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PRICING STRATEGIES FOR HYBRID REMANUFACTURING SYSTEMS WITH CONSIDERATION OF CARBON EMISSION AND CONSUMER HETEROGENEITY

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Abstract— In the past, firms merely considered economic benefits to maximize their own profit. However, as climate change and the greenhouse effects have become more and more serious, not only firms do gradually take the initiative in dealing with the environmental issues but also the governments make relevant environmental policies to control the carbon emissions. Therefore, managers currently should consider both their benefits and the environmental regulations when making decisions. Firms have to change their business models and reduce carbon emissions to create a win-win situation where both the environment and the economy are maximized. Therefore, remanufacturing has become one of the most important issues for enterprises.
This study investigates the impacts that carbon emission policies and consumer characteristics have on the hybrid-remanufacturing system in which the carbon emissions of new and remanufactured products during the two-periods production are considered, and the carbon emission policies are categorized into three types: (1) carbon tax policy, (2) carbon trading policy, and (3) carbon penalty policy. In considering the carbon reduction effect, high and low carbon-reduction levels are considered, and the corresponding optimal prices of new and remanufactured products are obtained respectively. Comparative analysis among policies is performed and the result shows that with a high degree of carbon abatement for remanufactured products, the carbon penalty policy is preferred. However, with a low degree of carbon abatement, the carbon trading policy is preferred. Moreover, among all factors, the efficiency of carbon abatement has the most influence on the carbon emission while the carbon penalty and trading policies.
Index Terms—Carbon emission policy, Hybrid remanufacturing system, Carbon reduction effect of remanufactured products, Consumer preference.

I. INTRODUCTION

Since the industrial revolution in the 18th century, the frequent exploitation and use of fossil fuels have promoted the rapid development of the manufacturing industry. As a result, although the economy is booming, it has also caused severe environmental pollution. The great amount of greenhouse gas emissions has led to expeditious climate changes, and thus the frequent occurrence of natural disasters worldwide. Therefore, governments and international organizations begin to pay attention to the environmental issues and develop relevant regulations to reduce greenhouse gas emissions. For example, in 1997, the "Kyoto Protocol" was signed in Kyoto, Japan, and its content included the abatement of greenhouse gas emissions by industrialized countries and the confinement of the current existing emission indicators, which can be purchased among diversified countries. Many EU countries have responded with policies such as carbon taxes and carbon trading caps. The Paris Agreement was signed in France in 2015, and what differs from the past is that the major industrial exhaust emission countries, such as the United States, can control the greenhouse gas emissions by participating in the carbon trading market.

With the increasing awareness of environmental protection and the development of relevant regulations by governments, and the overwhelming issues of sustainable development, numerous countries have implemented the relevant emission restrictions to effectively regulate the greenhouse gas emissions [1], [2], [3], [4]. Firms change their production methods to reduce the cost increase that is caused by regulations cost and effectively reduce greenhouse gas emissions [5]. Therefore, many firms recycle their products and remanufacture them, i.e., they operate with a hybrid remanufacturing system. Compared with new products, remanufactured products have lower production costs and carbon emissions, and therefore, in response to the impacts of the three environmental policies regulated by the government, i.e., carbon tax, carbon trading, and carbon penalty, the production of remanufactured products can not only lower the cost burden brought by the environmental policies but also effectively reduce carbon emissions, and is able to achieve a win-win situation for the environment and the economy [6]; [7], [8], [9], [10], [11].

Although recycling, sorting, repairing, and inspecting may bring additional costs, remanufacturing can save the cost of producing new key components which usually can bring a greater profit [12]. Moreover, since plenty of production processes are eliminated, energy consumption and carbon emissions are generated during manufacturing are greatly reduced [13], [14], [15], [16]. Therefore, after considering environmental policies, remanufactured products can bring better income than new products. Due to the rise of consumers' environmental awareness, consumers' demand for green products has increased [17]. In general, consumers can distinguish between new and remanufactured products. Ordinary consumers make purchases based on product quality whilst green consumers purchase eco-friendly products. Consequently, this study considers a hybrid manufacturing system which produces both new and remanufactured products, and takes the consumer behaviors of green consumers into account to develop the optimal pricing strategy when facing the three environmental policies.

The remainder of this study is organized as follows: Section 2 reviews the related literature, investigating and integrating the related fields of this study. Section 3 states the research problem and assumptions. In Section 4, we constructed the model and, by the model derivation deriving, under different environmental policies, the optimal pricing strategy of new and remanufactured products can be derived. Section 5 compares three environmental policies. Section 6 is the contextual example application and the sensitivity analysis. Section 7 concludes and offers suggestions for future research.

I. RELATED LITERATURE

This section mainly discusses the relevant literature on environmental policies and consumption characteristics in the production and pricing of hybrid systems of manufacturing and in-process production. This chapter is mainly divided into four subsections to discuss: carbon emissions, green investment, product recycling, and pricing strategies for new and remanufactured products.

2.1. Carbon emissions

To mitigate the negative impacts that greenhouse gas has on the environment, governments have already levied taxes on the carbon emissions from firms and developed carbon trading mechanisms to balance between the environmental impacts and economic development. Some studies focused on carbon taxes and analyzed the effects of abatement of carbon emissions [2], [18].

Integrating the supply chain with mutual benefits among the members can not only increase the profits of the members for enhancing their competitiveness but also cooperate to effectively reduce the carbon emissions. Research on the impact that the collaboration in the supply chain has on the environment and profits has been studied. Wang et al. (2017) found higher carbon emissions will have impacts on both the profit of the manufacturer and the social welfare, so the manufacturer has to utilize effective operations management and manufacturing technology to reduce the carbon emissions [19].

The implementation of carbon trading allows firms to resell emission rights before reaching the upper bound of emissions, which enhances the firms to effectively reduce carbon emissions. Therefore, the price for carbon trading would be influenced by the upper bond of carbon emission [20], [21]. He et al. considered the economic ordering quality under the carbon tax and cap policies, and investigated the impacts that the two policies have on the carbon emissions of the firm, and found that the set up and the holding costs of the inventory are equal, both policies will have the same optimal emissions [22].

Nowadays, numerous industries make greening investments in decarbonization by considering carbon trading to coordinate with the emissions in the supply chain [23], [24]. Dong et al. considered a supply chain with a manufacturer and a retailer under the carbon cap and trading policies, in which the continuous investments are feasible, and found that the profit-sharing contractual agreement can coordinate the supply chain better, while both buyback and tariff contractual agreements fail to effectively coordinate the supply chain [25].

2.2. Green investment

Enterprises should have social responsibilities owing to the fact that the frequent production and transportation activities in the supply chain would have substantial impacts on the environment. Therefore, research on the green investment in the supply chain has been extensively investigated [26], [27].Wu et al. investigated that the impacts that carbon emission abatement has on the operations of the supply chain and financial decisions, and found that a green supply chain with a contractual agreement brings more substantial profits when compared to the one without a contractual agreement [28].

Research also investigated the impact that the green investment has on the production and inventory in a supply chain under the restrictions of carbon emissions [23]; [29]. Toptal et al. stated that carbon policies can control the carbon emissions of the firms by, which firms can either change their manufacturing plans or invest in green technologies to comply with the carbon policies [30].

The scale of firms' green investments can affect consumer demand and the supplier's decision behaviors, which affects the revenue of the entire supply chain [31]. Wang et al. considered a supply chain which is composed of an e-retailer and a supplier, in which the green production investment of the supplier will affect the e-retailer's willingness to make the green investment, and found that if the platform cost and the investment are both high, the supplier prefers the market platform [32].

2.3. Product Regeneration

Upon recycling the used items, the key components will be disassembled, sorted, repaired, inspected, and finally classified according to their quality and specifications for remanufacturing. This can reduce waste and enable firms to obtain more profits [33]. Jabber et al. investigated the impacts that the environmental regulations have on the inventory control policy of a hybrid manufacturing system, and found that the green inventory policy is beneficial for abating the carbon emissions and has better cost control when compared with the conventional ones [10].

A manufacturer who simultaneously produces both new and remanufactured products, operates with a hybrid system with manufacturing and remanufacturing. The recycling rate, the quality of the remanufactured product, and the uncertainty of the supply source of the recycled product, may all have impacts on the production volume, purchase quantity, and product prices of the entire hybrid production system [34], [35].

Apart from the uncertainty about recycling products, production planning also has a great impact on the inventory control of the hybrid production system. Kenné et al. considered a recovery production plan for a hybrid manufacturing system in which three inventory are considered: the new, remanufactured, and recycled products, and found that the lower the degree of recycle, the higher the cost is. Moreover, the threshold required for remanufacturing will decrease [36]. Teunter and Flapper stated that the uncertainty quality for recycled materials in the remanufacturing system, and the uncertainty of demand enables firms to purchase more quantity as a safety stock, and as the uncertainty of demand increases, the cost deficit caused by the quality uncertainty can be mitigated [37].

Moreover, some fiscal measures may reduce the negative impact of uncertainty factors. Sun et al. considered a hybrid production system with a financial hedging program, in which a risk-aversion manufacturer avoids the risk by purchasing some financial products, and found that the use of the fiscal hedging programs can dramatically reduce the uncertainties caused by remanufacturing reduce operational risks [38].

2.4. Strategies of new and remanufactured products

Wang et al. investigated the optimal production strategy of the new and remanufactured products in a hybrid manufacturing system, and found that under the condition of limited capital, encouraging manufacturers to remanufacture can significantly abate carbon emissions and manufacturers can manufacture more remanufactured products to earn more profits under the carbon emission restrictions [19]. Chai et al. stated that remanufacturing can enhance production operations in an environmentally friendly and profitable way, and the total carbon emission cap and trade mechanism will affect the profit of the manufacturer, and considered the single-period manufacturing and remanufacturing of an oligopolistic manufacturer with consideration of the carbon cap, and found that due to the characteristic of the lower carbon emissions of remanufactured products, manufacturers can consider remanufacturing with the carbon cap and trade mechanism whilst the proportion of green consumers also have impacts on the remanufacturing of manufacturers [11]. Research on adopting the three environmental policies to develop production plans for hybrid remanufacturing systems has been conducted.

