer i’s product. To investigate the impact of $\alpha_i$ on the greenness degree of M1’s green product, the first derivatives of $g$ w.r.t. $\alpha_i$ in each of the distribution channel structures are obtained as follows:

$$\frac{dg^{SS}}{\alpha_i} = A_3(8 - 3\beta^2),$$

$$\frac{dg^{CC}}{\alpha_i} = c_m A_7 - A_3(4A_3 + \beta A_4),$$

$$\frac{dg^{CS}}{\alpha_i} = 4\lambda_1,$$

$$\frac{dg^{SC}}{\alpha_i} = 3c_m(4 - \beta^2) - 2\lambda_1(2\lambda_1 - \beta\lambda_2),$$

$$\frac{dg^{CS}}{\alpha_i} = 8(4\lambda_1 - \beta\lambda_2),$$

$$\frac{dg^{CS}}{\alpha_i} = 6c_m(16 - 7\beta^2) - (8\lambda_1 - 5\beta\lambda_2)(4\lambda_1 - \beta\lambda_2),$$

$$\frac{dg^{CO}}{\alpha_i} = \frac{2\lambda_1}{2c_m(4 - \beta^2) - \lambda_1(2\lambda_1 - \beta\lambda_2}).$$

From equations (24) and (25), we find that the numerator in each equation is positive. So, if the denominator in each equation is positive, then the potential market demand affects the greenness degree positively. That is, for $i = 1, 2$, the following relationship can be established:

$$\frac{dg^{SS}}{\alpha_i} > 0, \text{ if } c_m A_7 > A_3(4A_3 + \beta A_4),$$

$$\frac{dg^{CC}}{\alpha_i} > 0, \text{ if } 3c_m(4 - \beta^2) > 2\lambda_1(2\lambda_1 - \beta\lambda_2),$$

$$\frac{dg^{CS}}{\alpha_i} > 0, \text{ if } 6c_m(16 - 7\beta^2) > (8\lambda_1 - 5\beta\lambda_2)(4\lambda_1 - \beta\lambda_2),$$

$$\frac{dg^{CO}}{\alpha_i} > 0, \text{ if } 2c_m(16 - 7\beta^2) > \lambda_1(2\lambda_1 - \beta\lambda_2).$$

(26)
From equations (1) and (26), we can infer the following. As the market size grows, more consumers are likely to prefer to purchase green products, which in turn promote the demand for green products. This therefore implies that manufacturers will be more devoted to developing green products as the market size increases.

5.2. Effect of $\beta$ on 3PL's Carbon Emission Reduction. The parameter $\beta$ in the demand function $q_i$ indicates the competition intensity between M1 and M2. To investigate the impact of $\beta$ on the 3PL's carbon emission reduction, the first derivatives of $e$ w.r.t. $\beta$ in each of the distribution channel structures are obtained as follows:

$$\frac{de_{SS}}{d\beta} = \frac{2\mu(t_m + t_r)}{c_1(2 + \beta)^2} > 0,$$

$$\frac{de_{CS}}{d\beta} = \frac{de_{SC}}{d\beta} = \frac{\mu(t_m + t_r)}{6c_3} > 0,$$

$$\frac{de_{CC}}{d\beta} = \frac{de_{CO}}{d\beta} = 0. \tag{27}$$

As shown in equation (27), 3PL’s effort to reduce their carbon emissions is positively influenced by the manufacturers’ competition for the SS, CS, and SC structures. In other words, if at least one of the manufacturers chooses a single distribution channel, the greater the competition between manufacturers becomes, the more carbon emissions the 3PL must reduce. It should be noted that in the case of the CC and CO structures, the 3PL’s carbon emission reduction is not affected by the competition between the manufacturers because its first derivatives are equal to zero. Given this fact, if each manufacturer’s product is distributed through both retailers, the competition between manufacturers does not affect the 3PL’s carbon emission reduction strategy.

It is also interesting to compare the 3PL’s carbon emission reduction strategies for the five distribution channel structures. After some mathematics, we have the following relationship:

$$e_{CO} < e_{SS} < e_{CS} = e_{SC} < e_{CC}. \tag{28}$$

It follows from equation (28) that retailers’ cooperation in the green supply chain leads to the least effort by the 3PL to reduce their carbon emissions. We also find that more manufacturers adopting cross-distribution channels will force the 3PL to exert more effort to reduce their carbon emissions.

