Integration of manufacturing and pricing for downward substitution products decision-making

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Abstract

With a cap-and-trade policy and green technology as inputs, we built a manufacturing ordering and pricing joint decision-making model for two downward substitution products to identify the conditions for optimal order quantities and prices of products under the additive demand case. Considering the case of a single period model, the conditions required for optimal manufacturing quantities and pricing were discussed, and the construction of the model was analyzed; furthermore, a study of the tactical choices between green technology inputs and manufacturing decisions was conducted, and the conditions required for green technology manufacturing input were obtained.

Keywords Stochastic demand · Cap-and-trade · Green technology investment · Downward substitution · Manufacturing and pricing strategy

Introduction

Ever since the time of the industrial revolution, which was marked by the extensive use of steam engines, fossil fuels such as coal, oil and natural gas have been used widely as energy sources. While generating tremendous power and benefits for industrial production and the lives of human beings, they inevitably caused terrible environmental problems [1]. In the Fifth Assessment Report of the IPCC—Climate Change 2014, the United Nations Intergovernmental Panel on Climate Change (IPCC) pointed out that during the 10 years between 2003 and 2012, the global average surface temperature increased by 0.78 (0.72–0.85 °C) compared with the average temperature from 1850 to 1990. From 1901 to 2010, the global average sea level has risen by approximately 19 cm. Since the 1950s, most of the global warming has been caused by greenhouse gas emissions, such as carbon dioxide and methane from human activities [2]. To confront the ongoing environmental degradation of the

global climate, governments around the world have proactively taken actions to formulate policies and set goals. Relevant industries improve the optimization of the service efficiency, but obviously not enough, e.g., Zhao et al. [3]. At present, the major carbon emission reduction policies implemented worldwide are as follows: carbon cap, carbon tax and carbon cap-and-trade, Jin, Granda-Marulanda and Down [4]. Among them, the carbon cap-and-trade policy allows enterprises to trade carbon emissions rights freely, which makes carbon emission restrictions a kind of a “soft restriction” as well as one of the most common and effective carbon emissions reduction policies.

With the increasing pressure to reduce carbon emissions, enterprises, which are the main carbon dioxide emitters, are facing unprecedented pressure [5, 6]. To take effective production decisions under the restrictions of carbon emission reduction policies, enterprises can obtain additional carbon emission rights by producing low-carbon products and investing in green low-carbon technology (green technology) in addition to the carbon emission rights allocated by the government [7, 8]. At the same time, with the increasing awareness of environmental protection, low-carbon consumption has become fashionable [9]. Research shows that consumers prefer green products and are willing to pay higher prices for lower carbon emissions in their production and consumption process, Echeverría, Moreira, Sepúlveda and Wittwer [10]. Therefore, an increasing

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number of enterprise decision makers have come to realize that investing in low-carbon green technology and reducing carbon dioxide emissions can not only satisfy the consumers' demand for a green life but also gain more competitive advantage and higher profits than competitors [11, 12].

Literature review

Schultz and Williamson [13] and Gong et al. [14] studied the impacts of climate change and different carbon emission reduction policies on enterprise decision-making. He demonstrated that companies must consider carbon emission rights to be as important resources similar to capital, human resources, products and services in terms of their direct and potential impacts. Benjaafar et al. [15] and Tang et al. [16] took the lead in introducing carbon emission factors into the supply chain system. His research found that carbon emission factors have an impact on the overall operational decision-making of supply chain enterprises. Giraud-Carrier [17] studied the operational decision-making process of manufacturing enterprises under three kinds of carbon emission reduction policy constraints and proved that any kind of a carbon emission reduction policy constraint will reduce the optimal output of a manufacturing enterprise; however, when environmental pollution is very serious, these carbon emission reduction policies will improve the overall social welfare. Ma et al. [18] studied the production decision-making 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 optimal decision-making. Ma et al. [19] extended the newsboy model and incorporated green technology input into the model. The intertemporal production decision-making of manufacturing enterprises with two production cycles under the constraint of a carbon trading policy was studied. Jian et al. [20] studied the pricing problem of competitive and cooperative products in a two-oligopoly market under the carbon cap policy constraint. Based on the extended Bertrand game model, the optimal decision-making under the two conditions of competition and cooperation was obtained. He and Ma [21] studied the production decision-making problem of two-product manufacturing enterprises under a carbon trading policy, solved and obtained the optimal production mix of manufacturing enterprises, and analyzed the impact of the carbon trading policy on the optimal decision-making of manufacturing enterprises.

