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Information Sharing in Competing Supply Chains with Carbon Emissions Reduction Incentives

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Abstract: This paper investigates the incentives of firms to share demand information in two competing supply chains. We consider a model in which each supply chain consists of a manufacturer and a retailer, and the manufacturers decide their products' carbon emissions reduction levels. Through information sharing, manufacturers can adjust their wholesale price and the level of carbon emissions reduction according to the demand signal. The results reveal that information sharing always benefits the manufacturer. Information-sharing arrangements are more likely to occur when the manufacturer's carbon emissions reduction efficiency or the customer's low-carbon product preference is relatively high. Moreover, under Cournot competition, the retailer's incentive to share information increases when information is less accurate or the competition is less intense. By sharing demand information, manufacturers will invest more in reducing the carbon emissions of their products. Therefore, there are two effects of information sharing: the "economic effect" on the benefits of all parties and the "environmental effect" on reducing carbon emissions. Our findings highlight the economic and environmental incentives of information sharing in the supply chain and the synthesis impacts of low-carbon preferences, efficiency of carbon emissions reduction, and the competition intensity on the retailer's incentives to share information.

Keywords: information sharing; low-carbon preference; carbon reduction; game theory

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1. Introduction

There is a general consensus that greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), are the main cause of global warming. In recent years, as global warming has become an increasingly serious threat, the requirements for effectively curbing GHG emissions have increased sharply. Consumers are becoming increasingly environmentally conscious. For example, a survey conducted by the Carbon Trust reveals that there is an increasing demand for low-carbon products and services, even in a difficult economic environment, and 45% of shoppers would be prepared to stop buying their favourite brand if they refused to measure their product's carbon footprint, a figure that has doubled from 22% last year [1–8]. In addition, research shows that a large proportion of people are prepared to make lifestyle changes to reduce their environmental impact if they do not have to pay more; in order to reduce their carbon footprint, 70% of interviewees said that they would follow simple energy-saving advice on product packaging.

To meet the increasing demand for low-carbon products and engage in corporate environmental responsibility, many companies have taken action to reduce their products' associated carbon emissions. For instance, manufacturers of air-conditioners, refrigerators, new-energy vehicles, etc., invest in R&D practices to develop low-carbon emissions products. Moreover, these products include carbon labels, such as from the Carbon Trust, Carbon Counted, and Climatop, to inform the customer about the carbon emissions levels of the products. Having products with low-carbon emission levels has become a competitive advantage for many enterprises.

In practice, carbon emissions reduction planning is often driven by customer demand. Because reducing carbon emissions requires a large investment but the economic returns are uncertain, firms face a great risk when they determine the carbon emissions reduction level. As research conducted by Boulstridge and Carrigan [9] notes, though the consumer intends to buy a brand that commits to being socially responsible, the most important factors when the consumer makes purchasing decisions are still economic factors, such as price, brand, and convenience. As a result, due to the increased price of low-carbon products, although consumers intend to buy these products, their actual willingness to pay is low. Other related research has also obtained similar results [10,11]. Therefore, the demand information is critical for firms to make appropriate decisions about the carbon emissions reduction level. For example, when a firm is expected to meet a larger demand according to the forecast, the firm can invest more in reducing carbon emissions but their profits will not be significantly affected. On the contrary, a lack of such information may reduce a firm's investment in carbon emissions reduction, which will not only reduce the competitiveness of the firm but also cause it to fail to grasp further opportunities to decrease the product's carbon emissions level.

In reality, because manufacturers are less informed about product demand relative to retailers, when a retailer shares demand information, the manufacturer can make more accurate carbon emissions reduction decisions and improve the competitiveness of the supply chain. However, it is well known that retailers may be reluctant to share private demand information with manufacturers because they worry that information sharing will cause manufacturers to misuse the information to raise the wholesale price and hurt retailers' profits. As many studies note, information sharing will make double marginalisation more significant and retailers' profits will be reduced if the manufacturers only make wholesale price decisions [12,13]. However, no studies have considered the impact of the practice of reducing carbon emissions on the incentive to share information between supply chain partners. Moreover, as Fung [14] noted, market competition has changed from competition between different firms to competition between different chains. This paper seeks to answer the above questions in two supply chains with competition when the manufacturers make both wholesale price and carbon emissions reduction investment decisions. More specifically, this research attempts to address the following questions: How do information-sharing incentives depend on carbon emissions reduction efficiency? How should the manufacturer jointly make wholesale price and carbon emissions reduction decisions based on information sharing? What is the impact of the degree of the customer's low-carbon product preference, information accuracy, and competitive intensity on the above questions?

To answer the above questions, we consider two cases in our model with and without a competing supply chain. Each supply chain includes a retailer and a manufacturer. The retailer sells products on the market, while the manufacturer makes decisions on the wholesale price and carbon emissions reduction investments. The demand for the product is not only impacted by the price but also by the product's carbon emissions reduction level. The event sequence is that each manufacturer provides an information fee to the corresponding retailer before the retailer decides whether to share demand information. The manufacturers then make carbon emissions reduction decisions and wholesale price decisions accordingly. Finally, retailers decide on ordering quantities and manufacturers produce the corresponding products to fill retailers' orders.

For the case without competition, that is, when there is only a single supply chain, the manufacturer can adjust the wholesale price and level of carbon emissions reduction based on the retailer's shared demand information. In this case, the manufacturer's level of carbon emissions reduction increases with demand signals. This is because, compared to the situation without information sharing, the manufacturer can make more accurate carbon emissions reduction decisions. Moreover, the manufacturer's wholesale price always increases with demand signals. Therefore, there is increasing double marginalisation, which hurts the supply chain, as described in the research of Li [12] and Li and Zhang [13].

As reducing a product's carbon emissions will stimulate more demand, it will benefit the retailer and the entire supply chain when the manufacturer effectively reduces carbon emissions or the customer's preference for low-carbon products is relatively high. Therefore, the net effects of negative double marginalisation and positive demand stimulation will influence the benefits of information in a supply chain. When the manufacturer's efficiency of carbon emissions reduction or the customer's preference for low-carbon products is relatively low, the manufacturer will set a lower carbon emissions reduction level, and the negative double marginalisation effect will dominate over the positive demand stimulation effect. In that situation, the supply chain will be hurt by information sharing. On the contrary, the manufacturer will set a higher carbon emissions reduction level, and the negative double marginalisation effect will be dominated by the positive demand stimulation effect. In this case, the value of the information is positive, and manufacturers tend to provide information fees to retailers in order to encourage them to share their private demand signals. In addition, when the customer's preference for low-carbon products is sufficiently high, retailers will benefit from information sharing and may voluntarily share information.

When considering two identical supply chains where the retailers compete on quantity, as in the study by Ha et al. [15], we distinguish two information-sharing effects: a direct effect and a competitive effect. The difference between the two effects is considering the impact of information sharing with or without the response of the rival supply chain. We find that, when the manufacturer's efficiency of carbon emissions reduction or the customer's low-carbon products preference is relatively high, the direct effect is positive, as with the single supply chain case. Moreover, the competitive effect will also be positive when the manufacturer's efficiency of carbon emissions reduction or the customer's low-carbon product preference further increases. Therefore, when the positive direct effect exceeds the negative competitive effect, or both the direct effect and the competitive effect are positive, the supply chain can benefit from information sharing. In addition, we find that information sharing is more likely to happen when there is less information accuracy or less competition intensity, which is consistent with Ha et al. [15]. We further discuss the environmental benefits of information sharing, and suggest that information sharing will enable a supply chain to achieve higher levels of carbon emissions reduction investment, which has been ignored in previous research. Therefore, when reducing carbon emissions, we should encourage information sharing. When the carbon emissions reduction efficiency of two supply chains is different, we conduct a number of numerical studies, which show that the main insights of our basic model are robust.

In summary, information sharing and whether manufacturers need to pay information fees to retailers are closely related with carbon emissions reduction efficiency and consumers' low-carbon products preference. Specifically, if the manufacturer's efficiency of carbon emissions reduction or the customer's low-carbon product preference is relatively high, information-sharing arrangements are more likely to occur. In addition, besides the economic effect, there is also an environmental effect of information sharing. That is, manufacturers will invest more in reducing carbon emissions of their products after retailers share their private demand information with manufacturers.

The rest of this paper is organised as follows. In Section 2, we briefly review the relevant literature. In Section 3, we formally introduce the model. In Section 4, we analyse the equilibrium state under different information-sharing arrangements in a single supply chain and study the optimal information-sharing decision. In Section 5, we further analyse the equilibrium of different information-sharing arrangements and the equilibrium information-sharing decisions. In Section 6, we conduct a numerical analysis of two competing supply chains with differences in carbon emissions reduction efficiencies. Finally, in Section 7, we draw conclusions.

2. Literature Review

There are two main bodies of literature relating to our study, i.e., information sharing and low-carbon supply chains. We review these two streams of research in Sections 2.1 and 2.2, respectively.

2.1. Information Sharing

The incentive for supply chain information sharing is closely related to our research. Based on supply chain structures with horizontal competition at the manufacturer or retailer level, we classify the existing literature into two classes. First, for supply chain structures with one manufacturer and n retailers or with one manufacturer and one retailer, Li [12] began by considering the incentives for retailers to share information with the manufacturer. Zhang [16] also considers vertical information exchange with duopoly retailers. Li and Zhang [13] examine the influence of confidentiality on retailers' incentives to share their private demand information. Zhang and Chen [17] consider an equilibrium information-sharing arrangement in a supply chain with a single supplier and a single retailer, in which both supplier and retailer possess partial demand information. Dai et al. [18] analyse the two-way information-sharing problem in a dual-channel supply chain when supply chain members obtain information through big data technology. Through the above literature, Li [12] and Zhang [16] show that, if the manufacturer only determines wholesale price and the retailer only determines order quantity, the retailer will not take the initiative to share their private demand information. However, Li and Zhang [13] research the ex ante information-sharing problem by considering a retailer and a make-to-stock upstream manufacturer, and find that there is an incentive for the retailer to voluntarily share information with the manufacturer when there is moderate demand uncertainty. This result is different from previous research, which shows that the retailer never shares information with a make-to-order manufacturer. Li et al. [19] investigate the influence of subsidisation and diversification on information sharing under disruption risk. Recently, Yu and Cao [20] also consider the impact of different information-sharing formats in a supply chain consisting of one manufacturer, one incumbent retailer with private demand information, and one new entrant retailer under the cap-and-trade mechanism. Their results show that a manufacturer's carbon emissions abatement capacity and demand uncertainty are two significant factors that influence an incumbent retailer's incentive and choice of information-sharing formats.