II. MODEL DESCRIPTION

3.1. The description of the problem

Consider a hybrid production system, which has into two production lines: new and remanufactured products. Suppose the production cost of new products per unit is C_n, which includes the acquisition cost of raw materials, personnel cost, and the set up cost of production equipment. The production cost of remanufactured product per unit is C_r, since the raw material cost and can be saved, it merely includes the costs of restoring, inspecting, classification, and production after recycling. Therefore, the unit cost of new products is higher than that of remanufactured products, i.e., $C_n > C_r$.

Since the manufacturer manufactures new products to gratify the demand of the new-product market in the first period, and recycle the used items sold in the first period from the new-product market for the production of remanufactured products in the second period, with the recycle rate r, $0 < r < 1$, the manufacturer thus manufactures both new and remanufactured products to gratify the market demand for the two products in the second period. The prices of the new and remanufactured products for the two periods are, p_{1n}, p_{2n}, and p_{2r}, respectively, where $p_{2n} > p_{2r}$.

During the second period, consumers are categorized into general and green consumers according to their diversified preferences and purchase behaviors. Suppose that the general consumers make purchases merely considering the quality and their perceived values of the product, v, is based on whether or not the product is new. In considering the heterogeneous consumers in the market is assumed to be uniformly distributed within $[0,Q]$[39], [5]. When a consumer acquires a remanufactured product which even the manufacturer claims that both the quality and function of it are the same as those of the new product, the consumer would have a discount factor η, $0 < \eta < 1$, and the perceived value of the remanufactured product is thus ηv. However, green consumers consider that the remanufactured product does not differ from the new products, and since remanufactured products are more environmentally friendly, green consumers will merely purchase the remanufactured products.

Suppose that the total market potential is $0 < \eta < 1 Q$, general consumers may purchase either new or remanufactured products while green consumers will only purchase remanufactured products. Suppose that the carbon emission for producing the new product per unit is e_n. Since carbon emissions for producing a remanufactured product is lower than that of a new product, the abatement of carbon emission per unit assumed to be is ε. Therefore, the carbon emissions per unit for remanufactured products is $e_n - \varepsilon$. The carbon tax regulations, carbon caps, carbon trading markets, and carbon penalties, which can all effectively reduce carbon emission, and they are explained as follows:

(1) Carbon tax policy: For the two-period production, the carbon emissions generated by new and remanufactured products are taxed, and the price of carbon tax per unit is t_1

(2) Carbon cap and carbon trading: Restrict the total amount of carbon emissions generated by the manufacturer in each period of production. The surplus from the cap limit L_1 is T, which can be resold at the price t_2 per unit. Conversely, if exceed the cap limit, the emission allowances have to be purchased via the trading market to comply with the policy regulations.

(3) Total carbon emissions limit: Limit the total carbon emissions produced by the manufacturer in each of the two periods. The carbon emissions cannot exceed the limit L_2 for each period, otherwise, there will be a penalty cost t_3.

Based on the above arguments, the assumptions of this study are as follows:

(1) The general consumers can distinguish the quality between new and remanufactured products, and therefore, their demand for remanufactured products would be according to their preference for remanufactured products.

(2) With consideration of the impacts on the environment, green consumers would merely purchase remanufactured products.

(3) The production cost of a remanufactured product is lower than that of a new product.

(4) A new product can be recycled only once, and recycled the remanufactured product has to be disposed of as waste.

(5) The costs of inventory and out-of-stock caused by uncertainty are not considered in this study.

(6) The raw materials of remanufactured products in the second period have to be recycled from the new product market in the first period.

3.2. The framework of the research

The manufacturer conducts a two-period hybrid manufacturing system in which the manufacturer recycles its own used items in the first period for remanufacturing in the second period, the carbon emissions generated during the production process under three environmental policies are considered. The research framework of this study is shown in Fig. 3.1, and the main notations are listed in Table 3.1.

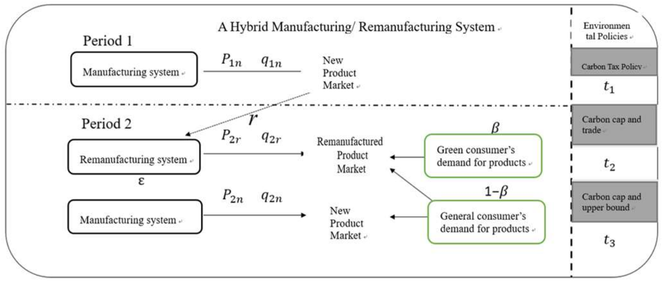

Fig. 3.1. The framework of the two-period hybrid manufacturing system

Table 3.1. Notation

Q	The total market potential
q_{1n}	The production quantity of new products in the first period
q_{2n}	The production quantity of new products in the second period
q_{2r}	The production quantity of remanufactured products in the second period
p_{1n}	The price of the new product in the first period
p_{2n}	The price of the new product in the second period
p_{2r}	The price of the remanufactured product in the second period
C_n	The production cost per unit of the new product
C_r	The production cost per unit of the remanufactured product
t_1	The carbon tax of carbon emissions per unit
t_2	The carbon trade price per unit of carbon emissions
L_1	The carbon emissions quota allowed in each period of the carbon trading market
L_2	The carbon emissions quota allowed in each period for the carbon penalty policy
e_n	The carbon emissions per unit of the new product
ε	The carbon emissions per unit saved from the remanufactured product
t_3	The carbon penalty
η	The preferential factor to the remanufactured product
r	The recycling ratio of the new product in the first period
β	The percentage of green consumers in the market
θ	The increasing rate of the carbon trade price in the second period

III. MODEL CONSTRUCT AND ANALYSIS

4.1. Model demand functions

In the second period, the manufacturer sells both new and remanufactured products. Suppose the perceived value of new products for general consumers is v, which is uniformly distributed as $v \sim U(0,1)$. Since general customers often consider the remanufactured product as an inferior product, so there is a discount factor, η, for the remanufactured product. Consumers would make purchases according to their utility functions: $U_{2n}^{0} = v - p_{2n}$, is the utility function of the general consumer for the new product, and $U_{2r}^{0} = \eta v - p_{2r}$ is the utility function of general consumers for the remanufactured products. Since green consumers consider the new and remanufactured products are similar, the utility functions of the new product and remanufactured product are given as $U_{2n}^{G} = v - p_{2n}$ and $U_{2r}^{G} = v - p_{2r}$, respectively. When $U_{2n}^{0} > 0$ and $U_{2n}^{0} > U_{2r}^{0}$, general consumers will purchase new products. When $U_{2r}^{0} > 0$ and $U_{2r}^{0} > U_{2n}^{0}$, general consumers will purchase the remanufactured products. When $U_{2r}^{G} > 0$, green consumers will purchase the remanufactured product.

According to Atasu et al., the demand in the first period is only for the new product [39]. Therefore, when $U_{1n}^{o} > 0$, consumers will purchase the new product and the demand is shown as:

$$q_{1n} = Q - p_{1n} \qquad (3.1)$$

In the market, manufacturers often adopt low-price strategies for remanufactured products to attract more general consumers to purchase. Therefore, $\eta p_{2n} > p_{2r}$. In general, when the manufacturer sells the remanufactured product at a lower price, demand for both new and remanufactured products will be generated. However, since green consumers primarily consider the environment, their demand for the remanufactured product is the only consideration.

Lemma 1.
$\eta < p_{2r} / p_{2n}$, the price of the remanufactured product would be higher, and therefore, general consumers will only purchase the new product.
Proof: See APPENDIX A.

Lemma 2.
When $\eta > 1 - (p_{2n} - p_{2r} / Q)$, general consumers have higher perceived values for the remanufactured products, and therefore, they will merely purchase remanufactured products.
Proof: See APPENDIX B.

Since the manufacturers sell the remanufactured products at a low price for attracting general consumers. We consider the case that general consumers have demand for both new and remanufactured products, as shown in Lemma 3:

Lemma 3.
For $1 - (p_{2n} - p_{2r} / Q) > \eta > p_{2r} / p_{2n}$, the general consumers will have demand for both new and remanufactured products, and the demand in the second period for the new and remanufactured products are respectively given as:

$$(q_{2n}^{o}, q_{2r}^{0}) = \left((1-\beta)(Q - p_{2n} - p_{2r} / 1-\eta), \\ (1-\beta)(Q - \eta p_{2n} - p_{2r} / \eta(1-\eta)) \right) \quad (3.2)$$

Proof: See APPENDIX C.

Since green consumers merely purchase the remanufactured products, the demand of green consumers for the remanufactured product is given by:

$$q_{2r}^{G} = \beta(Q - p_{2r}) \quad (3.3)$$

Therefore, the total demands of the new and remanufactured products are respectively obtained as: $q_{2n} = q_{2n}^{0}$ and $q_{2r} = q_{2r}^{0} + q_{2r}^{G}$.

4.2. Model construction

We develop the profit functions of the manufacturer under the three carbon emission policies, (a) the carbon tax policy, (b) the carbon trading policy, and (c) the carbon penalty policy.

(a) Carbon tax policy

Since the manufacturer manufactures only new products in the first period, in the first period, the manufacturer has to determine the price of the new product p_{1n}. In the second period, the manufacturer recycles the new product sold in the first period for remanufacturing. Therefore, in the second period, the manufacturer manufactures both the new and remanufactured products at the same time, and has to determine the price of the new product p_{2n} and the price of the remanufactured product p_{2r}. Under the carbon tax scenario, the unit carbon emission of the new product in the first period is e_n, and the cost of taxation per unit is t_1. The unit carbon emissions of the remanufactured product in the second period is $e_n - \varepsilon$. In sum, the manufacturer's profit is derived as:

$$\pi = (p_{1n} - C_n) q_{1n} + (p_{2n} - C_n) q_{2n} + (p_{2r} - C_r) q_{2r} \\ - t_1 \left(e_n * q_{1n} + e_n * q_{2n} + (e_n - \varepsilon) q_{2r} \right) \quad (3.4)$$

Since the remanufactured products in the second period are remanufactured from the recycled used items sold in the first period, the number of the remanufactured products in the second period is thus constrained to the number of recycled used items sold in the first period; that is, the inequality has to be satisfied which is given by:

$\gamma q_{1n} \geq q_{2r}$

In considering the recycling limitation, it is thus a non-linear progressing problem with the inequality constraints. Therefore, the problem can be formulated as:

$$\begin{aligned} Max\pi &= \left(p_{1n} - c_n\right)q_{1n} + \left(p_{2n} - c_n\right)q_{2n} \\ &+ \left(p_{2r} - c_r\right)q_{2r} \\ &- t_1\left(e_n * q_{1n} + e_n * q_{2n} + \left(e_n - \varepsilon\right)q_{2r}\right) \end{aligned} \quad (3.5)$$
$$s.t.\ \gamma q_{1n} \geq q_{2r}$$

Theorem 1.

