Game Mode in Supply Chain Considering Disassembly Engineering Technology under Carbon Trading

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Abstract: Under carbon trading, a supply chain consisting of a manufacturer and a remanufacturer was investigated, where the manufacturer introduced product disassembly engineering technology. The article constructed a supply chain game mode considering product disassembly level, obtained the optimal product disassembly level and the equilibrium result by using Maple 2018, and analyzed the influence of relevant parameters on the equilibrium result. The study found: The increase of the cost coefficient of product disassembly design will reduce manufacturers' enthusiasm for product disassembly design, which is not conducive to product sales and the development of the circular economy. When carbon trading prices increase, the manufacturer will reduce the level of product disassembly, leading to the higher product price and lower product demand. Increasing the cost-saving coefficient of disassembly level on new products is beneficial to the development of the low-carbon economy. Supply chain members should develop emission reduction technologies and introduce emission reduction equipment according to their own conditions to reduce the risk caused by carbon trading price fluctuations. The government should actively play a supervisory role to control carbon trading price within a reasonable range.

Keywords: supply chains; remanufacturing; disassembly engineering technology; carbon trading mechanism

1 Introduction

The low-carbon circular economy has been incorporated into development strategy of China. In 2021, the State Council issued the "Guidance on Accelerating the Establishment and Improvement of a Green and Low-Carbon Circular Development Economic System", which clearly proposes to strengthen the recycling and utilization of renewable resources and encourage enterprises to carry out green design. Remanufacturing means that used products are recycled and remanufactured using a special process. The quality and performance of remanufactured products are no less than that of new ones. Remanufacturing has the advantages of cost saving, energy saving and emission reduction, and is favored by the government and many enterprises. Green design refers to the consideration of environmental attributes of products in product design such as product disassembly, maintainability.

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Disassembly is an essential part of the remanufacturing process, and the level of product disassembly will affect the cost of remanufacturing. In practice, to weaken the cannibalization of new products by remanufactured products, original manufacturers will hinder remanufacturers from entering the market by reducing the level of product disassembly, but this will also reduce the assembly efficiency of new products. Facing of the competition, how should manufacturers determine the level of product disassembly? To control enterprise carbon emissions, the Chinese government fully launched the carbon trading mechanism in 2017. The carbon trading mechanism quantifies corporate carbon emissions. If the carbon emission exceeds the quota given by the state, the enterprise needs to buy carbon emission rights in the carbon trading market; otherwise, the excess quota can be sold for profit. The carbon trading mechanism will have an impact on enterprise profits, and it will also affect product design decisions for product disassembly. Under the carbon trading mechanism, how should manufacturers determine the level of product disassembly? How do supply chain members make production-pricing decisions? Studying these issues has important practical significance.

The topics related to this article include the influence of carbon trading mechanism and product disassembly design on supply chain members. With the implementation of the carbon trading mechanism, many scholars have studied the mechanism of carbon trading. Shen et al. developed a two-period model to compare manufacturers' optimal production decisions under mandatory emission reduction and carbon trading, and concluded that carbon trading is more beneficial to manufacturer [1]. Considering consumer preferences, Zhang et al. divided the market into high-end and low-end consumer market, and constructed a production decision model for a monopoly manufacturer that has the ability to produce new, remanufactured, and refurbished products under different carbon savings and carbon trading prices [2]. Chen et al. used nonlinear convex optimization theory to compare the maximum profit of remanufacturer under the three scenarios: no emission reduction, emission reduction of new products and emission reduction of remanufactured products. The above literatures have studied the impact of carbon trading mechanism on the production and operation decisions of supply chain members, but have not studied the impact of the implementation of carbon trading mechanism on the level of product disassembly [3]. Zhang et al. used the newsboy model to compare three manufacturer strategies: buy additional carbon quotas, adopt carbon emission reduction technology and a combination of the two strategies, and concluded that the combination of the two strategies is optimal [4]. Considering consumer differences, Gan et al. analyzed the impact of carbon quotas and consumer differences on product pricing and system profits under the carbon trading mechanism, and introduced revenue sharing contracts to coordinate the decentralized decision model. Regarding the impact of product disassembly design on decisions of remanufacturing supply chain members [5]. For the remanufacturing supply chain composed of an original equipment manufacturer and a third-party remanufacturer, Wu first develops a two-stage game model to study the manufacturer product disassembly design and the pricing strategy of supply chain members. Then, the two-stage decision-making was extended to multi-stage decision-making [6]. From the perspective of product disassembly and consumer preference, Cao et al. constructed a two-period production-pricing decision model, and analyzed the influence of product disassembly level and consumer preference on remanufacturers' decision to entry market [7]. Gao et al. constructed three kinds of models in which manufacturer undertakes remanufacturing, third-party remanufacturer undertakes remanufacturing and the two jointly undertake remanufacturing, and compared the impact of product disassembly level on manufacturer profit respectively [8]. By introducing government intervention in product design into the model, Xiao et al. studied the production decision of supply chain members under government intervention in the cases of recycling constrained and unconstrained remanufacturing [9]. Chen et al. gave the threshold of producers' three kinds of due diligence patterns under the restriction of circulation rate regulation, and analyzed the influence of product disassembly level on producers' due diligence patterns selection [10]. The above literatures on product disassembly design do not involve the impact of carbon trading mechanism on product disassembly design. With the gradual improvement of China's carbon trading market, the carbon trading mechanism has more and more important influence on decisions of supply chain members. Therefore, it is great important to study the remanufacturing supply chain decision-making that considers disassembly engineering technology under the carbon trading mechanism.