Second, for cases of n manufacturers and one retailer, or cases of n manufacturers and n retailers. Shang et al. [21] investigate the information-sharing problem in which two competing manufacturers sell alternative products through a common retailer. Their analyses shows that nonlinear production cost, competition intensity, and payment for information are three main factors that influence the retailer's intention to share information. Ha and Tong [22] investigate how the value of information sharing is affected by the contract type in two competing supply chains. Moreover, Ha et al. [23] investigate incentives of vertical information sharing under diseconomies of scale in production technologies in competitive supply chains. Guo et al. [24] study retailers' strategic information-sharing behaviour in two competing channels. They find that the retailer could strategically disclose low demand and withhold high demand information to induce their manufacturers to lower wholesale prices. Different from the existing studies. Ha et al. [15] investigate the influence of cost reduction on information sharing in two competing supply chains. In most of the above papers, the aim of the manufacturer and retailer's decisions is to achieve optimal economic benefits. Ha et al. [25] investigate the competing manufacturers' incentives to share audit information by taking responsibility violation risks into account. None of the papers consider environmental issues and information-sharing decisions jointly in their model, except Yu and Cao [20]. In contrast, we consider both the maximum economic profit of the supply chain and the optimal carbon emissions reduction level. Therefore, our study makes two contributions to the existing research: First, we extend the existing research by explicitly taking environmental protection issues into account, as fighting global warming and developing a low-carbon economy are becoming increasingly important around the world. Second, we show that the retailer could also benefit from information sharing when the manufacturer takes multiple actions (marketing and carbon emissions reduction decisions) based on the private information received from the retailer.

Our research also relates to the value of information sharing in supply chains. In this stream of research, the decisions commonly made by manufacturers are regarding the ordering quantity or inventory level, etc. For example, Lee et al. [26] quantify the benefits of demand information sharing in a two-level supply chain. They identify the drivers of these benefits and rank their importance. The results show that the value of demand information is high, especially when demand is significantly correlated with time. Cachon and Fisher [27] investigate the value of sharing demand and inventory data in the inventory management of one supplier, with N identical retailers in the supply chain. Yue and Liu [28] compare a traditional retail channel and a direct channel and evaluate the benefits of information sharing. Cui et al. [29] use empirical and theoretical models to evaluate the value of information sharing. The results reveal that improving the accuracy of upstream order fulfilment prediction is the main value of downstream sales information to an upstream firm. In a multi-stage supply chain that sells single products. Sabitha et al. [30] analyse the influence of information sharing on demand uncertainty and average (on-hand) inventory levels. The results show that information sharing is more valuable to upstream firms when demand correlations over time are high, lead times are long, or both. In a sustainable supply chain. Khan et al. [31] observe that information sharing leads to greater annual profits. Moreover, Lai et al. [32] explore the maritime supply chain's incentive and impact of information sharing, in which the port makes the market forecast information-sharing decisions and the carrier make the sustainability investment-level decisions. Their analysis implies that forecast sharing can not only improve both parties' profits, but also facilitate the carrier's sustainability investments. Zhang et al. [33] reveal that information sharing can promote supply chain performance and reduce the influence of uncertainty. There are many other representative studies, including Gavirneni et al. [34], Aviv [3–5], Fiala [35], Zhang [36], Trapero et al. [37], Dominguez et al. [7], Teunter et al. [38], Kovtun et al. [39], and Liu et al. [40]). Chen [41] provides a comprehensive review of earlier works. Except for Lai et al. [32], these studies mainly focus on how information sharing improves the firm's operational performance, such as through ordering quantity and inventory cost saving. In contrast, we focus on the retailer's incentive for information sharing when the manufacturer makes both wholesale price and carbon emissions reduction investment decisions. Additionally, we also examine how incentives of information sharing depend on the accuracy of private signals, the intensity of competition, and the efficiency of the manufacturer's carbon emissions reduction.

2.2. Low-Carbon Supply Chain

In terms of low-carbon supply chains, many of the recent studies investigate the impact of carbon emissions regulations on firms' operational decisions. Benjaafar et al. [42] develop a serious of models by incorporating the carbon emissions regulatory policies into the classic lot-sizing model. They show that, besides investing in energy-efficient technologies, carbon emissions can also be reduced by adjusting the firm's operational decisions. Absi et al. [43], Helmrich et al. [44], and Palak et al. [45] also study economic lot-sizing models with carbon regulatory policies. Chen et al. [46] and Hua et al. [47] both consider economic order quantity (EOQ) models with carbon emissions constraints. By incorporating the carbon cap and many other environmental regulation mechanisms into the classic EOQ model. Chen et al. [46] reveal that the relative reduction in carbon emissions will be much higher than the relative increase in costs. Similarly, under a carbon emissions trading mechanism. Hua et al. [47] investigate how a company could manage its carbon footprints in terms of inventory management. The results show that a cap-and-trade mechanism motivates retailers to reduce carbon emissions while potentially increasing their overall cost. Wang et al. [48] quantitatively study the effect of the carbon offsetting mechanism on the profits of emissions trading participants and industry output based on a duopoly model. Under cap-and-trade and carbon tax policies. Xu et al. [49] investigate the manufacturer's joint production and pricing problem. They find that the optimal production quantity is determined by the carbon price under cap-and-trade regulations and optimal quantity is determined by the cap under the tax rate. In contrast to these models, we do not consider explicit carbon emissions regulatory policies but do consider the consumer's preference for low-carbon products.

A few papers consider the coordination of different supply chain partners to jointly reduce the carbon footprint. Caro et al. [50] analyse the problem of carbon emissions in joint production. They find that carbon neutrality generally does not lead to optimal emissions reduction efforts, though it may be a worthy goal. To motivate companies to choose the best emission reduction efforts, it is necessary to double count emissions. In a decentralised make-to-order supply chain. Ren et al. [51] analyse the product-related carbon emissions abatement target (PCEAT) allocation problem and find that it is better to let leaders allocate PCEAT. Benjaafar et al. [42] also study the impact of cooperation between firms in the supply chain on their costs and carbon emissions, as well as incentives for firms to cooperate. Zhang et al. [52] build a model that considers the consumer environment awareness (CEA) and channel coordination in a supply chain with two alternative products. However, the main goal of their model is to analyse the influence of CEA on supply chain profits and the effectiveness of coordination mechanisms, rather than improving the environmental performance of the supply chain. Under the cap-and-trade policy. Luo et al. [53] consider the pricing and emissions reduction polices of two competing manufacturers with different emissions reduction efficiencies. They find that co-opetition will lead to more profits and fewer total carbon emissions compared to pure competition. Recently, Yang et al. [54] considered two supply chains with competition under the cap-and-trade mechanism, each consisting of a manufacturer and a retailer. By comparing the equilibrium solutions under different structures, they show that a higher carbon emissions reduction rate and lower retail prices can be achieved through vertical cooperation. Furthermore, horizontal collaboration of manufacturers will damage retailers' profits and customers' welfare compared to a situation where both supply chains are decentralised. Different from the above papers, we focus on the value of information sharing in terms of jointly reducing carbon emissions of the supply chain as well as the incentive for retailers to disclose their private information.

Table 1 summarises the studies that are most relevant to this paper. In summary, this research contributes to the existing literature in the following ways. First, we contribute to the supply chain information-sharing literature by explicitly taking carbon emissions reduction into account and analysing the influence of the efficiency of carbon emissions reduction, customers' low-carbon products preferences, and competition intensity on supply chain members' incentives to share demand information, while prior studies focused on corporate performance and mostly did not consider these environmental factors. Second, unlike some prior studies on carbon emissions reduction, we explicitly consider how the retailer sharing demand information with the manufacturer impacts the manufacturer's carbon emissions reduction decisions in a competitive environment.

Table 1. Position of this paper in the literature.

Paper	Supply Chain Structure	Demand Uncertainty	Corporate Performance	Carbon Emissions Reduction	Customer Preference	Insights
Lee et al. [26]	1M-1R	√	√	/	/	They identify the demand information benefits and rank the importance of drivers.
Zhang and Chen [17]	1M-1R	√	√	/	/	They find that, under single price contract, the quality and the correlation of the two firms' information and the competitor's information revelation behaviour are the main factors influence information sharing.
Cachon and Fisher [27]	1M-NR	√	√	/	/	They reveal the value of sharing demand and inventory data in inventory management.
Ha et al. [23]	2M-2R	√	√	/	/	They find that information-sharing decisions should not be made in isolation and the supply chain should be cautious when it improves information accuracy or decreases the production diseconomy.
Ha et al. [25]	2M-2R	√	√	/	/	They study competing manufacturers' incentives to share supplier audit information and find that audit information sharing will reduce the manufacturer's risk of supplier-responsibility violations.
Li [12]	1M-NR ($N \geq 2$)	√	√	/	/	They investigate the incentives of vertical information sharing in a two-level supply chain and identify the direct and indirect effects of information sharing, which will affect the profitability of firms.
Yu and Cao [20]	1M-2R	√	√	√	/	They reveal that the manufacturer's carbon emissions abatement capacity and demand uncertainty are two significant factors that influence incumbent retailers' incentives and choice of information-sharing formats.
Ha and Tong [22]	2M-2R	√	√	/	/	They reveal the importance of contract type to the value of information sharing and identify information sharing as a competitive advantage.
Dai et al. [18]	1M-1R	√	√	/	/	They investigate demand forecast information sharing in a dual-channel supply chain with big data technology. They find the influence of information sharing under different intensity of competition and the information symmetry cannot be realised in this supply chain structure.
Chen et al. [46]	1M-1R	/	√	√	/	They investigate how to effectively reduce carbon emissions under the EOQ model and analyse the applicability of their results under different environmental regulations, such as strict carbon caps, carbon tax, cap-and-offset, and cap-and-price.
Hua et al. [47]	1R	/	√	√	/	They find that the cap-and-trade mechanism induces the retailer to reduce carbon emissions, while it may increase the retailer's total cost.