(1) When $\varepsilon_{1b} < \varepsilon < \varepsilon_{1a}$, and $t_{1b}^* < t_1^* < t_{1a}^*$, the manufacturer will remanufacture all recycled products which has a high reduction degree of carbon abatement and the optimal prices of the new and remanufactured products in the two periods are given by:

$$\begin{aligned} P_{1n} &= 1/2A[Q + C_n + t_1 e_n - \left(\gamma\left(-1+\beta\right)\gamma\right)C_n \\ &+ \left(\gamma c_r - \gamma t_1 \varepsilon\right)B - \gamma\left(-1+\eta\right)(Q\eta\left(\beta - \gamma\right) \\ &+ t_1(-1+\beta-\beta\eta+\eta\gamma))] \end{aligned} \quad (3.6)$$

$$\begin{aligned} P_{2n} &= 1/w[-Q(-1+\beta(-1+\eta)^2) \\ &+ (1+\beta\left(-1+\beta\right))C_n \\ &+ t_1\left(1+\beta(-1+\eta)\right)e_n] \end{aligned}, \text{ and} \quad (3.7)$$

$$\begin{aligned} P_{2r} &= 1/C[\eta(Q(-1+\beta^2(-1+\eta)^2) \\ &+ \beta C(\eta^2 - (-1+\eta)^2\gamma) + t_1(1+\gamma)e_n + c_n) \\ &+ D - (t_1\varepsilon + c_r)E \\ &+ \eta\left((-1+\eta)\gamma(-1+\eta)\gamma(-1+\eta\gamma)\right)] \end{aligned}, \text{respectively,} \quad (3.8)$$

where

$A = \left(-1+\beta(1+(-1+\eta)\eta + (-1+\eta)\eta\gamma^2\right)$,

$B = \left(-1+\beta(1+(-1+\eta)\eta\right)$, $C = 2 + (1+\beta(-1+\eta)(-1+\beta(1+(-1+\eta))\eta + (-1+\eta)\eta\gamma^2)$,

$D = \eta\left(1+\beta(-1+\eta)(-1+\beta(1+(-1+\eta)\gamma)\right)$,

$E = \eta\left(1+\beta(-1+\eta)\right)(-1+\eta)\gamma^2$,

and $\omega = 2 + 2\beta(-1+\eta)$.

And the thresholds for carbon abatement and carbon tax are given by:

$$\begin{aligned} \varepsilon_{1b} &= 1/F[\eta(1-\eta+\gamma-\eta\gamma)c_n + (-1+ \\ &\beta(1+(-1+\eta)\eta)c_r + (-1+\eta) \\ &(Q\eta(-\beta+\gamma) + t_1 + \beta(-1+\eta) - \eta\gamma)e_n))] \end{aligned}, \quad (3.9)$$

$$\begin{aligned}\varepsilon_{1a} &= 1/t_1\eta\gamma^2[-Q(-1+\beta((-1+\eta)^2 \\ &+\eta\gamma(1+(-1+\eta)\gamma)+(-1+\beta-\beta\eta \\ &-\eta(-1+\gamma)\gamma)c_n+(\eta\gamma^2 c_r \\ &+t_1(-1+\beta-\beta\eta-\eta\gamma)e_n)]\end{aligned}, \quad (3.10)$$

$$\begin{aligned}t_{1b}^* &= 1/G[-Q(-1+\beta((-1+\eta)^2-\eta(-1+\eta)\gamma) \\ &+\eta^2 r^2+(-1+\beta-\beta\eta-\eta(-1+\gamma)\gamma)c_n \\ &+\eta\gamma^2 c_r]\end{aligned}, \text{ and} (3.11)$$

$$\begin{aligned}t_{1a}^* &= [Q(1-\beta+2\beta\eta-\beta\eta^2-\eta\gamma)c_n \\ &+\beta\eta c_n+\eta\gamma c_n] \\ &/[(-1-\beta+\beta\eta-\eta\gamma)e_n]\end{aligned}, \text{ respectively} (3.12)$$

,where $F = t_1\left(-1+\beta(1+(-1+\eta)\eta\right)$ and $G = \left(1+\beta(-1+\eta)+\eta(-1+\gamma)\gamma\right)e_n$.

(2) When $\varepsilon_{1c} \le \varepsilon \le \varepsilon_{1b}$ and $t_{1d}^* \le t_1 \le t_{1c}^*$, only part of the recycled products are remanufactured, which is a low reduction degree of carbon abatement. and the optimal prices of the new and remanufactured products in the two periods are given by:

$$P_{1n} = 1/2(Q+C_n+t_1 e_n) \quad (3.13)$$

$$\begin{aligned}P_{2n} &= 1/w[-Q(-1+\beta(-1+\eta)^2)+(1+\beta(-1 \\ &+\beta))C_n+t_1\left(1+\beta(-1+\eta)\right)(e_n-\varepsilon)]\end{aligned}, \text{ and} (3.14)$$

$$\begin{aligned}P_{2r} &= [Q\eta+(1+\beta(-1+\eta)c_r) \\ &+t_1(1+\beta(-1+\eta)(e_n-\varepsilon)]/\omega\end{aligned}, \text{ respectively.} (3.15)$$

And the thresholds and carbon tax are given by:

$$\begin{aligned}\varepsilon_{1c} &= 1/t_1 F[(\eta-\beta\eta)c_n+(-1+\beta(-1+\eta)\eta)c_r \\ &+(-1+\eta)(-Q\beta\eta+t_1(1+\beta(-1+\eta))e_n)]\end{aligned}, \quad (3.16)$$

$$t_{1c}^* = Q - c_n/e_n, \text{ and} \quad (3.17)$$

$$\begin{aligned}t_{1d}^* &= [Q\beta(-1+\eta)\eta)+(-1+\beta)\eta c_n \\ &+c_r+\beta(-1+\eta-\eta^2))c_r] \\ &/[(1+\beta(-1+\eta))(-1+\eta)e_n]\end{aligned}, \text{ respectively.} (3.19)$$

Proof: See APPENDIX D.

Proposition 1.

1. When the degree of carbon abatement for the remanufactured products is within the range $\varepsilon_{1b} < \varepsilon \leq \varepsilon_{1a}$
   I. The optimal prices of the new product in the first period and the remanufactured product in the second period decrease as the degree of carbon abatement of the remanufactured product for the manufacturer increases.
   II. Changes in the degree of carbon abatement of the remanufactured product do not affect the price of the new product in the second period.
2. When the carbon reduction degree of the remanufactured product is within the range $\varepsilon_{1c} < \varepsilon \leq \varepsilon_{1b}$
   I. Changes in the carbon abatement degree of the remanufactured product will not affect the price of the new product in both periods.
   II. The price of the remanufactured products in the second period will fall as the degree of carbon abatement for the remanufactured products of the manufacturer increases.

Proof: See APPENDIX E.

Proposition 1 indicates that in considering carbon tax, the cost of increasing emission incurs due to taxation, and therefore, the effectiveness of the carbon abatement for the remanufactured products becomes critical. With the high degree of carbon abatement, manufacturing more remanufactured products can wane the cost of carbon emissions caused by taxation. Therefore, the manufacturer can lower the price of the new product in the first period to attract more consumers to purchase, which can increase the number of recyclable first-period used items for the second period which can be used to produce more remanufactured products that and attract consumers to make purchases at a lower price, and thus earn more profits. On the other hand, with the low degree of carbon abatement, the cost saving due to carbon abatement is not substantial. The prices of the new product in both periods are not affected by the carbon abatement of the remanufactured product. However, the remanufactured product in the second period will still be sold at a lower price to attract more consumers to make purchases and increase revenue as the carbon abatement of remanufactured products increases.

We also investigate the impacts that the high and low degrees of carbon abatement has on the profits, and the result is shown in Fig. 4.1.

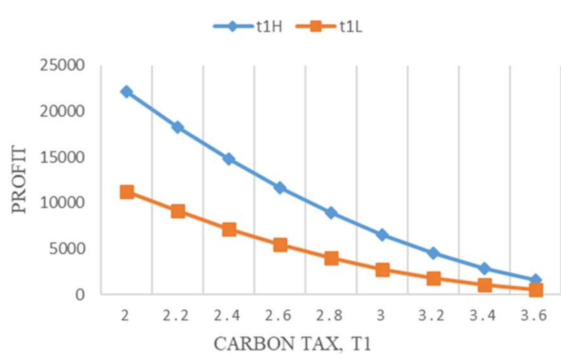

Fig. 4.1. Comparison of profits of the high and low levels in carbon abatement with carbon levy as a variable factor

From Fig. 4.1, as the carbon tax increases, no matter which carbon abatement strategy is adopted, profits will fall. However, the manufacturer should always adopt the high carbon abatement strategy to earn more profits by utilizing its high carbon abatement technology. In such a case, all the products recycled in the first period can be remanufactured.

(b) Carbon trading policy

The profit model under the carbon trading policy will be constructed below. It is expected that under the carbon trading policy, the optimal production price and production quantity that maximize the profits of the two-phase mixed production system can be found. This scenario is the result of the production of new products and remanufactured products in each of the two phases. The total amount of carbon emissions generated does not reach the emission balance generated by the limit amount L in each period. The first period is allowed to be sold at a per unit price t_2, and the second period is traded at a per unit price $(1+\theta)t_2$. Sell it to reduce cost expenditure. Otherwise, if the upper limit of the emission quota is exceeded, the emission rights must be purchased through the trading market. It is assumed that the transaction price is the average market price, and the emission quota cannot be stored or there is no emission balance to purchase. situation, the construction of a profit formula in the case of carbon trading, which mainly includes the production profits and emission costs of new products and remanufactured products in two periods, as well as carbon trading profits or costs, and the carbon emissions trading volume is subtracted from the emission upper limit of each period The total emissions of each period of production, and the recycling limit are finally considered, so it is a nonlinear problem of the non-equal limit equation, and the profit equation needs to be solved using KKT conditions, so the manufacturer's new profit equation is as follows:

$$\begin{aligned}\pi &= \left(p_{1n}-C_n\right)q_{1n}+\left(p_{2n}-C_n\right)q_{2n}\\&\quad+\left(p_{2r}-C_r\right)q_{2r}+t_2(L-(e_nq_{1n}))\\&\quad+(1+\theta)t_2\cdot(L-(e_nq_{2n}+\left(e_n-\varepsilon\right)q_{2r}))\end{aligned} \quad . \qquad (3.19)$$

Considering the situation of the manufacturer in carbon trading and meeting the conditions of KKT, the carbon reduction degree of two different remanufactured products can be obtained. The optimal selling price and production quantity of the different new products and remanufactured products will be determined by Theorem 2 to satisfy KKT. The best selling price and production quantity under the conditions.