With the rapid development of the social economy, consumer demand has become increasingly diversified and personalized. To better meet the needs of customers during the sales process, sellers need to consider demand substitution between products. Sellers often operate products with one-way substitution. These products can be divided into several

grades in terms of quality or function. If there is a surplus of high-quality products and low-quality products are out of stock, sellers can meet consumers' needs by selling high-quality products at low-quality prices. The management of alternative products has become a hot research topic in recent years. Most of the literature discusses price-driven substitution and inventory-driven substitution. Previously, Pentico [22] studied one-way inventory-driven substitution among products using a one-way substitution among products and obtained the optimal multiproduct production strategy by means of a dynamic programming method. Parlar [23] studied the inventory problem of two alternative products with a stochastic demand using game theory, and a Nash equilibrium solution was given. Chand et al. [24] established a part selection model with one-way substitution and used a dynamic programming algorithm to find the optimal part inventory combination. Bassok et al. [25] studied the multiproduct inventory problem of a single cycle with downward substitution and obtained the optimal multiproduct production strategy for a single cycle. Pineyro and Viera [26] studied the optimal pricing of new products and remanufactured products under non-batch production conditions. Piñeyro and Viera [27] further studied the batch problem of new products and remanufactured products by analyzing different demand flows in one-way substitutions and proposed a new algorithm to solve the model. Chen et al. [28] extended the newsboy model by incorporating product substitution into the model; in addition, the production decision-making problem of two-product manufacturing enterprises under the constraints of a carbon trading policy was studied.

There are plenty of studies on enterprise decision-making under carbon emissions trading and a one-way alternative product model, but the specifics of carbon emissions trading and of green technology investments in low-carbon products that are replacing high-carbon products is worth discussing. This paper combines one-way substitution of low-carbon products and high-carbon products with carbon emissions trading and incorporates green technology investments into the model to explore the optimal production and pricing strategy of one-way substitution of two products while analyzing green technology investments under the carbon quota and trading policy. The paper models enterprise production decision-making, considering one-way substitution and green technology as inputs under the constraints of a carbon quota and a trading policy. Generally, this is the direction in which enterprise production and sales are developing. Therefore, this paper intends to model and analyze this aspect.

Basic assumptions and parameters

The assumption is that there is a manufacturer that faces a stochastic demand and two consumer groups in the market. Let us take the light bulb market as an example, manufacturing enterprises produce two kinds of products, energy-saving low-carbon light bulbs and ordinary light bulbs, to meet the needs of different consumers. An energy-saving low-carbon light bulb is a kind of a green product that consumes less energy and is environmentally friendly in its production process and use. Although the cost is high, the price as well as the profit is also high. In contrast, an ordinary electric light bulb is a common product that consumes more energy is not environmentally friendly, and has a low cost, low price and a low profit. At the same time, assuming that green products, but not common products, are treated by a carbon emission purification process through a green technology input, the demand is stochastic. The different advances in technology necessitate that green products have higher prices than common products. When a common product 2 is out of stock and a green product 1 is in surplus, the seller will lower the price of the green product 1 to meet the demand for the common product 2. This is a common phenomenon in society.

On the other hand, in the context of a low-carbon economy, under the condition where there are three sources of carbon emission rights, namely, government quotas, carbon emissions trading and carbon emissions purification, as well as a single-cycle and single-emission production, the following assumptions are made:

1. Carbon emission rights are freely traded, and the market supply of carbon emission rights is adequate within a certain range.
2. The carbon emission per unit product will be a certain amount when the technology level is determined.
3. Carbon emissions of product 1 are purified by green technology T , and emission rights are saved. The cost of purification $c(T)$ increases with the increase of purification level T , which is consistent with reality.

