Differential Pricing Models on a Remanufacturing Supply Chain Considering Product Quality Upgrade under Carbon Trading Mechanism

Guangqiang Wu and Kaifu Yuan*
School of Business Administration, Guizhou University of Finance and Economics, Guiyang, China
*Corresponding author email: kaifuy@mail.gufe.edu.cn

Abstract. To study the influence of product quality upgrade on pricing decisions, a remanufacturing supply chain with a manufacturer and a retailer is investigated. Based on the carbon trading mechanism, differential pricing decision models for the remanufacturing supply chain without and with product quality upgrade are developed and solved by the backward induction through the mathematics and engineering calculation software maple18. Through the comparative analysis, we get the following results: (1) New product quality upgrade is beneficial to raise the sales price and expand market demand of new products and the profits of supply chain members and system, but it will increase total carbon emissions. (2) To reduce total carbon emission, the government should encourage enterprises to invest in emission reduction and guide consumers to buy remanufactured products.

Keywords: Remanufacturing supply chain; Differential pricing; Carbon trading; Product quality upgrade.

1. Introduction
At present, the manufacturing industry, as China’s pillar industry, faces two major problems: environmental pollution and industrial transformation and upgrading. Therefore, it is vital to coordinate the contradiction between environmental protection and economic development and improve the independent innovation capability of the manufacturing industry.

To reduce carbon emissions and enhance competitiveness, for manufacturers, on the one hand, they need to improve their independent innovation capabilities, and product quality upgrade is an effective way. Product quality upgrade refers to making products more competitive through measures such as product quality improvement, product performance improvement and product added value enhancement[1]. On the other hand, it is necessary to explore advanced production methods, and remanufacturing is an effective emission reduction production method. Remanufacturing refers to the batch production process of professionally repairing used automobile parts, construction machinery, machine tools, etc., and the quality and performance of remanufactured products is better than or as good as that of original new products (for short new products). However, due to low consumer acceptance of remanufactured products, their prices are lower than those of new products. In addition, under carbon cap and trading mechanism, by setting a cap on carbon emissions for every enterprise, total carbon emissions can be significantly reduced. Furthermore, carbon emission credits can be sold or bought in the carbon market. Obviously, when adopting carbon cap and trading mechanism and considering product quality upgrading, how to price new products and remanufactured products is an urgent problem to be solved.
2. Literature Review

Here, we only review the relevant literature on the influence of carbon trading mechanism and the product quality upgrade on supply chain pricing decision. Some scholars have studied the influence of carbon trading mechanism on the remanufacturing supply chain pricing decision. For an oligopolistic manufacturer, Chang et al established a manufacturing/remanufacturing production and pricing decision model under the carbon trading mechanism. The results showed that the carbon trading mechanism will affect the optimal production and pricing decisions[2]. Based on Chang et al. [2], considering consumers' low-carbon preferences and manufacturers' capital constraints, Chai et al. investigated their impact on pricing decision of the supply chain[3, 4]. Furtherly, introducing subsidy and carbon trading policies, Zhang et al studied the influence of these policies on pricing decisions of closed-loop supply chains[5].

Considering product quality upgrade, some scholars have studied the problems of supply chain pricing decisions. The work of Maiti et al. showed that product quality improvement is beneficial to enhance the supply chain member and system's profits[6]. Based on Maiti et al. [6], introducing the refurbished products, Christy et al discussed pricing decisions of the supply chain under different right structures[7]. Similarly, Giri et al further discussed the influence of two different coordination mechanisms on supply chain pricing decision-making[8]. Furtherly, considering two different sales channels, Taleizadeh et al investigated the pricing and quality decisions of supply chains, and argued that dual recycling channels under a dual sales channel are better[9]. Facing the increasing pressure on emission reduction, considering carbon emission reduction policies, Zhang et al studied the impact of product green innovation on manufacturer manufacturing/remanufacturing differential pricing under the carbon trading mechanism[10]. Based on Taleizadeh et al. [9], considering carbon emission reduction policy and different remanufacturing scenarios, Taleizadeh et al studied production and emission reduction decisions[11].