Theorem 2.

(1) When $\varepsilon_{2b} < \varepsilon < \varepsilon_{2a}$, and $t_{2b}^* < t_2^* < t_{2a}^*$, the manufacturer will remanufacture all recycled products which has a high reduction degree of carbon abatement and the optimal prices of the new and remanufactured products in the two periods are given by:

$$\begin{aligned} P_{1n} = 1/2H[&Q + C_n + t_2 e_n - \gamma\eta(-1+\beta \\ &+(-1+\eta)\gamma)C_n + (\gamma C_r - \gamma t_2(1+\theta)\varepsilon)L \\ &-\gamma(-1+\eta)(Q\eta(\beta-\gamma)) \\ &+t_2((-1+\beta-\beta\eta)(1+\theta)+\eta\gamma)e_n))] \end{aligned}, \qquad (3.20)$$

$$\begin{aligned} P_{2n} = 1/\omega[&-Q(-1+\beta(-1+\eta)^2) \\ &+(1+\beta(-1+\beta))C_n \\ &+t_2(1+\beta(-1+\eta))((1+\theta))e_n] \end{aligned} \text{, and} \qquad (3.21)$$

$$\begin{aligned} P_{2r} = 1/I[&\eta(Q(-1+\beta(\eta-1)^2+\beta(\eta^2 \\ &-(\eta-1)^2\gamma)+(t_2(1+\theta)e_n+c_r)J \\ &-(\eta-1)(1+\theta)\gamma^2\varepsilon)+\eta((\eta-1)\gamma\cdot \\ &(\eta\gamma-1))+K(c_n+e_n t_2) \\ &+\eta(1+\beta(-1+\eta))\cdot(e_n t_2\theta(-1+\beta))] \end{aligned} \text{, respectively} \qquad (3.22)$$

, where $H = \left(-1+\beta(1+(-1+\eta)\eta+(-1+\eta)\eta\gamma^2\right)$,

$L = \left(-1+\beta(1+(-1+\eta)\eta\right)$,

$$\begin{aligned} I = 2 + (1+\beta(-1+\eta)(-1+\beta(1+(-1+\eta)\eta) \\ +(-1+\eta)\eta\gamma^2) \end{aligned},$$

$J = \eta\left(1+\beta(-1+\eta)\right)(-1+\eta)\gamma^2$, and

$K = \eta\left(1+\beta(-1+\eta)\right)(-1+\beta+(-1+\eta)\gamma)$.

The threshold of high carbon abatement of remanufacturing and the carbon trading price are

$$\begin{aligned} \varepsilon_{2b} = 1/Ft_2[&\eta(1-\beta+\gamma-\eta\gamma)c_n \\ &+(-1+\beta(1+(\eta-1)\eta)c_r \\ &+(-1+\eta)(Q\eta(-\beta+\gamma) \\ &+t_2(1+\theta+\beta(-1+\eta)-\eta\gamma)e_n)] \end{aligned}, \qquad (3.23)$$

$$\begin{aligned} \varepsilon_{2a} = 1/N[&-Q(-1+\beta(\eta-1)^2+\eta\gamma(1+(\eta-1)\gamma) \\ &+(-1+\beta-\beta\eta-\eta(-1+\gamma)\gamma)c_n \\ &+(\eta\gamma^2 c_r + t_2(-(1+\beta(-1+\eta)+\eta\gamma)e_n)] \end{aligned}, \qquad (3.24)$$

$$t_{2b}^{*} = 1/O[-Q(-1+\beta(\eta-1)^2-\eta(\gamma-1)\gamma+\eta^2\gamma^2) + (-1+\beta-\beta\eta-\eta(-1+\gamma)\gamma)c_n+\eta\gamma^2 c_r]$$, and(3.25)

$$t_{2a}^{*} = [a(1-\beta+2\beta\eta-\beta\eta^2-\eta\gamma)-c_n - \beta\eta c_n+\beta c_n+\eta\gamma c_n] /[(1-\beta+\beta\eta-\beta\theta+\beta\eta\theta-\eta\gamma)e_n]$$, respectively.(3.26)

,where $N = t_2\eta\gamma^2(1+\theta)$, and
$O=(1+\theta+\beta(-1+\eta)(1+\theta)-\eta\gamma+\eta\gamma^2+\eta\theta\gamma^2)e_n$.

(2) When $\varepsilon_{2c} < \varepsilon < \varepsilon_{2b}$ and $t_{2d}^{*} < t_2^{*} < t_{2c}^{*}$, merely part of the recycled products will be remanufactured into remanufactured products, and the optimal prices of new and remanufactured products and the production quantity of the products in the two periods are given by:

$$P_{1n} = 1/2(Q+c_n+t_2e_n),$$ (3.27)

$$P_{2n} = 1/\omega[-Q(-1+\beta(-1+\eta)^2) + (1+\beta(-1+\eta))c_n + t_2(1+\beta(-1+\eta))(1+\theta)e_n]$$, and (3.28)

$$P_{2\gamma} = 1/\omega[Q\eta+(1+\beta(-1+\eta)c_r) + t_1(1+\beta(-1+\eta))(1+\theta)(e_n-\varepsilon)]$$, respectively.(3.29)

The threshold of low carbon abatement and the trading prices are given by:

$$\varepsilon_{2c} = 1/t_2F[(\eta-\beta\eta)c_n+(-1+\beta(1+(\eta-1)\eta)c_r + (\eta-1)(-Q\beta\eta+t_2(1+\beta(\eta-1))(1+\theta)e_n)]$$,(3.30)

$$t_{2c}^{*} = Q-c_n/e_n$$, and (3.31)

$$t_{2d}^{*} = [Q(\beta\eta^2-\beta\eta)+(\beta-1)\eta c_n - (\beta-1+\beta\eta-\beta\eta^2)c_r] /[(\eta-1)(-\beta\theta+\beta\eta\theta-\eta\gamma)e_n]$$, respectively.(3.32)

Proof: See APPENDIX F.

Proposition 2.

1. When the degree of carbon abatement for the remanufactured product is within the range $\varepsilon_{2b} \le \varepsilon \le \varepsilon_{2a}$
   I. The optimal prices of the new product in the first period and the remanufactured product

in the second period decrease as the degree of carbon abatement of the remanufactured product increases.

II. Changes in the degree of carbon abatement of the remanufactured product do not affect the price of the new product in the second period.

2. When the degree of carbon abatement for the remanufactured product is within the range $\varepsilon_{2c} \leq \varepsilon \leq \varepsilon_{2b}$

I. Changes in the degree of carbon abatement of the remanufactured product do not affect the prices of the new product in both periods.

II. The price of the remanufactured product in the second period decreases as the degree of carbon abatement for the remanufactured product increases.

Proof: See APPENDIX G.

Proposition 2 indicates that in considering carbon trade, the manufacturer can purchase more carbon emission right due to its own carbon abatement efficiency, and thus the carbon abatement of the remanufactured product will enhance the overall revenue. When the carbon abatement efficiency is high, producing more remanufactured products can reduce the cost of carbon emissions incurred from exceeding the carbon cap, and even earn the additional revenue by selling the carbon right. Therefore, the manufacturer can lower the price of the new product in the first period to attract more consumers to make purchases, and, in the meantime, increase the quantity of recycled products which can thus be used to produce more remanufactured products, more consumers in the second period can also be attracted by setting a lower price for the remanufactured product which can eventually earn more overall profit. When the carbon abatement efficiency is low, the prices of the new product for both periods will not be substantially affected by the degree of carbon abatement. However, when the carbon abatement increases, the remanufactured product in the second period can still be sold at a lower price to attract more consumers to make purchases, and the profit can thus be increased.

The impacts that the carbon abatement efficiency has on the profit are also investigated, and the results are shown in Fig. 4.2.

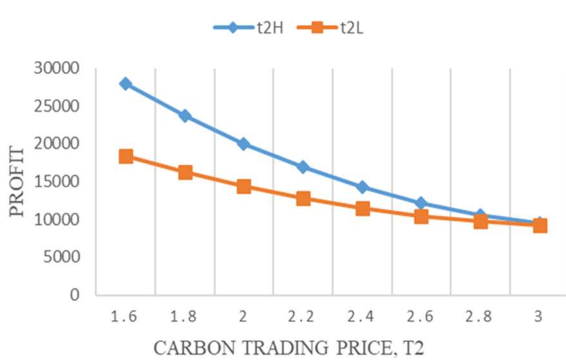

Fig. 4.2. Comparison of profits of the high and low levels in carbon abatement with carbon trading as a variable factor

From Fig. 4.2, as the carbon trading price increases, no matter which carbon abatement strategy is adopted, the profits will decline. However, the manufacturer should always adopt the high carbon abatement strategy to earn more profits by utilizing its own carbon abatement technology. In such a case, all the products produced in the first period will be recycled and remanufactured, and the manufacturer can earn more profit even under the environmental protection policies.

(C) Carbon penalty policy

Under the carbon penalty scenario, the total carbon emissions generated by producing the new and remanufactured products in the two periods have to comply with the carbon cap, L, regulated by the government. If the carbon emissions exceed the carbon cap, an amount of penalty cost due to exceeding the carbon cap would incur as t_3. Therefore, the manufacturer's profit is derived as:

$$\begin{aligned}\pi_3 &= (P_{1n} - c_n)q_{1n} + (P_{2n} - c_n)q_{2nn} + (P_{2\gamma} - c_r)q_{2r} \\ &- t_3\left((e_n q_{1n} - L) - t_3\left(e_n q_{2n} + (e_n - \varepsilon)q_{2\gamma}\right)) - L\right) \\ &+ \lambda\left(\gamma q_{1n} - q_{2r}\right)\end{aligned} \quad (3.33)$$

Theorem 3.

