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LOW-CARBON MANUFACTURING DECISIONS CONSIDERING CARBON EMISSION TRADING AND GREEN TECHNOLOGY INPUT

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Abstract

From the perspective of Micro-Low-Carbon Economy, this paper studies the low-carbon manufacturing decision model of manufacturing enterprises considering carbon emission trading and green technology input under the carbon cap. The paper shows that the manufacturing enterprises have optimal output and this is unique under the carbon cap. The low-carbon manufacturing decision is addressed under three situations: carbon emission trading, green technology input and joint decision. The research shows that carbon emission trading brings more flexibility to manufacturing enterprises and enables enterprises to increase their profits, however, the maximum expected profit of manufacturing enterprises in carbon emission trading (higher than, equal to, or lower than the profit without carbon cap constraint) mainly depends on the carbon cap that initially granted by the government. The marginal cost per unit of carbon emission is the best evidence that manufacturing enterprise carries on carbon emission reduction technology, obtained after green technology input is lower than the price per unit of carbon emission in the market. The good effects of green technology input on reducing carbon emission per unit product is illustrated in more carbon dioxide reduction, so that the profits of enterprises will increase. Therefore, the enterprises will be more interested to input in carbon emission reduction technology.

Keywords: carbon emissions trading, green technology input, low-carbon manufacturing decision, random demand

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1. Introduction

In China's economic system, the industrial sector is the main source of carbon dioxide emissions. As an important part of China's industrial system, the manufacturing industry has become the main force of carbon dioxide emission reduction (Liu et al., 2019). In 2001, the total carbon emissions of China's industrial sector were 938 million tons, while in 2011, the total carbon emissions of China's industrial sector exceeded 2.5 billion tons. Carbon dioxide emissions increased by 272% over the decade, with manufacturing accounting for 60% of the total carbon emissions in the industrial sector. The accelerating industrialization process promotes the rapid development of China's economy but also promotes the rapid increase of China's carbon dioxide emissions (OECD, 2017).

Moreover, with the increasing awareness of environmental protection, low-carbon consumption has become a trend. Research shows that when green low-carbon products (green products) and ordinary products appear in the market at the same time, although the production cost and price of green products are higher, consumers are not only willing to buy products with low-carbon labels, but also willing to buy such products because of the lower carbon emissions in the production and consumption process, which can bring additional utility to consumers (Olatunji et al., 2019). Buying behavior pays a higher

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price. Therefore, in the face of the government's carbon emission reduction policy and consumer demand, manufacturing enterprises must implement effective low-carbon manufacturing decisions through the production of low-carbon products, the implementation of green low-carbon technology (referred to as "green technology") for carbon emission purification treatment and other low-carbon manufacturing methods to obtain additional carbon emission rights. Enterprises can meet the demand of consumers for green life and the policy pressures of low-carbon emission reduction. They can also gain more competitive advantages and higher profits than their competitors.

2. Literature review

Schultz and Williamson (2005) demonstrated that companies must consider carbon emission rights as important resources as capital, human resources, products, services in both direct and potential impacts. Benjaafar et al. (2012) took the lead in introducing carbon emission factors into the supply chain system. Through the research, carbon emission factors were found to have an impact on the overall operational decisions of supply chain enterprises. Giraud-Carrier (2014) studied the operational decision-making process of manufacturing enterprises under three kinds of carbon emission reduction policy constraints and proved that any kind of carbon emission reduction policy constraints will reduce the optimal output of manufacturing enterprises; however, when the environmental pollution is very serious, these carbon emission reduction policies will improve the overall social welfare. Ma et al. (2016, 2017) studied the production decision-making problem of carbon-sensitive product manufacturers under the constraints of a carbon quota policy and analyzed the impact of the carbon quota policy and product carbon sensitivity on the optimal decision making. He and Ma (2018) studied the production decision-making problem of two-product manufacturing enterprises under carbon trading policy, solved and obtained the optimal production mix of manufacturing enterprises, and analyzed the impact of a carbon trading policy on the optimal decision-making of manufacturing enterprises. Jian et al. (2019) studied the pricing problem of products considering competition and cooperation in a two-oligopoly market under the constraint of a carbon quota policy. Based on the extended Bertrand game model, the optimal decision making under the two situations of competition and cooperation was obtained. Braun and Wield (1994) first put forward the concept of green technology under the background of environmental pollution and considered that green technology is an externality technology that reduces the transmission of the ecological environment generated by people in the process of production and consumption. Krass et al. (2013) studied the investment and selection of carbon emission reduction technology for manufacturing enterprises under the constraint of a carbon tax policy. Toptal et al. (2014) studied the joint decision making of inventory replenishment and green technology investment of retail enterprises under three major carbon emission reduction policies and analyzed the impact of three major carbon emission reduction policies on the investment choice of enterprises. Rocha et al. (2015) studied the pricing and green technology investment in the process of power market restructuring under the constraints of a carbon cap-and-trade policy. Drake et al. (2016) studied the technology choice and capacity decision-making of two carbon emission reduction policies: carbon tax and carbon trading.

The research on enterprise decision-making under the carbon emissions trading and green technology investment models is very rich. Considering the particularity of carbon emissions trading and green low-carbon technology investment in low-carbon manufacturing decision-making, this paper combines carbon emissions trading with green technology investment and constructs a low-carbon manufacturing decision-making model for manufacturing enterprises under carbon quota constraints, which considers both carbon emissions trading and green technology investment.

3. Problem description and hypothesis

In a free market, considering a manufacturing enterprise that produces a single product, the market demand it faces is random. At the end of the sales period, the remaining inventory will be processed according to the residual value. In addition, the manufacturing enterprises will also face shortage losses. Under the carbon limit, the government has set a maximum carbon emission limit, that is the carbon limit $K(>0)$. To express conveniently, the meanings of the symbols in the model are shown in Table 1.

On the other hand, under the background of low-carbon economy and the consideration of the three sources of carbon emission rights, namely, government quotas, carbon emission trading and green technology input for carbon emission purification treatment, as well as single-cycle production and single emission, manufacturing enterprises will make decision under different situations such as carbon emission trading, green technology input, etc.(Fig. 1.) The following assumptions are made according to the reality:

(1) The product is in a short-sale cycle, and the market is relatively stable. The price of the product remains unchanged during the sales period.

