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Article

The Carbon Subsidy Analysis in Remanufacturing Closed-Loop Supply Chain

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Abstract: Carbon subsidy is an important measure for the government to encourage enterprises to reduce carbon emission. This paper analyzes the impact of carbon subsidy on remanufacturing closed-loop supply chain (RCLSC). We explore the profits and the carbon emission quantities of three types of a supply chain: forward supply chain, remanufacturing closed-loop supply chain, and RCLSC with the carbon subsidy. This paper also discusses when and how the government implements the policy of carbon subsidy to encourage an enterprises' behavior of cutting carbon emission from the view of RCLSC. We provide the close form of the conditions under which the government should implement the carbon subsidy strategy and the carbon subsidy of government could increase the profits of agents of the supply chain and deduce the carbon emission of the whole supply chain simultaneously. It is found that the government should implement the carbon subsidy strategy only when the recycling price is within a certain range, and the carbon subsidy of government should be within a reasonable range.

Keywords: low-carbon economy; remanufacturing; closed-loop supply chain; carbon emission; carbon subsidy

1. Introduction

Recently, global warming has become an important environmental problem that the world faces. One measure to slow down the global warming trend is to reduce the emission of greenhouse gases, such as carbon dioxide (CO_2). A series of concepts, related to low-carbon, have emerged. These concepts have more and more impacts on governments, enterprises, and related policy-makers around the world [1]. For example, many famous enterprises have regarded reducing carbon emission and offering carbon-labeled products as the development direction of measuring corporate social responsibility and realizing a new leap. Simultaneously, many governments have put low-carbon economy in a high strategic position and have formulated some policies, such as carbon subsidy, to encourage enterprises to reduce carbon emission.

In the life cycle of a unit product, the accumulated CO_2 equivalent released from raw materials, production process, to the final disposition, is called the product's carbon footprint. From the definition of the carbon footprint, it can be found that the carbon footprint of a product is related to its entire supply chain. In order to reduce carbon emission, enterprises need to consider the whole supply chain. Especially, if the waste products in a supply chain can be recycled for remanufacturing new products, which is called closed-loop supply chain, carbon emission should be able to be reduced dramatically.

Closed-loop supply chain management has attracted more and more attention from enterprises, many companies, such as IBM, Ford, Kodak, Xerox, Caterpillar, Muji, and Timberland, have established remanufacturing and recycling systems, and achieved important successes. Closed-loop supply chain management has the following advantages. Firstly, environmental legislation compels enterprises to be responsible for the products that maybe cause environmental pollution. Secondly, consumers are given more rights, such as returning products that do not satisfy the demand of consumers to retailers. Lastly, enterprises have realized that building reasonable closed-loop supply chain system can raise revenue and explore new markets [2]. Guide and van Wassenhove considered closed-loop supply chain as the means of creating value, as much as possible, by systematic design, control, and operation [3]. In addition, considering the whole life cycle of products, and using different manners of product recycling, are also advantages of a closed-loop supply chain. Closed-loop supply chain management is the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value [4].

There is plenty of literature on the structure of closed-loop supply chains. Savaskan *et al.* analyzed the optimal channel structure of a closed-loop supply chain [5]. They proved that the reverse logistics channel, controlled by retailers, is better than that controlled by manufacturers, even better than those controlled by the third party logistics. Savaskan and van Wassenhove studied the interaction between reverse channel selection and product pricing strategy. They found that the channel profit of a supply chain depends on the influence of the recycling effort in the direct channel that the manufacturer engages in recycling, and the competition degree among retailers in the indirect channel [6]. Paksoy *et al.* considered a closed-loop supply chain network problem, which is related to the trade-offs between operational and environmental performance measures. They discovered that costs of environmental impacts are still not as apparent as operational measures. As such, the use of reusable products seems to lessen the operational costs of the supply chain but places a burden on the environmental costs [7]. Thierry *et al.* proposed that the reuse manners of recycling products mainly divided into reusing directly, repairing, regeneration, and remanufacturing [8]. Qiu and Huang summarized the network structure of a closed-loop supply chains into four types: reusing, remanufacturing, recycling, and commercial return. In these four types of closed-loop supply chains, reusing, remanufacturing, and recycling are closely related to low-carbon economy [9]. Choi *et al.* considered a supply chain consisting of a retailer, a collector, and a manufacturer. They examined the performance of different closed-loop supply chains under different channels of leadership [10]. Ramezani *et al.* presented a robust design model for a multi-product, multi-echelon, closed-loop logistic network, in an uncertain environment [11]. Zhang *et al.* examined a dynamic capacitated production-planning problem for a steel enterprise, and presented a closed-loop supply chain with the remanufacturing model [12]. We focus on the remanufacturing closed-loop supply chain (RCLSC) in this paper.