6. Numerical Experiments and Managerial Insights

This section numerically investigates the effects of certain parameters on the equilibrium quantities. In the numerical experiments conducted here, we assume the following market situations. First, although environmental awareness by consumers is higher than ever, the market size for green products is smaller than that for nongreen products (i.e., $\alpha_1 < \alpha_2$). Second, according to Assumption 1, the number of consumers who give up buying the nongreen product must be positive (i.e., $\lambda_1 > \lambda_3$). Third, M1’s unit greening cost is higher than the 3PL’s unit carbon reduction cost (i.e., $c_m > c_j$). Fourth, given that the manufacturers outsource storage as well as shipping to the 3PL, the unit transportation cost borne by the manufacturers is greater than that paid by the retailers (i.e., $t_m > t_r$). Finally, the values of $\beta$ and $\mu$ must be determined to satisfy the SOC of each problem. Considering these assumptions, the main dataset used for the analysis is given as follows: $\alpha_1 = 100$, $\alpha_2 = 150$, $\beta = 0.5$, $\lambda_1 = 3$, $\lambda_3 = 1.5$, $\mu = 2$, $c_m = 15$, $c_j = 5$, $t_m = 10$, and $t_r = 8$.

For this dataset, we obtain the equilibrium decision of each member in the green supply chain in the next sections.

6.1. Effect of $\beta$ on the Equilibrium Quantities. Once again, the parameter $\beta$ in the demand function $q_i$ indicates the competition intensity between two manufacturers. We are interested in an investigation of the effects of the competition intensity on equilibrium decisions. To do this, we consider the main dataset and vary $\beta$ from 0.3 to 0.7. The equilibrium quantities of the decision variables and the obtained profits for different values of $\beta$ are plotted in Figure 2. As the value of $\beta$ increases, we observe the following:

- The greenness degree of M1’s product increases.
- The wholesale prices and the selling quantities increase for both manufacturers.
- With the CC and CO structures, the 3PL’s efforts to reduce their carbon emissions remain constant. On the other hand, with the SS, CS, and SC structures, the 3PL’s efforts to reduce their carbon emissions increase.
- The profits of all members in the green supply chain increase. Subsequently, the total profit of the green supply chain also increases.

From the facts observed above, we suggest the following managerial insight.

6.1.1. Insight 1. The intense competition between the manufacturers in the supply chain encourages M1’s product to be greener. When M1’s product becomes more environmentally friendly, M1’s selling quantity increases. Benefiting from M1’s increased sales, M2’s selling quantity also increases. Due to the increased manufacturers’ selling quantities, the retailers’ and the 3PL’s profit also increases, implying that the total profit of the supply chain increases. Summarizing these facts, competition between manufacturers has a positive impact on the degree of greenness and on profitability.

6.2. Effect of $\lambda_1$ on the Equilibrium Quantities. The parameter $\lambda_1$ in the demand function $q_i$ indicates the positive impact of greenness degree on the selling quantity of the green product. We conduct a sensitivity analysis of $\lambda_1$. While varying $\lambda_1$ from 1.6 to 5, we record the equilibrium
quantities of the decision variables and the obtained profits in Figure 3. As the value of $\lambda_1$ increases, we observe the following:

The greenness degree of M1’s product increases.

There is no effect of $\lambda_1$ on 3PL’s carbon emission reduction.

The wholesale price, the selling quantity, and the profit of M1 all increase.
The wholesale price, the selling quantity, and the profit of M2 initially decrease to a certain level; i.e., they all reach a minimum, after which they increase again. The profits of R1, R2, and 3PL increase. In addition, the total profit of the green supply chain increases.

From the facts observed above, we suggest the following managerial insight:

6.2.1. Insight 2. The stronger the impact of the greenness of a product on the demand, the more committed M1 is to green
product development. As a result, the selling quantity and profit of M1, producing a green product, all increase. On the other hand, when the impact of greenness on the level of demand is relatively weak, the selling quantity and profit of M2 gradually decrease. However, if the influence of greenness exceeds a certain value, the increased selling quantity of a green product has a positive effect on the selling quantity of a nongreen product, which causes M2’s profit to increase. As a result, the profits of all other members increase.

6.3. Effect of $\lambda_2$ on the Equilibrium Quantities. The parameter $\lambda_2$ in the demand function $q_2$ indicates the negative impact of greenness degree on the selling quantity of the nongreen product. When varying $\lambda_2$ from 0.01 to 2.9, we plot the equilibrium quantities of the decision variables and the obtained profits in Figure 4. As the value of $\lambda_2$ increases, we observe the following:

- The greenness degree of M1’s product decreases. In particular, with the SS and CS structures, in which M2 chooses a single distribution channel, the greenness degree decreases drastically compared to that in other distribution channel structures.
- There is no effect of $\lambda_2$ on the 3PL’s carbon emission reduction.
- The wholesale prices and the selling quantities of both manufacturers all decrease.
- The profits of R1, R2, and 3PL decrease. As a result, the total profit of the green supply chain also decreases.

From the facts observed above, we suggest the following managerial insight.

