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SUPPLY CHAIN DECISION-MAKING CONSIDERING GREEN TECHNOLOGY EFFORT: EFFECT ON RANDOM OUTPUT AND RETAIL PRICE WITH FAIRNESS CONCERNS

Abstract. *In the context where the random output and retail prices of green products depend on green technology effort, this study considers three cases: only the supplier or retailer has fairness concerns, and both are risk neutral. A two-level supply chain complete information dynamic game model, comprising the follower supplier and dominant retailer, is constructed to study the respective supply chain decision-making problem. The results show that: (1) the supplier's expected profit is the highest when they have fairness concerns, followed by the cases wherein both are risk neutral and the retailer has fairness concerns, respectively; (2) the retailer's expected profit (retail price) is the highest in a risk-neutral situation, followed by the cases wherein the retailer (supplier) and the supplier (retailer) have fairness concerns, respectively; (3) the magnitudes of order quantity, wholesale price, and green technology effort in the three situations are complicated and depend on each parameter's size.*

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JEL Classification: C70, C72, C73

1. Introduction

With the continuous improvement in people's living standards, the need for green products is also constantly improving. At the same time, the output of products, influenced by numerous uncertain environmental factors (such as weather, hardware equipment, and human effort), is stochastic (Fang et al., 2020; Wan, 2021; Rasi & Hatami, 2019). To improve production and green degree of the products, enterprises or individuals can increase labour, improve technology (Shah et al., 2022; Kim & Ha, 2022), upgrade equipment, and enhance the environment to step up green technology effort. This can improve green product quality, thereby justifying the increase in the retail prices of such green products. Therefore, green supply chain managers need to balance the benefits of higher retail prices with the cost of green technology effort to achieve a subgame perfect Nash equilibrium.

Each enterprise in the green supply chain node pursues its own interests and profit maximisation. Enterprise managers may thus raise concerns regarding fairness in profit distribution and compare their own profits with those of others; if found to be lesser, they may indulge in unfair psychological activities. Enterprises that feel wronged will undertake retaliatory measures such as increasing the wholesale and retail prices and decreasing order quantity and production input to reduce the other party's share in the total channel surplus (Ho et al., 2014).

To understand how participants' fairness concerns influence supply chain management, Haitao Cui et al. (2007) first introduced the concept of fairness concerns into the supply chain to study the coordination effectiveness of a wholesale price contract. Based on Haitao Cui et al. (2007), the existing literature mainly focuses on two aspects:

(1) The impact of fairness concerns on supply chain coordination in the context of retailers' fairness concerns. Caliskan-Demirag et al. (2010) analysed supply chain coordination under linear demand and non-demand function, whereas Yang et al. (2013) discussed supply chain coordination with cooperative advertising. In subsequent extensions, scholars continued to explore supply chain coordination comprising one supplier and two retailers (Ho et al., 2014; Wei et al., 2017; Yoshihara & Matsubayashi, 2021), dual-channel supply chain coordination (Li & Li, 2016), supply chain coordination with a green retailer (Zhang et al., 2021), three-level closed-loop supply chain coordination (Zheng et al., 2019), sustainable supply chain coordination based on a cooperative game (Liu et al., 2021), and the horizontal and vertical perspective coordination problems of a

duopoly competitive supply chain (Zhang et al., 2018). Supply chain-based studies by Wang et al. (2019) and Wang et al. (2020) included a manufacturer and an e-commerce platform and considered a coordination problem involving the manufacturer's fairness concerns. Yan et al. (2020) analysed the supply chain coordination of agricultural products in two scenarios: when only the manufacturer has fairness concerns, and when both the manufacturer and the retailer have fairness concerns.

(2) The influence of fairness concerns on supply chain decision-making when the retailer has fairness concerns. Researchers have mainly investigated supply chain decision-making when there is private cost information (Qin et al., 2016), supply chain performance when retailers are constrained by funds (Chen et al., 2017), closed-loop supply chain decision-making under the influence of market efforts (Ma et al., 2017), pricing and carbon emission decision-making in the green supply chain (Li et al., 2018; Zhang et al., 2019), the blood distribution problem of fairness concerns (Zhou et al., 2021), closed-loop supply chain pricing decision-making when the retailer has risk aversion and fairness concerns (Li et al., 2021), a two-level supply chain decision-making problem comprising two manufacturers and a single retailer (Pan et al., 2020), and a supply chain decision-making problem in which the retailer has overconfidence and fairness concerns (Zhang et al., 2020). Wang et al. (2022) studied supply chain decision-making under information symmetry and asymmetry, respectively, based on the manufacturer having fairness concerns.