(2) $p \geq c > v > 0$; this condition indicates that every product sold in the consumer market will bring profit growth for manufacturing enterprises. However, if a product is not sold, the manufacturing enterprise will suffer a loss of profits.

(3) Assuming that manufacturing enterprises must maintain normal production and are rational, they will weigh the benefits and costs of carbon emissions trading and green technology input.

(4) Carbon emission rights are freely traded, and the market supply of carbon emission rights is sufficient within a certain range;

(5) The carbon emission per unit of product will be a certain amount when the technology level is determined.

(6) Consider that manufacturing enterprises can reduce carbon emissions by investing in green technology; when discussing the input cost of green technology, scholars at home and abroad generally believe that the input cost function of green technology should be consistent with the actual situation and usually assume that the input cost of green technology will increase rapidly with the increase of the input level of green technology. Therefore, the unit production cost of green technology input is $c(T)$, and it is continuous and differentiable and increases rapidly with the increase of the level of green technology input T. The value of T ranges from 0 to 1, as shown in Fig. 2; $c'(T) > 0$, $c''(t)=0$, $c(0)=c$. $k(T)$ is the carbon emission per unit of product for enterprises to invest in green technology, $k'(T)\geq 0$, $k''(T)\geq 0$, and $k(0)=k$.

(7) It is defined $\theta(Q)=\frac{1}{k(T)}\frac{d\pi(Q)}{dQ}$ as the expected profit increase of manufacturing enterprises brought about by carbon emission rights per unit, i.e.

$$\theta(Q)=\frac{1}{k(T)}\left(\left(p+r-c(T)\right)-(p+r-v)F(Q)\right).$$

When $T=0$, $\theta(Q)$ degenerates into:

$$\theta(Q)=\frac{1}{k}\left(\left(p+r-c\right)-(p+r-v)F(Q)\right).$$

4. Basic model

X is the random demand of the product; x obeys the distribution of probability density function of $f(\cdot)$; $f(\cdot)$ is the random demand distribution function of the product. p, c, v and r are the retail price, production cost, residual value at the end of the sales period and opportunity cost of out-of-stock inventory for each unit of product, respectively. μ is the average of the out-of-stock quantity per unit of product. If production capacity of manufacturing enterprises is Q, the expected profit function of manufacturing enterprises without a carbon quota constraint is as Eq. (1):

$$\pi^n(Q)=pE\min(Q,x)+vE(Q-x)^+-rE(x-Q)^+-cQ \quad (1)$$

In this case, the decision-making goal of manufacturing enterprises is to maximize the expected profits.

Table 1. Symbols and meanings

Parameter	***Parametric meaning***
$f(\cdot)$	Probabilistic Density Function of Stochastic Demand for Products
$F(\cdot)$	Random Demand Distribution Function of Products
p	Unit product price
r	Out-of-stock opportunity cost per unit product
v	Residual value of each unit product at the end of the sales period
K	Government-mandated maximum carbon emissions
W	Trading Volume in External Carbon Trading Market
w	Price per Unit of Carbon Emission Rights
Q	Product Output
Q_K	Product Output in the case of carbon cap decision
Q_e	Product Output in the case of carbon emission trading decision
Q_t	Product Output in the case of green technology input decision
Q_c	Product Output in the case of portfolio decision
T	Green technology input Level of Manufacturing Enterprises
c	Cost of production per unit of product without green technology input
$c(T)$	Production cost per unit of product after green technology input
k	Carbon emissions per unit of product without green technology input
$k(T)$	Carbon emissions per unit of product after green technology input

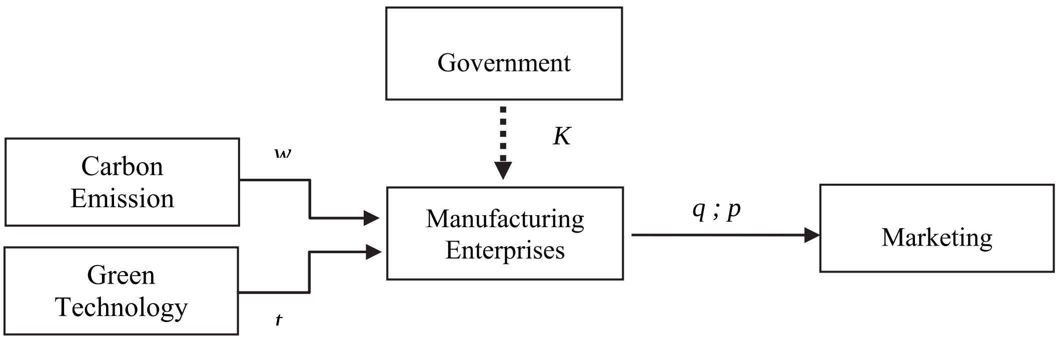

Fig. 1. Manufacturing enterprise decision description

*E*min*(Q,x)* expresses the expected sales volume, *E(Q-x)*$^+$ represents the expected residual, and *E(x-Q)*$^+$ expresses the expected shortage. Because:

$$E\min(Q,x)=Q-\int_0^Q F(x)dx,$$

$E(Q-x)^+ = Q - E\min(Q,x)$, and

$E(x-Q)^+ = \mu - E\min(Q,x)$, Formula 1 can be reduced to:

$$\pi^n(Q)=(p+r-c)Q-(p+r-v)\int_0^Q F(x)dx-r\mu.$$

The $\pi^n(Q)$ first-order partial derivative of Q is:

$$\frac{\partial\pi^n(Q)}{\partial Q}=-(p+r-v)F(Q)+p+r-c$$

The $\pi^n(Q)$ second-order partial derivative of Q is:

$$\frac{\partial^2\pi^n(Q)}{\partial Q^2}=-(p+r-v)f(Q)<0$$

Therefore, the function $\pi^n(Q)$ is a convex function of Q. According to the classical Newsboy Model, an optimal production quantity for manufacturing enterprises exists, and the optimal production quantity Q^* satisfies the expression $F(Q^*)=\dfrac{p+r-c}{p+r-v}$.

