Two-period Production Decisions in a Hybrid Manufacturing/Remanufacturing System with Consumer Preferences under Carbon Cap and Trade Mechanism

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Abstract. We develop a two-period profit-maximization nonlinear programming model to research the impact of carbon cap and trade mechanism as well as the consumer preferences on the enterprises remanufacturing decision and pricing decision. The results illustrate that: with the greater consumer's preference for remanufacturing products, the enterprise will be more positive to conduct remanufacturing, and the profit will be greater as well. The enterprises’ manufacturing/remanufacturing decision and pricing decision is related to carbon trading price but which is not influenced by the initially allocated carbon emission quotas from government.

Introduction

Reasonable production decision can help enterprise utilize the production resources effectively. The total carbon dioxide emissions will drop 40% -45% in 2020 compared to 2005\textsuperscript{[1]}. Currently, there are two main types of carbon emission reduction policies: carbon cap and trade mechanism and carbon tax. Remanufacturing activities can effectively reduce the carbon emissions to achieve the sustainable development of the enterprise. Remanufacturing is a good strategy for enterprise in respond to carbon emissions policy.

Hua et al. derived the optimal order quantity, and examined the impacts of carbon trade, carbon price, and carbon cap on order decisions, carbon emissions [2]. Benjaafar et al. developed a math model to illustrate how carbon emission concerns could be integrated into operational decision-making with regard to procurement, production, and inventory management [3]. Xiangyun Chang et al. propose two profit-maximization models for the independent demand market (ID-market) and the substitutable demand market (SD-market) [4]. Arda Yenipazarli investigates the impact of emissions taxes on the optimal production and pricing decisions of a manufacturer who could remanufacture its own product [5].

Consumers’ acceptances of new products and remanufactured products are different. Jiaping Xie studies the influence of advertisements on customer preference [6]. Cao et al. develop the game theory to establish a two-period profit-maximizing model to characterize the effect of cost savings, parameters associated with product design, consumers’ preference to remanufactured products on the equilibrium decisions and profits [7].
In addition, Jean-Pierre Kenne et al. discuss the production planning and control of a single product involving combined manufacturing and remanufacturing operations [8]. Su et al. develop a novel fuzzy multi-objective linear programming (FMOLP) model with a piecewise linear membership function to solve integrated, procurement/production [9]. Liu et al. develop two-period decision model to research the optimal product design strategy and production decision [10].

The above studies only consider the external carbon constraints or the consumer preference for new products and remanufactured products. However, in reality, the manufacturing/remanufacturing production decision may be influenced by consumer preferences and carbon trading mechanism at the same time. In this paper, we develop a two-period profit-maximization nonlinear programming model to research the impact of carbon cap and trade mechanism and the consumer preferences on the enterprises remanufacturing production decision.

Problem Statement and Assumption

The basic idea of the model diagram is shown in figure 1.

![Figure 1. Basic Thought of the Model.](image)

We consider a hybrid manufacturing/remanufacturing system consisting of a monopolist manufacturer over two periods. In the first period, the monopolist manufacturer produces new products using virgin materials and sells the new products to the market. In the second period, to reduce its carbon emissions under the influence of the carbon trading mechanism, manufacturer can produce new products and remanufactured products at the same time. For each production period, a quota of carbon emission is allocated to the manufacturer by an external regulatory body. The manufacturer can buy or sell carbon credit on a trading market of carbon emission to meet its production needs.

Assumption:

(1) Don’t consider the production lead time and preparation time;
(2) Size of the potential market is known in every period;
(3) There is no difference between new products and remanufactured products;
(4) Consumer acceptance of new products and remanufactured products is different;
(5) Carbon emissions of unit new products is greater than unit remanufactured products;
(6) The unit cost of production of new products is greater than the remanufactured product unit cost of production.

**Parameters symbol:**

- $Q_t$: Size of the potential market in period $t$ ($t=1,2,3,4,\ldots$)
- $q_N, p_N$: The production quantity and unit sale price of the new product
- $q_R, p_R$: The production quantity and unit sale price of the remanufactured product
- $q_{1N}, p_{1N}$: The production quantity and unit sale price of the new product in period 1
- $q_{2N}, p_{2N}$: The production quantity and unit sale price of the new product in period 2
- $q_{2R}, p_{2R}$: The production quantity and unit sale price of the remanufactured product in period 2
- $P$: The carbon price
- $L$: The carbon cap allocated to the manufacturer by an external regulatory body in a period
- $T$: The carbon trading quantity
- $c$: Production cost per new product
- $s$: Cost savings per remanufactured product, $s < c$
- $e$: Carbon emission for producing one unit of new product
- $w$: Carbon emission saving per remanufactured product, $w < e$
- $\gamma$: The biggest recovery ratio, $0 < \gamma < 1$
- $V_N, V_R$: Consumer's willingness to pay for new product and remanufactured product, subject to uniform distribution, $V_N \sim [0, v]$
- $\delta$: Consumer preferences for remanufactured product coefficient $V_R = \delta V_N$, $\delta \in (0,1)$
- $U_N, U_R$: Utility function of the new product and the remanufactured product for consumer