Table 1. *Cont.*

Paper	Supply Chain Structure	Demand Uncertainty	Corporate Performance	Carbon Emissions Reduction	Customer Preference	Insights
Zhang et al. [52]	1M-1R	√	√	/	√	They investigate how to effectively coordinate the effects of consumer environmental awareness (CEA) in a supply chain, where environmental and traditional products are considered. The results show that retailers' profits increase while manufacturers' profits become convex with CEA.
Luo et al. [53]	2M	√	√	√	/	They show that co-opetition will lead to more profit and less total carbon emissions compared to pure competition.
Yang et al. [54]	2M-2R	√	√	√	/	They show that vertical cooperation leads to a higher carbon emissions reduction rate and lower retail prices
Our paper (2022)	2M-2R	√	√	√	√	This paper investigates the incentive of firms to share demand information in two competing supply chains with the consideration of carbon emissions reduction and consumers' preference for low-carbon products.

M denotes Manufacturer and R denotes Retailer.

3. The Model

Consider two supply chains in competition that sell a partially substitutable product, with each chain consisting of one manufacturer and one retailer. We consider retailers to be engaged in Cournot competition. Moreover, as consumers become more environmentally aware of products, the demand for the product is impacted by both the price and the product's carbon emissions reduction level. The inverse demand function under Cournot competition for retailer i is given by:

$$p_i = a + \theta - q_i - \lambda q_j + \gamma e_i \quad (1)$$

where p_i is the retail price and q_i is the selling quantity of retailer. Parameter $\lambda \in (0, 1)$ represents the intensity of competition between the two supply chains and e is a measure of the carbon emissions reduction level of the product (though we cannot observe a product's carbon emissions reduction level directly, we can obtain a reverse index of such a measure through the product's energy efficiency statement, which is disclosed for most home appliances and automobile manufacturers). Parameter $\gamma > 0$ indicates the consumer's preference for low-carbon products. Finally, θ is a random variable with a mean of zero and variance σ^2, which represents the demand uncertainty. In addition, the manufacturer's unit production cost is c.

Manufacturer i makes an effort to reduce their product's carbon emissions level by an amount e_i at a cost of $\frac{1}{2}m_i e_i^2$. Here, m_i represents the manufacturer's efficiency in carbon emissions reduction. A higher m_i indicates a greater cost to reach the same level of carbon emissions reduction. This function denotes the increasing marginal cost of the effort, which is similar to Ha et al. [15,23]. Note that this cost is the manufacturer's investment in reducing carbon emissions. We also refer to this investment as the manufacturer's carbon emissions reduction investment, denoted hereafter by I. We normalise the constant marginal operating cost of the retailer to zero.

Before making quantity or price decisions, each retailer i observes a private signal Y_i about θ, and decides whether to share it with manufacturer i. We assume that observed signal Y_i is an unbiased estimator of θ, i.e., $E[Y_i|\theta] = \theta$. Moreover, we assume that the conditional expectation of θ on signals is linear and two signals are statistically independent, conditional on θ. Many studies assume the same information structure, including Li, Wu and Zhang, and Ha et al. [12,15,55]. We define expected conditional precision of the signal as $t_i = 1/E[Var[Y_i|\theta]]$. Specifically, if the demand signal is perfect so that $Y_i = \theta$, then $Var[Y_i|\theta] = 0$ and $t_i = \infty$. According to Ericson [56], we have $E[\theta|Y_i] = E\left[Y_j|Y_i\right] = \frac{t_i\sigma^2}{1+t_i\sigma^2}Y_i$.

We assume that the information structure is common knowledge. Interested readers should refer to Vives [57] for more details. The model timeline is shown in Figure 1 and model structures are shown in Figure 2.

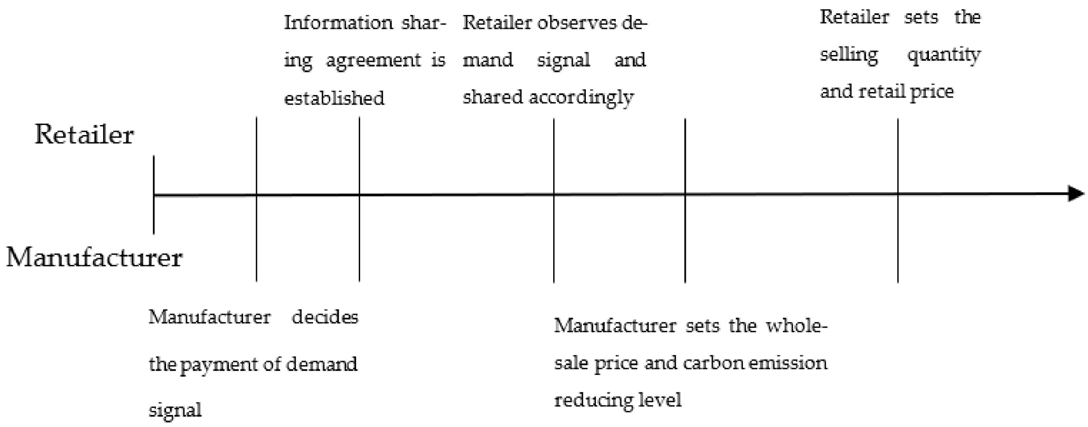

Figure 1. Model timeline.

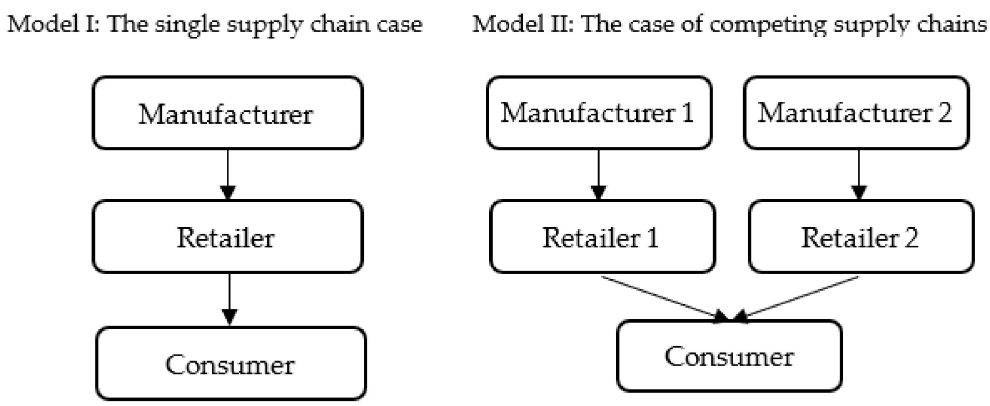

Figure 2. Model structures.

The event sequence is as follows:

(1) Before retailer i knows the private signal Y_i, manufacturer i offers a payment T_i for Y_i to retailer i who decides whether to accept the payment. If retailer i accepts the payment T_i and shares the observed signal Y_i with manufacturer i accurately, we call the supply chain i as communicative, and vice versa.

(2) Each manufacturer i determines the wholesale price ω_i and the carbon emission reducing level e_i based on demand information they do or do not receive from the retailer.

(3) Given a wholesale price ω_i, retailer i determines the selling quantity q_i and products are sold at a market-clearing price p_i $(i = 1,\ 2)$. After receiving the orders of retailer i, manufacturer i produces the products to meet the demand of retailer i. Finally, firms' profits are realised.

In this paper, similar to Ha et al. [15,23], we make the following specific assumptions:

(1) We assume that the information-sharing agreements are longer-term decisions (Zhang et al. [58]; Hu et al. [59]), whereas carbon emissions reduction decisions

(Andersson and Karpestam [60]; Carroll and Stevens [61]) and wholesale contracts (Zhou et al. [62]; Li and Liu [63]) are short-term decisions. Making an information-sharing arrangement between the supply chain partners requires the partners to make a long-term commitment and to establish systems and business processes for information transmission. As a result, it is not easy for firms to alter decisions frequently. However, investing in reducing carbon emissions or renegotiating the wholesale price can occur more frequently in practice.

(2) The rival supply chain can observe whether supply chain i is communicative or not, which means that such information is relatively easily obtained (Ha et al. [15]; Choi et al. [64]). However, the payment T_i, the wholesale price, and the firm's carbon emissions reduction efficiency cannot be observed by the rival supply chain. In practice, this information is regarded as strictly confidential and is not allowed to be distributed publicly.

(3) In line with the related research of Guo [65] and Shang et al. [21], we assume that the information the retailer shares with the manufacturer is truthful. We do not consider a case in which the retailer deliberately manipulates their demand signal, as they aim to maintain a long-term relationship with the supplier. Moreover, the shared information may be tangible and easily verifiable, such as the POS data.

(4) To avoid the equilibrium price, ordering quantity, and the carbon emissions reduction level being negative with a probability close to one, and to ensure that the Hessian matrix of the profit function is negative definite, we assume that $m > m_0 = max\left\{\frac{c}{3a}\gamma^2, \frac{1}{4}\gamma^2\right\}$ and that both c and σ are small relative to a. Li and Zhang [13] and Ha et al. [15] also make similar assumptions in their studies.

Our setting corresponds to several practical scenarios. For example, considering the automotive industry, dealers regularly share POS data with the automaker. Moreover, in a low-carbon economy, automakers seek to continuously improve the fuel efficiency of vehicles and reduce carbon emissions during the vehicle use stage. Such a fuel consumption level is an important factor that determines consumers' buying decisions. Furthermore, different dealers sell different brands of automobiles exclusively. Thus, competition between different automakers is chain-to-chain competition. Such a supply chain structure is common in the automotive industry. In addition to the automotive industry, our model can also be applied to other industries with similar supply chain structures and carbon emissions reduction requirements, including air conditioners, refrigerators, etc.