The expected profits of manufacturing enterprises without a carbon limitation are as follows:

$$\pi^n(Q^*)=(p+r-c)Q^*-(p+r-v)\int_0^{Q^*} F(x)dx-r\mu$$

When the government sets a maximum carbon emission limit, that is, carbon quota $K(>0)$, the carbon dioxide emissions generated by manufacturing enterprises in the course of production activities cannot exceed the mandatory limit set by the government. In this case, the expected profit function of manufacturing enterprises is as Eq. (2):

$$\begin{cases}\pi^K(Q)=pE\min(Q,x)+vE(Q-x)^+-rE(x-Q)^+-cQ\\ s.t.\ kQ\le K\end{cases} \tag{2}$$

By discussing the optimal decision-making of manufacturing enterprises in this situation, the following propositions are obtained:

Proposition 1: When the government establishes a carbon quota *K* (>0), the optimal production volume that maximizes the expected profits of manufacturing enterprises exists and is unique, that is, $Q_K^*=\begin{cases}Q^* & K\ge kQ^*\\ \dfrac{K}{k} & K<kQ^*\end{cases}$.

Corollary 1: Under the constraint of a carbon quota, the optimal production volume of manufacturing enterprises is $Q_k^*\le Q^*$, and the expected profit of manufacturing enterprises is $\pi^K(Q_K^*)\le\pi^n(Q^*)$.

Proposition 1 and corollary 1 show that the manufacturing decision of manufacturing enterprises will be affected by a carbon quota because of the carbon quota constraints formulated by the government. The optimal production and expected profit of manufacturing enterprises will not be higher than the optimal production and expected profit without carbon quota constraints. Further analysis shows when $K\ge kQ_k^*$, the initial carbon quota index set by the government is too high, which is higher than the carbon dioxide emissions generated by the manufacturing enterprises when they made the optimal decision without the carbon quota. At this time, there is a carbon emission right surplus. When $K<kQ_k^*$, the manufacturing decision-making of manufacturing enterprises is constrained by the government's carbon quota, at which time there is no residual carbon emission rights.

5. Extended model

A carbon cap-and-trade policy is a policy means to regulate carbon emissions through the market. Under the restriction of the carbon cap-and-trade policy, the government stipulates a maximum carbon emission, that is carbon cap *K>0*. Manufacturing enterprises increasingly realize that the implementation of green technology input in the production process of carbon emissions purification treatment can reduce the carbon dioxide emissions per unit of product and achieve carbon emission rights savings. Therefore, this part will discuss the following three ways:

(1) Under the constraint of a carbon quota, manufacturing enterprises will consider the decision-making of carbon emission trading.

(2) Under the constraint of a carbon quota, manufacturing enterprises will consider the decision-making of green technology input.

(3) Under the constraint of a carbon quota, manufacturing enterprises will consider the combined decision of carbon emission trading and green technology input.

5.1. Case 1: carbon emission trading decisions

Case 1 is the decision-making of manufacturing enterprises to trade carbon emissions under the constraint of carbon quotas. W is the trading volume of carbon emission rights in the external carbon trading market, and w is the price of carbon emission rights per unit. In this case, the expected profit function of manufacturing enterprises is as Eq. (3):

$$\begin{cases} \pi^e(Q) = \\ pE\min(Q,x) + vE(Q-x)^+ - \\ rE(x-Q)^+ - cQ - wW \\ s.t.\ kQ = K + W \end{cases} \quad (3)$$

kQ=K+W means that the total carbon emissions of manufacturing enterprises must be equal to the sum of the government's initial carbon quota and the amount of carbon emissions trading in the external carbon trading market. When *W>0*, manufacturers would buy carbon quotas from external carbon trading markets. When *W=0*, manufacturers would not trade carbon emissions rights in the external carbon trading market. When *W<0*, manufacturers would sell unused quotas on external carbon trading markets.

By discussing the optimal decision-making of manufacturing enterprises in this situation, the following propositions are obtained:

Proposition 2: Manufacturing enterprises make decisions on carbon emissions trading so that the optimal production volume for maximizing the expected profits of manufacturing enterprises exists and is unique, which is $Q_e^* = F^{-1}\left(\frac{p+r-c-wk}{p+r-v}\right)$; the optimal production volume meets the conditions of $\theta(Q_e^*)=w$, and the carbon emissions trading volume is $W_e^*=kQ_e^*-K$

Proposition 2 shows that**,** when trading carbon emission rights, namely, $\theta(Q_e^*)>w$, the profit per unit of carbon emission rights is higher than the price of one unit of carbon emission rights. Manufacturers will buy carbon emission rights from the external carbon trading market to produce more products to obtain more profits. When $\theta(Q_e^*)<w$, the profit generated by carbon emission rights per unit was lower than the price of carbon emission rights per unit. Manufacturers will sell carbon emission rights on the external carbon trading market. When $\theta(Q_e^*)=w$, the profit generated by a unit of carbon emission rights was equal to the price of a unit of carbon emission rights. Manufacturers will not trade carbon emission rights in the external carbon trading market. At this time, there is an optimal production decision for manufacturing enterprises, which makes the expected profits of enterprises the largest.

Corollary 2:

(1) If $\theta(Q_K^*) = w$, then $Q_e^* = Q_K^* < Q^*$;

(2) If $\theta(Q_K^*) < w$, then $Q_e^* < Q_K^* < Q^*$;

(3) If $\theta(Q_K^*) > w$, then $Q_K^* < Q_e^* < Q^*$.

Corollary 2 shows that when trading carbon emission rights, the optimal production of manufacturing enterprises is not higher than the optimal production without carbon quota constraints. Whether the optimal production is higher than the optimal production under carbon quota constraints depends mainly on the expected profit increase per unit of carbon emission rights under carbon quota constraints.

Corollary 3:

When $K^* = kQ_e^* + \frac{1}{w}\left(\pi^n(Q^*) - \pi^e(Q_e^*)\right)$,

(1) If $K > K^*$, $\pi^e(Q_e^*) > \pi^n(Q^*) \geq \pi^K(Q_K^*)$;

(2) If $K = K^*$, $\pi^e(Q_e^*) = \pi^n(Q^*) > \pi^K(Q_K^*)$;

(3) If $K < K^*$, $\pi^n(Q^*) > \pi^e(Q_e^*) \geq \pi^K(Q_K^*)$.