2 Problems description and assumptions

Here we study the remanufacturing supply chain system composed of a manufacturer and a remanufacturer, as shown in Figure 1. In this system, the manufacturer is responsible for new product production and product disassembly design, and the remanufacturer is responsible for remanufactured product production, and the manufacturer’s product disassembly level β will affect the remanufacturer’s production activities. New and remanufactured goods are sold and compete in the same market, and the prices are P_n and P_r respectively, $P_n > P_r$. The manufacturer and remanufacturer are subject to the carbon trading mechanism during the production process and need to trade carbon emission rights in the carbon trading market. The unit carbon emission right transaction price is P_e .

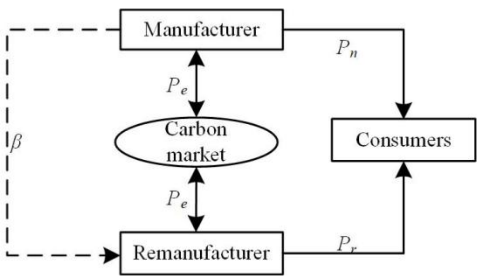

Figure 1 Remanufacturing supply chain system

This article makes the following assumptions:

(1) Assume that consumers’ willingness to pay for new products is V and their willingness to pay for remanufactured products is θV , $\theta \in [0,1)$, $V \sim U(0,1)$, θ represents the consumer's preference for remanufactured products.

(2) Referencing literature Xiao et al. (2017), we standardize the market size to 1, and the

utility functions for consumers to purchase new products and remanufactured products are $U_n = V - P_n$ and $U_r = \theta V - P_r$ respectively. When $U_n \geq U_r$ and $U_n \geq 0$, consumers buy new products, the market demand for new products is $Q_n = \int_{\frac{P_n - P_r}{1-\theta}}^{1} f(V)dV = 1 - \frac{P_n - P_r}{1-\theta}$. When $U_r \geq U_n$ and $U_r \geq 0$, consumers buy remanufactured products, the market demand for remanufactured products is $Q_r = \int_{\frac{P_r}{\theta}}^{\frac{P_n - P_r}{1-\theta}} f(V)dV = \frac{\theta P_n - P_r}{\theta(1-\theta)}$. Correspondingly $P_n = 1 - Q_n - \theta Q_r$ and $P_r = \theta(1 - Q_n - Q_r)$.

(3) According to Wu (2013), the cost of disassembly design is $\varepsilon\beta^2 / 2$ for the manufacturer, where β is the product disassembly level, $\beta \in [0,1]$; ε is product disassembly design cost coefficient, $\varepsilon > 0$.

(4) The change of product disassembly level will affect the assembly efficiency of new products and remanufactured products, and it will also affect the disassembly difficulty and utilization ratio of waste products. Therefore, it is assumed that the cost-saving coefficient of the disassembly level on the remanufactured product is greater than that of the disassembly level on the new product, namely $K_r > K_n$.

(5) Remanufacturing can always meet the market demand, and enterprises produce according to market demand.

The definitions of related symbols used in this article are shown in Table 1.