To sum up, literature [2]-[5] does not consider the impact of product quality upgrade, while literature [6]-[9] does not take into account the impact of carbon trading mechanism. Even though the literature [10] considers both carbon trading mechanism and product green upgrade, the product green upgrade focuses on the carbon emissions reduction while product quality upgrade focuses on the improvement of product quality in our paper. In addition, literature [11] takes into account the carbon trading mechanism and product quality efforts, but it assumes that new products are homogeneous with remanufactured products. Therefore, this paper assumes that new products and remanufacturing are heterogeneous, and studies the differential pricing of remanufacturing supply chain considering product quality upgrading and carbon trading mechanism.

3. Problem Description and Assumption

A remanufacturing supply chain considering quality upgrade of products under carbon trading mechanism is presented in Figure 1. The manufacturer produces new and remanufactured products (the production cost and carbon emissions per new (remanufactured) product are $c (c - s)$ and $e (e - w)$, where $s$ and $w$ represent unit production cost savings and carbon emission savings of the remanufactured product), and sell them to the retailer at the unit wholesale prices $w_n$ and $w_r$. Then, the retailer sells new and remanufactured products to customers at the unit retail prices $p_n$ and $p_r$.

Facing the increasing pressure on emissions reduction and competition, the manufacturer upgrades the quality of new products, where quality levels of new products before and after the quality upgrade are $q_0$ and $q_1$, and the one-time investment for quality upgrade is $K(q_1 - q_0)^2$, and $K$ represents the investment scale factor[12]. The manufacturer recycles and remanufactures used products, where the recycling cost per used product is $A$. Meanwhile, to decrease carbon emissions, a free carbon emissions quota $G$ is granted to the manufacturer. When the total carbon emissions of the manufacturer are greater (less) than $G$, the manufacturer can purchase insufficient carbon emissions rights (sell the excess carbon emissions rights) at the unit carbon trading price $p_c$ through the carbon trading market. The corresponding decision sequence is as follows: firstly, the manufacturer decides quality level of new products and wholesale prices of new and remanufactured products. Then, the retailer decides retail prices of new and remanufactured products.
To simplify the problem, the related assumptions are given as follows:

Assumption 1. Since remanufactured products have a clear remanufacture logo, new products and remanufactured products can easily be distinguished by consumers, and they are priced differently and sold in independent markets. What’s more, market capacities for new products and remanufactured products are \( \phi \) and \( (1 - \phi) \phi \), where \( \phi \) is the total market capacity and \( \phi \) is the proportion, \( 0 < \phi < 1 \).

Assumption 2. As the quality upgrading can improve the quality, function and utility of new products, it will have a positive impact on demand. Therefore, when upgrading new product quality, the demand for new products is \( D^N = \phi Q - ap_n + b(q_1 - q_0) \), where \( a \) is the consumer's sensitivity on new product price, \( b \) is the consumer's sensitivity on product quality variation, \( Q \) represents the case with quality upgrade, and the demand for remanufactured products is \( D^R = (1 - \phi)Q - ap_r \). When the manufacturer does not upgrade new product quality, the demand for new products is \( D^N = \phi Q - ap_n \), and the demand for remanufactured products is \( D^R = (1 - \phi)Q - ap_r \), where \( N \) represents the case without quality upgrade. \( \pi_i \) represents the corresponding profit, where \( i = M, R, T \) refer to the manufacturer, the retailer, and the system.