Corollary 3 shows when carbon emissions trading is conducted, the maximum expected profits of manufacturing enterprises are always higher than those without carbon emissions trading. Carbon emissions trading brings more flexibility to manufacturing enterprises and can increase their profits. However, whether the maximum expected profit of manufacturing enterprises in carbon emission trading is higher than, equal to, or lower than the profit without carbon quota constraints depends on the carbon quota given by the government at the beginning of the period.

Based on the above analysis, when the carbon dioxide emissions generated by the optimal production of manufacturing enterprises are lower than the carbon quota set by the government, the enterprises have the possibility of a carbon emission rights surplus, and the enterprises can sell the remaining carbon emission rights in the external carbon trading market for profit. In contrast, when the carbon dioxide emissions generated by the optimal production of manufacturing enterprises are higher than the carbon quota set by the government, the manufacturing decisions of enterprises are affected by the carbon quota set by the government. Manufacturing enterprises will be able to purchase carbon emission rights to maintain production in the external carbon trading market.

5.2. Case 2: decision-making on green technology input

Case 2 is under the constraint of a carbon quota; manufacturing enterprises will implement green technology input for carbon emission purification treatment to achieve carbon emission right savings and obtain additional carbon emission rights in a disguised form.

In this case, the expected profit function of manufacturing enterprises is as Eq. (4):

$$\begin{cases} \pi^t(Q,T) = \\ pE\min(Q,x) + vE(Q-x)^+ - \\ rE(x-Q)^+ - c(T)Q \\ s.t.\ k(T)Q \leq K \end{cases} \quad (4)$$

By discussing the optimal decision-making of manufacturing enterprises in this situation, the following propositions are obtained:

Proposition 3: Manufacturing enterprises make decisions on green technology input so that the optimal green technology input and the optimal production volume exist and are unique; the optimal production volume is $Q_t^* = \begin{cases} Q^* & K \geq kQ^* \\ \dfrac{K}{k(T^*)} & K < kQ^* \end{cases}$, and the optimal green technology input is $T^* = \begin{cases} 0 & K \geq kQ^* \\ T^* \in (0,1) & K < kQ^* \end{cases}$.

Proposition 3 shows when the carbon dioxide emissions from the optimal production of enterprises are lower than the carbon quota established by the government, the manufacturing decision of enterprises is not affected by the carbon quota stipulated by the government. At this time, manufacturing enterprises will not make green technology input, and the optimal decision of enterprises is the optimal decision without carbon quota constraints. In contrast, when the carbon dioxide emissions generated by the optimal production of manufacturing enterprises are higher than the carbon quota set by the government, the manufacturing decisions of manufacturing enterprises are affected by the carbon quota set by the government. At this time, manufacturing enterprises will invest in green technology.

Corollary 4: $Q_K^* \leq Q_t^* \leq Q^*$.

Corollary 4 shows that the optimal production quantity of manufacturing enterprises after the decision of green technology input is lower than the optimal production quantity under carbon quota constraints.

Corollary 5: $\pi^K(Q_K^*) \leq \pi^t(Q_t^*, T^*) \leq \pi^n(Q^*)$

Corollary 5 shows that manufacturing enterprises can increase their expected profits by implementing green technology input for carbon emission purification treatment.

5.3. Case 3: portfolio decision of carbon emission trading and green technology input

Case 3 is that under the constraint of a carbon quota, manufacturing enterprises will implement the combined decision of carbon emission trading and green technology input. In this case, the expected profit function of manufacturing enterprises is as Eq. (5):

$$\begin{cases} \pi^c(Q,T) = \\ pE\min(Q,x) + vE(Q-x)^+ - \\ rE(x-Q)^+ - c(T)Q - wW \\ s.t.\ k(T)Q = K + W \end{cases} \quad (5)$$

$k(T)Q = K + W$ means that the total carbon emissions of manufacturing enterprises must be equal to the sum of the government's initial carbon quota, and the amount of carbon emission trading in the external carbon trading market.

Among them, when $W>0$, manufacturers will buy carbon quotas from external carbon trading markets. When $W=0$, manufacturers will not trade carbon emissions rights in the external carbon trading market. When $W<0$, manufacturers will sell unused quotas on external carbon trading markets.

$\theta(T) = \dfrac{((c(T)-c)Q)_T'}{((k-k(T))Q)_T'}$ is the marginal cost per unit of carbon emission rights generated by green technology input, namely, $\theta(T) = -\dfrac{c'(T)}{k'(T)}$.

By discussing the optimal decision-making of manufacturing enterprises in this situation, the following propositions are obtained:

Proposition 4: Manufacturing enterprises make decisions on the combination of carbon emission trading and green technology input so that the optimal level of green technology input and the optimal production volume for maximizing the expected profits of manufacturing enterprises exist and are unique. The optimal production volume is $Q_c^* = F^{-1}\left(\dfrac{p+r-c(T^*)-wk(T^*)}{p+r-v}\right)$ and satisfies $\theta(Q_c^*) = \theta(T_c^*) = w$. The optimal green technology input is $T_c^* \in (0,1)$, and the volume of carbon emission trading is $W_c^* = k(T^*)Q - K$.

Proposition 4 shows when $\theta(T_c^*)>w$, the cost per unit of carbon emission rights generated by green technology input is higher than the price per unit of carbon emission rights in the market. Green technology input will reduce the expected profits of manufacturing enterprises. Manufacturing enterprises will not invest in green technology but purchase carbon emission rights in the external carbon trading market to carry out production activities. When $\theta(T_c^*)=w$, the cost per unit of carbon emission rights generated by green technology input was equal to the price per unit of carbon emission rights in the market. Enterprises can choose or invest in green technology or trade in carbon emission rights. When $\theta(T_c^*)<w$, the unit carbon emission right after green technology input was lower than the price of the unit carbon emission right in the market.