Table 1 Definition of symbol

Symbol	Definition
P_e	The unit carbon emission right selling price
β	Product disassembly level
ε	Product disassembly design cost coefficient
K_n / K_r	The cost-saving coefficient of disassembly level on new / remanufactured products
$C_n - K_n\beta$ / $C_r - K_r\beta$	Production cost per new / remanufactured product
E_M / E_R	Free carbon quota for the manufacturer/the remanufacturer
e_n / e_r	Carbon emission per new /remanufactured product
π_M / π_R	Manufacturer/ remanufacturer profit

3 Model development and solution

Here, the manufacturer firstly determines the level of product disassembly and the output of new products. Then, the remanufacturer decides the output of remanufactured products. The profit function of the manufacturer and the remanufacturer are as follows:

$$Max\pi_M = (P_n - C_n + K_n\beta)Q_n + (E_M - e_nQ_n)P_e - \frac{\varepsilon\beta^2}{2} \quad (1)$$

$$Max\pi_R = (P_r - C_r + K_r\beta)Q_r + (E_R - e_rQ_r)P_e \tag{2}$$

Equation (1) is the manufacturer profit function, where the first term is the manufacturer profit from selling new products, the second term is the cost or profit of the manufacturer trading carbon emission rights, and the third term is the manufacturer's product disassembly design cost. Equation (2) is the remanufacturer profit function, where the first term is the remanufacturer profit from selling remanufactured products, and the second term is the cost or profit of the remanufacturer trading carbon emission rights.

Theorem 1: If $\varepsilon > \varepsilon_0$, the optimal disassembly level of the product is β^*, the optimal demand for new and remanufactured products are(Q_n^*, Q_r^*), and the optimal pricing strategy are (P_n^*, P_r^*).

$$\beta^* = \frac{(2K_n - K_r)A}{-4w} \tag{3}$$

$$Q_n^* = \frac{\varepsilon A}{-2w} \tag{4}$$

$$Q_r^* = \frac{BD + C(C_r + e_rP_e - \theta)}{4\theta w} \tag{5}$$

$$P_n^* = \frac{(B - 4\varepsilon)(e_nP_e + C_n) + (C + 2\varepsilon)(C_r + e_rP_e - \theta + 2)}{-4w} \tag{6}$$

$$P_r^* = \frac{(4\varepsilon\theta - B)(D + \theta) - (C + 2\varepsilon\theta)(e_rP_e + C_r + \theta)}{4w} \tag{7}$$

Proof: Solving $\frac{\partial \pi_M}{\partial Q_r} = 0$, we get $Q_r = \frac{Q_n\theta - \beta K_r + e_rP_e + C_r - \theta}{-2\theta}$. Substituting Q_r into equation (1), we obtain the Hessian matrix $H(\pi_M) = \begin{bmatrix} \theta - 2 & K_n - \frac{K_r}{2} \\ K_n - \frac{K_r}{2} & -\varepsilon \end{bmatrix}$ of π_M. When $w = \varepsilon(2-\theta) - (K_n - \frac{K_r}{2})^2 > 0$, namely $\varepsilon > \varepsilon_0 = \frac{(2K_n - K_r)^2}{4(2-\theta)}$, the Hessian matrix $H(\pi_M)$ is negative definite. By $\frac{\partial \pi_M}{\partial Q_n}=0$ and $\frac{\partial \pi_M}{\partial \beta}=0$, we get the equilibrium solution of Q_n and β, i.e. $Q_n^*=\frac{\varepsilon A}{-2w}$ and $\beta^*=\frac{(2K_n-K_r)A}{-4w}$. Substituting Q_n^* and β^* into $Q_r=\frac{Q_n\theta-\beta K_r+e_rP_e+C_r-\theta}{-2\theta}$, we get the equilibrium solution of Q_r as $Q_r^*=\frac{B(e_nP_e+C_n-1)+C(C_r+e_rP_e-\theta)}{4\theta w}$. Finally, we can obtain the equilibrium solutions P_n^* and P_r^* of the product price by Q_n^*, β^* and Q_n^*. Where

$A=2e_nP_e-e_rP_e+2C_n-C_r+\theta-2$, $B=2\varepsilon\theta-2K_nK_r+K_r^2$, $C=\varepsilon\theta+2K_n^2-K_nK_r-4\varepsilon$, $D=e_nP_e+C_n-1$.

Corollary 1: $\frac{\partial \beta^*}{\partial \varepsilon}<0$, $\frac{\partial Q_n^*}{\partial \varepsilon}<0$; $\frac{\partial Q_r^*}{\partial \varepsilon}<0$, $\frac{\partial P_n^*}{\partial \varepsilon}>0$; $\frac{\partial P_r^*}{\partial \varepsilon}>0$, $\frac{\partial \pi_M^*}{\partial \varepsilon}<0$; $\frac{\partial \pi_R^*}{\partial \varepsilon}<0$.