(1) When the carbon abatement efficiency $\varepsilon_{3b} \le \varepsilon \le \varepsilon_{3a}$, and $t_{3b}^* < t_3^* < t_{3a}^*$, the manufacturer will utilize all recycled products for remanufacturing and the optimal prices of the new and remanufactured products in the two periods are given by:

$$\begin{aligned}P_{1n} &= 1/2A[Q + C_n + t_3 e_n - \left(\gamma\left(\beta - 1\right)\gamma\right)C_n \\ &+ \left(\gamma c_r - \gamma t_3 \varepsilon\right)B - \gamma\left(-1 + \eta\right)(Q\eta\left(\beta - \gamma\right), \\ &+ t_3(-1 + \beta - \beta\eta + \eta\gamma)e_n)]\end{aligned} \quad (3.34)$$

$$\begin{aligned}P_{2n} &= 1/\omega[-Q(-1 + \beta(\eta - 1)^2) + (1 + \beta\left(\eta - 1\right))C_n \\ &+ t_3\left(1 + \beta(\eta - 1)\right)e_n]\end{aligned}$$, and(3.35)

$$\begin{aligned}P_{2r} &= 1/c[\eta(Q(-1 + \beta^2(\eta - 1)^2) + \beta(\eta^2 \\ &- (\eta - 1)^2\gamma) + D(c_n + t_3(1 + \gamma)e_n) \\ &+ t_3(1 + \gamma)e_n + E(c_r - t_3\varepsilon) \\ &+ \eta(Q(\eta - 1)\gamma(\eta\gamma - 1)))]\end{aligned}$$, respectively

(3.36)

,where $A = \left(-1 + \beta(1 + (-1 + \eta)\eta + (-1 + \eta)\eta\gamma^2\right)$,

$B = \gamma\left(-1 + \beta(1 + (-1 + \eta)\eta)\right)$,

$$\begin{aligned}C &= (2 + (1 + \beta(-1 + \eta)(-1 + \beta(1 + (-1 + \eta)\eta) \\ &+ (-1 + \eta)\eta\gamma^2)\end{aligned}$$,

$D = \eta\left(1+\beta(-1+\eta)\right)(-1+\beta+(-1+\eta)\gamma)$,

$E = \left(1+\beta(-1+\eta)\right)(-1+\eta)\gamma^2$

, and $\omega = 2+2\beta(-1+\eta)$.

The thresholds for the high degree carbon abatement and the carbon penalty fee are given as:

$$\begin{aligned}\varepsilon_{3b} = 1/\mathrm{t}_3 F[&\eta(1-\eta+\gamma-\eta\gamma)c_n \\ &+(-1+\beta(1+(\eta-1)\eta)c_r \\ &+(\eta-1)(Q\eta(\gamma-\beta) \\ &+t_3(-1+\rho(\eta-1)-\eta\gamma)e_n))]\end{aligned}, \quad (3.37)$$

$$\begin{aligned}\varepsilon_{3a} = 1/t_3\eta\gamma^2[&-Q(-1+\beta(\eta-1)^2 \\ &+\eta\gamma(1+(\eta-1)\gamma)+(-1+\beta-\beta\eta-\eta(\gamma-1)\gamma)c_n \\ &+(\eta\gamma^2 c_r+t_3(-1+\beta-\beta\eta+\eta\gamma)e_n)]\end{aligned}, \quad (3.38)$$

$$\begin{aligned}t^*_{3a} = [&Q(1-\beta+2\beta\eta-\beta\eta^2-\eta\gamma)c_n \\ &+\beta\eta c_n+\eta\gamma c_n]/[(1-\beta+\beta\eta-\eta\gamma)e_n]\end{aligned}, \text{ and} \quad (3.39)$$

$$\begin{aligned}t^*_{3\mathrm{b}} = 1/G[&-Q(-1+\beta(\eta-1)^2-\eta(\gamma-1)\gamma \\ &+\eta^2\gamma^2+(\beta-1-\beta\eta-\eta(\gamma-1)\gamma)c_n \\ &+\eta\gamma^2 c_r]\end{aligned}, \text{ respectively} \quad (3.40)$$

,where $F = (-1+\beta(1+(-1+\eta)\eta))$, and $G = (-1+\beta-\beta\eta-\eta(-1+\gamma)\gamma)c_n$

(2) When $\varepsilon_{3c} \le \varepsilon \le \varepsilon_{3b}$ and $t^*_{3d} \le t_3 \le t^*_{3c}$, only part of the recycled products are remanufactured, and the optimal prices of the new and remanufactured products in the two periods are given as:

$$p_{1n} = 1/2(Q+c_n+t_3e_n), \quad (3.41)$$

$$\begin{aligned}p_{2n} = 1/w[&-Q(-1+\beta(\eta-1)^2)+(1+\beta(\eta-1))c_n \\ &+t_3\left(1+\beta(-1+\eta)\right)(e_n-\varepsilon)]\end{aligned}, \text{ and} \quad (3.42)$$

$$\begin{aligned}p_{2r} = [&Q\eta+(1+\beta(-1+\eta)c_r) \\ &+t_3(1+\beta(-1+\eta)(e_n-\varepsilon)]/\omega\end{aligned}, \text{ respectively.} \quad (3.43)$$

The thresholds for the carbon abatement and the carbon penalty fee are given as:

$$\varepsilon_{1c} = 1/(t_3 F)[(\eta - p\eta)c_n + (-1 + p(1+(\eta-1)\eta)c_r + (\eta-1)(-Qp\eta + t_3(1+p(\eta-1))e_n)], \quad (3.44)$$

$t_{3c}^* = (Q - c_n)/e_n$, and (3.45)

$$t_{3d}^* = [Q\beta(\eta-1)\eta) + (\beta-1)\eta c_n + c_r + \beta(\eta - 1 - \eta^2))c_r] / [(1+\beta(-1+\eta))(-1+\eta)e_n], \text{ respectively.} \quad (3.46)$$

Proof: See APPENDIX H.

Proposition 3.

1. When the carbon abatement for producing the remanufactured product is within the range $\varepsilon_{3b} < \varepsilon \le \varepsilon_{3a}$
   I. The optimal prices of the new product in the first period and the remanufactured product in the second period decrease as the carbon abatement of the remanufactured product increases.
   II. Changes in the degree of carbon abatement of the remanufactured product do not affect the price of the new product in the second period.
2. When the carbon reduction degree for producing the remanufactured products is within the range $\varepsilon_{3c} < \varepsilon \le \varepsilon_{3b}$
   I. Changes in the carbon abatement degree of the remanufactured product do not affect the price of the new product in both periods.
   II. The price of the remanufactured product in the second period will decline as the degree of carbon abatement for producing the remanufactured product increases.

Proof: See APPENDIX I.

Proposition 3 indicates that in considering the carbon penalty policy, if the carbon emissions exceed the carbon cap, the cost of the carbon penalty is incurred for the extra carbon emissions. Therefore, the carbon abatement of the remanufactured products becomes critical. With the high degree of carbon abatement, producing more remanufactured products will not increase the cost of carbon penalty incurred, so the manufacturer can lower the price of the new product in the first period to attract more consumers to make purchases, which can increase the quantity of recyclable used items in the first period for furthermore remanufacturing in the second period. Moreover, if more consumers can be attracted to purchase the remanufactured product at a lower price, more profits can also be earned. However, with the low degree of carbon abatement, the prices of new products in both periods are not affected by the carbon abatement of the remanufactured product. In such a case, the remanufactured products in the second period can still be sold at a lower price to attract more consumers to purchase for increasing the profit as the degree of carbon abatement of remanufactured products increases.

The impacts that high and low degrees of carbon abatement have on the profits are also investigated, and the results are shown in Fig. 4.3.

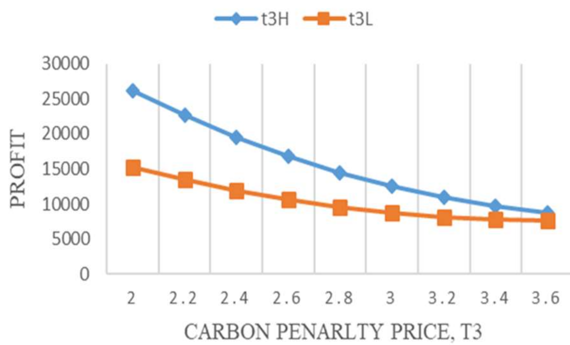

Fig. 4.3. Comparison of high and low carbon abatement profit with carbon penalty price as the change factor

From Fig. 4.3, as the carbon penalty increases, no matter which carbon abatement strategy is adopted, profits will decline. However, the manufacturer should always adopt the high carbon abatement strategy to earn more profits by utilizing its own carbon abatement technology. In such a case, the products recycled in the first period should all be remanufactured.

IV. COMPARISON OF THREE ENVIRONMENTAL POLICIES

When the manufacturer is encountered with diversified carbon emission policies in different regions, they have to consider the impacts that different policies have on the profits. Assume that t_3 is a constant value, and compare the changes in carbon factors t_1 and t_2.

5.1. Comparison of carbon emission policies

For adopting a High carbon abatement of remanufactured product, the impacts of the carbon factors t_1 and t_2 are investigated, and the results are shown in Fig. 5.1 and Fig. 5.2.