The main parameter symbols used in this paper are as follows:

p_1, p_2 are the prices of green product 1 and common product 2 as determined by the market and enterprises, respectively.

c_1, c_2 are the unit production costs of green product 1 and common product 2, respectively.

h_1, h_2 are the unit inventory costs of green product 1 and common product 2, respectively.

s_1, s_2 are the unit out-of-stock costs of green product 1 and common product 2, respectively.

q_1, q_2 are the production quantities of green product 1 and common product 2, respectively. The following are the decision variables:

$CE(q_1), CE(q_2)$ are the actual amounts of carbon emissions produced by green products 1 and common products 2, respectively. They are the functions of the output with generality. Since the amount of carbon emissions per unit output is e_1 and e_2 , we obtain $CE(q_1) = e_1 q_1, CE(q_2) = e_2 q_2$.

c_{m1}, c_{m2} are the transaction prices of carbon emission permits per unit in the green product market of green product 1 and common product 2, respectively.

CE_{m1}, CE_{m2} are the carbon emission permits obtained through market transactions for green products 1 and common products 2, respectively. When $CE_{mi} > 0$, the permit is purchased, or it is sold.

$p_1(q_1), p_2(q_2)$ are the market prices of green product 1 and common product 2, respectively, and they are determined by the output. These are the formulas for the linear inverse demand function: $p_1(q_1) = k - a q_1, p_2(q_2) = k - a q_2$.

T is the input level of green technology, and $0 \leq T < 1$.

CEp_1 is the production of carbon emissions from the purified treatment of green product 1; $0 \leq CEp_1 \leq CE(q_1)$.

CEs_1 is the net emission permit obtained by the purification treatment for the production of green product 1; $CEs_1 = Te_1 q_1$.

Model construction

It is assumed that the price of common product 2 p_2 is determined by the market and that the price of green product 1 p_1 is determined by the enterprise. Since the two products belong to the same product category, the price of the green product will affect not only its own demand but also the demand of the common product, as shown in Fig. 1.

This study assumes that the demand function of green products is

$$D_1 = d_1(p_1, \epsilon_1), \left(\frac{\partial D_1}{\partial p_1} < 0 \right)$$

$$D_2 = d_2(p_2, \epsilon_2), \left(\frac{\partial D_2}{\partial p_2} > 0 \right)$$

In the formula, ϵ_1 and ϵ_2 are the random variables on intervals $[A_1, B_1], [A_2, B_2]$, respectively.

Assume that $F_1(\cdot), f_1(\cdot), F_2(\cdot)$, and $f_2(\cdot)$ are the probability distribution function and the density function of two random variables, respectively. Since the common products are facing a competitive market, when the demand of the low-end market is not satisfied, the demand will flow to the competitors; therefore, as long as the green products are in stock, the producers will use the green products to meet the

Fig. 1 Model describes

market demand when the common products are out of stock. Therefore, the manufacturer's decision is how to determine the order quantities q_1 and q_2 of green products and common products, respectively, and the price of green products p_1 , under the condition of one-way substitution and the price factors, to achieve the optimal total expected profit for the enterprise.

Assume that the fixed production cost is 0 (or that it can be set as an arbitrary constant without affecting the results of the model; in this case, the calculation is simply set to 0), the unmet demand will be lost at the end of the cycle, the value of the surplus product will be 0 (the model can be easily extended to the case where the residual value is not zero) and that $[x]^+$ means $\max\{0, x\}$, the profit function of the manufacturer can be expressed as follows.

At the same time, according to the hypothesis, there are three channels for the producers' carbon emission permits: government quotas CEg_1 , CEg_2 , carbon savings Te_1q_1 achieved by the introduction of green technology to produce green product 1, and purchasing portions CEm_1 and CEm_2 from the carbon emission rights market. Ultimately, the emissions will not exceed the authorized load. Namely,

$$CE(q_1) \leq CEg_1 + Te_1q_1 + CEm_1. \quad (1)$$

$$CE(q_2) \leq CEg_2 + CEm_2. \quad (2)$$

In the case of a single cycle, once the emission rights reach a surplus, the producer will place them on the trading market for sale. Thus, the above inequalities can be converted into:

$$CE(q_1) = CEg_1 + Te_1q_1 + CEm_1. \quad (3)$$

$$CE(q_2) = CEg_2 + CEm_2. \quad (4)$$

As a result, the emission rights that the producers bought on the market are CEm_1 and CEm_2 (if these values are negative, this means "sell").