4. Model Construction and Solution

Case 1. Without quality upgrade (for short \( N \))

In case 1, the manufacturer does not upgrade new product quality. At this time, the demands for new and remanufactured products are:

\[
D^N = \phi Q - ap_n, \quad D^R = (1 - \phi)Q - ap_r. \tag{1}
\]

We get profits for the manufacturer and retailer as follows:

\[
\pi^M_N = (w_n - c)D^N + (w_r - c + s - A)D^R - p_c[eD^N + (e - w)D^R - G]. \tag{2}
\]

\[
\pi^R_N = (p_n - w_n)D^N + (p_r - w_r)D^R. \tag{3}
\]

Theorem 1. The optimal pricing decisions for the manufacturer and the retailer are \((w^N, p^N)\) and \((p^N, p^N)\). Then, substituting \(p^N, p^N\) into formula (1), we get the demand for new and remanufactured products \((D^N, D^R)\), where

\[
w^N = \frac{\phi Q + a(ep_c + c)}{2a}, \quad w^R = \frac{(1-\phi)Q + a[(e-w)p_r + (c-s) + A]}{2a}. \tag{4}
\]

\[
p^N = \frac{3\phi Q + a(ep_c + c)}{4a}, \quad p^R = \frac{3(1-\phi)Q + a[(e-w)p_r + (c-s) + A]}{2a}. \tag{5}
\]

\[
D^N = \frac{\phi Q - a(ep_c + c)}{4}, \quad D^R = \frac{(1-\phi)Q - a[(e-w)p_r + (c-s) + A]}{4}. \tag{6}
\]

Similarly, substituting \(w^N, w^R, p^N, p^R, D^N, D^R\) into formulae (2) and (3), we get the manufacturer profit and the retailer profit.

Case 2. With quality upgrade (for short \( Y \))

In case 2, the manufacturer upgrades new product quality, and we have the following demands for new products and remanufactured products:

\[
D^Y = \phi Q - ap_n + b(q_1 - q_0), \quad D^Y = (1 - \phi)Q - ap_r. \tag{7}
\]
We get the profit functions for the manufacturer and retailer as follows:

\[ \pi_M = (w_n - c)D_n^Y + (w_r - c - s - A)D_r^Y - p_c[eD_n^Y + (e - w)D_r^Y - G] - K(q_1 - q_0)^2. \quad (8) \]

\[ \pi_R = (p_n - w_n)D_n^Y + (p_r - w_r)D_r^Y. \quad (9) \]

**Theorem 2.** When \( b^2 < 8aK \), the optimal quality level of new products is \( q_1^Y \) and the optimal pricing decisions for the manufacturer and the retailer are \((w_n^Y, w_r^Y)\) and \((p_n^Y, p_r^Y)\). Then, substituting \( q_1^Y, w_n^Y, p_n^Y \) into formula (7), we get the demand for new and remanufactured products \((D_n^Y, D_r^Y)\) as follows:

\[ q_1^Y = q_0 + \frac{b[\varphi Q-a(ep_c+c)]}{8aK-b^2}. \quad (10) \]

\[ w_n^Y = \frac{4K[\varphi Q+a(ep_c+c)-b^2(ep_c+c)]}{8aK-b^2}, \quad w_r^Y = \frac{(1-\varphi)Q+a[(e-w)p_c+(c-s)+A]}{2a}. \quad (11) \]

\[ p_n^Y = \frac{2K[3\varphi Q+a(ep_c+c)-b^2(ep_c+c)]}{8aK-b^2}, \quad p_r^Y = \frac{3(1-\varphi)Q+a[(e-w)p_c+(c-s)+A]}{2a}. \quad (12) \]

\[ D_n^Y = \frac{2aK[\varphi Q-a(ep_c+c)]}{8aK-b^2}, \quad D_r^Y = \frac{(1-\varphi)Q-a[(e-w)p_c+(c-s)+A]}{4}. \quad (13) \]

Similarly, substituting \( q_1^Y, w_n^Y, w_r^Y, p_n^Y, p_r^Y, D_n^Y, D_r^Y \) into formulae (8) and (9), we get the manufacturer profit and the retailer profit.

**Comparison of case 1 and case 2**

When \( b^2 < 8aK \), by comparison, we get the following relationships between decision variables, market demand and profits.