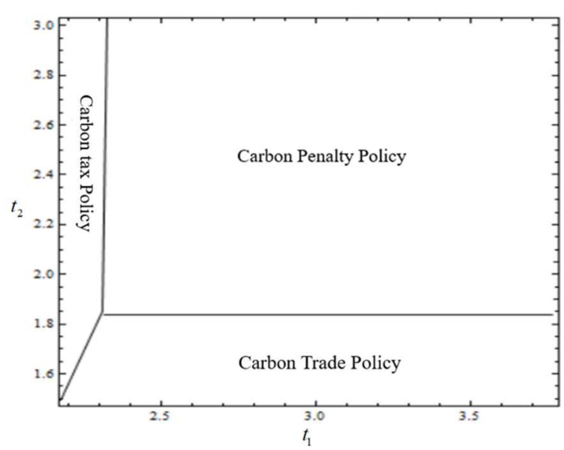

Fig. 5.1. Comparison of strategies for the changing factors of carbon tax and carbon trading price

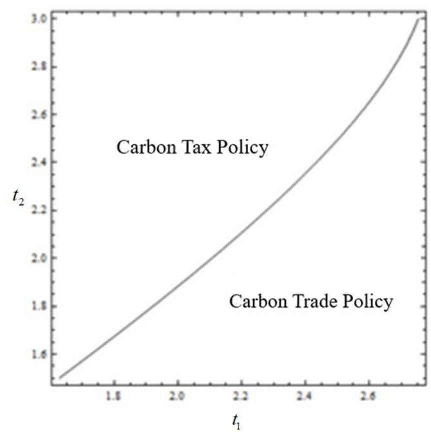

Fig. 5.2. Comparison of strategies for the changing factors of the carbon tax and carbon trading price

From Fig. 5.1 and Fig. 5.2, if the manufacturer has more advanced carbon abatement technology, a high carbon abatement efficiency and a low carbon penalty fee would enable the carbon penalty policy to be more advantageous. In a carbon trading market, better profit can be achieved via trading, whilst the carbon penalty incurs only when carbon emissions exceed. Therefore, the management of carbon emissions will enhance the revenue. Only when the carbon tax is extremely low and the carbon trading price is extremely high, operating under the carbon taxation policy is preferred. Moreover, when both the carbon trading price and carbon tax are considerably higher, operating under the carbon penalty policy is preferred. For a high carbon penalty fee as the price of carbon tax rises, operating under the carbon trading policy is adopted, and as the carbon trading price rises, operating under the carbon tax policy is performed. We found that when the carbon penalty is too high, regardless of the changes in the carbon tax and the carbon-trading price, operating under the carbon penalty is not preferred.

5.2. The contextual comparison of key parameters of emission policy

(1) The contextual comparison of the upper bounds of the carbon tax and carbon trading

The carbon tax and carbon trading policies are compared by investigating the impacts of the carbon tax t_1 , and the upper bound of carbon emission L_1 , and the results are shown in Fig. 5.3.

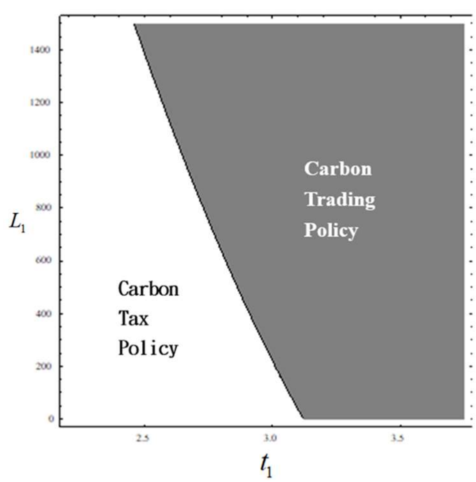

Fig. 5.3. Comparison of strategies with the upper bound of carbon tax and carbon trading as a variable factor

From Fig. 5.3, when the carbon tax is low and a more stringent emission constraint is regulated, the manufacturer can choose to operate under the carbon tax policy can earn better profits. When the carbon tax is high, a more loosen emission constraint is regulated, the manufacturer can choose to operate under the carbon trading emission policy to earn better profits.

(2) The contextual comparison of the upper bounds of the carbon tax and carbon trading
The carbon tax policy and the carbon trading policy are compared by investigating the impacts of the carbon tax t_1, and the upper bound of carbon emission L_2, and the results are shown in Fig. 5.4.

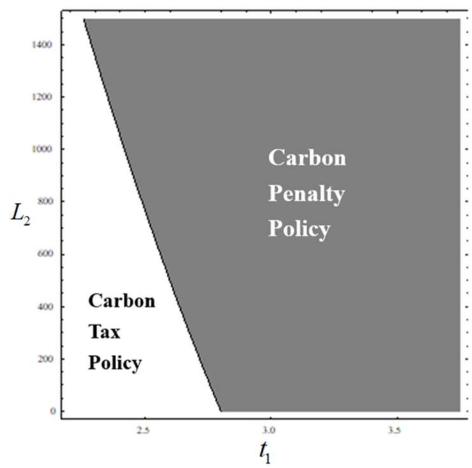

Fig. 5.4. Comparison of strategies with the upper bounds of the carbon tax and carbon penalty as a variable factor

From Fig. 5.4, when the carbon tax is low and a stricter emission constraint for carbon penalty is regulated, the manufacturer can choose to operate under the carbon tax policy to earn better profits. When the carbon tax is high and a more loosen emission constraint for carbon penalty is regulated, the manufacturer can choose to operate under the carbon penalty emission policy to earn better profits.

(3) The contextual comparison of the upper bounds of the carbon penalty and carbon trading
The impacts of the upper bound of carbon penalty policy is the upper bound of carbon emissions L_2 are also investigated, and the results are shown in Fig. 5.5.

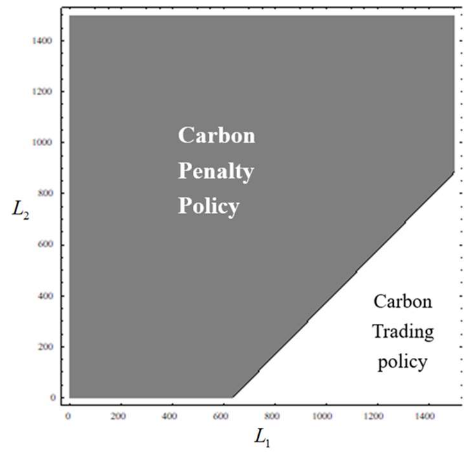

Fig. 5.5. Comparison of strategies with the upper bounds of the carbon trading and carbon penalty as a variable factor

From Fig. 5.5, when the upper constraint of the carbon penalty is stricter and the upper constant of the carbon trading policy is loosened, the manufacturer can choose to operate under the carbon trading policy to earn better profits. When the upper constraints of the carbon penalty are loosened and the upper constraints of the carbon trading policy are stricter, the manufacturer can choose to operate under the carbon trading policy to earn better profits.

V. CASE STUDY AND SENSITIVITY ANALYSIS

6.1. The description and parameter setting of the example

A manufacturer produces both new and remanufactured products and makes remanufacturing decisions based on its carbon abatement capability with consideration of general and green consumers in the market. In general, green consumers are often fewer, so we set $\beta = 0.4$. The manufacturer recycles the products sold in the first period and the recycling rate is $r = 0.87$ when limits the quantity of remanufactured products in the second period. The unit production cost of the new product is $C_n = 200$, with the emissions $e_n = 80$, and the unit production cost of the remanufactured product is $C_r = 170$. However, the emissions of the remanufactured product will depend on the manufacturer's decision of carbon abatement, with regard to the three environmental policies, the corresponding factors are carbon tax $t_1 = 2.5$, carbon trading price $t_2 = 2.5$, and carbon penalty fee $t_3 = 2.8$. In addition, the increasing rate of trading price $\theta = 0.2$ is also considered. The market potential is $Q = 500$, and the preference factor of the remanufactured product for general consumers is $\eta = 0.8$. The settings of the relevant parameters in this section are summarized in Table 6.1.

Table 6.1. Parameter settings.

Parameter	Value
Q	500
C_n	200
C_r	170
t_1	2.5
t_2	2.5
t_3	2.8
η	0.8
r	0.87
L_1	1200
L_2	1000
e_n	80
β	0.4
θ	0.2

First, when the manufacturer has higher carbon abatement capability of remanufacturing, comparing the profits under the three policies, operating under the carbon penalty policy is more profitable. The comparative results are summarized in Table 6.2.

Table 6.2. Comparison of the profits for the three Policies

Policy	Carbon Factor	Carbon abatement degree	Profit
Carbon tax	$t_1 = 2.5$	13	6275.5
Carbon trading market	$t_2 = 2.5$	14	10967.1
Carbon penalty	$t_3 = 2.8$	14	9594.7

Next, when the manufacturer has lower carbon abatement capability of remanufacturing, comparing the profits under the three policies, operating under the carbon trading policy is more profitable, and the comparative results are summarized as Table 6.3.

Table 6.3. Comparison of the profits for the three Policies

Policy	Carbon Factor	Carbon abatement degree	Profit
Carbon tax	$t_1 = 2.5$	13	6275.5

Carbon trading market	$t_2 = 2.6$	14	10967.1
Carbon penalty	$t_3 = 2.8$	14	9594.7

6.2. Sensitivity Analysis

6.2.1. Carbon tax policy

We first investigate the impacts that the carbon-abatement of the remanufactured product under the carbon tax policy have on the prices and profits of the new and remanufactured products in the two periods, and the results are shown in Tables 6.4 and 6.5.

Table 6.4 The numerical table of the impacts that the degree of carbon abatement ε has on the price and profit under the
reasonable range of high carbon abatement

ε	p_{1n}	p_{2n}	p_{2r}	q_{1n}	q_{2n}	q_{2r}	π_1^h
37.8	435.0	467.4	372.4	65	15	56	8777.5
44.1	429.2	467.4	371.2	70	11	61	9708.5
50.4	423.4	467.4	370.0	76	7	66	10718.8
56.7	417.6	467.4	367.8	82	4	71	11808.5
63	413.0	467.4	367.4	87	0	77	13158.2

As can be seen in Table 6.4, for a high degree of carbon abatement, as the degree of carbon abatement decreases, the prices of the new product in the first period and the remanufactured product in the second period increase, whilst their demands decrease. However, the price of the new products is not affected by the degree of carbon abatement in the second period, and its demand is on the rise. As a result, it can be seen that when the carbon abatement decreases, the overall profit will decrease.

Table 6.5 The numerical table of the impacts that the degree of carbon abatement ε has on the price and profit under the
reasonable range of low carbon abatement

ε	p_{1n}	p_{2n}	p_{2r}	q_{1n}	q_{2n}	q_{2r}	π_1^l
13	450	467.4	386.1	50	56	0	6275.5
14.	450	467.4	384.5	50	51	6	6285.5
15.6	450	467.4	383.0	50	46	13	6317.4
16.9	450	467.4	381.3	50	41	19	6371.1
18.2	450	467.4	379.6	50	36	26	6446.8

As can be seen in Table 6.5, for a low degree of carbon abatement, as the degree of carbon abatement increases, the prices of the new products in the two periods are not affected whilst the demand for the new product in the second period wanes. In the second period, the price of the remanufactured product rises and its demand declines. The entire profit is also on the rise with the increase of carbon abatement.