$$CEm_1 = CE(q_1) - CEg_1 - Te_1q_1. \quad (5)$$

$$CEm_2 = CE(q_2) - CEg_2. \quad (6)$$

The profit function of the manufacturer can then be expressed as follows:

$$\Pi(q_1, q_2, p_1) = \begin{cases} p_1D_1(p_1, \varepsilon_1) - c_1q_1 - h_1[q_1 - D_1(p_1, \varepsilon_1)] + p_2D_2(p_1, \varepsilon_2) - c_2q_2 \\ -h_2[q_2 - D_2(p_1, \varepsilon_2)] - c_{m1}CEm_1 - c(T) - c_{m2}CEm_2 \\ D_1(p_1, \varepsilon_1) \leq q_1, D_2(p_2, \varepsilon_2) \leq q_2 \\ p_1q_1 - c_1q_1 - s_1[D_1(p_1, \varepsilon_1) - q_1] + p_2D_2(p_1, \varepsilon_2) - c_2q_2 \\ -h_2[q_2 - D_2(p_1, \varepsilon_1)] - c_{m1}CEm_1 - c(T) - c_{m2}CEm_2 \\ D_1(p_1, \varepsilon_1) > q_1, D_2(p_2, \varepsilon_2) \leq q_2 \\ p_1D_1(p_1, \varepsilon_1) - c_1q_1 - h_1[q_1 - D_1(p_1, \varepsilon_1) - D_2(p_1, \varepsilon_2) + q_2]^+ \\ + p_2\{q_2 + \min\{[q_1 - D_1(p_1, \varepsilon_1)], [D_2(p_1, \varepsilon_2) - q_2]\}\} - c_2q_2 \\ -s_2[D_2(p_1, \varepsilon_2) - q_2 - q_1 + D_1(p_1, \varepsilon_1)]^+ - c_{m1}CEm_1 - c(T) - c_{m2}CEm_2 \\ D_1(p_1, \varepsilon_1) \leq q_1, D_2(p_2, \varepsilon_2) > q_2 \\ p_1q_1 - c_1q_1 - s_1[D_1(p_1, \varepsilon_1) - q_1] + p_2q_2 - c_2q_2 - s_2[D_2(p_1, \varepsilon_2) - q_2] \\ -c_{m1}CEm_1 - c(T) - c_{m2}CEm_2 \\ D_1(p_1, \varepsilon_1) > q_1, D_2(p_2, \varepsilon_2) > q_2 \end{cases}. \quad (7)$$

The above profit function shows the following:

1. When both of the demands of the two products are smaller than their outputs, the profit of the enterprise equals the income of the two products minus the sum of the ordering cost and the inventory cost;
2. When the green products are out of stock and the common products are in surplus, the common products cannot replace the green products; thus, the total profit of the enterprise equals the total income of the two products minus the sum of the total production cost, the shortage cost of the green products and the inventory cost of the common products.
3. When the green products are in surplus and the common products are out of stock, the producer will use the surplus green products to meet the demand of the common products. The profit of the enterprise equals the total income of the two products minus the sum of the total order cost and the inventory cost of the surplus green products, while replacing the common products or the shortage cost of the green products by green products.
4. When the demand for both products is greater than their respective outputs, the profit of the enterprise equals the total income of the two products minus the sum of the total order cost and the shortage cost.