**Models**

**Demand Function**

We consider that the consumer utility will be affected by the product type and price. Consumer's utility function of new products: $U_N = V_N - p_N$, $V_N$ denote consumer's willingness to pay (WTP) for new products, $p_N$ denote the price of new products. Consumer's utility function of remanufactured products: $U_R = V_R - p_R$, $V_R$ denote consumer's willingness to pay (WTP) for remanufactured products, $p_R$ denote the price of remanufactured products. This paper assumes that the consumer's willingness to pay (WTP) for remanufactured products and consumer willingness to pay (WTP) for new products is linear relationship:
\( V_r = \delta V_N, \delta \in (0,1) \), that is to say \( U_r = \delta V_N - p_r \). If consumers consider that there is no difference between buying remanufactured products and buying new products: \( U_r = U_n \), that is to say \( V_n - p_n = \delta V_N - p_r \), consumer’s willingness to pay can be obtained at this critical value: \( V_2 = \left( p_N - p_r \right) / (1 - \delta) \). If consumers consider that buying new products has no value: \( U_r = 0 \), that is to say \( V_N - p_N = 0 \), consumer’s willingness to pay can be obtained at this critical value: \( V_1 = p_N \). If consumers consider that buying remanufactured products has no value: \( U_r = 0 \), that is to say \( \delta V_N - p_r = 0 \), consumer’s willingness to pay can be obtained at this critical value: \( V_0 = p_r / \delta \).

We assume that \( V_N \) subject to uniform distribution, \( V_N \sim [0, v] \).

The cumulative probability density function can be obtained:
\[
F(V_2) = \frac{V_2}{v} = \frac{(p_N - p_r) / (1 - \delta v)}{v}; \quad F(V_1) = \frac{V_1}{v} = \frac{p_N}{v}; \quad F(V_0) = \frac{V_0}{v} = \frac{p_r / (\delta v)}{v}
\]

If there are both new products and remanufactured products on the market, new products’ demand distribution should be higher than \( F(V_2) \), and remanufactured products’ demand distribution should be between \( F(V_1) \) and \( F(V_0) \). If there are only new products on the market, new products’ demand distribution should be higher than \( F(V_1) \).

If there are both new products and remanufactured products on the market, the demand functions of new products and remanufactured products are:
\[
q_N = Q[1 - (p_N - p_r) / (1 - \delta v)]; \quad q_r = Q[(p_N - p_r) / (1 - \delta v) - p_r / (\delta v)]. \tag{1}
\]

If there are only new products on the market, the demand function of the new products is: \( q_N = Q[1 - p_N / v] \).

If there are both new products and remanufactured products on the market, it can be obtained by the equation (1):
\[
p_N = [Q - \delta q_r - q_N] v / Q; \quad p_r = [Q - q_N] v / Q.
\]

If there are only new products on the market, \( p_N = v - q_N v / Q \).

**Decision Model**

In the objective function, the first three terms represent the profits from selling products in both periods, and the fourth is costs or profits associated with carbon trading in period 1 and period 2. \( 2L - T = e(q_1 + q_{2N}) + (e - w)q_{2R} \) describes the carbon constraint in period 1 and in period 2.

\[
\max E_M = (p_1 - c) q_1 + (p_{2N} - c) q_{2N} + [p_{2R} - (c - s)] q_{2R} + PT
\]

\[
\begin{align*}
\gamma q_1 & \geq q_{2R} \\
p_1 & = v - q_1 v / Q \\
p_{2N} & = [Q_2 - \delta q_{2R} - q_{2N}] v / Q_2 \\
p_{2R} & = [Q_2 - q_{2N} - q_{2R}] \delta v / Q_2 \\
2L - T & = e(q_1 + q_{2N}) + (e - w)q_{2R} \\
q_1, q_{2N}, q_{2R} & \geq 0 \\
q_1, q_{2N}, q_{2R} & \in Z
\end{align*}
\tag{2}
\]
Optimal Production Strategy

Solving equation (2) by Kuhn – Tucker, we can get the optimal production strategy.

Analysis

We set $Q = 10000$, $c = 200$, $s = 100$, $e = 80$, $V = 2000$, $\delta = 0.6$, $\gamma = 0.6$, $L = 150000$, $P = 15$.

Consumer Preferences Factor's Influence on Optimal Production Strategy

We vary the value of the consumer preferences factor $\delta$ from 0.1 to 1 and keep other parameters unchanged. We can find that with the greater consumer's preference for remanufactured products, the enterprise will be more positive to conduct remanufacturing, and the profit will be greater as well.

Carbon Trading Price's Influence on Optimal Production Strategy

We vary the value of the carbon trading price $P$ from 5 to 25 and keep other parameters unchanged. We can find that when the trading price of unit carbon emissions within a certain range increases, the enterprise will reduce new product production level, at the same time increase the remanufacturing production levels. But when the trading price of unit carbon emissions increases to a certain extent, remanufacturing production levels may also be reduced. When the trading price of unit carbon emissions within a certain range increases, the profit will decrease, then, when the trading price of unit carbon emissions increases to a certain extent, the profit will increase.