As can be seen in Tables 6.4 and 6.5, when the manufacturer adopts a high degree of carbon abatement strategy, producing the remanufactured product in the second period is predominant while adopting a low degree of carbon abatement, especially when the carbon abatement efficiency is rather low, the new product should be mainly manufactured. Therefore, the better the carbon abatement efficiency of the remanufactured product is, the more the remanufactured products should be produced. As a result, in addition to effectively reducing the impacts that the new product have on the environment, better profits can also be earned. Fig. 6.1-6.3 show the results of the investigation:

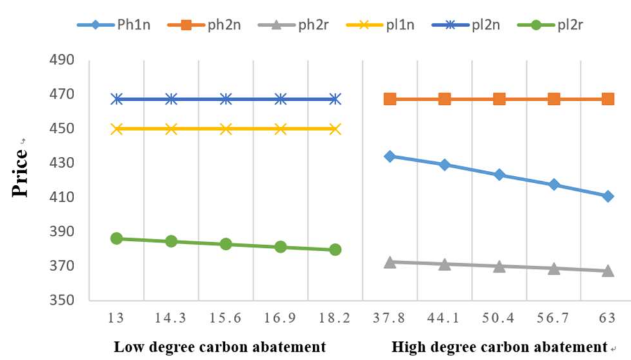

Fig. 6.1 The degree of carbon abatement and the changes in price under the carbon tax

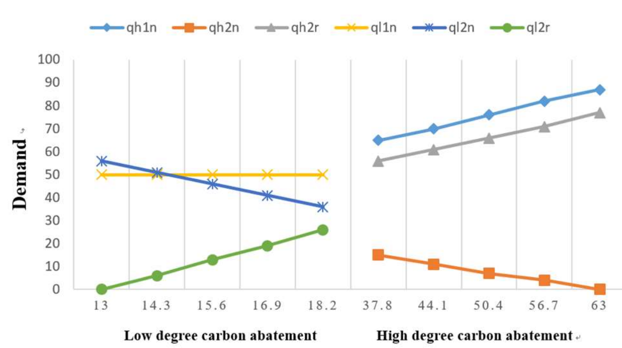

Fig. 6.2 The degree of carbon abatement and the changes in demand under the carbon tax

As can be seen in Fig. 6.1 and Fig. 6.2, regardless of the degree of carbon abatement for remanufacturing, as the carbon abatement escalates, the price of the remanufactured product should be set lower to attract more consumers, and in the meantime, the manufacturer should produce less new products. For a high carbon abatement for the remanufactured products, the price of the new product in the first period should also be set lower with the increase of the carbon abatement to attract more consumers to purchase the new product which can be recycled and remanufactured in the second period, and therefore, the better environment and profit can be achieved.

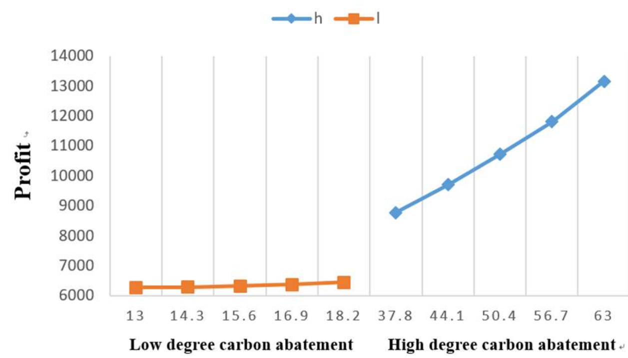

Fig. 6.3 The degree of carbon abatement and the change in the profit under the carbon tax

As can be seen in Fig. 6.3, under the carbon tax policy, as the degree of carbon abatement increases, no matter low or high carbon abatement policy is employed, the manufacturer can earn more profit. However, with the low carbon abatement, the revenue slightly rises as the degree of carbon abatement increases, while with high carbon abetment, as the degree of carbon abatement increases, the revenue increases dramatically. Therefore, under the carbon tax policy, adopting the high carbon abatement policy can earn more profit.

6.2.2 Carbon trading policy

We then investigate the impacts that the carbon abatement for remanufacturing has on the price and profit of the new and remanufactured products in the two periods under the carbon trading policy, and the results are shown in Tables 6.6 and 6.7.

Table 6.6. The numerical table of the impacts that carbon abatement ε has on the price and profit under the reasonable
range of high carbon abatement

ε	p_{1n}	p_{2n}	p_{2r}	q_{1n}	q_{2n}	q_{2r}	π_2^h
23.2	448.2	487.4	389.7	51	6	45	11640.1
26.4	444.7	487.4	388.9	55	4	48	10877.5
29.7	441.0	487.4	388.1	58	2	51	12579.8
30	437.4	487.4	387.4	62	0	54	13107.1

As can be seen in Table 6.6, for a high carbon abatement, as the carbon abatement decreases, the prices of the new product in the first period and the remanufactured product in the second period increase, whilst the demand decreases. In the second period, the price of the new product is not affected by the degree of carbon abatement, but the demand rises. The overall profit decreases with the increase of carbon abatement.

Table 6.7. The numerical table of the impacts that the degree of carbon abatement ε has on the price and profit under the reasonable range of low carbon abatement

ε	p_{1n}	p_{2n}	p_{2r}	q_{1n}	q_{2n}	q_{2r}	π_2^l
15	450	487.4	400.5	50	39	0	10967.1
16.5	450	487.4	397.6	50	30	11	11001.6
18	450	487.4	395.4	50	24	21	11076.4
19.5	450	487.4	393.1	50	17	30	11193.3
21	450	487.4	390.9	50	10	39	11352.2

As can be seen in Table 6.7, for a low carbon abatement , as the degree of the carbon abatement increases, the prices of the new product in the two periods are not affected, while the demand for the new product in the second period decreases. The price of the remanufactured products in the second period rises and its demand declines. The overall profit rises with the increase of carbon abatement.

As can be seen in Tables 6.6 and 6.7, when the manufacturer adopts a high carbon abatement strategy, producing the remanufactured products in the second period is predominant, whilst if the manufacturer adopts a high carbon abatement with a low carbon abatement efficiency, the new products should be mainly produced. Therefore, for a better carbon abatement efficiency, more remanufactured products can be produced to effectively reduce the impacts that the new products have on the environment, and thus more profits can be obtained. Fig. 6.4-6.6, show the results of the investigation.

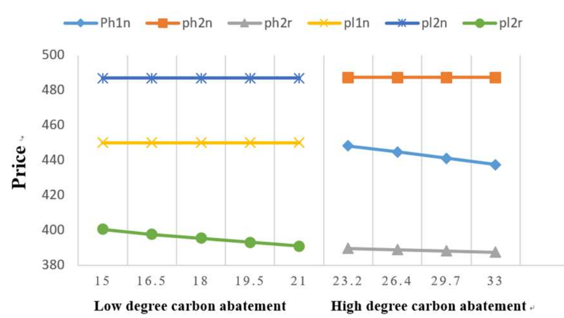

Fig. 6.4 The degree of carbon abatement and the price changes under the carbon trading policy

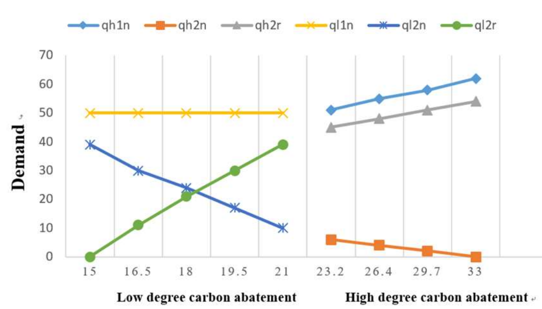

Fig. 6.5. The degree of carbon abatement and changes in demand under carbon trading policies

As can be seen in Fig. 6.4 and Fig. 6.5, similar to the case of the carbon tax, regardless of the low or high carbon abatement strategy, the price of the remanufactured product decreases with the increase of carbon abatement, which can attract more consumers to purchase the remanufactured product. Therefore, the demand for the remanufactured product would increase, and the manufacturer can thus produce fewer new products. In particular, when the carbon abatement reaches some extremely high degree, no new products will be produced. When the high carbon abatement strategy is adopted, the price of the new product in the first period will decrease with the increase of the carbon abatement. Therefore, the manufacturer can lower the price to attract more consumers to purchase the new product in the first period, which can then be recycled for remanufacturing in the second period. By remanufacturing all the recycled items, a better environment and profits will thus be achieved.

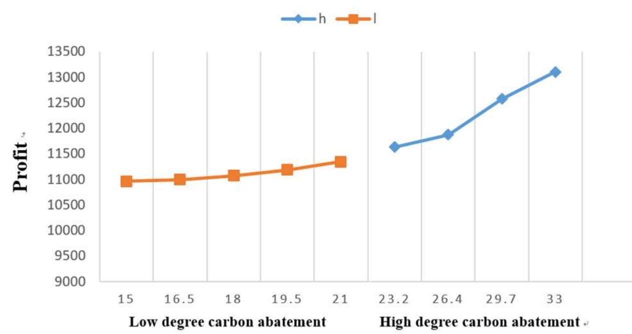

Fig. 6.6. Changes in the degree of carbon reduction and profit under the carbon trading policy

As can be seen in Fig. 6.6, under the carbon trading policy, as the degree of carbon abatement increases, no matter the high or low carbon abatement strategy is adopted, the manufacturer can earn more profits. However, for the low carbon abatement strategy, the increase in revenue is rather small, and for the high carbon abatement strategy, the revenue significantly increases with the increase of carbon abatement. Therefore, when operating under the carbon trading policy, adopting the high carbon abatement strategy can earn more profits.

6.2.3. Carbon Penalty Policy

We further investigate the impacts that the carbon abatement of remanufacturing under the carbon penalty policy have on the prices and profits of the new and remanufactured products in the two periods, and the results are shown in Tables 6.8 and 6.9.