However, the literature considers neither the uncertainty of output nor the impact of green technology effort on random output and retail price. Therefore, integrating theory and practice, this study further expands the relevant output and an inverse demand function model based on a two-level green product supply chain composed of a single follower supplier and a single dominant retailer. Specifically, it aims to bridge the following theoretical gaps:

1. Considering that the supplier's green technology effort directly impacts product output and retail price (because the green technology effort affects green product quality), the stochastic output model and the retail price model dependent on green technology effort are constructed.

2. The influence of the supplier’s and retailer's fairness concerns on green supply chain decision-making are studied by considering three scenarios: supplier's fairness concerns, retailer's fairness concerns, and risk neutrality.

3. The supply chain decision-making and expected profit size of the supplier and retailer in the three different cases are compared and analysed to evaluate which parameters affect their decision-making and expected profit size.

This paper is organised as follows: Section 2 provides the assumptions and a description of the model. Section 3 presents the model construction, including the risk-neutral model (Case 1), supplier’s fairness concerns model (Case 2), and retailer's fairness concerns model (Case 3). Section 4 contains a comparative analysis of the three cases. Section 5 concludes.

2. Model Description and Assumptions

We consider a two-level supply chain system consisting of one supplier and one retailer, in which the retailer is the leader and the supplier is the follower. The game order of the green supply chain is as follows: the retailer first decides the order quantity q and wholesale price w according to the observed output uncertainty; the supplier then decides the production input q (assuming that the production input is equal to the actual output under normal conditions) and the level of green technology effort e according to the retailer's order quantity. At the time of the sale, the retailer purchases goods from the supplier through a wholesale price contract; finally, the retailer sells the product to the market, and the demand is fulfilled. The structure diagram of this study is shown in Figure 1.

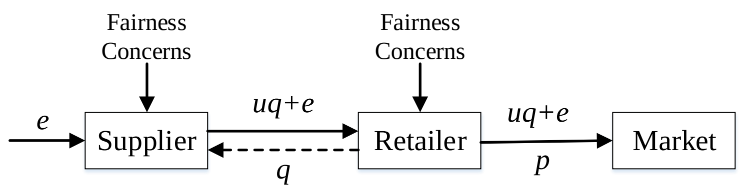

Figure 1. The structure diagram

The mathematical model presented in this study is based on the following assumptions:

Assumption 1: The green product output of the supplier is uncertain, and it is affected by the green technology effort, that is, the actual output is $Q = (uq + e)$. Where u is a random factor, q is the production input, and e is the green technology effort. The green technology effort cost is $C(e) = e^2$ (Cachon and Lariviere, 2005), and the expected value and mean square deviation of u are $E(u) = \mu$ and $V(u) = \delta$, respectively.

Assumption 2: The green product's retail price p is inversely proportional to the quantity $(uq + e)$ and directly proportional to the green technology effort e. This is because the level of green technology effort invested is proportional to product quality; likewise, product quality is proportional to the price. Based on the models of Cachon and Lariviere (2005) and Hu et al. (2020), the retail price function of the green product is shown in Equation (1), where A is a constant.

$$p = A - (uq + e) + ke \tag{1}$$

Assumption 3: To simplify the model, on the premise of not affecting the conclusion, we suppose that the supplier's production cost is $c = 0$.

Assumption 4: Three scenarios are considered: both the supplier and the retailer are risk neutral, or either the supplier or the retailer has fairness concerns.