**Corollary 1.** \( w_n^N < w_n^Y, \quad w_r^N < w_r^Y, \quad p_n^N < p_n^Y, \quad p_r^N = p_r^Y, \quad D_n^N < D_n^Y, \quad D_r^N = D_r^Y, \quad \pi_M^N < \pi_M^Y, \quad \pi_R^N < \pi_R^Y, \quad \pi_T^N < \pi_T^Y. \)

Corollary 1 indicates that compared with the case without quality upgrade, upgrading new product quality will be helpful to raise its sales price and market demand, which leads to the increase of the profits for the system and its members, but it causes total carbon emissions increase. Consequently, to enhance the profits for the system and its members, the manufacturer should upgrade new product quality. Of course, facing the increasing pressure for carbon emission reduction, the government should encourage enterprises to make an investment to reduce emission and guide consumers to buy more energy-saving and emission-reducing remanufactured products.

**5. Conclusion and Remarks**

Considering carbon trading mechanism, a remanufacturing supply chain with a manufacturer and a retailer is investigated. Differential pricing decision models for the remanufacturing supply chain without and with product quality upgrade are developed, and the corresponding formulae for decision variables are derived. By comparison, we get the following results: (1) Upgrading the quality of new products is helpful to raise their sales price and market demand, which make the profits for the system and its members and total carbon emissions increase. (2) To reduce total carbon emission, the government should encourage enterprises to invest in emission reduction and guide consumers to buy remanufactured products.

Although we only consider the case of new product quality upgrade here, the cases with the quality upgrade of remanufactured products or both need to be investigated in the future.

**Acknowledgement**

This research is financially supported by the National Natural Science Foundation of China [grant number 71661003] and the school-level project of Guizhou University of Finance and Economics [grant number 2019ZXSY15].

**References**

[1] Y.S. Mao, J.C. Wang, Research on independent innovation path based on product upgrade, Management World. 05 (2006) 114-120.
[2] X. Chang, H. Xia, H. Zhu, et al., Production decisions in a hybrid manufacturing-remanufacturing system with carbon cap and trade mechanism, Int. J. Prod. Econ. 162 (2015) 160-173.

[3] Q. Chai, Z. Xiao, K-h. Lai, et al., Can carbon cap and trade mechanism be beneficial for remanufacturing?, Int. J. Prod. Econ. 203 (2018) 311-321.

[4] Y. Wang, W. Chen, B. Liu, Manufacturing/remanufacturing decisions for a capital-constrained manufacturer considering carbon emission cap and trade, J. Clean. Prod. 140 (2017) 1118-1128.

[5] H.M. Zhang, B.H. Liu, E.C. Li, et al., The influence of carbon trading and subsidy policy on remanufacturing closed-loop supply chain, China Surface Engineering. 31 (2018) 165-174.

[6] T. Maiti, B.C. Giri, A closed loop supply chain under retail price and product quality dependent demand, J. Manuf. Syst. 37 (2015) 624-637.

[7] A.Y. Christy, B.N. Fauzi, N.A. Kurdi, et al., A Closed-Loop Supply Chain under Retail Price and Quality Dependent Demand with Remanufacturing and Refurbishing, Journal of Physics: Conference Series. 855 (2017).

[8] B.C. Giri, B. Roy, T. Maiti, Coordinating a three-echelon supply chain under price and quality dependent demand with sub-supply chain and RFM strategies, Appl. Math. Model. 52 (2017) 747-769.

[9] A.A. Taleizadeh, M.S. Moshtagh, I. Moon, Pricing, product quality, and collection optimization in a decentralized closed-loop supply chain with different channel structures: Game theoretical approach, J. Clean. Prod. 189 (2018) 406-431.

[10] Z. Zhang, B. Gong, J. Tang, et al., The joint dynamic green innovation and pricing strategies for a hybrid system of manufacturing and remanufacturing with carbon emission constraints, Kybernetes. 48 (2019) 1699-1730.

[11] A.A. Taleizadeh, N. Alizadeh-Basban, S.T.A. Niaki, A closed-loop supply chain considering carbon reduction, quality improvement effort, and return policy under two remanufacturing scenarios, J. Clean. Prod. 232 (2019) 1230-1250.

[12] G. Zhang, Research on Quality-Price Decision in Two-level Supply Chain, D. Huazhong University of Science and Technology, 2011.