By substituting Formula (5) and Formula (6) into Formula (7), the following results can be obtained:

To facilitate the analysis of the model, the form of the demand function is set as an additive form: $D(p, \epsilon) = d(p) + \epsilon$. The profit function is simplified as $z_1 = q_1 - d_1(p_1)$ and $z_2 = q_2 - d_2(p_2)$ to represent the level of the risk-free inventory, Thowsen [29], selected by

$$\Pi(q_1, q_2, p_1) = \begin{cases} p_1 D_1(p_1, \epsilon_1) - c_1 q_1 - h_1 [q_1 - D_1(p_1, \epsilon_1)] + p_2 D_2(p_1, \epsilon_2) - c_2 q_2 - h_2 [q_2 - D_2(p_1, \epsilon_2)] \\ - c_{m1} CE(q_1) + c_{m1} CEg_1 + [c_{m1} Te_1 q_1 - c(T)] - c_{m2} CE(q_2) + c_{m2} CEg_2 \\ D_1(p_1, \epsilon_1) \leq q_1, D_2(p_2, \epsilon_2) \leq q_2 \\ p_1 q_1 - c_1 q_1 - s_1 [D_1(p_1, \epsilon_1) - q_1] + p_2 D_2(p_1, \epsilon_2) - c_2 q_2 - h_2 [q_2 - D_2(p_1, \epsilon_1)] \\ - c_{m1} CE(q_1) + c_{m1} CEg_1 + [c_{m1} Te_1 q_1 - c(T)] - c_{m2} CE(q_2) + c_{m2} CEg_2 \\ D_1(p_1, \epsilon_1) > q_1, D_2(p_2, \epsilon_2) \leq q_2 \\ p_1 D_1(p_1, \epsilon_1) - c_1 q_1 - h_1 [q_1 - D_1(p_1, \epsilon_1) - D_2(p_1, \epsilon_2) + q_2]^+ + p_2 \{q_2 + \min\{[q_1 - D_1(p_1, \epsilon_1)], \\ [D_2(p_1, \epsilon_2) - q_2]\}\} - c_2 q_2 - s_2 [D_2(p_1, \epsilon_2) - q_2 - q_1 + D_1(p_1, \epsilon_1)]^+ \\ - c_{m1} CE(q_1) + c_{m1} CEg_1 + [c_{m1} Te_1 q_1 - c(T)] - c_{m2} CE(q_2) + c_{m2} CEg_2 \\ D_1(p_1, \epsilon_1) \leq q_1, D_2(p_2, \epsilon_2) > q_2 \\ p_1 q_1 - c_1 q_1 - s_1 [D_1(p_1, \epsilon_1) - q_1] + p_2 q_2 - c_2 q_2 - s_2 [D_2(p_1, \epsilon_2) - q_2] \\ - c_{m1} CE(q_1) + c_{m1} CEg_1 + [c_{m1} Te_1 q_1 - c(T)] - c_{m2} CE(q_2) + c_{m2} CEg_2 \\ D_1(p_1, \epsilon_1) > q_1, D_2(p_2, \epsilon_2) > q_2 \end{cases} \quad (8)$$

the enterprises for the two types of products. The simplified enterprise profit function is expressed as follows:

$$\prod(q_1, q_2, p_1) = \begin{cases} p_1[d_1(p_1) + \varepsilon_1] - c_1[d_1(p_1) + z_1] - h_1[z_1 - \varepsilon_1] + p_2[d_2(p_1) + \varepsilon_2] - c_2[d_2(p_1) + z_2] - h_2[z_2 - \varepsilon_2] \\ - c_{m1}e_1[d_1(p_1) + z_1] + c_{m1}CEg_1 + [c_{m1}Te_1q_1 - c(T)] - c_{m2}e_2[d_2(p_1) + z_2] + c_{m2}CEg_2 \\ \varepsilon_1 \leq z_1, \varepsilon_2 \leq z_2 \\ p_1[d_1(p_1) + \varepsilon_1] - c_1[d_1(p_1) + \varepsilon_1] - s_1[\varepsilon_1 - z_1] + p_2[d_2(p_1) + \varepsilon_2] - c_2[d_2(p_1) + z_2] - h_2[z_2 - \varepsilon_2] \\ - c_{m1}e_1[d_1(p_1) + z_1] + c_{m1}CEg_1 + [c_{m1}Te_1q_1 - c(T)] - c_{m2}e_2[d_2(p_1) + z_2] + c_{m2}CEg_2 \\ \varepsilon_1 > z_1, \varepsilon_2 \leq z_2 \\ p_1[d_1(p_1) + \varepsilon_1] - c_1[d_1(p_1) + z_1] - h_1[z_1 - \varepsilon_1 - z_2 + \varepsilon_2] + p_2\{d_2(p_1) + \varepsilon_2 + \min\{[z_1 - \varepsilon_1], [\varepsilon_2 - z_2]\}\} \\ - c_2[d_2(p_1) + z_2] - s_2[\varepsilon_2 - z_2 - z_1 + \varepsilon_1] - c_{m1}e_1[d_1(p_1) + z_1] + c_{m1}CEg_1 + [c_{m1}Te_1q_1 - c(T)] \\ - c_{m2}e_2[d_2(p_1) + z_2] + c_{m2}CEg_2 \\ \varepsilon_1 \leq z_1, \varepsilon_2 > z_2 \\ p_1[d_1(p_1) + \varepsilon_1] - c_1[d_1(p_1) + z_1] - s_1[\varepsilon_1 - z_1] + p_2[d_2(p_1) + \varepsilon_2] - c_2[d_2(p_1) + z_2] - s_2[\varepsilon_2 - z_2] \\ - c_{m1}e_1[d_1(p_1) + z_1] + c_{m1}CEg_1 + [c_{m1}Te_1q_1 - c(T)] - c_{m2}e_2[d_2(p_1) + z_2] + c_{m2}CEg_2 \\ \varepsilon_1 > z_1, \varepsilon_2 > z_2 \end{cases} \quad (9)$$