3. Model Construction and Analysis

3.1 Risk-neutral Model (Case 1)

If both the supplier and the retailer are risk neutral, they will aim to maximise their expected profits. In this case, the expected profits of the supplier π_M^N and the retailer π_R^N are as follows.

$$\pi_M^N(e) = E[wQ - e^2] \tag{2}$$

$$\pi_R^N(q,w) = E[(p - w)Q] \tag{3}$$

The inverse induction method is used to solve the equation. From Equation (2), we have $\partial^2\pi_M^N/\partial e^2 = -2 < 0$; then, π_M^N is concave in e; if $\partial\pi_M^N/\partial e = 0$, we can obtain the supplier's optimal green technology effort as follows:

$$e^{N*} = \frac{w}{2} \tag{4}$$

By substituting e^{N*} into π_R^N, we can get:

$$\pi_R^N(q,w) = \frac{1}{4}\{[2A - (3-k)w](w + 2q\mu) - 2qw\mu - 4q^2(\mu^2 + \delta^2)\} \tag{5}$$

The Hessian matrix of π_R^N with respect to (q,w) is:

$$H = \begin{bmatrix} \frac{\partial^2\pi_R^N}{\partial q^2} & \frac{\partial^2\pi_R^N}{\partial q\partial w} \\ \frac{\partial^2\pi_R^N}{\partial w\partial q} & \frac{\partial^2\pi_R^N}{\partial w^2} \end{bmatrix} = \begin{bmatrix} -2(\mu^2+\delta^2) & \frac{1}{2}\mu(k-4) \\ \frac{1}{2}\mu(k-4) & \frac{1}{2}(k-3) \end{bmatrix} \tag{6}$$

It is easy to verify that $\frac{\partial^2\pi_R^N}{\partial q^2} < 0$ and $|H| = (3-k)\delta^2 - \frac{1}{4}\mu^2(k-2)^2$. Therefore, when the parameter satisfies Equation (7), π_R^N is a strictly concave function with respect to (q,w).

$$4(3-k)\delta^2 - \mu^2(k-2)^2 > 0 \tag{7}$$

By solving $\frac{\partial\pi_R^N}{\partial q} = 0$ and $\frac{\partial\pi_R^N}{\partial w} = 0$, the only optimal production input q^{N*} and wholesale price w^{N*} can be obtained as follows:

$$q^{N*} = \frac{A\mu(2-k)}{4(3-k)\delta^2-\mu^2(k-2)^2}, \; w^{N*} = \frac{2A[2\delta^2-\mu^2(2-k)]}{4(3-k)\delta^2-\mu^2(k-2)^2} \tag{8}$$

Substituting q^{N*} and w^{N*} into the equation above, we get:

$$e^{N*} = \frac{A[2\delta^2-\mu^2(2-k)]}{4(3-k)\delta^2-\mu^2(k-2)^2}, \; p^{N*} = \frac{2A[(5-k)\delta^2-\mu^2(2-k)]}{4(3-k)\delta^2-\mu^2(k-2)^2} \tag{9}$$

$$\pi_M^{N*} = \frac{A^2[4\delta^4-\mu^4(2-k)^2]}{[4(3-k)\delta^2-\mu^2(k-2)^2]^2}, \pi_R^{N*} = \frac{A^2\delta^2}{4(3-k)\delta^2-\mu^2(k-2)^2} \tag{10}$$

3.2 Supplier's Fairness Concern Model (Case 2)

We assume that the supplier has fairness concerns, and the retailer is risk neutral. In this case, the expected utility function of the supplier U_M^M and the expected profit function of the retailer π_R^M can be obtained by referring to the literature Ho et al. (2014), Zheng et al. (2019) and Chen et al. (2017):

$$U_M^M(e) = \pi_M^N - \lambda_M(\pi_R^N - \pi_M^N) \tag{11}$$

$$\pi_R^M(q,w) = E[(p-w)Q] \tag{12}$$

The inverse induction method is used to solve the model. As $\frac{\partial^2 U_M^M}{\partial e^2} = -2(1+k\lambda_M) < 0$, U_M^M is concave in e. Let $\partial U_M^M/\partial e = 0$, we can then obtain the following:

$$e^{M*} = \frac{w-\lambda_M[A-2w+(k-2)q\mu]}{2+2k\lambda_M} \tag{13}$$

Substituting e^{M*} into π_R^M, the retailer's expected profit is as follows:

$$\pi_R^M(q,w) = E[(A-uq-e^{M*}+ke^{M*}-w)(uq+e^{M*})] \tag{14}$$

Similarly, the optimal w^{M*} and q^{M*} can be obtained by solving $\frac{\partial \pi_R^M}{\partial w} = 0$ and $\frac{\partial \pi_R^M}{\partial q} = 0$ simultaneously:

$$w^{M*} = \frac{2A\{2\delta^2[1+4\lambda_M+(2+k)\lambda_M^2]+\mu^2(k-2)(1+\lambda_M)^2\}}{\Delta_0}, q^{M*} = \frac{A\mu(2-k)(1+\lambda_M)^2}{\Delta_0} \tag{15}$$

Substituting w^{M*} and q^{M*} into the above equation, we get:

$$e^{M*} = \frac{A(1+\lambda_M)[\delta^2(2+4\lambda_M)+\mu^2(k-2)(1+\lambda_M)]}{\Delta_0} \tag{16}$$

$$p^{M*} = \frac{2A\{\delta^2(1+2\lambda_M)[5+k(\lambda_M-1)+3\lambda_M]+\mu^2(k-2)(1+\lambda_M)^2\}}{\Delta_0} \tag{17}$$

$$\pi_R^{M*} = \frac{A^2\delta^2(1+\lambda_M)^2}{\Delta_0} \tag{18}$$

$$\pi_M^{M*} = \frac{A^2(1+\lambda_M)\{4\delta^4(1+2\lambda_M)[1+5\lambda_M+2(1+k)\lambda_M^2]-\mu^4(k-2)^2(1+\lambda_M)^3\}}{\Delta_0^2} \tag{19}$$

$$\Delta_0 = 4\delta^2(1+2\lambda_M)(3-k+2\lambda_M) - \mu^2(k-2)^2(1+\lambda_M)^2 > 0 \tag{20}$$

3.3 Retailer's Fairness Concern Model (Case 3)

We suppose that the retailer has fairness concerns, and the supplier is risk neutral. In this case, the expected profit of the supplier π_M^R and the expected utility of the retailer U_R^R can be obtained by referring to the literatures Ho et al. (2014), Zheng et al. (2019) and Chen et al. (2017):

$$\pi_M^R(e) = w(\mu q + e) - e^2 \tag{21}$$

$$U_R^R(q,w) = \pi_R^N - \lambda_R(\pi_S^N - \pi_R^N) \tag{22}$$

As mentioned above, the inverse induction method is used to solve the equation. From Equations (21) and (22), we obtain:

$$q^{R*} = \frac{A\mu(2-k)(1+\lambda_R)^2}{\Delta_1}, w^{R*} = \frac{2A(1+\lambda_R)[2\delta^2(1+\lambda_R)+\mu^2(k-2-4\lambda_R+k\lambda_R)]}{\Delta_1} \tag{23}$$

$$e^{R*} = \frac{A(1+\lambda_R)[2\delta^2(1+\lambda_R)+\mu^2(k-2-4\lambda_R+k\lambda_R)]}{\Delta_1} \tag{24}$$

$$p^{R*} = \frac{2A[\delta^2(1+\lambda_R)(5-k+7\lambda_R-k\lambda_R)+\mu^2(k-2-9\lambda_R+3k\lambda_R-9\lambda_R^2+2k\lambda_R^2)]}{\Delta_1} \tag{25}$$

$$\pi_R^{R*} = \frac{\begin{pmatrix} A^2(1+\lambda_R)\{4\delta^4(1+\lambda_R)^2(3-k+5\lambda_R-k\lambda_R)-\delta^2\mu^2(1+\lambda_R) \\ [4+32\lambda_R+44\lambda_R^2+k^2(1+\lambda_R)^2-4k(1+4\lambda_R+3\lambda_R^2)]+4\lambda_R^2\mu^4(3-k+5\lambda_R-k\lambda_R)\} \end{pmatrix}}{\Delta_1^2} \tag{26}$$

$$\pi_M^{R*} = \frac{A^2(1+\lambda_R)^2[2\delta^2(1+\lambda_R)+\mu^2(2-k-k\lambda_R)][2\delta^2(1+\lambda_R)-\mu^2(2-k-k\lambda_R+4\lambda_R)]}{\Delta_1^2} \quad (27)$$

$$\Delta_1 = 4\delta^2(1+\lambda_R)(3-k-k\lambda_R+4\lambda_R)-\mu^2[k^2(1+\lambda_R)^2 -4k(1+3\lambda_R+2\lambda_R^2)+4(1+5\lambda_R+5\lambda_R^2)]>0 \quad (28)$$