Remanufacturing closed-loop supply chain has received increasing attention from academia due to its good performance in increasing profit and improving the environment. Ferrer and Swaminathan found that if the profits of remanufacturing are very impressive, a manufacturer may abandon some marginal profits of the first period to a lower price and increase the remanufacturing amount of products of the second period. If the competition becomes more intensive, a manufacturer may lower the sale price of remanufacturing products [13]. Majumder and Groenevelt proposed a two-period supply chain model among competitive remanufacturers. They suggested that incentives should be provided to original equipment manufacturers to enhance the percentage of remanufacturing or to decrease the cost of remanufacturing [14]. Mitra and Webster analyzed a two-period supply chain model, including the competition between a manufacturer and a remanufacturer. They found that different subsidy strategies bring different effects to manufacture and remanufacture activities [15]. Yi presented three RCLSC game models: the Stackelberg models leaded by the manufacturer and retailer, and the Nash equilibrium model between the manufacturer and retailer. Under the different game structures, the author studied the scenario that a manufacturer gives a subsidy to a retailer according to two factors: one is the recycling behavior, the other is the impact of the subsidy on retail price and the rate of product recycling [16]. In addition, some papers incorporated the reward-penalty mechanism of government into the research of RCLSC. Guan *et al.* built a multiple-echelon RCLSC model in which a third party is responsible for recycling. They designed a reward-penalty function between the government and the manufacturer. Then, they discussed the optimal strategy in three scenarios. They also analyzed the impact of parameter changes on the recycling rate and enterprises' income [17]. Wang and Da studied the decision-making problem of the collection and remanufacturing of electronic products. Assuming that the manufacturer is responsible for the recycling of electronic products, they designed a reward-penalty mechanism that gives the lowest rate of recycling and the proper degree of reward on the basis of the recycling rate. They concluded that a manufacturer will recycle waste products only when remanufacturing has a cost advantage [18]. Wang *et al.* considered the government's penalty policy for a manufacturer and reward policy for a collector. They studied the influence of the parameters changing on the closed-loop supply chain equilibrium result by numerical examples [19]. In addition to carbon subsidy, there are other carbon policies, such as carbon emission trade and carbon tax. Hua *et al.* examined the EOQ model under the carbon emission trading mechanism, and investigated the impacts of carbon trade, carbon price, and carbon cap on order decisions, carbon emissions, and total cost [20]. Choi constructed a multi-period risk minimization inventory models for fashion product purchasing, and extended it to incorporate carbon emission tax and carbon quota [21]. Choi studied how to design a carbon footprint taxation scheme to enhance a QR system's environmental sustainability, such as employing a local manufacturer [22]. Choi studied a multi-stage optimal supplier selection problem in the fashion-apparel supply chain carbon emission tax [23].

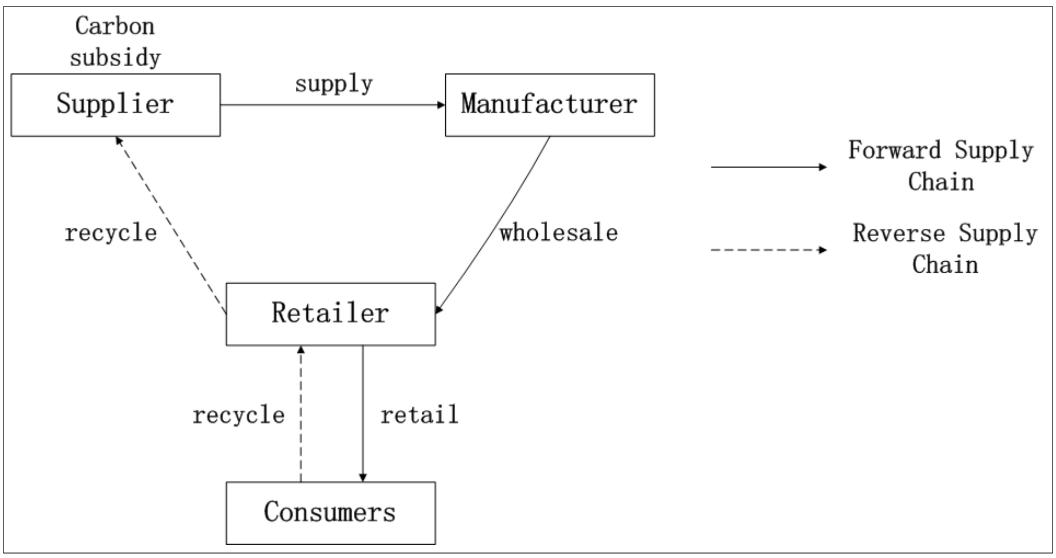
The above articles mainly studied the two-echelon closed-loop supply chain, consisting of a manufacturer and retailer. Most of them put emphasis on the impact of recycling quantity on recycling rate, retail price, and enterprises income. In addition, most of the previous papers analyzed the RCLSC from the perspective of economic benefits. The study from the perspective of environmental benefits has received much less attention. This paper investigates, not only the profit, but also the carbon emission of a three-echelon closed-loop supply chain, which includes supplier, manufacturer and retailer. We study the impact of remanufacturing and carbon subsidy on the profit and the carbon emission of a whole supply chain in three different scenarios.

The rest of this paper is organized as follows. The problem is introduced and formulated in Section 2. Section 3 analyzes the equilibrium strategy of the supply chain under three different scenarios. In Section 4, numerical results are presented to investigate the impact of remanufacturing and carbon subsidy. Conclusions and suggestions for future research are given in Section 5.

2. Model Assumption and Notations

In this paper, we study a three-echelon closed-loop supply chain consisting of a supplier, a manufacturer, and a retailer. The closed-loop supply chain consists of a forward supply chain and a reverse supply chain. The government, as the fourth party, provides a carbon subsidy to the supplier according to the reducing quantity of carbon emission. In the forward supply chain, the supplier can produce raw materials directly from nature or from waste products. The manufacturer gets the raw materials from the supplier and sells products to the retailer. Then, the retailer can sell products to consumers. In the reverse supply chain, the retailer needs to recycle waste products from consumers and sell them to the supplier. After that, the supplier can use the waste products to produce raw materials (Figure 1)

Figure 1. CLSC model with remanufacturing and carbon subsidy.



In addition, the following assumptions are made:

Assumption 1. $D(p_r) = \alpha - \beta p_r$, where both α and β are positive constants subject to $\alpha > \beta p_r$.

Assumption 2. The RCLSC model is analyzed in a single-period framework.

Assumption 3. The information among supply chain members is symmetric.

Assumption 4. For the convenience of calculation, this paper only considers carbon emission produced in the process of producing raw materials from nature, disposal of waste products, and manufacturing the final product. In addition, it is assumed that $E_s > E_m$.

Assumption 5. A unit waste product can be transformed to the amount of raw materials, which is needed to produce unit new product.