From the simplified profit function, it can be observed that the inventory will be generated when the risk-free inventory levels z_1 and z_2 chosen by the enterprise exceed the actual quantities ε_1 and ε_2 . When the risk-free inventory levels z_1 and z_2 are lower than the actual quantities ε_1 and ε_2 , this will lead to a shortage, so the expected profit of the enterprise can be expressed as follows:

The expected profit function can be rewritten as follows:

$$E[\prod(z_1, z_2, p_1)] = \Psi(p_1) - L(z_1, z_2, p_1) \\ - c_{m1}e_1[d_1(p_1) + z_1] + c_{m1}CEg_1 \\ + [c_{m1}e_1q_1 - c(T)] + c_{m2}e_2[d_2(p_1) + z_2] \\ + c_{m2}CEg_2 \quad (11)$$

Among them,

$$E[\prod(z_1, z_2, p_1)] = p_1 \left\{ \int_{A_1}^{z_1} [d_1(p_1) + x]f_1(x)dx + \int_{z_1}^{B_1} [d_1(p_1) + z_1]f_1(x)dx \right\} + p_2 \left\{ \int_{A_1}^{z_1} \int_{A_2}^{z_1+z_2-x} [d_2(p_1) + y]f_2(y)f_1(x)dydx \right. \\ + \left\{ \int_{A_1}^{z_1} \int_{z_1+z_2-x}^{B_2} [d_2(p_1) + z_2 + z_1 - x]f_2(y)f_1(x)dydx \right\} - s_1 \int_{z_1}^{B_1} (x - z_1)f_1(x)dx - h_2 \int_{A_2}^{z_2} (z_2 - y)f_2(y)dy \\ - h_1 \int_{z_2}^{B_2} \int_{A_1}^{z_1+z_2-x} [z_1 - x - z_2 - y]f_1(x)f_2(y)dx dy - s_2 \int_{A_1}^{z_1} \int_{z_1+z_1-x}^{B_2} (y - z_2 + x - z_1)f_2(y)f_1(x)dydx \\ - c_1[d_1(p_1) + z_1] - c_2[d_2(p_1) + z_2] - c_{m1}e_1[d_1(p_1) + z_1] + c_{m1}CEg_1 + [c_{m1}Te_1q_1 - c(T)] + c_{m2}CEg_2 \quad (10)$$

$\Lambda_1(z_1) = \int_{A_1}^{z_1} (z_1 - x)f_1(x)dx$, $\Lambda_2(z_2) = \int_{A_2}^{z_2} (z_2 - y)f_2(y)dy$. This represents the possibility that a shortage occurs when the risk-free inventory level z_1, z_2 chosen by the enterprise is too low.

$\Phi(z_1, z_2) = \int_{z_2}^{B_2} \int_{A_1}^{z_1+z_2-y} (z_1 - x + z_2 - y)f_1(x)f_2(y)dx dy$. This indicates the possibility that green products will still be in stock after replacing common products.