Green technology input would increase the expected profits of manufacturing enterprises, and manufacturing enterprises would invest in green technology to obtain more profits. Therefore, when the cost per unit of carbon emission rights obtained after green technology input is lower than the price per unit of carbon emission rights in the market, manufacturing enterprises will choose to invest in green technology. When the cost of carbon emission rights per unit obtained after green technology input is higher than the price of carbon emission rights per unit in the market, manufacturing enterprises will choose to make carbon emission rights trading decisions.

Furthermore, after manufacturing enterprises make carbon emissions trading decisions, when $\theta(Q_c^*)>w$, the profit per unit of carbon emission rights was higher than the price per unit of carbon emission rights. Manufacturers would buy carbon emission rights from the external carbon trading market to produce more products to obtain more profits. When $\theta(Q_c^*)<w$, the profit generated by carbon emission rights per unit was lower than the price of carbon emission rights per unit. Manufacturers would sell carbon emission rights on the external carbon trading market. When $\theta(Q_c^*)=w$, the profit generated by a unit of carbon emission rights was equal to the price of a unit of carbon emission rights. Manufacturers would not trade carbon emission rights in the external carbon trading market. At this time, the manufacturing enterprise has an optimal decision, which makes the expected profit of the enterprise the largest.

Corollary 6:

(1) If $\theta\left(Q_K^*\right) > w$, then $Q_K^* < Q_c^* < Q^*$,

(2) If $\theta\left(Q_K^*\right) = w$, then $Q_c^* = Q_K^* < Q^*$,

(3) If $\theta\left(Q_K^*\right) < w$, then $Q_c^* < Q_K^* < Q^*$.

Corollary 6 shows that the optimal production volume of a manufacturing enterprise in the combination of carbon emission trading and green technology input is higher than that without carbon quota constraints. The relationship between the optimal production volume and carbon quota constraints depends on the profit generated by the increase of carbon emission rights per unit.

Corollary 7:

When:

$$K^* = k(T)Q_c^* + \frac{1}{w}\left(\pi^n\left(Q^*\right) - \pi^c\left(Q_c^*, T_c^*\right)\right):$$

(1) If $K > K^*$,

then $\pi^c\left(Q_c^*, T_c^*\right) > \pi^n\left(Q^n\right) > \pi^K\left(Q_K^*\right)$,

(2) If $K = K^*$,

then $\pi^c\left(Q_c^*, T_c^*\right) = \pi^n\left(Q^n\right) > \pi^K\left(Q_K^*\right)$,

(3) If $K < K^*$,

then $\pi^n\left(Q^*\right) > \pi^c\left(Q_c^*, T_c^*\right) \geq \pi^K\left(Q_K^*\right)$.

Corollary 7 shows that the maximum expected profit of manufacturing enterprises in the combination of carbon emission trading and green technology input is not less than the expected profit under the carbon quota constraint, and whether the maximum expected profit is higher than the expected profit under the noncarbon quota constraint mainly depends on the size of the government's initial carbon quota.

6. Numerical analysis

Considering a single product manufacturer in a free market, the market demand is subject to normal distribution. At the end of the sales period, the remaining inventory will be processed according to the residual value. Manufacturing enterprises will also face shortage losses. The values of the parameters are shown in Table 2.

6.1. Carbon limit free and carbon limit constraints

By solving the problem, the optimal production capacity of a manufacturing enterprise without a carbon limitation is Q^*=230, π^*=10143. Under the restriction of a carbon quota, the carbon quota (unit) established by the government is K=150 (unit). By solving the problem, under the constraint of a carbon quota, the optimal production capacity of manufacturing enterprises is Q_k^*=150. π_k^*=7534. The comparison of the optimal production volume and expected profit of manufacturing enterprises under the conditions of unlimited constraints and a carbon quota is shown in Fig. 2.

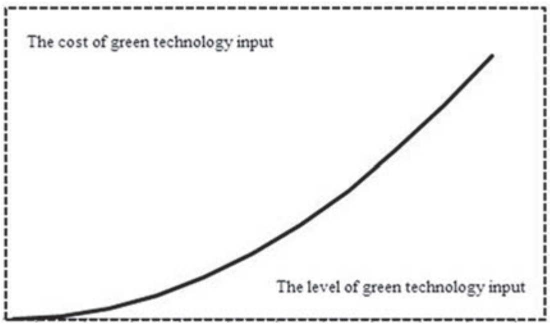

Fig. 2. Green technology input function

Through numerical analysis, the following can be seen:

1. The carbon quota formulated by the government will have an impact on the optimal decision-making of manufacturing enterprises.

2. Because of the existence of the carbon quota stipulated by the government, the optimal production capacity of manufacturing enterprises under the carbon quota constraint is 150 units, and the expected profit is 7534, which will not exceed 230 units and 10143 units under the noncarbon quota constraint. The conclusion shows that under the carbon quota constraint, the optimal production volume and expected profit of manufacturing enterprises will not exceed the optimal production volume and expected profit without a carbon quota constraint.

3. Fig. 3 shows the gap between the expected profits of manufacturing enterprises under carbon quota constraints and those under unlimited constraints, that is, the space for enterprises to improve through decision-making optimization such as carbon emissions trading or green technology input.

Table 2. Model parameters

	ρ	c	r	v	k
Value	100	40	20	10	1

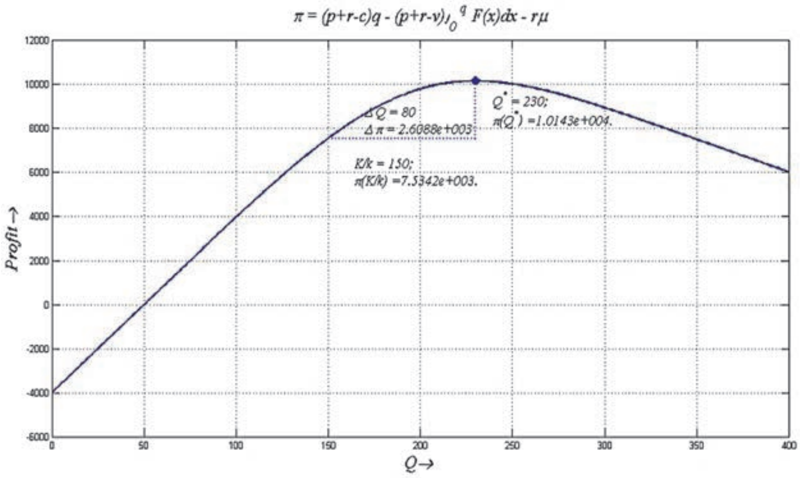

Fig. 3. Expected profit of manufacturing enterprises under carbon limit constraints