The above assumptions are not strict, in fact, these assumptions can be found in related literature. For example, Assumption 1 states that the demand is linear, which is one of the most popular demand functions in literature [10,24]. Assumption 2 was used in [22].

3. The Optimal Profits and Carbon Emission under Different Scenarios

In order to evaluate the performance of RCLSC in increasing profit and reflect the effect of carbon subsidy in reducing carbon emission, this section explores the performance of a supply chain in three different scenarios: forward supply chain, RCLSC, and RCLSC with a carbon subsidy.

3.1. Forward Supply Chain

In this scenario, the supplier produces raw materials from nature. Then, the manufacturer purchases raw materials from the supplier to produce final products. All products are wholesaled to the retailer. The retailer sells the final products to consumers. This is a dynamic game. The sequence of events is as follows. The supplier determines p_s firstly. Then, the manufacturer determines p_m according to p_s. Lastly, the retailer determines p_r according to p_m.

The expected profits of the supplier, the manufacturer, and the retailer are as follows:

$$\pi_s = (p_s - C_s)D(p_r) \tag{1}$$

$$\pi_m = (p_m - p_s - C_m)D(p_r) \tag{2}$$

$$\pi_r = (p_r - p_m)D(p_r) \tag{3}$$

Maximizing the above profits, we obtain the equilibrium price decisions of the game as follows:

$$p_s^* = \frac{\alpha}{2\beta} + \frac{C_s - C_m}{2} \tag{4}$$

$$p_m^* = \frac{3\alpha}{4\beta} + \frac{C_s + C_m}{4} \tag{5}$$

$$p_r^* = \frac{7\alpha}{8\beta} + \frac{C_s + C_m}{8} \tag{6}$$

The derivation of the equilibrium price decisions is provided in the following part. We use backwards induction to solve this dynamic games problem. According to the demand function, $D(p_r) = \alpha - \beta p_r$, and the profit function (3), we can conclude that:

$$\pi_r = (p_r - p_m)(\alpha - \beta p_r) = \alpha p_r - \beta p_r^2 - \alpha p_m + \beta p_m p_r \tag{7}$$

$$\frac{\partial \pi_r}{\partial p_r} = \alpha - 2\beta p_r + \beta p_m \tag{8}$$

Let $\frac{\partial \pi_r}{\partial p_r} = 0$, we have:

$$p_r^* = \frac{\alpha}{2\beta} + \frac{p_m}{2} \tag{9}$$

Substitute Formula (9) into profit function (2), we have:

$$\pi_m = \frac{\alpha}{2} p_m - \frac{\beta}{2} p_m^2 - \frac{\alpha}{2} p_s + \frac{\beta}{2} p_m p_s - \frac{\alpha}{2} C_m + \frac{\beta}{2} C_m p_m \tag{10}$$

$$\frac{\partial \pi_m}{\partial p_m} = \frac{\alpha}{2} - \beta p_m + \frac{\beta}{2} p_s + \frac{\beta}{2} C_m \tag{11}$$

Let $\frac{\partial \pi_m}{\partial p_m} = 0$, we have:

$$p_m^* = \frac{\alpha}{2\beta} + \frac{1}{2} p_s + \frac{1}{2} C_m \tag{12}$$

Substitute the formula (12) into the Formula (9), we have:

$$p_r^* = \frac{3\alpha}{4\beta} + \frac{1}{4} p_s + \frac{1}{4} C_m \tag{13}$$

Substitute the Formula (13) into the profit function (1), we have:

$$\pi_s = \frac{\alpha}{4} p_s - \frac{\beta}{4} p_s^2 - \frac{\beta}{4} C_m p_s - \frac{\alpha}{4} C_s + \frac{\beta}{4} C_s p_s + \frac{\beta}{4} C_s C_m \tag{14}$$

$$\frac{\partial \pi_s}{\partial p_s} = \frac{\alpha}{4} - \frac{\beta}{2} p_s - \frac{\beta}{4} C_m + \frac{\beta}{4} C_s \tag{15}$$

Let $\frac{\partial \pi_s}{\partial p_s} = 0$, we have:

$$p_s^* = \frac{\alpha}{2\beta} + \frac{C_s - C_m}{2} \tag{16}$$

Substitute the Formula (16) into the Formula (12), we have:

$$p_m^* = \frac{3\alpha}{4\beta} + \frac{C_s + C_m}{4} \tag{17}$$

Substitute the Formula (16) into the Formula (13), we have:

$$p_r^* = \frac{7\alpha}{8\beta} + \frac{C_s + C_m}{8} \tag{18}$$

Then the Formulas (16)–(18), consist of the equilibrium price decisions of the game.

Then we can get the corresponding profits of the supplier, the manufacturer, and the retailer as follows:

$$\pi_s^* = \frac{[\alpha - \beta(C_s + C_m)]^2}{16\beta} \tag{19}$$

$$\pi_m^* = \frac{[\alpha - \beta(C_s + C_m)]^2}{32\beta} \tag{20}$$

$$\pi_r^* = \frac{[\alpha - \beta(C_s + C_m)]^2}{64\beta} \tag{21}$$

The corresponding profit of the whole supply chain is given by:

$$\pi_t^* = \pi_s^* + \pi_m^* + \pi_r^* = \frac{7[\alpha - \beta(C_s + C_m)]^2}{64\beta} \tag{22}$$

The carbon emission quantities of the supplier and the manufacturer in the process of producing raw materials from nature and manufacturing final products are given by:

$$E_s = e_s D(p_r) \tag{23}$$

$$E_m = e_m D(p_r) \tag{24}$$

According to the equilibrium decision p_r^*, the corresponding carbon emission quantities of the supplier and the manufacturer are given by:

$$E_s^* = \frac{\alpha - \beta(C_s + C_m)}{8} e_s, \tag{25}$$

$$E_m^* = \frac{\alpha - \beta(C_s + C_m)}{8} e_m. \tag{26}$$

The corresponding carbon emission quantity of the whole supply chain is given by:

$$E_t^* = E_s^* + E_m^* = \frac{[\alpha - \beta(C_s + C_m)](e_s + e_m)}{8} \tag{27}$$

Based on the above analysis, there is the following result.