4. The Single Supply Chain Case

In Section 4, we first consider a single supply chain consisting of one retailer and one manufacturer, which are denoted by M and R, respectively. The information-sharing arrangement is denoted by the superscript $X = S$ or $X = N$. S implies that retailer agrees to share information with manufacturer, and N otherwise. Following the decision sequence that we give in Section 3, we use backward induction. That is, given X, we first derive the optimal wholesale price, and the carbon emissions reduction level. We then compute the corresponding optimal profits for each party of the supply chain, under information-sharing arrangement $X = S$ or $X = N$. Finally, we analyse the equilibrium of the first-stage information-sharing decisions.

4.1. The Equilibrium Analysis of the Game for Different Information-Sharing Arrangements

When the retailer makes the decision to sell quantity q, the inverse demand function can be rewritten as follows:

$$p = a + \theta - q + \gamma e \tag{2}$$

and the retailer aims to maximise the expected profit function as follows:

$$\pi_R = (p - \omega)q = (a + E(\theta|Y) - q + \gamma e - \omega)q \tag{3}$$

By applying the first-order condition to the retailer's expected profit function, we obtain the optimal selling quantity of the retailer:

$$q^* = \frac{1}{2}(a + E(\theta|Y) + \gamma e - \omega) \tag{4}$$

The manufacturer sets wholesale price ω and carbon emissions reduction level e in anticipation of the retailer ordering quantity q^* in the last stage. For an informed manufacturer, because the manufacturer received the demand information from the retailer, the expected sales quantity of the product is $E[q^*(\omega)|Y]$. Note that by substituting q^* from Equation (4) into $E[q^*(\omega)|Y]$, we obtain $E[q^*(\omega)|Y] = \frac{1}{2}(a + E(\theta|Y) + \gamma e - \omega)$. As a result, the manufacturer aims to maximise their expected profits as follows:

$$\pi_M = (\omega - c)q - \frac{1}{2}me^2 = \frac{1}{2}(\omega - c)(a + E(\theta|Y) + \gamma e - \omega) - \frac{1}{2}me^2 \tag{5}$$

Note that the Hessian matrix of π_M with respect to ω and e is negative definite when $m > \frac{1}{4}\gamma^2$, which is satisfied by our assumption. Therefore, by applying the first-order conditions to π_M, we obtain the optimal wholesale price ω^S and carbon emissions reduction level e^S of the manufacturer as:

$$\omega^S = \frac{2ma + (2m - \gamma^2)c}{4m - \gamma^2} + \frac{2m}{4m - \gamma^2}E(\theta|Y) \tag{6}$$

$$e^S = \frac{\gamma(a - c)}{4m - \gamma^2} + \frac{\gamma}{4m - \gamma^2}E(\theta|Y) \tag{7}$$

Substituting ω^S and e^S back into Equation (4), we obtain the retailer equilibrium decision as follows:

$$q^S = \frac{m(a - c)}{4m - \gamma^2} + \frac{m}{4m - \gamma^2}E(\theta|Y) \tag{8}$$

Similarly, in the absence of information sharing, the manufacturer makes their wholesale price ω and carbon emissions reduction level decisions e based on their estimation of the retailer's ordering quantity, which is $E[q^*(\omega)] = \frac{1}{2}(a + \gamma e - \omega)$. Therefore, the manufacturer maximises expected profit as follows:

$$\pi_M = (\omega - c)q - \frac{1}{2}me^2 = \frac{1}{2}(\omega - c)(a + \gamma e - \omega) - \frac{1}{2}me^2 \tag{9}$$

by choosing

$$\omega^N = \frac{2ma}{4m - \gamma^2} + \frac{2m - \gamma^2}{4m - \gamma^2}c \tag{10}$$

$$e^N = \frac{\gamma(a - c)}{4m - \gamma^2} \tag{11}$$

Moreover, by substituting ω^N and e^N back into Equation (4), the retailer's equilibrium decision is as follows:

$$q^N = \frac{m(a - c)}{4m - \gamma^2} + \frac{1}{2}E(\theta|Y) \tag{12}$$

Lemma 1. *e^S and ω^S are increasing in signal Y.*

Lemma 1 implies that after receiving a higher demand signal, the manufacturer is more willing to reduce their product's carbon emissions level because a higher demand signal means demand is more likely to be higher. Therefore, the cost of reducing carbon emissions per product decreases and the manufacturer is inclined to reduce the product's carbon emissions to further increase demand. Moreover, a larger Y will also induce the manufacturer to increase their wholesale price ω^S to mitigate the cost of reducing carbon emissions and maintain their profit margin. The proofs are given in the online supplement (see Supplementary Materials).

According to the above equilibrium decisions, we derive corporate ex ante profits π_R^S, π_R^N, π_M^S, and π_M^N; ex ante carbon emissions reduction investment I^S, I^N (i.e., $\frac{1}{2}me^{S2}$ and $\frac{1}{2}me^{N2}$); and the supply chain's total ex ante profits $\pi^S = \pi_R^S + \pi_M^S$, $\pi^N = \pi_R^N + \pi_M^N$ as follows. The superscripts S and N denote whether the supply chain is communicative or not. Moreover, subscripts R and M denote the retailer and manufacturer, respectively. By comparing these profits, we obtain the following results.

$$\pi_R^S = \frac{m^2(a-c)^2}{(4m-\gamma^2)^2} + \frac{m^2}{(4m-\gamma^2)^2}E[(E[\theta|Y])^2] \tag{13}$$

$$\pi_R^N = \frac{m^2(a-c)^2}{(4m-\gamma^2)^2} + \frac{1}{4}E[(E[\theta|Y])^2] \tag{14}$$

$$\pi_M^S = \frac{m(a-c)^2}{2(4m-\gamma^2)} + \frac{m}{2(4m-\gamma^2)}E[(E[\theta|Y])^2] \tag{15}$$

$$\pi_M^N = \frac{m(a-c)^2}{2(4m-\gamma^2)} \tag{16}$$

$$I^S = \frac{\gamma^2}{(4m-\gamma^2)^2}((a-c)^2 + E[(E[\theta|Y])^2]) \tag{17}$$

$$I^N = \frac{\gamma^2}{(4m-\gamma^2)^2}(a-c)^2 \tag{18}$$

$$\pi^S = \frac{m(6m-\gamma^2)(a-c)^2}{2(4m-\gamma^2)^2} + \frac{m(6m-\gamma^2)}{2(4m-\gamma^2)^2}E[(E[\theta|Y])^2] \tag{19}$$

$$\pi^N = \frac{m(6m-\gamma^2)(a-c)^2}{2(4m-\gamma^2)^2} + \frac{1}{4}E[(E[\theta|Y])^2] \tag{20}$$

where $E[(E[\theta|Y])^2] = \frac{t\sigma^4}{1+t\sigma^2}$.

Proposition 1. *The manufacturer's profit is always higher under the information-sharing case; in addition, it benefits the retailer when* $m < \frac{1}{2}\gamma^2$ *and it benefits the supply chain when* $m < \frac{(3+\sqrt{5})}{4}\gamma^2$.

Proposition 1 implies that sharing information will always benefit the manufacturer, as they can adjust the wholesale price and carbon emissions reduction level to deal with demand fluctuation after they receive the demand information. In addition, when the manufacturer fails to effectively reduce their product's carbon emissions or the consumer's low-carbon products preference is low (i.e., $m > \frac{1}{2}\gamma^2$), the retailer will be worse off by sharing the private demand signal. On the contrary, when $m < \frac{1}{2}\gamma^2$, the manufacturer's efficiency at reducing carbon emissions is relatively high, and so it is better for the retailer to share information. This result is in contrast to Li [12], who found that demand information sharing is always harmful to the retailer's profits when the manufacturer only makes wholesale price decision. Therefore, in this situation, without information sharing, there is only one equilibrium.

Whether the supply chain will benefit from information sharing depends on its net effect on the manufacturer and retailer. When $m_0 < m \leq \frac{1}{2}\gamma^2$, the manufacturer, retailer, and supply chain are all better off. However, when $\frac{1}{2}\gamma^2 < m \leq \frac{(3+\sqrt{5})}{4}\gamma^2$, the retailer is worse off, whereas the whole supply chain is still improved. This result indicates that unless the manufacturer's inefficiency at reducing carbon emissions is very high relative to the consumer's low-carbon emissions product preferences (i.e., $m > \frac{(3+\sqrt{5})}{4}\gamma^2$), the supply chain will always benefit from information sharing.

By comparing the manufacturer's ex ante investments in carbon emissions reduction, we obtain Proposition 2, which implies that demand information sharing will stimulate the manufacturer to invest more in reducing the product's carbon emissions.

Proposition 2. *The manufacturer's investment in reducing the carbon emissions level is higher under the information-sharing case.*

Next, we consider the influence of demand variability on corporate profits. Proposition 3 indicates that the informed firms (i.e., manufacturer and retailer with information sharing and retailer without information sharing) will benefit more from information sharing when the demand variability is higher. However, the uninformed firm's (i.e., manufacturer without information sharing) profits will not change.

Proposition 3. *With increasing demand variability, that is, a larger σ, (a) when the supply chain is communicative, the manufacturer, retailer, and whole supply chain will all have higher profits; (b) when the supply chain is noncommunicative, the retailer and the supply chain will have higher profits, but the profit of the manufacturer will not change.*

4.2. The Equilibrium Information-Sharing Decisions

When the retailer benefits from information sharing, i.e., $\pi_R^N \leq \pi_R^S$, they will share their private demand information without any payment, and the manufacturer can earn all the increased profits from π_M^N to π_M^S without any payment.