6.2. Carbon emission trading

Under the restriction of a carbon quota, manufacturing enterprises make the decision as in case 1, that is, only make the decision of carbon emission trading. w is the price of carbon emission rights per unit, W is the trading volume of carbon emission rights in the external carbon trading market. When $w \in [0, 60]$, the study of the influence of the price of carbon emission rights per unit w on the optimal production, trading volume and expected profits of manufacturing enterprises in the corresponding intervals can be seen in Table 3 and Fig. 3:

1. In the case of carbon quota constraints, the carbon emission trading of manufacturing enterprises is helpful to optimize the decision-making of manufacturing enterprises. The expected profits π_e^* of manufacturing enterprises in the case of carbon emission trading are mostly between the expected profits π^* in the case of unlimited constraints and the expected profits π_k^* in the case of carbon quota constraints.

2. Theoretically, when the price of carbon emission rights per unit W is lower than the marginal profit generated by the increase of carbon emission rights per unit of manufacturing enterprises, manufacturing enterprises will purchase carbon emission rights. As the price of carbon emission permits per unit decreases, the optimal production, trading volume of carbon emission permits and expected profits will increase. When the extreme situation arises and the price of carbon emission rights per unit is very low, manufacturing enterprises will purchase carbon emission rights in large quantities, and the optimal production volume and expected profit are close to the optimal production volume and expected profit under the condition of no carbon quota constraints.

3. Theoretically, when the price of carbon emission rights per unit w is higher than the marginal profit generated by the increase of carbon emission rights per unit of manufacturing enterprises, enterprises will not purchase carbon emission rights.

6.3. Green technology input

Under the restriction of a carbon quota, manufacturing enterprises make decision as in case 2, that is, only green technology input is used to save carbon emission rights, and additional carbon emission rights are obtained in a disguised form.

The corresponding functions and parameters are set as follows: $c(T) = c + \frac{1}{2}\alpha T^2; c = 40; \alpha \in [0, 40]$.

Table 3. Changes in main parameters in the case of carbon emission trading

w	W	Q_e^*	π_e^*
10	68	218	9408
20	56	206	8796
30	44	194	8299
40	32	182	7918
50	20	170	7659
60	4	154	7539

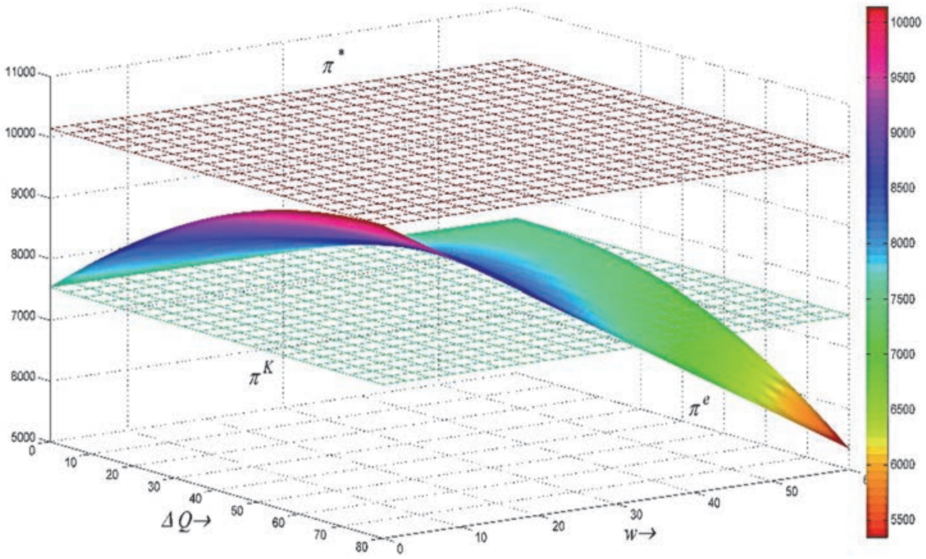

Fig. 4. Expected profit of manufacturing enterprises in the case of carbon emission trading

α shows the elasticity coefficient of green technology input that leads to the increase of unit product cost, and the larger the elasticity coefficient α, the higher the unit product cost $c(T)$ caused by green technology input. $k(T)=k-\beta T$, $\beta=[0, 0.4]$; β shows the elasticity coefficient of the reduction of carbon emissions per unit product caused by green technology input, and the larger the elasticity coefficient β, the better the effect of green technology on reducing carbon emissions per unit of product. When α and β are in the corresponding intervals, the impact of changes on the optimal green technology input level, optimal production volume and expected profit of manufacturing enterprises can be seen in Table 4 and Figs. 4-6:

1. In the case of carbon quota constraints, green technology input of manufacturing enterprises is helpful to optimize the decision-making of manufacturing enterprises. Most of the expected profits π^t of manufacturing enterprises in the case of green technology input are above the expected profits π^k in the case of carbon quota constraints.

2. When β is confirmed and the level of green technology input to reduce carbon emissions per unit is certain, with the increase of green technology input level, enterprise profits will increase first and then gradually decrease, and there is an optimal level of green technology input. With the increase of α, that is, the unit product cost caused by green technology input, the profits of enterprises will continue to decline.

3. When α is confirmed and the unit product cost caused by green technology input is certain, with the increase of green technology input, enterprise profits will increase first and then gradually decrease, and there is an optimal level of green technology input. With the increase of β, that is, the green technology input, the better the effect of reducing carbon emissions per unit, and the profits of enterprises will continue to increase.

4. When the input of green technology is fixed, with the increase of β, that is, the better the effect of green technology input on reducing carbon emissions per unit, the profits of enterprises will continue to increase. With the increase of β, that is, the unit product cost caused by green technology input, the profits of enterprises will continue to decline.