Theorem 3.1. In a forward supply chain, there exists the unique equilibrium price of the dynamic game, *i.e.*, $\left(p_s^* = \frac{\alpha}{2\beta} + \frac{C_s - C_m}{2}, p_m^* = \frac{3\alpha}{4\beta} + \frac{C_s + C_m}{4}, p_r^* = \frac{7\alpha}{8\beta} + \frac{C_s + C_m}{8} \right)$. The corresponding profits of the supplier, the manufacturer, the retailer, and the whole supply chain are $\pi_s^* = \frac{[\alpha - \beta(C_s + C_m)]^2}{16\beta}$, $\pi_m^* = \frac{[\alpha - \beta(C_s + C_m)]^2}{32\beta}$, $\pi_r^* = \frac{[\alpha - \beta(C_s + C_m)]^2}{64\beta}$, and $\pi_t^* = \frac{7[\alpha - \beta(C_s + C_m)]^2}{64\beta}$, respectively. The corresponding carbon emission quantities of the supplier, the manufacturer, the whole supply chain are given by $E_s^* = \frac{\alpha - \beta(C_s + C_m)}{8} e_s$, $E_m^* = \frac{\alpha - \beta(C_s + C_m)}{8} e_m$, and $E_t^* = \frac{[\alpha - \beta(C_s + C_m)](e_s + e_m)}{8}$, respectively.

3.2. Remanufacturing Closed-Loop Supply Chain

In the remanufacturing closed-loop supply chain, the supplier can choose to produce raw materials directly from nature or from the waste products. For convenience in calculating, we only consider one special case where all raw materials are produced by remanufacturing. In a reverse supply chain, the retailer needs to recycle waste products from consumers. Then the supplier pays the retailer for recycling the waste products. From recycling waste products to selling final products, the retailer not only needs to sell products but also has to recycle waste products. The sequence of events is as follows. The supplier determines p_s. Then, the manufacturer determines p_m according to p_s. Finally, the retailer determines p_r according to p_m.

The profits of the supplier, the manufacturer and the retailer are as follows:

$$\pi_s = p_s D(p_r) - (p_s^{'} + C_s^{'}) D(p_r), \tag{28}$$

$$\pi_m = (p_m - p_s - C_m) D(p_r), \tag{29}$$

$$\pi_r = (p_r - p_m) D(p_r) + (p_s^{'} - p_r^{'}) D(p_r). \tag{30}$$

The equilibrium price can be derived similarly as the derivation of the first scenario. The optimal price decisions are obtained as follows:

$$p_s^{**} = \frac{\alpha}{2\beta} + \frac{1}{2}(2p_s^{'} - p_r^{'} - C_m - C_s^{'}), \tag{31}$$

$$p_m^{**} = \frac{3\alpha}{4\beta} + \frac{1}{4}(4p_s^{'} - 3p_r^{'} + C_m - C_s^{'}), \tag{32}$$

$$p_r^{**} = \frac{7\alpha}{8\beta} + \frac{1}{8}(p_r^{'} + C_m - C_s^{'}). \tag{33}$$

Then, we can get the corresponding profits of the supplier, the manufacturer and the retailer as follows:

$$\pi_s^{**} = \frac{\left(\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})\right)^2}{16\beta} \tag{34}$$

$$\pi_m^{**} = \frac{\left(\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})\right)^2}{32\beta} \tag{35}$$

$$\pi_r^{**} = \frac{\left(\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})\right)^2}{64\beta} \tag{36}$$

The corresponding profit of the whole supply chain is given by:

$$\pi_t^{**} = \pi_s^{**} + \pi_m^{**} + \pi_r^{**} = \frac{7\left(\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})\right)^2}{64\beta} \tag{37}$$

In this scenario, carbon emission is produced in the process of producing raw materials from waste products and manufacturing. The carbon emission quantities of the supplier and the manufacturer are given by:

$$E_s = e_s^{'} D(p_r) \tag{38}$$

$$E_m = e_m D(p_r) \tag{39}$$

According to the equilibrium decision p_r^{**}, the optimal carbon emission quantities of the supplier and the manufacturer are given by:

$$E_s^{**} = \frac{\alpha}{8} e_s^{'} - \frac{\beta}{8}(p_r^{'} + C_m - C_s^{'})e_s^{'} \tag{40}$$

$$E_m^{**} = \frac{\alpha}{8} e_m - \frac{\beta}{8}(p_r^{'} + C_m - C_s^{'})e_m \tag{41}$$

The corresponding carbon emission quantity of the whole supply chain is given by:

$$E_t^{**} = E_s^{**} + E_m^{**} = \frac{1}{8}[\alpha - \beta(p_r^{'} + C_m - C_s^{'})](e_s^{'} + e_m) \tag{42}$$

Theorem 3.2. In a remanufacturing closed-loop supply chain, there exists the unique equilibrium of the game, *i.e.*, $\left(p_s^* = \frac{\alpha}{2\beta} + \frac{2p_s^{'} - p_r^{'} - C_m - C_s^{'}}{2}, p_m^* = \frac{3\alpha}{4\beta} + \frac{4p_s^{'} - 3p_r^{'} + C_m - C_s^{'}}{4}, p_r^* = \frac{7\alpha}{8\beta} + \frac{p_r^{'} + C_m - C_s^{'}}{8} \right)$. The corresponding profits of the supplier, the manufacturer, the retailer, and the whole supply chain are $\pi_s^* = \frac{[\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})]^2}{16\beta}$, $\pi_m^* = \frac{[\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})]^2}{32\beta}$, $\pi_r^* = \frac{[\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})]^2}{64\beta}$, and $\pi_t^* = \frac{7[\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})]^2}{64\beta}$, respectively. The corresponding carbon emission quantities of the supplier, the manufacturer, the whole supply chain are given by $E_s^* = \frac{\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})}{8} e_s$, $E_m^* = \frac{\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})}{8} e_m$, and $E_t^* = \frac{[\alpha\text{-}\beta(p_r^{'} + C_m - C_s^{'})](e_s + e_m)}{8}$, respectively.