When retailers are worse off due to information sharing, there are still some situations in which manufacturers and the entire supply chain are all better off. In these cases, the manufacturer will decide to spend payment T in exchange for the private information from the retailer. By using $X = S$ (sharing) or $X = N$ (not sharing) to denote the retailer's decision, and applying the tie-breaking rule that the retailer will always choose sharing when there is a tie between sharing or not sharing, we find that when the manufacturer gives payment T, the retailer's optimal decision is formulated as follows:

$$X = \begin{cases} S, & if\ T \geq \pi_R^N - \pi_R^s \\ N, & otherwise \end{cases}$$

Proposition 4. *(a) When $m < \frac{1}{2}\gamma^2$, the retailer shares information with the payment $T = 0$, and $X^* = S$ is the unique equilibrium decision. (b) When $\frac{1}{2}\gamma^2 \leq m \leq \frac{(3+\sqrt{5})}{4}\gamma^2$, the manufacturer pays $\pi_R^N - \pi_R^S \leq T \leq \pi_M^S - \pi_M^N$ to buy the information, and $X^* = S$ is the unique equilibrium decision. (c) When $m > \frac{(3+\sqrt{5})}{4}\gamma^2$, $X^* = N$ is the unique equilibrium decision.*

Proposition 4 gives the Nash equilibrium decisions of the information-sharing game in a single supply chain case. Proposition 4 implies that when the manufacturer is relatively efficient in reducing carbon emissions of their product or the customer's low-carbon emissions products preference is relatively high (i.e., $m \leq \frac{(3+\sqrt{5})}{4}\gamma^2$), the equilibrium decision is sharing the information, and vice versa. In addition, Ha et al. [15] find that information sharing may be the unique Nash equilibrium when the manufacturer is efficient at cost reduction. Our results further show that information sharing may still be the unique Nash equilibrium when the demand is not only impacted by the price but also by the product's other characteristics, such as the environmental friendliness of the product and, especially, the carbon emissions level.

5. The Case of Competing Supply Chains

In Section 5, we consider the case in which two supply chains are symmetric. Specifically, we assume $m_1 = m_2 = m$, $c_1 = c_2 = c$, and $t_1 = t_2 = t$.

Following the event sequence in Section 3, a company in each supply chain first decides whether to make an information-sharing arrangement. We use X_i to denote the information-sharing arrangement in supply chain i. In particular, $X_i = S$ represents that the retailer agrees to share information with manufacturer in supply chain i, and $X_i = N$ otherwise. Given the arrangement (X_i, X_j), we first calculate the equilibrium wholesale price, carbon emissions reduction level, and the retailer's optimal ordering quantity (for Cournot competition). We then use these results to determine the firms' ex ante profits. Finally, we use these profits to analyse equilibrium information-sharing decisions under different conditions.

5.1. Equilibrium Analysis under Different Information-Sharing Arrangements

The manufacturer and retailer in supply chain i can observe whether there is information sharing in supply chain j, but they cannot observe wholesale price ω_j or carbon emissions reduction level e_j. In this incomplete information game, the manufacturer and retailer in supply chain i do not know the other supply chain's action but can only make conjectures regarding q_j.

For the Cournot competition, we follow a similar process to that used in Section 4, except that we replace retailer i's inverse demand function (2) as follows:

$$p_i = a + E(\theta|Y_i) - q_i - \lambda E(q_j|Y_i) + \gamma e_i \tag{21}$$

We obtain retailer i's equilibrium decision as follows:

$$q_i^S = \frac{m}{4m-\gamma^2}\left(a + E(\theta|Y_i) - \lambda E(q_j|Y_i) - c\right) \tag{22}$$

Similarly, for the case in which information is not shared, manufacturer i decides wholesale price ω and carbon emissions reduction level decisions e based on their estimation of the retailer's ordering quantity, which is $E[q_i^*(\omega_i)] = \frac{1}{2}\left(a - \lambda E(q_j) + \gamma e_i - \omega_i\right)$. We also follow a similar calculation process and obtain retailer i's equilibrium decision as follows:

$$q_i^N = \frac{m}{4m-\gamma^2}(a-c) + \frac{1}{2}\left(E(\theta|Y_i) - \lambda E(q_j|Y_i) + \frac{2m-\gamma^2}{4m-\gamma^2}\lambda E(q_j)\right) \tag{23}$$

We conduct a similar analysis for supply chain j. Here, we use the concept of Bayesian Nash equilibrium as the solution; given information-sharing arrangement (X_i, X_j), we can deduce the equilibrium manufacturer's wholesale price ${\omega_i}^{X_iX_j}$, carbon emissions reduction level ${e_i}^{X_iX_j}$, the retailer's ordering quantity ${q_i}^{X_iX_j}$, and retail price ${p_i}^{X_iX_j}$ as follows.

Lemma 2. *For Cournot competition, we can obtain the unique equilibrium under the two supply chains' interaction as follows:*

$$q_i^{X_iX_j} = \frac{m(a-c)}{(4+\lambda)m-\gamma^2} + C_i^{X_iX_j}Y_i = \overline{q} + C_i^{X_iX_j}Y_i \tag{24}$$

$$\omega_i^{X_iX_j} = \frac{2ma + \left(2m + m\lambda - \gamma^2\right)c}{(4+\lambda)m-\gamma^2} + \alpha_i^{X_iX_j}Y_i = \overline{\omega} + \alpha_i^{X_iX_j}Y_i \tag{25}$$

$$e_i^{X_iX_j} = \frac{\gamma(a-c)}{(4+\lambda)m-\gamma^2} + \beta_i^{X_iX_j}Y_i = \overline{e} + \beta_i^{X_iX_j}Y_i \tag{26}$$

where

$$C_i^{SS} = \frac{mt\sigma^2}{(4+4t\sigma^2+\lambda t\sigma^2)m - (1+t\sigma^2)\gamma^2} \tag{27}$$

$$C_i^{SN} = \frac{\left[2 + (2-\lambda)t\sigma^2\right]mt\sigma^2}{[8(1+t\sigma^2)^2 - \lambda^2 t^2\sigma^4]m - 2\gamma^2(1+t\sigma^2)^2} \tag{28}$$

$$C_i^{NS} = \frac{\left[\left(4 + 4t\sigma^2 - \lambda t\sigma^2\right)m - \gamma^2\left(1+t\sigma^2\right)\right]t\sigma^2}{[8(1+t\sigma^2)^2 - \lambda^2 t^2\sigma^4]m - 2\gamma^2(1+t\sigma^2)^2} \tag{29}$$

$$C_i^{NN} = \frac{t\sigma^2}{2(1+t\sigma^2) + \lambda t\sigma^2} \tag{30}$$

$$\alpha_i^{SX_j} = \frac{2m}{4m-\gamma^2}(1-\lambda C_j^{X_jS})\frac{t\sigma^2}{1+t\sigma^2},\ \alpha_i^{NX_j} = 0 \tag{31}$$

$$\beta_i^{SX_j} = \frac{\gamma}{4m-\gamma^2}\left(1-\lambda C_j^{X_jS}\right)\frac{t\sigma^2}{1+t\sigma^2},\ \beta_i^{NX_j} = 0 \tag{32}$$

In the above lemma, for brevity, we use $\overline{q}$, $\overline{\omega}$, and $\overline{e}$ to denote the intercepts $\frac{m(a-c)}{(4+\lambda)m-\gamma^2}$, $\frac{2ma+\left(2m+m\lambda-\gamma^2\right)c}{(4+\lambda)m-\gamma^2}$, and $\frac{\gamma(a-c)}{(4+\lambda)m-\gamma^2}$, respectively. Moreover, coefficients $\alpha_i^{X_iX_j}$, $\beta_i^{X_iX_j}$, and $C_i^{X_iX_j}$ denote the responsiveness of the companies' decisions related to the demand signal Y_i. According to Lemma 2, we can find Lemma 3.

Lemma 3. *For Cournot competition, (a) $e_i^{X_iX_j}$ and $\omega_i^{X_iX_j}$ are increasing in Y_i; (b) information sharing in supply chain i makes q_i less responsive to Y_i and q_j more responsive to Y_j when $m \geq \frac{1}{2}\gamma^2$.*

For Lemma 3(a), the informed manufacturer i will adjust wholesale price and carbon emissions reduction level in the same direction as the demand signal because a larger Y_i indicates that the demand is higher, and the value of the carbon reduction will be very high. Therefore, the manufacturer will put more effort into reducing the product's carbon emissions level and increasing the wholesale price. This result is consistent with Lemma 1, which is the result under the single supply chain case. For Lemma 3(b), note that q_i is increasing in Y_i, and when $m \geq \frac{1}{2}\gamma^2$, ω_i is also increasing in Y_i. However, retailer i would decrease the retail quantity q_i as the wholesale price ω_i increases. Therefore, supply chain i would make q_i less responsive to Y_i under information sharing. Moreover, because the two products are substitutive, and the two signals are positively correlated, information sharing in supply chain i would make the competitor supply chain's retail quantity q_i more responsive to Y_i.