4. Comparative Analysis of the Three Cases

The expected profits and decisions of the supplier and retailer in the above three cases are compared below. From the equations solved in the earlier models, we obtain:

$$q^{N*} - q^{M*} = \frac{4A\mu\lambda_M\delta^2(2-k)(2+\lambda_M+k\lambda_M)^2}{\Delta_0[4(3-k)\delta^2-\mu^2(k-2)^2]} > 0 \quad (29)$$

$$q^{N*} - q^{R*} = \frac{4A\mu\lambda_R(2-k)[\delta^2(1+\lambda_R)-\mu^2(3-k+4\lambda_R-k\lambda_R)}{\Delta_1[4(3-k)\delta^2-\mu^2(k-2)^2]} \quad (30)$$

$$q^{M*} - q^{R*} = \frac{A\mu(2-k)[(1+\lambda_M)^2\Delta_1-(1+\lambda_R)^2\Delta_0]}{\Delta_0\Delta_1[4(3-k)\delta^2-\mu^2(k-2)^2]} \quad (31)$$

$$\Delta_0 = 4\delta^2(1+2\lambda_M)(3-k+2\lambda_M)-\mu^2(k-2)^2(1+\lambda_M)^2 > 0 \quad (32)$$

$$\Delta_1 = \begin{array}{l}4\delta^2(1+\lambda_R)(3-k-k\lambda_R+4\lambda_R)-\mu^2[k^2(1+\lambda_R)^2 \\ -4k(1+3\lambda_R+2\lambda_R^2)+4(1+5\lambda_R+5\lambda_R^2)]>0\end{array} \quad (33)$$

From Equations (29)–(31), Proposition 3 is obtained.

Proposition 3. ①When $\lambda_R^0 < 0$, $q^{M*} < q^{N*} < q^{R*}$; ②when $\lambda_R > \lambda_R^0 > 0$, $q^{M*} < q^{N*} < q^{R*}$; ③when $\lambda_R^1 < \lambda_R < \lambda_R^0$ ($\lambda_R^0 > 0$), $q^{M*} < q^{R*} < q^{N*}$; ④ when $\lambda_R < \lambda_R^1$ ($\lambda_R^0 > 0$), $q^{R*} < q^{M*} < q^{N*}$.

$$\lambda_R^0 = \frac{\delta^2-\mu^2(3-k)}{\mu^2(4-k)-\delta^2} \quad (34)$$

λ_R^1 satisfies $A\mu(2-k)[(1+\lambda_M)^2\Delta_1-(1+\lambda_R)^2\Delta_0] = 0$ (35)

From Proposition 3, if the parameters (δ,μ,k) meet $\lambda_R^0<0$, or the retailer's fairness concern is high $(\lambda_R>\lambda_R^0>0)$, we can infer that the retailer's order quantity is the highest when it has fairness concerns, followed by the risk-neutral situation and that of the supplier with fairness concerns; if the retailer's fairness concern is general, that is, $\lambda_R^1<\lambda_R<\lambda_R^0$ $(\lambda_R^0>0)$, the retailer has the highest order quantity in the risk-neutral situation, followed by those of the retailer and the supplier having fairness concerns, respectively; if the retailer's fairness concern is low, that is, $\lambda_R<\lambda_R^1$ $(\lambda_R^0>0)$, the retailer has the highest order quantity in the risk-neutral situation, followed by those of the supplier and the retailer having fairness concerns, respectively. Case ①–④ are shown in Figure 2.