The above analysis shows that the level of green technology such as low-carbon emission reduction determines the effect of carbon emission reduction on the one hand. On the other hand, under the carbon quota and trading mechanism, enterprises that master the core low-carbon emission reduction technology will have more competitive advantages in reducing carbon emission reduction ability and gaining more profits.

6.4. Joint decision-making of carbon emission trading and green technology input

Under the constraint of a carbon quota, manufacturing enterprises make decisions as in case 3, that is, the joint decision-making of carbon emission trading and green technology input.

Table 4. Changes of main parameters under green technology input

α β	**0.1**	**0.2**	**0.3**	**0.4**
10	(0.62;159;7838)	(0.9;183;8532)	(0.82;199;9139)	(0.72;211;9495)
20	(0.32;155;7697)	(0.56;169;8103)	(0.6;183;8614)	(0.64;202;9031)
30	(0.18;153;7643)	(0.34;161;7925)	(0.54;179;8328)	(0.5;188;8726)
40	(0.18;158;7619)	(0.28;159;7837)	(0.42;172;8153)	(0.46;184;8526)

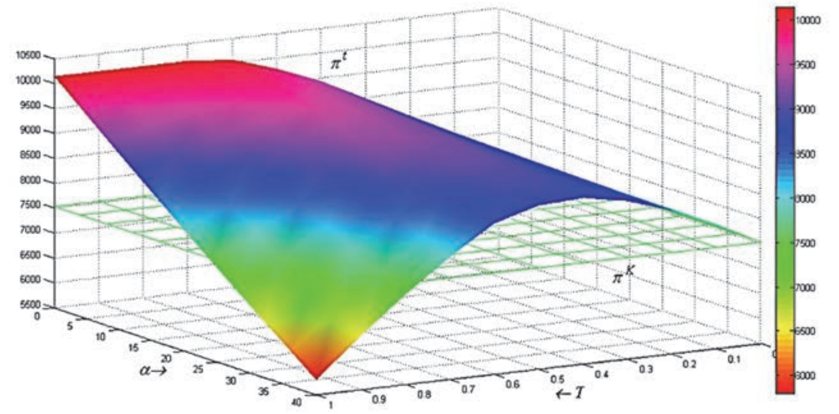

Fig. 5. Changes in α , T and expected profit under green technology input

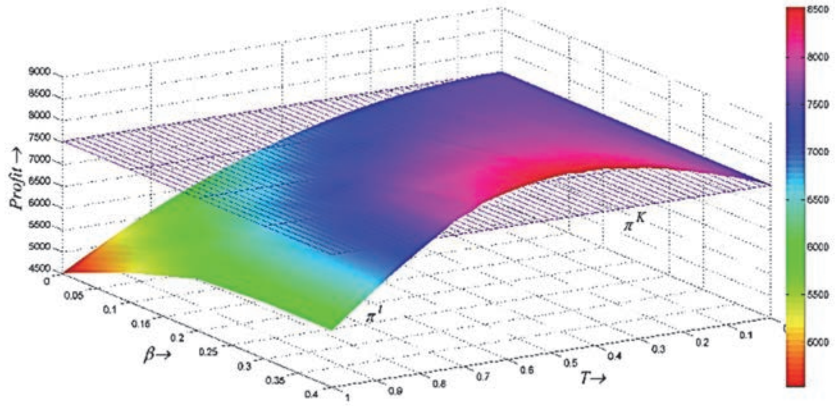

Fig. 6. Changes in β , T and expected profit under green technology input

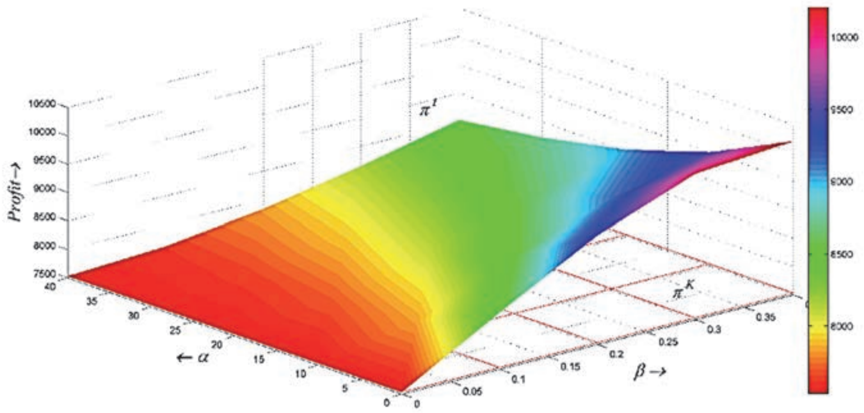

Fig. 7. Changes in *α, β* and expected profit under green technology input

The corresponding functions and parameters are set as follows:

$$c(T) = c + \frac{1}{2}\alpha T^2; c = 40$$

$$k(T) = k - \beta T; \beta \in [0, 0.4]; \ w \in [0, 60] .$$

Set up $w \in [0, 60]$, $\alpha \in [0, 40]$, $\beta \in [0, 0.4]$. When the changes of *w*, *α* and *β* in the corresponding intervals affect the optimal green technology input level, optimal production, expected profits and carbon emissions trading volume of manufacturing enterprises are shown in Table 5 and Fig. 8:

1. When *w* is confirmed, that is, when the price of carbon emissions per unit is fixed, with the increase of *α*, the unit product cost caused by green technology input, the profits of enterprises will continue to decline. With the increase of *β*, that is, when the level of green technology to reduce carbon emissions per unit increases, the enterprise profits will increase.

2. When *α* is confirmed, that is, when the unit product cost caused by green technology input is certain, with the increase of *w*, the unit carbon emission price, the profit of enterprises will increase first and then decrease. With the increase of *β*, that is, when the level of green technology to reduce carbon emissions per unit increases, the enterprises profits will increase.

3. When β is confirmed, that is, the level of green technology to reduce carbon emissions per unit is certain, with the increase of α, that is, the unit product cost caused by green technology input increases, the profits of enterprises will continue to decline. With the increase of β, the price of carbon emissions per unit, the profits of enterprises will increase first and then decrease.