According to the above equilibrium decisions, we compute the companies' ex ante profits. In general, companies in supply chain i make their best decisions after estimating the strategy q_i in supply chain j. For the Cournot competition, when this strategy is given by $q_j^{X_jX_i} = \overline{q} + C_j^{X_jX_i}Y_j$, supply chain i has an inverse demand function as follows:

$$p_i = a_i + \theta_i - q_i + \gamma e_i \tag{33}$$

where $a_i = a - \lambda\overline{q}$, $\theta_i = \theta - \lambda C_j^{X_jX_i}Y_j$. Thus, the firms' ex ante profits $\pi_{R_i}^S$, $\pi_{R_i}^N$, $\pi_{M_i}^S$, and $\pi_{M_i}^N$ in supply chain i, and the total ex ante profits $\pi_i^S = \pi_{R_i}^S + \pi_{M_i}^S$ and $\pi_i^N = \pi_{R_i}^N + \pi_{M_i}^N$ can be deduced, following a similar process to that used for the single supply chain case in Section 4. The only difference is replacing the inverse demand function (2) with (33). Therefore, the detailed expressions of the firms' ex ante profits $\pi_{R_i}^S$, $\pi_{R_i}^N$, $\pi_{M_i}^S$, and $\pi_{M_i}^N$ in supply chain i and the total ex ante profits $\pi_i^S = \pi_{R_i}^S + \pi_{M_i}^S$ and $\pi_i^N = \pi_{R_i}^N + \pi_{M_i}^N$ are as follows:

$$\pi_{R_i}^S\left(C_j^{X_jX_i}\right) = \frac{m^2(a-c)^2}{(4m+m\lambda-\gamma^2)^2} + \frac{m^2}{(4m-\gamma^2)^2}E[(E[\theta_i|Y_i])^2] \tag{34}$$

$$\pi_{M_i}^S\left(C_j^{X_jX_i}\right) = \frac{m\left(4m-\gamma^2\right)(a-c)^2}{2(4m+m\lambda-\gamma^2)^2} + \frac{m}{2(4m-\gamma^2)}E[(E[\theta_i|Y_i])^2] \quad (35)$$

$$\pi_{i}^S\left(C_j^{X_jX_i}\right) = \frac{m\left(6m-\gamma^2\right)(a-c)^2}{2(4m+m\lambda-\gamma^2)^2} + \frac{m\left(6m-\gamma^2\right)}{2(4m-\gamma^2)^2}E[(E[\theta_i|Y_i])^2] \quad (36)$$

$$\pi_{R_i}^N\left(C_j^{X_jX_i}\right) = \frac{m^2(a-c)^2}{(4m+m\lambda-\gamma^2)^2} + \frac{1}{4}E[(E[\theta_i|Y_i])^2] \quad (37)$$

$$\pi_{M_i}^N\left(C_j^{X_jX_i}\right) = \frac{m\left(4m-\gamma^2\right)(a-c)^2}{2(4m+m\lambda-\gamma^2)^2} \quad (38)$$

$$\pi_{i}^N\left(C_j^{X_jX_i}\right) = \frac{m\left(6m-\gamma^2\right)(a-c)^2}{2(4m+m\lambda-\gamma^2)^2} + \frac{1}{4}E[(E[\theta_i|Y_i])^2] \quad (39)$$

where $E[(E[\theta_i|Y_i])^2] = (1-\lambda C_j^{X_jX_i})^2\frac{t\sigma^4}{1+t\sigma^2}$.

5.2. The Effect of Information Sharing

In this section, we consider the impact of information sharing on the supply chain and each supply chain partner. First, we make the following proposition about how companies' profits will change under different information-sharing conditions.

Proposition 5. *For Cournot competition, regarding information sharing in supply chain i, (a) retailer j is better off when $m \geq \frac{1}{2}\gamma^2$, regardless of whether supply chain j is communicative, and (b) manufacturer j is better off when supply chain j is communicative and $m \geq \frac{1}{2}\gamma^2$. Moreover, manufacturer j is indifferent when supply chain j is noncommunicative.*

According to Lemma 3(b), when $m \geq \frac{1}{2}\gamma^2$, information sharing in supply chain i makes q_i less responsive to Y_i under Cournot competition. As a result, the demand intercept of supply chain j, i.e., $a+\theta-\lambda q_i$, becomes more variable. Following Proposition 3, it is then easy to show that if a supply chain is communicative, a higher demand variability will make the retailer and manufacturer better off, and the supply chain will be more profitable. However, the manufacturer's profits will not change under a noncommunicative supply chain.

We now consider how information sharing across the supply chain affects the whole supply chain's profits. For Cournot competition, when the information-sharing arrangement on supply chain j is already known, the value of information sharing in supply chain i is defined as follows:

$$\begin{aligned} V_i^{X_j} &= \pi_i^{SX_j} - \pi_i^{NX_j} \\ &= \pi_i^S\left(C_j^{X_jS}\right) - \pi_i^N\left(C_j^{X_jN}\right) \\ &= \left\{\pi_i^S\left(C_j^{X_jN}\right) - \pi_i^N\left(C_j^{X_jN}\right)\right\} + \left\{\pi_i^S\left(C_j^{X_jS}\right) - \pi_i^S\left(C_j^{X_jN}\right)\right\} \end{aligned}$$

Similar to Ha et al. [15,23], we divide the value of information sharing $V_i^{X_j}$. into two parts: a direct effect and a competitive effect. While the direct effect captures the profit changes if supply chain j does not correspondingly alter the retailer quantity (i.e., q_j remains unchanged as $\overline{q}+C_j^{X_jN}Y_j$), the competition effect reflects the profit changes due to such a change (i.e., q_j changes to $\overline{q}+C_j^{X_jS}Y_j$).

Proposition 6. *For Cournot competition, when $m < \frac{(3+\sqrt{5})}{4}\gamma^2$, the direct effect of information sharing is positive; when $m < \frac{1}{2}\gamma^2$, the competitive effect of information sharing is positive.*

Proposition 6 implies that when ignoring supply chain j's reaction, the direct effect of information will be positive if $m < \frac{(3+\sqrt{5})}{4}\gamma^2$, which is the same as in a single supply chain (See Proposition 1). In addition, for the competitive effect, from Lemma 3, when $m < \frac{1}{2}\gamma^2$, supply chain i makes q_j less responsive with information sharing, which, in turn, makes the demand intercept of supply chain i, i.e., $a + \theta - \lambda q_j$, more variable. Therefore, according to Proposition 3, there is a positive competitive effect when $m < \frac{1}{2}\gamma^2$.

Next, we investigate the value of information sharing on carbon emissions reducing level. Given the information-sharing arrangement X_j, we compare the ex ante carbon emissions reduction investment of manufacturer i when supply chain i is communicative or noncommunicative. By defining the difference in carbon emissions reduction investment $\Delta E\left[I_i^{X_j}\right]$ as follows, we obtain Proposition 7.

$$\begin{aligned}\Delta E\left[I_i^{X_j}\right] = E\left[\tfrac{1}{2}me_i^{SX_j2} - \tfrac{1}{2}me_i^{NX_j2}\right] \\ = m\bar{e}\left(\beta_i^{SX_j} - \beta_i^{NX_j}\right) + \frac{tm}{2(1+t\sigma^2)}\left(\beta_i^{SX_j2} - \beta_i^{NX_j2}\right)\end{aligned}$$

Proposition 7. *For Cournot competition, when there is information sharing in supply chain i, (a) information sharing in supply chain i will increase carbon emissions reduction investment, regardless of whether supply chain j's arrangement is $X_j = S$ or N; (b) when $m < \frac{1}{2}\gamma^2$, the increment of carbon emissions reduction investment in supply chain i is higher when supply chain j's arrangement is $X_j = S$, compared to $X_j = N$.*

Figure 3 illustrates the results of Proposition 7. The red and blue dotted lines represent the difference in carbon emissions reduction investment of manufacturer i when supply chain i is communicative or noncommunicative, given supply chain j is communicative or not, respectively. In particular, Proposition 7 implies that information sharing will cause the supply chain to achieve a higher carbon emissions reduction investment level. Moreover, when the rival supply chain j is communicative, it will further increase the investment carbon emissions reduction level in supply chain i when $m < \frac{1}{2}\gamma^2$. Therefore, from the perspective of carbon emissions reduction, we should encourage information sharing in supply chains. Proposition 7 implies that there is not only an economic incentive to share information in the supply chain, but also that there is a strong environmental incentive for sharing information between supply chain partners, which has been ignored in previous research.

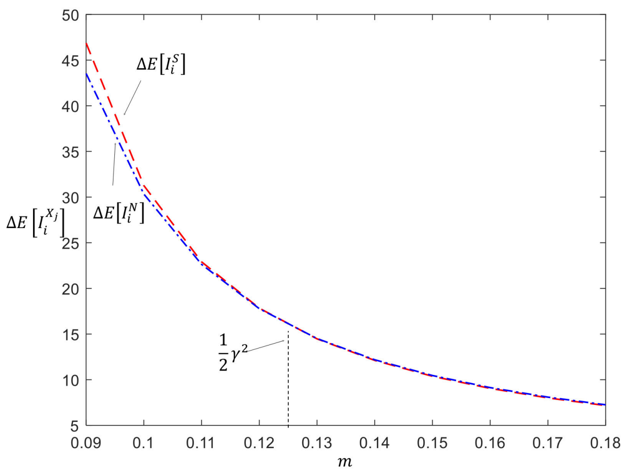

Figure 3. The increment of carbon emissions reduction investment in supply chain i ($a = 100$, $c = 50$, $t\sigma^2 = 80$, $\gamma = 0.5$, $\lambda = 0.5$).

Proposition 8. *For Cournot competition, there exist m^S and m^N such that (a) $V_i^S > 0$ when $m < m^S$ and $V_i^N > 0$ when $m < m^N$; (b) $\frac{1}{2}\gamma^2 < m^N < m^S < \frac{(3+\sqrt{5})}{4}\gamma^2$; (c) m^S and m^N are decreasing in t and λ, and increasing in γ.*

We can use the direct effect and competitive effect to explain this result. For part (a), as Proposition 1 shows, when the manufacturer's efficiency in reducing carbon emissions or the consumer's low-carbon products preference is relatively high (i.e., $m < m^S$, where m^S is increasing in γ), information-sharing benefits the supply chain. This result still holds for the two competing supply chain cases, no matter the information-sharing arrangement in the rival supply chain. For part (b), from Proposition 6, the value of information sharing depends on the net effect of the direct effect and competition effect, which are positive when $m < \frac{(3+\sqrt{5})}{4}\gamma^2$ and $m < \frac{1}{2}\gamma^2$, respectively. As a result, m^N and m^S fall between $\frac{1}{2}\gamma^2$ and $\frac{(3+\sqrt{5})}{4}\gamma^2$. Moreover, when $m \geq \frac{1}{2}\gamma^2$, information sharing in supply chain j weakens the response of q_j to Y_j and, accordingly, the negative competitive effect of supply chain j is weakened. Therefore, $m^N < m^S$. Part (c) shows the impact of information accuracy t, the competition intensity λ, and the consumer's preference for low-carbon products γ on the thresholds m^S and m^N, which indicates that when the accuracy of information is high, the competition on the market is very strong, or when the preference towards low-carbon products is low, the negative competitive effect is very strong when $m > \frac{1}{2}\gamma^2$. To ensure a positive information-sharing value, we need to improve the direct effect to compensate for the influence of the negative competitive effect. A smaller threshold m can bring a stronger direct effect; therefore, m^S and m^N are decreasing in t and λ, and increasing in γ.