Proof: From $w>0$ and theorem 2, we have $2K_n-K_r>0$, $A<0$, $BD+C(C_r+e_rP_e-\theta)>0$. So we can get

$$\frac{\partial \beta^*}{\partial \varepsilon}=\frac{(2K_n-K_r)(8-4\theta)A}{(-4w)^2}<0 \tag{8}$$

$$\frac{\partial P_n^*}{\partial \varepsilon}=\frac{(2K_n-K_r)(2K_n+K_r)(\theta-2)A}{(-4w)^2}>0 \tag{9}$$

$$\frac{\partial P_r^*}{\partial \varepsilon}=\frac{(2K_n-K_r)(2K_n\theta-3K_r\theta+4K_r)A}{-(-4w)^2}>0 \tag{10}$$

$$\frac{\partial Q_n^*}{\partial \varepsilon}=\frac{2(2K_n-K_r)^2A}{(-4w)^2}<0 \tag{11}$$

$$\frac{\partial Q_r^*}{\partial \varepsilon}=\frac{(2K_n-K_r)(2K_n\theta+K_r\theta-4K_r)A}{-\theta(-4w)^2}<0 \tag{12}$$

$$\frac{\partial \pi_M^*}{\partial \varepsilon}=\frac{(2K_n-K_r)^2A^2}{-2(-4w)^2}<0 \tag{13}$$

$$\frac{\partial \pi_R^*}{\partial \varepsilon}=\frac{2(2K_n-K_r)(2K_n\theta+K_r\theta-4K_r)AB}{\theta(-4w)^3}<0 \tag{14}$$

Corollary 1 shows: The product disassembly level, product demand and profits of supply chain members are inverse proportional to the cost coefficient of product disassembly design, and the product price is in proportional to it. The greater the cost coefficient of product disassembly design, the greater the manufacturer's cost for product disassembly design, and the less willing for the manufacturer to improve the product disassembly level. The low product disassembly level will increase the production costs of the manufacturer and the remanufacturer, resulting in higher product prices, lower product demand, and lower profits for supply chain members. This shows that the increase of the cost coefficient of product disassembly design is bad to the sales of remanufactured products and the development of the low-carbon circular economy.

Corollary 2: $\frac{\partial \beta^*}{\partial P_e} < 0$, $\frac{\partial Q_n^*}{\partial P_e} < 0$; $\frac{\partial Q_r^*}{\partial P_e} < 0$, $\frac{\partial P_n^*}{\partial P_e} > 0$; $\frac{\partial P_r^*}{\partial P_e} > 0$, if $\lambda E_n < A\varepsilon(2e_n - e_r)$, $\frac{\partial \pi_M^*}{\partial P_e} > 0$, otherwise, $\frac{\partial \pi_M^*}{\partial P_e} \leq 0$; if $(-4w)^2 \theta E_r > -2\delta$, $\frac{\partial \pi_R^*}{\partial P_e} > 0$, otherwise, $\frac{\partial \pi_R^*}{\partial P_e} \leq 0$ .Here $\lambda = (2kn - kr)^2 + 4\varepsilon(\theta - 2)$, $\delta = (Ce_r + Be_n)(BD + C(C_r + e_r P_e - \theta))$.

The proof of Corollary 2 is similar to that of Corollary 1.

Corollary 2 shows: The product disassembly level and product demand are inverse proportional to the carbon trading price, and the product price is in proportional to it, and the impact of carbon trading price on the profit of supply chain members is jointly determined by parameters such as free carbon quotas and consumer preference for remanufactured products. Increasing the carbon trading price will increase the cost of carbon emissions, the manufacturer will reduce their investment in product disassembly design, resulting in the lower product disassembly level, the higher product price, and the less product demand. This shows that the increase in carbon trading price is bad for the manufacturer to improve product disassembly level, and to expand the market new products and remanufactured products.

Corollary 3: $\frac{\partial \beta^*}{\partial K_n} > 0$, $\frac{\partial Q_n^*}{\partial K_n} > 0$; $\frac{\partial Q_r^*}{\partial K_n} > 0$, $\frac{\partial P_n^*}{\partial K_n} < 0$; $\frac{\partial P_r^*}{\partial K_n} < 0$, $\frac{\partial \pi_M^*}{\partial K_n} > 0$; $\frac{\partial \pi_R^*}{\partial K_n} > 0$.