3.3. Remanufacturing Closed-Loop Supply Chain with Carbon Subsidy

In order to encourage enterprises to participate in carbon emission reduction activities, the government would provide a carbon subsidy to the members of a supply chain. In this paper, it is supposed that the government only provides a carbon subsidy to the supplier. The workflow of RCLSC does not change but the fund flow does. The sequence of events and the decision variables are the same as in the second scenario.

The expected profits of the supplier, the manufacturer and the retailer are as follows:

$$\pi_s = p_s D(p_r) - (p_s^{'} + C_s^{'})D(p_r) + s(e_s - e_s^{'})D(p_r) \tag{43}$$

$$\pi_m = (p_m - p_s - C_m)D(p_r) \tag{44}$$

$$\pi_r = (p_r - p_m)D(p_r) + (p_s^{'} - p_r^{'})D(p_r) \tag{45}$$

The equilibrium price decisions are obtained as follows:

$$p_s^{***} = \frac{\alpha}{2\beta} + \frac{1}{2}[2p_s^{'} - p_r^{'} - C_m + C_s^{'} - s(e_s - e_s^{'})] \tag{46}$$

$$p_m^{***} = \frac{3\alpha}{4\beta} + \frac{1}{4}[4p_s^{'} - 3p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})] \tag{47}$$

$$p_r^{***} = \frac{7\alpha}{8\beta} + \frac{1}{8}[p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})] \tag{48}$$

Then, we can obtain the corresponding profits of the supplier, the manufacturer, and the retailer as follows:

$$\pi_s^{***} = \frac{\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)^2}{16\beta} \tag{49}$$

$$\pi_m^{***} = \frac{\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)^2}{32\beta} \tag{50}$$

$$\pi_r^{***} = \frac{\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)^2}{64\beta} \tag{51}$$

The corresponding profit of the whole supply chain is:

$$\pi_t^{***} = \pi_s^{***} + \pi_m^{***} + \pi_r^{***} = \frac{7\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)^2}{64\beta} \tag{52}$$

Inspired by the carbon subsidy, the supplier will engage in the remanufacturing work positively. The function of carbon emission quantity does not change. The carbon emission quantities of the supplier and the manufacturer are given by:

$$E_s = e_s^{'} D(p_r) \tag{53}$$

$$E_m = e_m D(p_r) \tag{54}$$

According to the equilibrium decision p_r^{***}, the corresponding carbon emission quantities of the supplier and the manufacturer are given by:

$$E_s^{***} = \frac{\alpha}{8} e_s^{'} - \frac{\beta}{8} e_s^{'}[p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})] \tag{55}$$

$$E_m^{***} = \frac{\alpha}{8} e_m - \frac{\beta}{8} e_m [p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})] \tag{56}$$

The corresponding carbon emission quantity of the whole supply chain is given by:

$$E_t^{***} = E_s^{***} + E_m^{***} = \frac{1}{8}\left\{\alpha - \beta[p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})]\right\}(e_s^{'} + e_m) \tag{57}$$

Theorem 3.3. In a remanufacturing closed-loop supply chain with carbon subsidy, there exist unique equilibrium prices of the dynamic game, *i.e.*,

$(p_s^{***} = \dfrac{\alpha}{2\beta} + \dfrac{2p_s^{'} - p_r^{'} - C_m + C_s^{'} - s(e_s - e_s^{'})}{2}, p_m^{***} = \dfrac{3\alpha}{4\beta} + \dfrac{4p_s^{'} - 3p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})}{4},$
$p_r^{***} = \dfrac{7\alpha}{8\beta} + \dfrac{p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})}{8})$.

The corresponding profit of the supplier, the manufacturer, the retailer, and the whole supply chain are $\pi_s^{***} = \dfrac{\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)^2}{16\beta}$, $\pi_m^{***} = \dfrac{\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)^2}{32\beta}$, $\pi_r^{***} = \dfrac{\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)^2}{64\beta}$, and $\pi_t^{***} = \dfrac{7\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)^2}{64\beta}$, respectively. The corresponding carbon emission quantities of the supplier, the manufacturer, the whole supply chain are $E_s^{***} = \dfrac{\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)}{8} e_s^{'}$, $E_m^{***} = \dfrac{\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)}{8} e_m$, and $E_t^{***} = \dfrac{\left(\alpha\text{-}\beta\left(p_r^{'} + C_m + C_s^{'} - s(e_s - e_s^{'})\right)\right)(e_s^{'} + e_m)}{8}$, respectively.

3.4. Selection between the Three Scenarios

In the three scenarios, the equilibrium prices, the corresponding profits, and the corresponding carbon emission quantities are obtained, respectively. It is interesting to investigate the following important research questions: (i) Which scenario do the agents of the supply chain prefer? (ii) When and how does the government provide the subsidy? By comparing the corresponding profits and carbon emission quantities, it is straightforward to obtain the following theorem that presents the conditions under which the agent of the supply chain selects one certain type of scenarios and the subsidy strategy of the government.

Theorem 3.4. In each scenario, the profits of every agent of supply chain and the whole supply chain are coincident with each other.