6.3.1. Insight 3. It is interesting to note that $\lambda_2$ has a negative effect on the greenness degree of M1’s product. As the greenness degree decreases, consumers’ preference for the green product gradually decreases, which also reduces the preference for the nongreen product. The reduced demand adversely affects the profitability of the entire supply chain. In light of this fact, the manufacturer selling a nongreen product is required to reduce the impact of the greenness degree of a green product on the demand for a nongreen product.

6.4. Effect of $\mu$ on the Equilibrium Quantities. The parameter $\mu$ indicates the positive impact of the 3PL’s carbon emission reduction on the selling quantities of the green and nongreen products. With varying $\mu$ from 0 to 5, we plot the equilibrium quantities of the decision variables and the obtained profits in Figure 5. As the value of $\mu$ increases, we observe the following:

- The greenness degree of M1’s product increases
- The 3PL’s carbon emission reduction increases
- The selling quantities of the green and nongreen products all increase

Not only the profits of the all participants in the supply chain but also the total profit of the supply chain increase.

From the facts observed above, we suggest the following managerial insight.

6.4.1. Insight 4. Lowering carbon emission with a 3PL has a positive impact on product sales. As the sales volume of products increases, so does the volume of product shipments, which results in an increase in the 3PL’s profit. In addition, as $\mu$ increases, the green product becomes greener, which causes an increase in product sales. In other words, a reduction in carbon emission by the 3PL has a positive impact on the profitability of the supply chain.

6.5. Effect of $c_3$ on the Equilibrium Quantities. The parameter $c_3$ in the profit function $\pi_3$ indicates the marginal cost of the 3PL’s efforts to reduce their carbon emissions. While varying $c_3$ from 3 to 10, we record the equilibrium quantities of the decision variables and the obtained profits in Figure 6. As the value of $c_3$ increases, we observe the following:

- The greenness degree of M1’s product decreases.
- The wholesale prices of both manufacturers decrease.
- The 3PL’s effort to reduce carbon emissions decreases.
- The selling quantities of both manufacturers decrease.
- The profits of all members in the green supply chain decrease. Subsequently, the total profit of the green supply chain also decreases.

From the facts observed above, we suggest the following managerial insight.

6.5.1. Insight 5. Increasing the cost of the 3PL’s effort to reduce carbon emissions without increasing the transportation charges of the products will cause the effects of the 3PL to reduce their carbon emissions to be negative. Decreasing the 3PL’s effort to reduce their carbon emissions causes a decrease in the level of demand for both green and nongreen products, implying that all members of the supply chain experience decreased profits.

6.6. Effect of $t_m$ on the Equilibrium Quantities. The parameter $t_m$ in the profit function $\pi_3$ represents the shipping benefit of the 3PL from the manufacturers per unit shipment. When varying $t_m$ from 3 to 10, we record the equilibrium quantities of the decision variables and the obtained profits in Figure 7. As the value of $t_m$ increases, we observe the following:

- The greenness degree of M1’s product increases.
- The wholesale prices and the selling quantities of both manufacturers increase.
- The 3PL’s effort to reduce their carbon emissions increases.
The profits of all members in the green supply chain increase. Hence, the total profit of the green supply chain also increases.

From the facts observed above, we suggest the following managerial insight.

6.6.1. Insight 6. As the transportation cost per unit of product increases, M1 increases the sales of green products by increasing the greenness degree. By increasing the sales of green products, M1 can compensate for the increased shipping cost. The sales of M2’s nongreen products also benefit from the increase in the sales of green products. As
sales of both green and nongreen products increase, so does the profitability of the supply chain.

The effects of $t_r$ on the equilibrium quantities are identical to those of $t_{wi}$; therefore, we omit the sensitivity analysis of $t_r$ for brevity.

6.7. Comparison among the Five Distribution Channel Structures. It is also interesting to evaluate and compare the performance outcomes of different distribution channels. Under our numerical setting and from Figures 2–7, we can find the following relationships:

\begin{figure}[h]
\centering
\subfloat{(a)}
\hfill
\subfloat{(b)}
\hfill
\subfloat{(c)}
\hfill
\subfloat{(d)}
\hfill
\subfloat{(e)}
\hfill
\subfloat{(f)}
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\subfloat{(g)}
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\subfloat{(h)}
\hfill
\subfloat{(i)}
\hfill
\subfloat{(j)}
\hfill
\subfloat{(k)}
\hfill
\subfloat{(l)}
\caption{Effect of $\mu$ on the equilibrium quantities.}
\end{figure}
Figure 6: Effect of $c_3$ on the equilibrium quantities.
Figure 7: Effect of $t_m$ on the equilibrium quantities.
The CO distribution channel structure is the worst in terms of the profitability of manufacturers. While the competition between manufacturers is maintained in the market, the cooperation between retailers adversely affects the manufacturers’ profits. For each retailer, the best distribution channel structure is that one manufacturer chooses a single channel, while the other chooses a cross channel. By doing so, retailers can maximize their selling quantities and profits. If both manufacturers choose cross-channels, the total shipments of green and nongreen products are maximized, thus maximizing the 3PL’s profit. Figures 2–7 show that for each supply chain member, the optimal distribution channel structure is different. However, our numerical experiments suggested that for sustainability and profitability of the supply chain, the CC structure is best.