The Initial Carbon Emission Quota Influence on Optimal Production Strategy

We vary the value of the carbon trading price $L$ from 100000 to 200000 and keep other parameters unchanged. We can find that the optimal production quantities are not influenced by the initially allocated carbon emission quotas from government, but with the initial enterprise carbon emission quota increases, the total profit of enterprises will increase as well.

Conclusions

In this paper, we develop a two-period profit-maximization nonlinear programming model to research the impact of carbon cap and trade mechanism as well as the consumer preferences on the enterprises remanufacturing decision and pricing decision. The results illustrate that: with the greater consumer's preference for remanufacturing products, the enterprise will be more positive to conduct remanufacturing, and the profit will be greater as well; The enterprises manufacturing/remanufacturing decision and pricing decision is related to unit carbon emissions trading price but which is not influenced by the initially allocated carbon emission quotas from government. In future study, it is interesting to consider different recycling channels and capacity constraints.
Optimal production strategy

1. If: \(-\gamma(c-s) - \gamma P(e-w) + y\delta c + y\delta P + v - c - Pe > 0\)
   \(2\gamma^2 Q_i Q_j (c-s) - \gamma P(e-w) + y\delta c + y\delta P + v - c - Pe > 0\)
   \(2\gamma^2 (1-\delta)v Q_i + 2Q_i v\)
   \(c + v + Pe > 2Q_i [c - v + Pe + \gamma(c-s) - y\delta c + y\gamma P + v - c - Pe]/[2\gamma^2 (1-\delta)Q_j + 2Q_j v]\)
   \(q'_i = Q_j (c - v - Pe)/(2v)\)
   \(q_{2N} = Q_j (v - c - Pe)/(2v)\)
   \(q_{2R} = 0\)

2. If: \(v - c - Pe > 0\)
   \(\delta c + \Delta Pe - (c - s) - P(e-w) \leq 0\)
   then: \(q'_i = Q_j (c - v - Pe)/(2v)\)
   \(q_{2N} = Q_j (v - c - Pe)/(2v)\)
   \(q_{2R} = 0\)

3. If: \(v - c - Pe > 0\)
   \(v(1-\delta) - s - Pw > 0\)
   \(s - c - Pe + Pw + \delta c + \Delta Pe > 0\)
   \(Q_j (c - s + \delta c - Pe + Pw + \delta Pe)\)
   \(2\delta (\delta - 1)v\)
   \(= - \gamma Q_j (c - v + Pe) \geq 0\)
   then: \(q'_i = Q_j (v - c - Pe)/(2v)\)
   \(q_{2N} = Q_j [v(1-\delta) - s - Pw][2v(1-\delta)]\)
   \(q_{2R} = (Q_j - 2\delta Q_j)v - Q_j (c + Pe)/(2\delta v)\)

4. If: \(s - c + \delta c - Pe + Pw + \delta Pe \leq (c + Pe - v)/\gamma\)
   \(v - c - Pe > 0\)
   \(s - c + \delta c - Pe + Pw + \delta Pe > 0\)
   then: \(q'_i = Q_j (v - c - Pe)/(2v)\)
   \(q_{2N} = 0\)
   \(q_{2R} = 0\)

5. If: \(v - c - Pe > 0\)
   \(v - s - \delta v - Pw \leq 0\)
   \(Q_j (c - s - \delta v + P(e-w)) - \gamma Q_j (c - v + Pe) \geq 0\)
   \(2\delta v\)
   \(\delta v - (c - s) - P(e-w) > 0\)
   then: \(q'_i = Q_j (v - c - Pe)/(2v)\)
   \(q_{2N} = 0\)
   \(q_{2R} = Q_j (\delta v - (c - s) - P(e-w))/[2\delta v]\)

6. If: \(\gamma(\delta v - (c - s) - P(e-w)) + v - c - Pe > 0\)
   \(v(\delta v + 2\gamma^2 Q_i Q_j (c - v + \gamma(c - s - \delta v + P(e-w)) + Pe))\)
   \(2\delta Q_j v^2 + 2Q_j v\)
   \(Q_j (c - s - P(e-w)) - Pe - c \leq 0\)
   then: \(q'_i = Q_j Q_j (\gamma(\delta v - (c - s) - P(e-w)) + v - c - Pe)/(2\gamma^2 \delta v Q_i + 2Q_j v)\)
   \(q_{2N} = 0\)
   \(q_{2R} = \gamma q'_i\)
   \(\gamma = (Pe + 2Q_j v)/Q_i + c - v)/\gamma\)

7. If: \(v - c - Pe \leq 0\)
   \(\delta v - (c - s) - P(e-w) \leq 0\)
   or \(\delta v - (c - s) - P(e-w) \leq 0\)
   \(v - c - Pe \leq 0\)
   \(\delta v - (c - s) - P(e-w) > 0\)
   then: \(q'_i = 0\)
   \(q_{2N} = 0\)
   \(q_{2R} = 0\)

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References