(i) If $p_r^{'} - c_s^{'} \le c_s$, every agent of the supply chain will prefer the remanufacturing closed-loop supply chain to the forward supply chain since they can obtain more profit.
(ii) If $2c_s^{'} \le s(e_s - e_s^{'})$, every agent of the supply chain will prefer the remanufacturing closed-loop supply chain with the carbon subsidy to the remanufacturing closed-loop supply chain since they can obtain more profit.

(iii) If $p_r^{'} + c_s^{'} \le c_s + s(e_s - e_s^{'})$, every agent of the supply chain will prefer the remanufacturing closed-loop supply chain with carbon subsidy to the forward supply chain since they can obtain more profit.

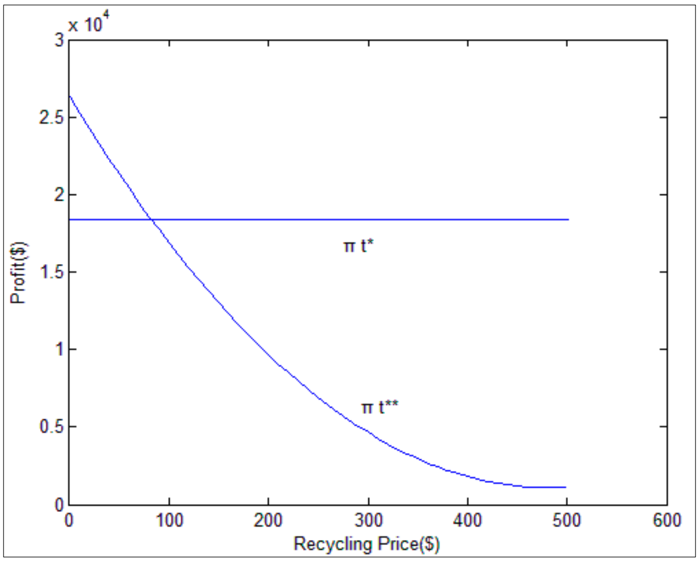
Theorem 3.5. Only if $p_r^{'} - c_s^{'} > c_s$, the government should provide the carbon subsidy to encourage the supplier to select the remanufacturing technology. If and only if $\frac{p_r^{'} - C_s + C_s^{'}}{e_s - e_s^{'}} \le s \le \frac{[\alpha - \beta(C_s + C_m)](e_s + e_m)}{\beta(e_s - e_s^{'})(e_s^{'} + e_m)} - \frac{\alpha - \beta\left(p_r^{'} + C_m + C_s^{'}\right)}{\beta(e_s - e_s^{'})}$, the subsidy can increase the profits of agents of the supply chain and deduce the carbon emission of the whole supply chain simultaneously.

4. Numerical Examples

In this section, some numerical examples are used to examine the impact of remanufacturing and carbon subsidy. Based on the previous analysis, we can compare the profits and carbon emission quantities in different scenarios.

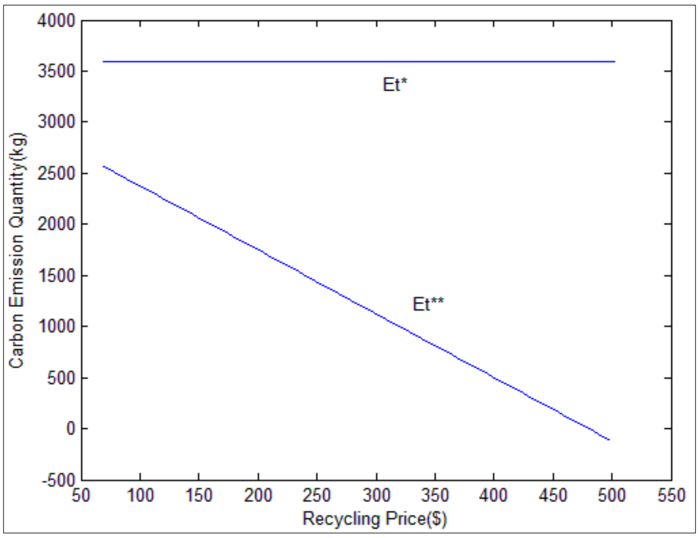
Let $C_s = \$40$; $C_s^{'} = \$30$; $C_m = \$50$; $\alpha = 500$; $\beta = 1$; $e_s = 40kg$; $e_s^{'} = 20kg$; $e_m = 30kg$. In the first scenario, $\pi_t^* = \$18385.9$ and $E_t^* = 3587.5kg$. To compare with the first scenario, we consider the second scenario. Given the actual situation, $p_r^{'}$ should satisfy $p_r^{'} < p_r^{**}$. At the same time, the recycling price should be higher than \$0. Then, the range of suitable recycling price is (\$0, \$502.8). We reflect the profit change of the whole supply chain, of two scenarios, in Figure 2.

Figure 2. Profits of forward supply chain and RCLSC.



The intersection point in Figure 2 is $p_r^{'} = \$68.8$. As the figure shows, $\Pi_t^{**} < \Pi_t^*$ when $p_r^{'} \in (\$68.8, \$502.8)$. Under this condition, we reflect the carbon emission quantities of the whole supply chain in Figure 3.