6.7.1. Insight 7. The CO distribution channel structure is the worst in terms of the profitability of manufacturers. While the competition between manufacturers is maintained in the market, the cooperation between retailers adversely affects the manufacturers’ profits. For each retailer, the best distribution channel structure is that one manufacturer chooses a single channel, while the other chooses a cross channel. By doing so, retailers can maximize their selling quantities and profits. If both manufacturers choose cross-channels, the total shipments of green and nongreen products are maximized, thus maximizing the 3PL’s profit. Figures 2–7 show that for each supply chain member, the optimal distribution channel structure is different. However, our numerical experiments suggested that for sustainability and profitability of the supply chain, the CC structure is best.

7. Conclusion

In this study, we discussed the equilibrium decisions of pricing, the greenness degree, and carbon emission reduction efforts in a three-chelon supply chain consisting of two competing manufacturers, two retailers, and one third-party logistics firm. Under Cournot competition by the manufacturers, we assumed five different distribution channel structures, established a three-stage game model for each of them, and solved the models analytically. Finally, extensive numerical experiments were conducted to investigate the effects of the parameters on the equilibrium quantities. Our findings reveal that competition between the two manufacturers promotes not only sustainability but also profitability of the supply chain. As the competition becomes more intense, a green product becomes greener, leading to increases in the sales volumes of both green and nongreen products. In short, competition is one of the main factors increasing the sustainability and profitability of the supply chain. We also found that each member of the supply chain prefers a different distribution channel structure. However, for the overall profit of the supply chain, manufacturers learned that choosing a cross-distribution channel is an advantage over other distribution channel structures. The contributions of this study to the literature on the green product market are as follows: (i) This study is the first to address the effects of single and cross-distribution channels in a market where green and nongreen products coexist. (ii) This study identifies a strategy that can be used by a 3PL firm to reduce its carbon emissions under single and cross-distribution channels of a green product. (iii) The study provides guidelines to those making strategic decisions for manufacturers of green products and 3PL firms when they attempt to reduce their carbon footprint. The results of this study can also help policymakers to devise a variety of monetary benefit policies, such as subsidies for green products and/or carbon tax exemptions.

Several future research studies related to this topic are possible. One can modify our supply chain model to consider collusion behavior between manufacturers. Determining how such collusion affects equilibrium decisions and the selection of the distribution channel can be a promising extension of this study. Another extension is to apply the newsvendor model to retailers. While this paper argues that the retailers sell all products that they ordered, the assumption of uncertain demands for green and nongreen products is more realistic. This type of stochastic demand may lead to different results. Finally, this paper assumed no shipping cost between retailers and consumers. However, the distance, means, and speed of transportation between retailers and consumers can affect the efforts made by a 3PL firm to reduce their carbon emission levels. Considering these aspects can serve a possible extension of this study.

Appendix

\[
A_1 = \alpha_1 (2 - \beta^2) + \alpha_2 \beta - tr (2 - \beta) (1 - \beta^2),
\]
\[
A_2 = \alpha_2 (2 - \beta^2) + \alpha_1 \beta - tr (2 - \beta) (1 - \beta^2),
\]
\[
A_3 = \lambda_1 (2 - \beta^2) - \beta \lambda_2,
\]
\[
A_4 = \beta \lambda_1 - \lambda_2 (2 - \beta^2),
\]
\[
A_5 = 2 t_m + \frac{A_1}{1 - \beta^2} + \frac{me^{SS} (2 - \beta)}{1 - \beta},
\]
\[
A_6 = 2 t_m + \frac{A_2}{1 - \beta^2} + \frac{me^{SS} (2 - \beta)}{1 - \beta},
\]
\[
A_7 = 64 - 84 \beta^2 + 21 \beta^4 - \beta^6,
\]
\[
B_1 = \alpha_1 - tr (1 - \beta),
\]
\[
B_2 = \alpha_2 - tr (1 - \beta),
\]
\[
C_1 = \alpha_1 + \alpha_2 \beta - tr (1 - \beta^2),
\]
\[
C_2 = 2 \alpha_1 - \alpha_2 \beta - tr (2 - 3 \beta + \beta^2),
\]
\[
D_1 = 2 \alpha_2 - \alpha_1 \beta - tr (2 - 3 \beta + \beta^2),
\]
\[
D_2 = \alpha_1 \beta + \alpha_2 - tr (1 - \beta^2).
\]
Data Availability
No data were used to support this study.

Conflicts of Interest
The author declares that there are no conflicts of interest.

References