The above analysis further confirms that the effect of green technology on reducing carbon emission rights per unit has a very important impact on corporate profits. The price of carbon emission rights in the external carbon trading market will affect the trading volume and the expected profits of enterprises. Set up w=30, α=40, β=0.2, the influence of the change of T in the corresponding interval on the optimal production volume and expected profit of the manufacturing enterprise is shown in Fig. 8. As seen from Fig. 9. In case of carbon quota constraints, manufacturing enterprises make decisions as in case 3. Under given parameters, a green technology input level, production volume and expected profit exists that maximizes the expected profit of manufacturing enterprises.

7. Conclusions

In recent years, under the environment of low carbon economy, the pressure of carbon emission reduction of manufacturing enterprises is increasing. Based on the new requirements faced by manufacturing enterprises under the pressure of carbon emission reduction, this paper studied the issue of low-carbon manufacturing decision of single product manufacturing enterprises with random demand considering both carbon trading and green technology input under the carbon cap.

Table 5. Changes of main parameters under green technology input

w	**20**		**40**		**60**	
α / β	**0.2**	**0.4**	**0.2**	**0.4**	**0.2**	**0.4**
10	(0.1;206;8868;52)	(0.1;206;8951;48)	(0.1;183;8056;29)	(0.1;184;8203;27)	(0.1;156;7718;3)	(0.1;158;7906;2)
20	(0.1;206;8858;52)	(0.1;206;8941;48)	(0.1;183;8047;29)	(0.1;184;8193;27)	(0.1;156;7710;3)	(0.1;158;7898;2)
30	(0.1;205;8848;51)	(0.1;206;8930;48)	(0.1;183;8037;29)	(0.1;184;8184;27)	(0.1;156;7702;3)	(0.1;158;7890;2)
40	(0.1;205;8837;51)	(0.1;206;8920;48)	(0.1;183;8028;29)	(0.1;184;8175;27)	(0.1;156;7694;3)	(0.1;158;7882;2)

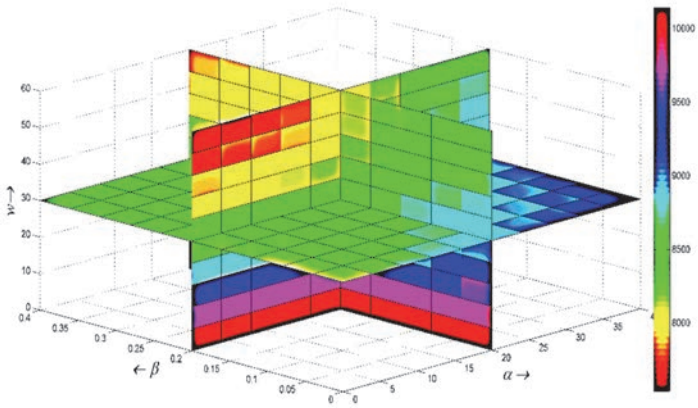

Fig. 8. α , β , T and expected profits under a portfolio decision of carbon emissions trading and green technology input

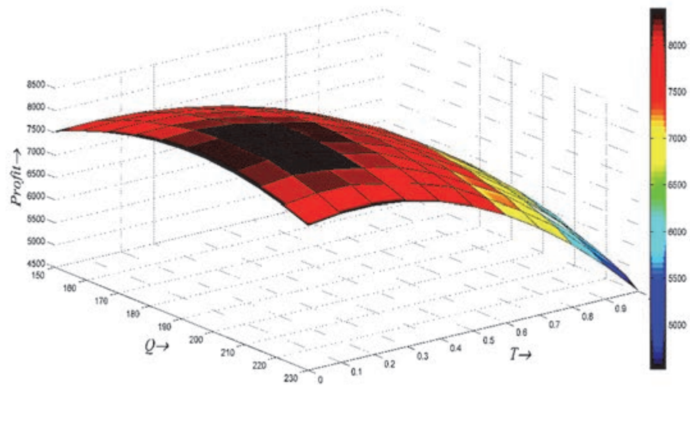

Fig. 9. Expected profits of manufacturing enterprises under given parameters

Through the research, it can be found that the carbon cap established by the government will have an important impact on the optimal decision of manufacturing enterprises, and carbon emission trading and green technology input can both optimize and improve the low-carbon manufacturing decision of enterprises to a certain extent. However, it is worth mentioning that though carbon emission trading bring more flexibility to manufacturing enterprises and increase their profits, the maximum expected profit of manufacturing enterprises in carbon emission trading (higher than, equal to or less than the profit in the absence of carbon cap constraint) depends on the carbon cap which initially granted to manufacturing enterprises by the government. Therefore, the important task for the government is to set the initial carbon cap scientifically and rationally.

The premise of carbon emission reduction technology investment by manufacturing enterprises is that the marginal cost per unit carbon emission right after green technology input is lower than the price per unit carbon emission right in the market. In addition, the better the effect of green technology input in reducing unit carbon emission is, the more carbon dioxide will be reduced, the more profit the enterprise will increase, and the more willing the enterprise will be to invest in carbon emission reduction technology. Therefore, the government should guide and encourage manufacturing enterprises to conduct research, development and investment of carbon emission reduction technology through tax reduction, financial subsidies and other means, so as to improve the effect of carbon emission reduction technology on reducing carbon dioxide emissions.

Under the carbon cap, it is all related to the development stage and environment, as well as the resources and low-carbon emission reduction technology capacity of manufacturing enterprises whether the enterprises choose carbon emission trading decision, green technology investment decision, or the joint decision of carbon emission trading and green technology investment.

When the manufacturing enterprise is in the growth stage of development, or has less resources, or limited ability of low-carbon emission reduction technology, then the enterprise is more willing to choose the decision of carbon emission trading under the carbon cap; when the manufacturing enterprise is in the mature stage of development, or has more resources an strong capacity of low-carbon emission reduction technology, then the enterprise is more willing to choose green technology input for low-carbon manufacturing decision; when a manufacturing enterprise is in the development stage between growth and maturity, or its resources and low-carbon emission reduction technology capability are in the middle level, then the enterprise is more willing to choose to joint method of combination of the two decisions for its low-carbon manufacturing decision.

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