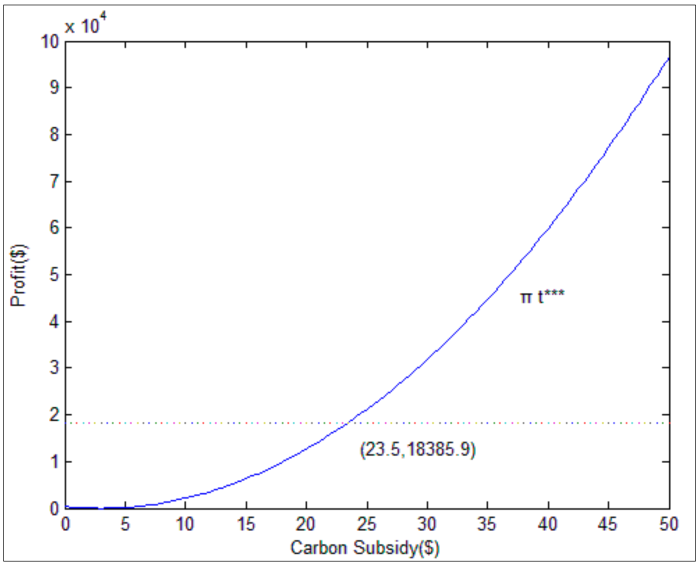
Figure 3. Carbon emission quantities of forward supply chain and RCLSC.



We can observe that $E_t^{**} < E_t^{*}$ when $p_r^{'} \in (\$68.8, \$502.8)$. In order to reduce carbon emission of the whole supply chain more, and make profit higher, the government needs to implement the carbon subsidy strategy. The ultimate objective is to reduce the carbon emission quantity of a whole supply chain on the basis of increasing profit.

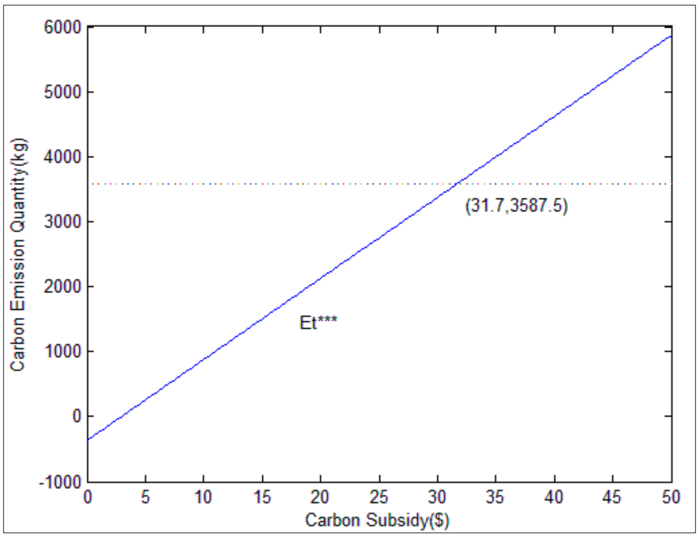
From the above observation, it can be found that the overall profit of the second scenario is the lowest when $p_r^{'} = \$480$. On the base of that, we investigate the impact of the subsidy to the supplier in terms of profit. The results are reflected in Figure 4.

Figure 4. Change of RCLSC's profit with respect to the carbon subsidy.



The intersection point in Figure 4 denotes the profit equality of forward supply chain and RCLSC with a carbon subsidy. If we want the profit of RCLSC to be more than the profit of the forward supply chain, a carbon subsidy should satisfy $s > \$23.5$. The members of the supply chain are willing to take part in remanufacturing only when profit increases. Under this condition, we explore the impact of the carbon subsidy on the carbon emission quantity of the whole supply chain in Figure 5.

Figure 5. Change of RCLSC's carbon emission quantity with respect to the carbon subsidy.



From Figure 5, we can observe that the carbon emission quantity is increasing in carbon subsidy. In addition, $E_t^{***} \geq E_t^*$ when $s \geq \$31.7$. If we want the carbon emission quantity of RCLSC to be less than that of a forward supply chain, s should satisfy $s < \$31.7$. In RCLSC, the reasonable range of a carbon subsidy is $s \in (\$23.5, \$31.7)$. At this time, the profit of RCLSC is greater than that of a forward supply chain. Additionally, the carbon emission quantity of RCLSC is less than that of a forward supply chain.

Based on the above observations, it can be found that the overall profit of RCLSC is lower than the overall profit of a forward supply chain when the recycling price is in a range. In addition, the carbon emission quantity is decreasing in the recycling price. When the recycling price belongs to this range, the government needs to use carbon subsidy strategy to enhance the profit of RCLSC. The strategy needs to make sure that the profit of RCLSC is greater than, and the carbon emission quantity is less than, those of the forward supply chain, respectively. Based on the above analysis, it can be found that the carbon subsidy should be implemented only when it belongs to a reasonable range.

5. Conclusions

A reasonable strategy of carbon subsidy is important to reduce carbon emission. The carbon subsidy of a government can form an incentive mechanism, which can reduce carbon emission and increase profits at the same time.

In this paper, we study a three-echelon supply chain, including a supplier, a manufacturer, and a retailer. We explore the profits and the carbon emission quantities of three types of supply chains: forward supply chain, remanufacturing closed-loop supply chain, and RCLSC with the carbon subsidy. We also develop the theoretical analysis of when and how the subsidy should be provided by the government. We provide the close form of the conditions under which the government should implement the carbon subsidy strategy, and the specific interval that the carbon subsidy of government should belong to. It is found that the government should implement the carbon subsidy strategy only when the recycling price falls in a certain range.

Collection of carbon tax is another popular trend of low-carbon economy. Governments can make a carbon subsidy strategy be complementary to carbon tax. In addition, it also provides a formula for the reasonable use of carbon tax. How to use carbon subsidy and carbon tax together is a valuable future research direction.

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Author Contributions

Jian Li contributed to questionnaire development and trade-off between the different scenarios. Weihao Du contributed to writing of the paper and results analysis of manuscript. Fengmei Yang is responsible for conducting this research. Guowei Hua contributed to the application of game theory in this paper and the revisions.