The proof of Corollary 3 is similar to that of Corollary 1.

Corollary 3 shows: The product disassembly level, the product demand and the profit of the supply chain members are in proportion to the cost-saving coefficient of disassembly level on new products, and the product price is inverse proportion to it, which shows that with the increase of the cost-saving coefficient of disassembly level on new products, the manufacturer will improve the level of product disassembly. The higher level of product disassembly is good to reduce the production cost of the manufacturer and the remanufacturer, which leads to the lower product price, the higher product demand and higher profits of supply chain members. Therefore, the increase of the cost-saving coefficient of disassembly level on new products is not only good for the members of the supply chain, but also good for to the development of the low-carbon economy.

4 Conclusions and future research

Under the carbon trading mechanism, we investigate a remanufacturing supply chain composed of a manufacturer and a remanufacturer, and get the following conclusions:

(1) Increasing the cost coefficient of product disassembly design will reduce manufacturers' enthusiasm for product disassembly design, which will inhibit the expansion of the product market, and is bad for the development of the circular economy. The cost of product disassembly design is borne by the manufacturer, but the improvement of product disassembly level is more conducive to remanufacture. Therefore, when the product disassembly design cost coefficient is large, the remanufacturer should actively seek cooperation with the manufacturer and share the cost of product disassembly design.

(2) When the carbon trading price is too high, the manufacturer will reduce the level of product disassembly, which will increase the product price and reduce the product demand. This shows that reasonable carbon trading prices are helpful to develop the circular economy. Therefore, the government should play a supervisory role to control carbon trading prices within a reasonable range.

(3) The increase in the cost-saving coefficient of disassembly on new products is helpful to improve the disassembly level of new products, and to stimulate consumers to purchase products, and to develop the circular economy.

So far, the cost of product disassembly design is all borne by the manufacturer, so we can design a cost-sharing contract between the manufacturer and the remanufacturer to improve the product disassembly level, which will be the future research direction.

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References

[1] Shen, C.R., Xiong, Z.K. (2014) Production Decisions of the Manufacturer Remanufacturing under Carbon Constraint. J. of Systems Engineering, 29(04): 537-549(in Chinese).

[2] Zhang, H.Y., Li, Y.H., Han, Y.X. (2018) Research on Remanufacturing Strategy of Enterprises under Cap-and-Trade Mechanism. J. Soft Science, 32(06): 87-91(in Chinese).

[3] Chen, Y.Y., Li, B.Y., Bai, Q.G. (2020) Research on Production and Emission Reduction Investment Decisions of the Remanufacturing Enterprise under Carbon Trading Environment. J. of Control and Decision, 35(03): 695-703(in Chinese).

[4] Zhang, L.H., Dong, K., Zhang, R. (2019) Strategic Choice Analysis for Supply Chain in 'Cap and Trade' System and Carbon Emission Reduction Technology. J. Chinese Journal of Management Science, 27(01): 63-72(in Chinese).

[5] Gan, W.H., Han, L., Su, L., et al. (2019) Pricing and Coordination of Closed-Loop Supply Chain Considering WTP under Carbon Trading Policy. J. Ecological Economy, 35(08): 67-74(in Chinese).

[6] Wu, C.H. (2013) OEM Product Design in a Price Competition on with Remanufactured Product. J. Omega, 41(2): 287-298.

[7] Cao, X.G., Zhang, B.R., Wen, H. (2016) Joint Decision of Production and Pricing for Remanufacturing System Based on DFD Theory. J. of Management Engineering, 30(01): 117-123(in

Chinese).
[8] Gao, J.H., Liu, X.Y., Teng, J.H., et al. (2017) Decision-making of Remanufacturing Considering Product Disassemblability. J. Systems Engineering, 35(01): 110-118(in Chinese).
[9] Xiao, L., Wang, X.J., Qian, G.S., et al. (2017) The Incentives for Remanufacturing Based on Product Design and Effects of Government Intervention. J. Systems Engineering-Theory & Practice, 37(5): 1229-1242(in Chinese).
[10] Chen, Y.Y., Li, B.Y., Bai, Q.G. (2019) Impact of Recycling Rate Regulation Based on Design for Disassembly. J. Computer Integrated Manufacturing Systems, 25(07): 1817-1827(in Chinese).