$\Psi(z_1, z_2) = \int_{A_1}^{z_1} \int_{z_1+z_2-x}^{B_2} (x - z_1 + y - z_2)f_2(y)f_1(x)dy dx$. This indicates the possibility that green products will be out of stock after replacing the common products.

$$\Psi(p_1) \equiv (p_1 - c_1)[d_1(p_1) + \mu_1] + (p_2 - c_2)[d_2(p_1) + \mu_2]. \quad (12)$$

$$L(z_1, z_2, p_1) \equiv [c_1\Lambda_1(z_1) + h_1\Phi(z_1, z_2) + (p_1 + s_1 - c_1)\Theta_1(z_1)] \\ + [(c_2 + h_2)\Lambda_2(z_2) + (p_2 + s_2)\Psi(z_2, z_1) - c_2\Theta_2(z_2)]. \quad (13)$$

Formula (12) represents the risk-free profit function, which is a deterministic equilibrium problem, in which ε_1 and ε_2 are replaced by μ_1 and μ_2 . Formula (13) represents the loss function. Part 1 represents the loss caused by the

uncertainty of the green products, including the inventory loss $c_1\Lambda_1(z_1) + h_1\Phi(z_1, z_2)$ when output exceeds demand and the shortage loss $(p_1 + s_1 - c_1)\Theta_1(z_1)$ when the output is lower than the demand. Part 2 shows the loss of common products due to uncertainty, including the loss of inventory $(c_2 + h_2)\Lambda_2(z_2)$ when the output exceeds the demand and the loss of shortage $(p_2 + s_2)\Psi(z_2, z_1) - c_2\Theta_2(z_2)$ when the output is lower than the demand. Therefore, the total expected profit of the enterprise in Formula (11) can be described as the net surplus of the risk-free profit under deterministic conditions minus the expected loss due to uncertainty.

The goal of an enterprise is to maximize the total expected profits:

$$\text{Max}_{z_1, z_2, p_1} E[\Pi(z_1, z_2, p_1)]. \quad (14)$$

To simplify the research results, the demand function is assumed to be a linear function:

$$d_1(p_1) = a - bp_1 \quad (a > 0, b > 0)$$

$$d_2(p_1) = a + \beta p_1 \quad (a > 0, \beta > 0)$$

The First- and Second-Order Partial Derivatives of p_1 are found by pairing Formula (14) as follows:

$$\frac{\partial E[\Pi(z_1, z_2, p_1)]}{\partial p_1} = 2b(p_0 - p_1) - \Theta(z_1). \quad (15)$$

$$\frac{\partial^2 E[\Pi(z_1, z_2, p_1)]}{\partial p_1^2} = -2b. \quad (16)$$

Among them, $p_0 = \frac{a+bc_1+\mu_1+\beta(p_2-c_2)+bc_{m1}e_1-\beta c_{m2}e_2}{a+b(c_1+c_{m1}e_1)+\mu_1+\beta(p_2-c_2)-c_{m2}e_2}$, that is, $p_0 = \frac{a+b(c_1+c_{m1}e_1)+\mu_1+\beta(p_2-c_2)-c_{m2}e_2}{2b}$.

The risk-free price representing the optimal consideration of carbon emissions and trading is obtained by maximizing the risk-free profit function $\Psi(p_1)$ (when considering different carbon-rights trading markets for carbon emissions).

It can be observed from Formula (16) that under the given conditions of z_1 and z_2 , the expected profit function $E[\Pi(z_1, z_2, p_1)]$ is a strictly concave function of the price. Therefore, the optimal inventory level can be redetermined by first finding out the functional relationship between the optimal price p_1^* and z_1, z_2 through $\frac{\partial E[\Pi(z_1, z_2, p_1)]}{\partial p_1} = 0$ and then substituting it into Formula (14).