Abbreviation

The following notations are used in this paper:

C_s	unit cost of producing raw materials from nature;
$C_s^{'}$	unit cost of disposing waste products;
C_m	unit cost of manufacturing final product;
p_s	sale price of raw materials for manufacturing unit product that is determined by the supplier;
p_m	wholesale price of unit product determined by the manufacturer;
p_r	retail price of unit product determined by the retailer, $p_r > p_m > p_s > 0$;
$D(p_r)$	customer demand depends on p_r;
$p_r^{'}$	unit recycling price when the retailer recycles the waste products from consumers;
$p_s^{'}$	unit recycling price when the supplier recycles the waste products from retailer;
s	unit carbon subsidy that government provides to the supplier according to the carbon emission quantity reduced in the process of manufacturing raw materials;
e_s	carbon emission quantity produced by the supplier in the process of producing raw materials from nature that meet the demand of manufacturing unit product;
$e_s^{'}$	carbon emission quantity produced by the supplier in the process of acquiring raw materials from waste products that meets the demand of manufacturing unit product;
e_m	carbon emission quantity produced by the manufacturer in the process of manufacturing unit product;

π_s, π_m, π_r and π_t — profit of the supplier, the manufacturer, the retailer, and the whole supply chain, respectively;

E_s, E_m and E_t — carbon emission quantity of the supplier, the manufacturer, and the whole supply chain, respectively.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Li, J.; Xu, F.; Hua, G.W. On low-carbon supply chain management. In Proceedings of the 13th International Conference on Enterprise Information Systems, Beijing, China, 8 June 2011.
2. Jo van Nunen, A.E.E.; Zuidwijk, R.A. E-enabled closed-loop supply chains. *Calif. Manag. Rev.* **2004**, *46*, 40–54.
3. Guide, V.D.R., Jr.; van Wassenhove, L.N. Closed-loop supply chains: An introduction to the feature issue (Part1). *Prod. Oper. Manag.* **2006**, *15*, 345–350.
4. Guide, V.D.R., Jr.; van Wassenhove, L.N. The evolution of closed-loop supply chain research. *Oper. Res.* **2009**, *57*, 10–18.
5. Savaskan, R.C.; Bhattacharya, S.; van Wassenhove, L.N. Closed-loop supply chain models with product remanufacturing. *Manag. Sci.* **2004**, *50*, 239–252.
6. Savaskan, R.C.; van Wassenhove, L.N. Reverse channel design: the case of competing retailers. *Manag. Sci.* **2006**, *52*, 1–14.
7. Paksoy, T.; Bektaş, T.; Özceylan, E. Operational and environmental performance measures in a multi-product closed-loop supply chain. *Transport. Res. E-Log.* **2011**, *47*, 532–546.
8. Thierry, M.C.; Saloman, M.; van Nunen, J.; van Wassenhove, L. Strategic issues in product recovery management. *Calif. Manag. Rev.* **1995**, *37*, 114–135.
9. Qiu, R.Z.; Huang, X.Y. The progress of studies on structure of the closed-loop supply chain. *Manag. Rev.* **2007**, *19*, 49–55.
10. Choi, T.M.; Li, Y.J.; Xu, L. Channel leadership, performance and coordination in closed loop supply chains. *Int. J. Prod. Econ.* **2013**, *146*, 371–380.
11. Ramezani, M.; Bashiri, M.; Tavakkoli-Moghaddam, R. A robust design for a closed-loop supply chain network under an uncertain environment. *Int. J. Adv. Manuf. Tech.* **2013**, *66*, 825–843.
12. Zhang, J.; Liu, X.; Tu, Y.L. A capacitated production planning problem for closed-loop supply chain with remanufacturing. *Int. J. Adv. Manuf. Tech.* **2011**, *54*, 757–766.
13. Ferrer, G.; Swaminathan, J.M. Managing new and remanufactured products. *Manag. Sci.* **2006**, *52*, 15–26.
14. Majumder, P.; Groenevelt, H. Competition in manufacturing. *Prod. Oper. Manag.* **2001**, *10*, 125–141.
15. Mitra, S.; Webster, S. Competition in remanufacturing and the effects of government subsidies. *Int. J. Prod. Econ.* **2008**, *111*, 287–298.
16. Yi, Y.Y. Closed-loop supply chain game models with product remanufacturing. *Syst. Eng. Theor. Pract.* **2009**, *29*, 28–35.

17. Guan, Q.L.; Zhou, G.G.; Cao, J. Government constrained decision making model in recycling and remanufacturing closed-loop supply chain. *Ind. Eng. J.* **2009**, *12*, 40–44.
18. Wang, W.B.; Da, Q.L. The decision-making model of the electronic product manufacturer about collection and remanufacturing based on premium and penalty mechanism. *Chin. J. Manag. Sci.* **2008**, *16*, 57–63.
19. Wang, W.B.; Da, Q.L.; Hu, T.B.; Yang, G.F. Remanufacturing closed-loop supply chain network equilibrium model based on allowance and penalty. *Oper. Res. Manag. Sci.* **2010**, *19*, 65–72.
20. Hua, G.W.; Cheng, T.C.E.; Wang, S.Y. Managing carbon footprints in inventory management. *Int. J. Prod. Econ.* **2011**, *132*, 178–185.
21. Choi, T.M. Multi-period risk minimization purchasing models for fashion products with interest rate, budget, and profit target considerations. *Ann. Oper. Res.* **2013**, doi:10.1007/s10479-013-1453-x.
22. Choi, T.M. Local sourcing and fashion quick response system: The impacts of carbon footprint tax. *Transport. Res. E-Log.* **2013**, *55*, 43–54.
23. Choi, T.M. Optimal apparel supplier selection with forecast updates under carbon emission taxation scheme. *Comput. Oper. Res.* **2013**, *40*, 2646–2655.
24. Chen, X.; Simchi-Levi, D. Pricing and inventory management. In *The Oxford Handbook of Pricing Management*; Philips, R., Ozalp, O., Eds.; Oxford University Press: Oxford, UK, 2012; pp. 784–822.