Table 6.8. The numerical table of the impacts that the degree of carbon abatement ε has on the price and profit under the
reasonable range of high carbon abatement

ε	p_{1n}	p_{2n}	p_{2r}	q_{1n}	q_{2n}	q_{2r}	π_3^h
31.8	449.6	479.4	384.2	50	14	43	11158.6
37.1	444.1	479.4	383.0	55	10	48	11845.0

42.4	438.4	479.4	381.9	61	7	53	12601.9
47.7	433.2	479.4	380.7	66	4	58	13429.3
53	426.8	479.4	379.4	73	0	63	14489.4

As can be seen in Table 6.8, for a high degree of carbon abatement, as the degree of carbon abatement of the manufacturer decreases, the prices of the new product in the first period and the remanufactured product in the second period will increase, and their demand decreases. However, the price of the new product is not affected by the degree of carbon abatement in the second period, but its demand decreases with the increase of the carbon abatement. As a result, the overall profit also decreases.

Table 6.9. The numerical table of the impacts that the degree of carbon abatement ε has on the price and profit under the
reasonable range of low carbon abatement

ε	p_{1n}	p_{2n}	p_{2r}	q_{1n}	q_{2n}	q_{2r}	π_3^l
14.0	462	479.4	394.7	38	46	0	9594.7
15.4	462	479.4	392.8	38	38	7	9609.8
16.8	462	479.4	390.9	38	34	16	9656.8
18.2	462	479.4	388.9	38	28	24	9735.7
19.6	462	479.4	387.0	38	22	32	9846.5

As can be seen in Table 6.9, when adopting the low carbon abatement strategy, as the carbon abatement increases, the prices of the new product in the two periods are not affected while the demand for the new products in the second period decreases. In the second period, the price of the remanufactured product rises with the decline of the demand, and the overall profit is also on the rise.

As can be seen in Tables 6.8 and 6.9, under the carbon penalty policy, when the manufacturer adopts the high carbon abatement strategy, the remanufactured products should be mainly produced in the second period, whilst when adopting the low carbon abatement strategy, the new products should be mainly produced. Therefore, the better the carbon abatement efficiency is, the more the remanufactured products should be produced. This can not only effectively reduce the environmental impacts of the production of the new products, but also obtain better profits. The comparative results are shown in Figs. 6.7-6.9.

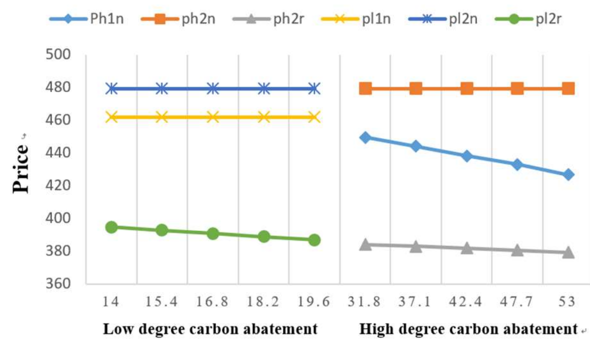

Fig. 6.7. The degree of carbon abatement and changes in prices under the carbon penalty policy

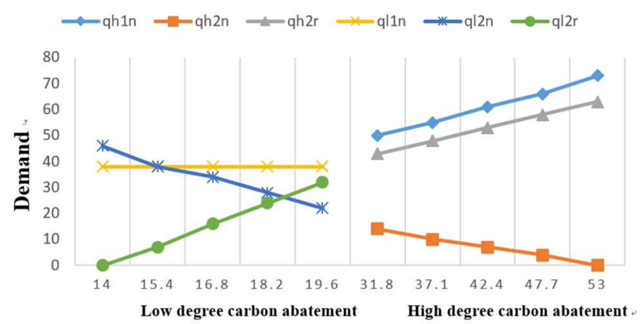

Fig. 6.8. The degree of carbon abatement and changes in demand under the carbon penalty policy

As can be seen in Fig. 6.7 and Fig. 6.8, similar to the previous two policies under the carbon penalty policy, regardless of adopting the low or high carbon abatement strategies, as the degree of carbon abatement increases, the price of the remanufactured product will decrease, which can lure more consumers to purchase the remanufactured product, so the demand for the remanufactured products greatly boosts, and the manufacturer will thus produce fewer new products. For the high carbon abatement strategy, the price of the new product will also increase with the increase in carbon abatement. Therefore, the manufacturer can lower the price to attract more consumers for the purchase of the new product in the first period, so that more new products are sold for recycling and remanufacturing in the second period. In such a case, the number of the remanufactured products will thus be increased and a better environment and profits can be achieved.

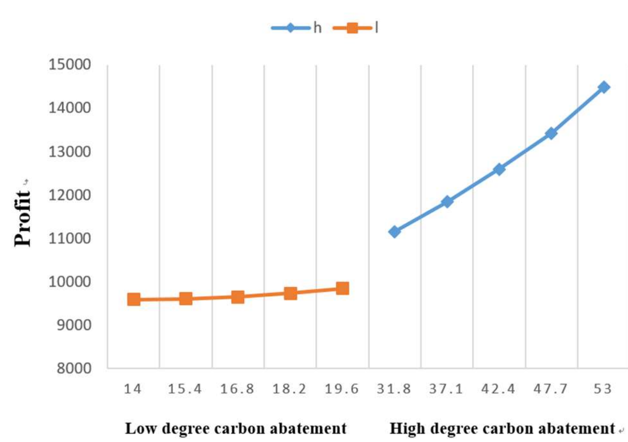

Fig. 6.9. Changes in the degree of carbon abatement and profit under the carbon penalty policy

As can be seen in Fig. 6.9, under the carbon penalty policy, as the degree of carbon abatement increases, no matter the low or high carbon abatement strategy is adopted, the manufacturer can earn better profits. However, for the low carbon abatement strategy, the increase in profit is rather small. For the high carbon abatement strategy, the profit increases dramatically with the increase of carbon abatement. Therefore, under the carbon trading policy, the manufacturer can adopt the high carbon abatement policy of the remanufactured products to obtain better profits.

Finally, with respect to the high and low carbon abatement strategies, the profits under different environmental policies are compared and the results are shown in Fig. 6.10 and Fig. 6.11.

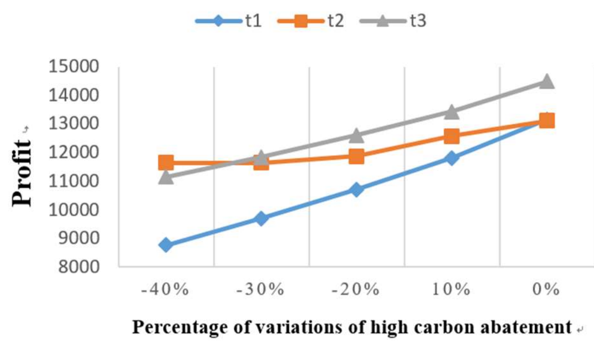

Fig. 6.10 Comparison of the profits of the three policies under a high degree of carbon reduction

As can be seen in Fig. 6.10, when adopting a high degree of carbon reduction strategy, comparing the three policies, for a high carbon abatement efficiency, operating under the carbon penalty policy is obviously more profitable than that of the other two policies. However, for a poor carbon abatement efficiency, operating under the carbon trading policy is superior to the other two policies. Thus, the carbon trading policy has to be adopted for such a case.

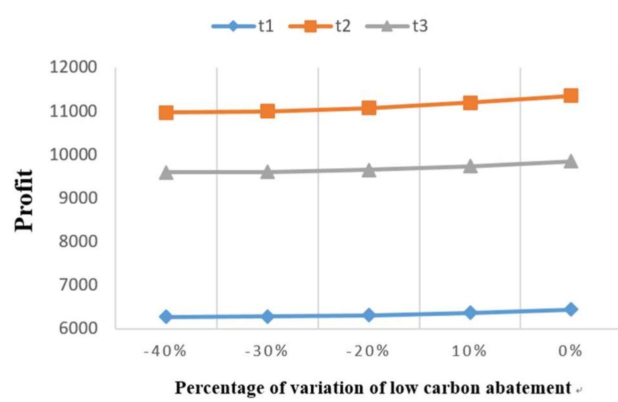

Fig. 6.11 Comparison of the profits of the three policies under low carbon abatement

As can be seen in Fig. 6.11, when the manufacturer adopts the low carbon abatement strategy, no matter how the carbon abatement efficiency changes, operating under the carbon trading strategy is always better than that of the other two carbon penalty policies. Therefore, when the manufacturer has a low carbon abatement efficiency, operating under the carbon trading policy is a better choice.

VI. CONCLUSIONS

7.1. Research Contribution

This study considers a two-period hybrid production system, which produces carbon emissions from the production of new and remanufactured products during the two periods, and investigates the impacts that the carbon emissions strategy has on the firm’s profit under the three policies respectively: (1) carbon tax policy, (2) carbon trading policy, and (3) carbon penalty policy. The corresponding optimal carbon abatement strategy and pricing of the new and remanufactured products under each policy are derived with consideration of the carbon abatement capability of the firm. It can assist managers in making overseas investment decisions under different policies regulated by different governments.

This study investigates the issue of the carbon abatement for remanufacturing, which is critical for both the environment and the economy. We investigate the significance of investing in carbon abatement under different environmental policies to assist the manufacturer in determining a proper strategy to reduce carbon emissions based on their own capability regarding carbon abatement efficiency. The results of this study can provide decision makers with relevant managerial implications, and assist them in developing the optimal strategy for taking more social responsibilities, and collaborating with the government to achieve better environmental and economic development.

7.2. Limitations and future research

Some limitations exist in our study and can be expanded in the following aspects. First, we only investigate that the manufacturer's production volume is not limited by capacity and is sufficient to meet any market demand in this paper. Uncertain demand and uncertain production can be considered in the future. Second, in practice, many countries have implemented recycling regulations to encourage manufacturers to dispose of end-of-life products. Therefore, Future study can be extended by considering government regulations which provide the recycling-related subsidies to encourage recycling. Subsidies can be provided according to the quantity of recycling. Finally, Since firms are often reluctant to passively reduce carbon emissions, future research suggests that Governments can collaborate with environmental agencies and provide with incentives, when the target amount of carbon abatement is achieved. Such incentives can be included in the model for further investigation.

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