Conclusion 1: under the condition that the demand function is in an additive form, the optimal price is p_1^* , the optimal output is $q_1^* = z_1^* + d_1(p_1^*)$, $q_2^* = z_2^* + d_2(p_1^*)$ and the optimal price and the optimal output satisfy the following conditions:

1. Under a given condition of z_1 and z_2 , the optimal price p_1^* is lower than the optimal risk-free price p_1 and is a

function of the risk-free inventory level. The functional relationship is as follows:

$$p_1^* = p_1(z_1) = p_0 - \frac{\Theta(z_1)}{2b}.$$

2. When the probability density function of a random variable satisfies

$$f_1(z_1) < \min\{2bs_1[r_1(z_1)]^2, r_1(z_1)r_2(z_2)/[r_1(z_1) + r_2(z_2)]\}.$$

When $(A_1 \leq z_1 \leq B_1, A_2 \leq z_2 \leq B_2)$, the expected profit function $E[\Pi(z_1, z_2, p_1(z_1))]$ is a strict concave function of z_1 and z_2 , and there are optimal risk-free inventory levels z_1^* and z_2^* .

Prove:

Conditions (1) can be obtained from Formula (15), which equals 0. $p_1^* = p_0 - \frac{\Theta(z_1)}{2b}$, since $\Theta(z_1)$ is nonnegative; Petrucci and Dada [30] obtained the same result for a product.

The proof of condition 2 is omitted.

Under the condition that the conclusion is satisfied, the optimal risk-free inventory levels z_1^* and z_2^* can be obtained by solving the following equations:

$$\begin{aligned} \frac{\partial E[\Pi(z_1, z_2, p_1(z_1))]}{\partial z_1} &= [p_0 - s_1 - \frac{\Theta(z_1)}{2b}][1 - F_1(z_1)] \\ &\quad + (p_2 + s_2)\{F_1(z_1)[1 - f_2(z_2 + z_1 - x)] \\ &\quad - f_1(z_1)\Theta_2(z_2)\} - c_1 - h_1[1 - F_2(z_2)] \\ &\quad F_1(z_1 + z_2 - y) = 0. \end{aligned}$$

Based on the optimal inventory level and actual demand, the optimal production volume can be obtained:

$$q_1^* = z_1^* + d_1(p_1^*)$$

$$q_2^* = z_2^* + d_2(p_1^*)$$

Obtain evidence.

Input of green technology and selection of the production strategy for green products

This section examines the problem of green technology input and green product production strategy selection; that is, it analyzes the relationship between $E[\Pi(z_1, z_2, p_3(z_1))]$ and T .

1. If $\frac{c'(T)}{e_1 q_1} < c_{m1}$, we can obtain $\frac{\partial E[\Pi(z_1, z_2, p_1)]}{\partial T} > 0$ from Formula (11), and $E[\Pi(z_1, z_2, p_1)]$ continuously increases along with T ; that is, the investment in green technology can increase the expected profits of enterprises through the

production of green product 1, and so the enterprises will invest in green technology to produce green product 1.

2. If $\frac{c'(T)}{e_1 q_1} = c_{m1}$, we can observe $\frac{\partial E[\prod(z_1, z_2, p_1)]}{\partial T} = 0$ from Formula (11), which means that the investment in green technology cannot increase the expected profits of enterprises by producing green product 1, and thus, enterprises will not invest in the green technology to produce green product 1.
3. If $\frac{c'(T)}{e_1 q_1} > c_{m1}$, we can observe $\frac{\partial E[\prod(z_1, z_2, p_1)]}{\partial T} < 0$ from Formula (11); that is, a continuous decline, which means that the investment in green technology will reduce the expected profits of enterprises while producing green product 1. Therefore, the enterprises will not invest in the green technology to produce green product 1.

Conclusion

In recent years, under the influence of a low-carbon economy, more and more enterprises have started to produce and sell alternative diversified products. This paper studies the joint decision-making involved in the production and pricing of two products with one-way substitution under the condition of carbon trading and green technology investment with a stochastic demand. In the case of a single cycle, when the distribution function of the random variables satisfies certain conditions, there is a unique optimal output and price for enterprises that conform to an additive demand function. At the same time, the conditions required for enterprises to consider including green technology in their production are obtained. In the future, further studies on the production and price decision-making in one-way substitutions of two products should be conducted by analyzing multicycle green technology investments under the conditions of carbon quotas and trading or asymmetric information structures.

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