5.3. The Equilibrium Information-Sharing Decisions

In this section, we derive the equilibrium of this information-sharing game for the case of two competing supply chains. First, manufacturer i decides if it offers a payment T_i to retailer i for their private demand signal Y_i, and retailer i make the decision to accept the payment or not before retailer observes Y_i. X_i is defined as the information-sharing arrangement in supply chain i, where $X_i = S$ or N for information sharing or not information sharing, respectively.

There are four possible equilibrium strategy combinations based on whether there is information sharing in each supply chain. As we assume that both supply chains decide information-sharing arrangement simultaneously, the firms in supply chain i cannot observe supply chain j's detailed arrangement X_j, and vice versa. Given the rival supply chain's information arrangement X_j, retailer i's profit is $\pi_{R_i}^{SX_j} + T_i$ when supply chain i is communicative, and $\pi_{R_i}^{NX_j}$ otherwise. In addition, manufacturer i's profit is $\pi_{M_i}^{SX_j} - T_i$ when supply chain i is communicative, and $\pi_{M_i}^{NX_j}$ otherwise. We next analyse the equilibrium strategies more specifically by considering the cases where $m \leq \frac{1}{2}\gamma^2$ or not.

When $m \leq \frac{1}{2}\gamma^2$, we can prove that $\pi_{R_i}^{NX_j} \leq \pi_{R_i}^{SX_j}$, regardless of whether $X_j = S$ or not. Therefore, retailer i decides to share information with manufacturer i voluntarily, and manufacturer i does not need to incur any expense to increase their profit from $\pi_{M_i}^{NX_j}$ to $\pi_{M_i}^{SX_j}$. In this situation, $(X_i, X_j) = (S, S)$ is the unique equilibrium.

When $m > \frac{1}{2}\gamma^2$, we can prove that $\pi_{R_i}^{SX_j} < \pi_{R_i}^{NX_j}$, and retailer i is unwilling to share private information with the manufacturer. As a result, manufacturer i should defray the payment to promote the information sharing.

Moreover, information sharing benefits manufacturer i if and only if $\pi_{M_i}^{SX_j} - \pi_{M_i}^{NX_j} \geq T_i$, which is equivalent to $V_i^{X_j} > 0$. Therefore, manufacturer i's optimal payment to retailer i is as follows:

$$\hat{T}_i^{X_j} = \begin{cases} \pi_{R_i}^{NX_j} - \pi_{R_i}^{SX_j}, & if\ \pi_{R_i}^{NX_j} > \pi_{R_i}^{SX_j} \\ 0, & otherwise \end{cases}$$

which induces the best response of retailer i, as follows:

$$\hat{X}_i\left(X_j, \hat{T}_i^{X_j}\right) = \begin{cases} S, & if\ \ \pi_{R_i}^{SX_j} + \hat{T}_i^{X_j} \geq \pi_{R_i}^{NX_j} \\ N, & otherwise \end{cases}$$

Proposition 9. *For Cournot competition, (a) when $m \leq \frac{1}{2}\gamma^2$ and $T_i = 0$, (S,S) is the unique equilibrium; (b) when $\frac{1}{2}\gamma^2 < m < m^N$, (S,S) is the unique equilibrium; (c) when $m^N < m < m^S$, (N,N) and (S,S) are possible equilibriums, and (S,S) is the Pareto optimal; and (d) when $m > m^S$, (N,N) is the unique equilibrium.*

We illustrate the results of Proposition 9 in Figure 4. More specifically, for Cournot competition, we can prove that $\pi_{R_i}^{SX_j} - \pi_{R_i}^{NX_j} \geq 0$ $(i = 1,\ 2)$ when $m \leq \frac{1}{2}\gamma^2$, that is, when the manufacturers are efficient at reducing carbon emissions, the retailers in both supply chains are willing to share their information with the manufacturer for free. However, when $\frac{1}{2}\gamma^2 < m < m^N$, V_i^N and V_i^S are both larger than 0 according to Proposition 8; as a result, S is the dominant strategy for both the supply chains. However, in this case, retailers are worse off if they share demand information with manufacturers for free. Manufacturers need to make a payment for retailers' demand information. When $m^N < m < m^S$, we have $V_i^N < 0$ and $V_i^S > 0$; therefore, both (N,N) and (S,S) could be possible equilibriums. However, as we can prove that $\pi_i^{SS} > \pi_i^{NN}$, (S,S) is the Pareto optimal. Finally, part (d) of Proposition 9 implies that neither supply chain is willing to share information when m is extremely high, i.e., the efficiency in reducing carbon emissions is very low (relative to parameter m^S). Moreover, Figure 4 also shows that both m^S and m^N are decreasing in λ and increasing in γ, which are consistent with what we presented in Proposition 8.

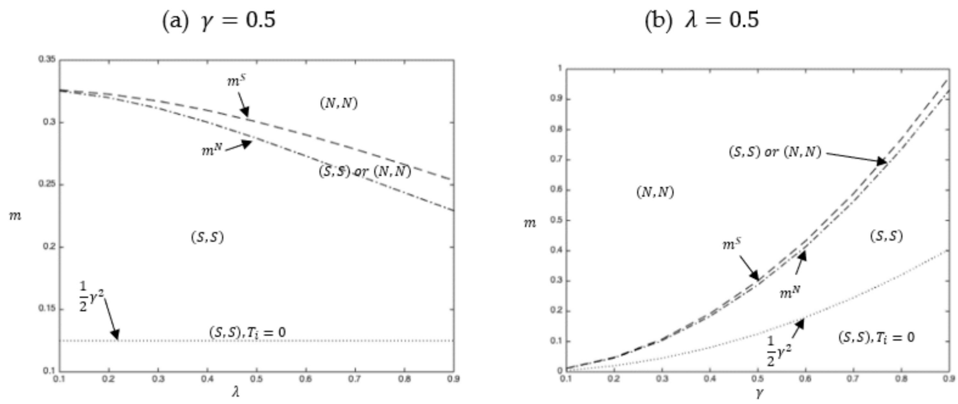

Figure 4. The equilibrium information-sharing decisions under Cournot competition ($a = 100, c = 50, t\sigma^2 = 80$).

6. Numerical Study

In the previous section, we considered the equilibrium information arrangement of two identical competing supply chains. In Section 6, we consider two competing supply chains with different carbon emissions reduction efficiencies numerically. Without a loss of generality, we assume that $m_1 \geq m_2$. Specifically, we consider the impact of different competition intensities and carbon preferences on information-sharing decision-making.

To explore the impact of different competition intensities on the information-sharing equilibriums, we vary λ from 0.1 to 0.9 with an increment of 0.1, with $t\sigma^2$ to be in the set $\{0.1,\ 1,\ 10,\ 20,\ 50,\ 80,\ 100,\ 500\}$. Moreover, we set $\gamma = 0.5$ to reflect consumers' preference for low-carbon products. In fact, we can vary γ to different values without our main results being altered. Therefore, without a loss of generality, we only consider $\gamma = 0.5$. In total, we consider 72 cases. For each case, we can numerically build functions $m_i^{X_j}(m_j)$ such that $V_i^{X_j} > 0$ if and only if $m_i < m_i^{X_j}(m_j)$; here, $i = 1$ **or** 2, $i \neq j$, and $X_j = S$ **or** N. Moreover, based on the analysis of payoffs of the firms in each supply chain, we can derive the optimal information-sharing decisions $(X_1^*,\ X_2^*)$ in the space of $\{(m_1,\ m_2)|m_1 \geq m_2\}$. These optimal decisions are illustrated in Figure 5. It can be shown that along the 45-degree line where $m_1 = m_2$, the equilibrium of the information-sharing game is symmetrical and consistent with Proposition 9.

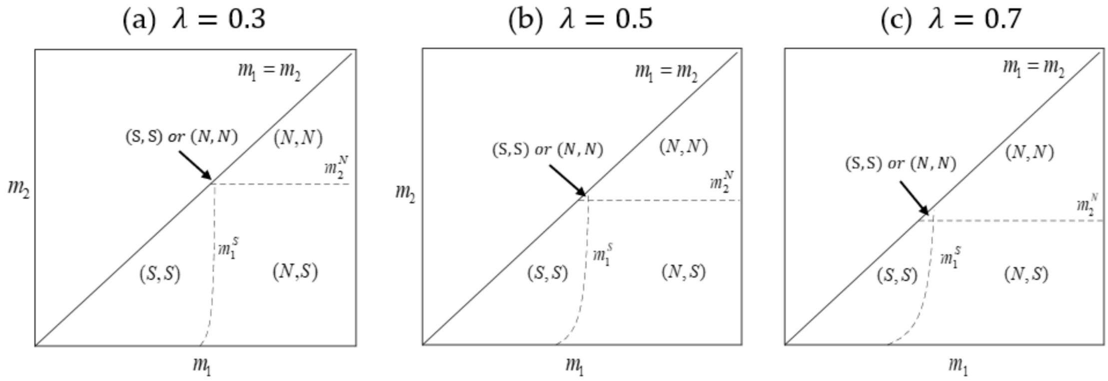

Figure 5. Information-sharing decisions under different competition levels ($a = 100$, $t\sigma^2 = 80$, $\gamma = 0.5$).

Moreover, we specifically analyse the equilibrium strategies of the firms when $m_1 \geq m_2$. The space of $\{(m_1,\ m_2)|m_1 \geq m_2\}$ can be divided into four regions by m_1^S and m_2^N. At first, when $m_1 \leq m_1^S$ and $m_2 \leq m_2^N$, both supply chains' efficiencies in carbon emissions reduction are so high that they will both adopt the information-sharing strategies. However, as its carbon emissions reduction efficiency decreases, when $m_1 > m_1^S$ and $m_2 \leq m_2^N$, supply chain 1 will become noncommunicative, while supply chain 2 will still be communicative. Third, when $m_1 > m_1^S$ and $m_2 > m_2^N$, both supply chains will be reluctant to adopt the information-sharing strategies. Finally, when $m_1 < m_1^S$ but $m_2 > m_2^N$, both (N, N) and (S, S) are possible equilibriums.

In addition, we can find that both m_1^S and m_2^N are decreasing in λ. As a result, the areas of equilibrium regions $(N,\ S)$ and (N, N) become larger as λ becomes larger. Because the efficiency in carbon emissions reduction of manufacturer 1 is lower, with an increasing intensity of product competition, firms of supply chain 2 dominate the sales of low-carbon products. Therefore, the firms in supply chain 1 will not share the information when λ is too large, and whether firms in supply chain 2 will share information depends on whether it benefits from information sharing.

Under the condition of different consumer preferences, we consider γ to vary from 0.1 to 0.9 at increments of 0.1, $t\sigma^2$ to be in the set $\{0.1,\ 1,\ 10,\ 20,\ 50,\ 80,\ 100,\ 500\}$, and $\lambda = 0.5$. Therefore, we consider 72 cases in total. Similarly, based on the analysis of payoffs of the firms in each supply chain, we derive the optimal information-sharing decisions $(X_1^*,\ X_2^*)$ in the space of $\{(m_1,\ m_2)|m_1 \geq m_2\}$ for each pair of γ and $t\sigma^2$. The results are shown in Figure 6.

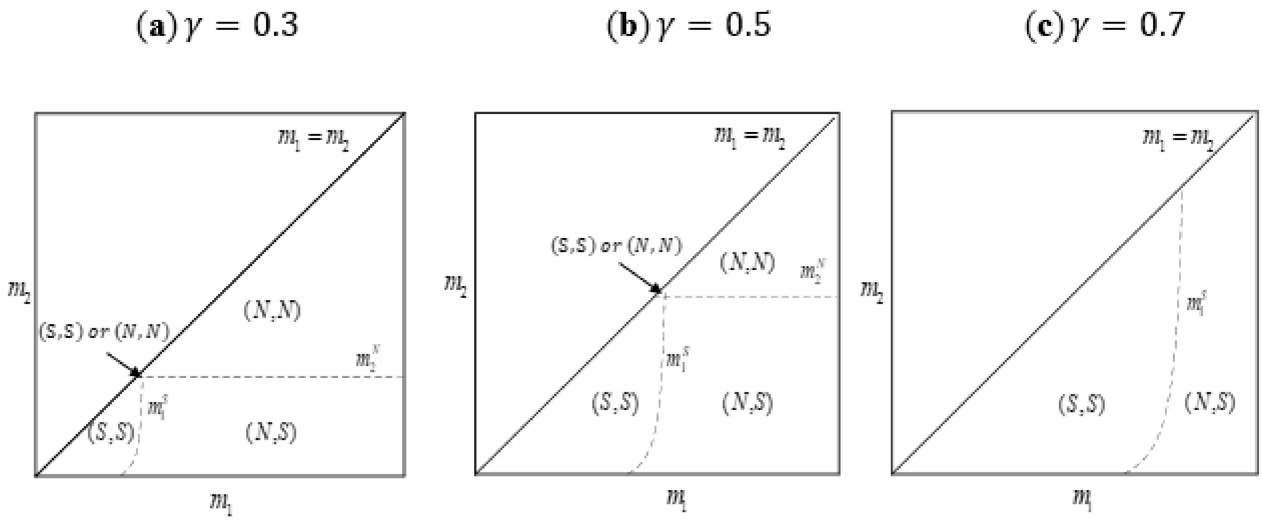

Figure 6. Information-sharing decisions under different consumer preferences ($a = 100$, $t\sigma^2 = 80$, $\lambda = 0.5$).

Similar to Figure 5, we find that there are multiple equilibrium strategies depending on the value of γ. Next, we also specifically analyse the equilibrium information-sharing strategy when $m_1 \geq m_2$. Information sharing in supply chain 2 is possible when either (1) $m_1 > m_1^S(m_2)$ and $m_2 < m_2^N(m_1)$ or (2) γ is larger and $m_1 > m_1^S(m_2)$. Additionally, as γ becomes larger, the region of $(S,\ S)$ becomes larger, while the regions of $(N,\ S)$ and $(N,\ N)$ become smaller and tend to disappear. Because consumers have more incentives to buy low-carbon products as their carbon preferences become higher, firms in each supply chain hope to accurately grasp the demand of consumers through information sharing. In this way, they can earn more profits by ordering more accurate quantities of the products.

From the above numerical analyses, we can see that our main results derived from Section 5 qualitatively still hold. Moreover, when considering that the two supply chains are characterised by different carbon emissions reduction efficiency levels, we can see that the high efficiency supply chain is more inclined to achieve information-sharing agreement, especially when the competition intensity is significant. This result not only provides guidance for the supply chain on when achieving an information-sharing agreement is most beneficial, but also suggests that the government should improve the consumer's environmental consciousness and invest in common technologies for carbon emissions reduction. In this way, the supply chain would more likely be communicated, and the manufacturer would invest more in reducing carbon emissions. Eventually, the carbon emissions of the supply chain would reduce significantly.

7. Conclusions

7.1. Summary

As competition is changing from firm level to supply chain level and concerns about the low-carbon economy are increasing, the operational and carbon emissions reduction joint decision has become an important problem. In this research, we focus on retailer's incentive for information sharing in competing supply chains when the manufacturer makes both wholesale price and carbon emissions reduction investment decisions, and how this incentive depends on the efficiency of the carbon emissions reduction, the accuracy of the information, the intensity of competition, and the consumer's low-carbon preference. By analysing the impact of information sharing on both economic and environmental benefits, we obtain the following insights.

When there are two identical supply chains, we establish a theoretical model and derive the equilibriums of the game under different conditions and analyse the equilibrium results. Our results show the following: (1) Whether information sharing occurs in the supply chain and whether manufacturers need to pay information fees to retailers depends on the relative size of the carbon emissions reduction efficiency and the consumer's low-carbon products preference. More specifically, when the consumer's preference for low-carbon emissions products is strong or carbon emissions reduction efficiency is high, both the retailer and manufacturer would benefit from information sharing, and the retailer will spontaneously share demand information with manufacturers. Therefore, the manufacturer's ability to efficiently reduce carbon emissions and the consumer's high preference for low-carbon products would be valuable because it would encourage retailers to share private information to achieve a win–win situation. (2) There is an environmental effect of information sharing. Our results reveal that information sharing will stimulate the manufacturer to invest more in reducing the product's carbon emissions. Information sharing allows the manufacturer to adjust their carbon emissions level according to the demand signal and ultimately benefit the environment. In addition, when the two supply chains differ in their carbon emissions reduction efficiencies, our numerical results further confirm the insights we obtain from identical supply chains and show that a higher carbon emissions reduction efficiency, a higher low-carbon preference, and a lower competitive intensity will result in more incentives for firms to share information. (3) In a competitive supply chain environment, there exist two effects of information sharing under Cournot competition: a direct effect and a competitive effect. While the direct effect is positive when the manufacturer's efficiency of carbon emissions reduction or the customer's low-carbon products preference is relatively high, the competitive effect is also positive when these two factors further increase. The supply chain will benefit from information sharing when the direct effect exceeds the competitive effect, and vice versa.

7.2. Theoretical Contributions and Managerial Implications

This study contributes to the existing literature in two main aspects. First, this research investigates information sharing in the competitive supply chain with consideration of carbon emissions reduction factors. Specifically, we focus on the effects of the efficiency of carbon emissions reduction, the customer's low-carbon products preference, and competition intensity among the supply chain members' incentive to share demand information. In addition, for the research on carbon emissions reduction, we consider how retailers sharing low-carbon product demand information with manufacturers impacts the manufacturers' carbon emissions reduction decisions in two competitive supply chain environments. To the best of our knowledge, this issue has not yet been considered in the literature.

There are many important management implications from our results. First, as the low-carbon economy develops, and with consumers becoming more conscious about global warming and more inclined to buy more low-carbon products, the retailer is more likely to voluntarily disclose their demand information to the manufacturer. Therefore, the manufacturer and the whole supply chain will benefit. Moreover, information sharing will stimulate the manufacturer to spend more on developing low-carbon products, thus further promoting the development of the low-carbon economy. Second, from the perspective of government, it should take measures to promote the development of the low-carbon economy, such as improving people's environmental consciousness, increasing consumers' desire to buy low-carbon products through subsidies, and/or enhancing research to reduce the cost of developing low-carbon products.

In practice, in order to realise information sharing within the supply chain, supply chain members need to take several actions. Firstly, the retailer and the manufacturer should reach an agreement that consists of the payment form, the amount of the payment, and the type of information to share. There are two types of cost when sharing information: fixed costs (infrastructure investments, information-sharing system construction costs, etc.) and variable costs (including information collection and transmission costs). Although these costs may be high, the results from our research and prior research, as well as many practices, show that the value of information sharing is enormous and that these costs are worthwhile, with the supply chain greatly benefiting from information sharing.

7.3. Future Research Directions

There are a few limitations of but also future research directions for this study. One of the limitations is that we do not consider many other types of information sharing, such as the consumer's low-carbon product preference or the manufacturer's cost of reducing products' carbon emissions. Considering these issues in the model would involve calculating the higher moments of the stochastic variables and would add much more complexity. Moreover, another future research direction is to take different supply chain structures into account, such as the manufacturer facing multiple competing retailers or multiple competing manufacturers facing one retailer. In addition, as two mostly utilised tools in regulating carbon emissions reduction, incorporating the cap-and-trade mechanism or carbon tax into the model and analysing the effects of these regulations on supply chain members' information-sharing decisions would also be an interesting direction. We shall address these issues in future research.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142013086/s1, File S1: Proofs of the Propositions.

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