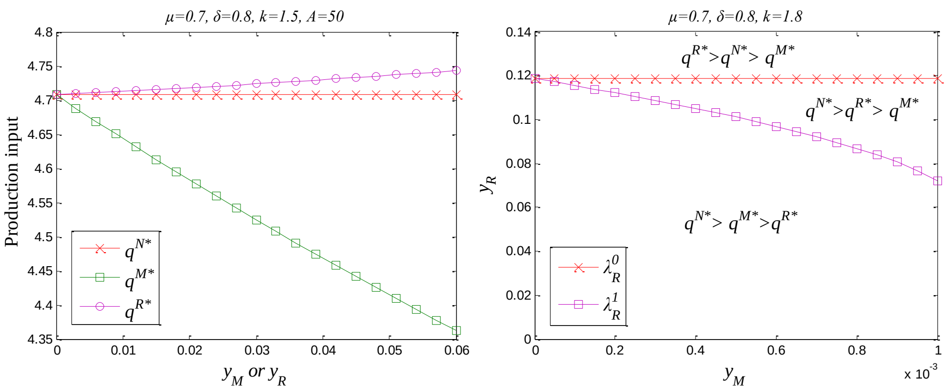

Figure 2. The effect of λ_M or λ_R on order quantity in the three cases

Based on the model solution results in Section 3, we obtain:

$$w^{N*}-w^{M*}=\frac{4A\lambda_M\delta^2(k-2)(2+\lambda_M+k\lambda_M)(4\delta^2+k\mu^2)}{\Delta_0[4(3-k)\delta^2-\mu^2(k-2)^2]}<0 \tag{36}$$

$$w^{N*}-w^{R*}=\frac{4A\lambda_R[2\delta^2\mu^2(2-k+4\lambda_R-k\lambda_R)+\mu^4(2-k)(k-4-6\lambda_R+k\lambda_R)-4\delta^4(1+\lambda_R)]}{\Delta_1[4(3-k)\delta^2-\mu^2(k-2)^2]} \tag{37}$$

$$w^{M*}-w^{R*}=\frac{\begin{pmatrix}2A\Delta_1\{2\delta^2[1+4\lambda_M+(2+k)\lambda_M^2]+\mu^2(k-2)(1+\lambda_M)^2\}\\-2A\Delta_0(1+\lambda_R)[2\delta^2(1+\lambda_R)+\mu^2(k-2-4\lambda_R+k\lambda_R)]\end{pmatrix}}{\Delta_0\Delta_1} \tag{38}$$

Proposition 4 can be obtained from Equations (36)–(38).

Proposition 4. ① When $\lambda_R^2 < 0$, $w^{M*} > w^{N*} > w^{R*}$; ② When $\lambda_R > \lambda_R^2 > 0$, $w^{M*} > w^{N*} > w^{R*}$; ③ When $\lambda_R^2 > \lambda_R > \lambda_R^3$ $(\lambda_R^2 > 0)$, $w^{M*} > w^{R*} > w^{N*}$; ④When $\lambda_R < \lambda_R^3$ $(\lambda_R^2 > 0)$, $w^{R*} > w^{M*} > w^{N*}$.

$$\lambda_R^2 = \frac{4\delta^4 - 2\delta^2\mu^2(2-k) + \mu^4(8-6k+k^2)}{2\delta^2\mu^2(4-k) - 4\delta^4 - \mu^4(12-8k+k^2)} \tag{39}$$

λ_R^3 satisfies
$$\begin{aligned}&2A\Delta_1\{2\delta^2[1+4\lambda_M+(2+k)\lambda_M^2]+\mu^2(k-2)(1+\lambda_M)^2\}\\&-2A\Delta_0(1+\lambda_R)[2\delta^2(1+\lambda_R)+\mu^2(k-2-4\lambda_R+k\lambda_R)]=0\end{aligned} \tag{40}$$

From Proposition 4, if the parameters (δ, μ, k) meet $\lambda_R^2 < 0$ or the retailer's fairness concern is high $(\lambda_R > \lambda_R^2 > 0)$, the supplier has the highest wholesale price when they have fairness concerns, followed by the risk-neutral situation and finally the retailer's fairness concern situation; if the retailer's fairness concern is general, that is $\lambda_R^2 > \lambda_R > \lambda_R^3$ $(\lambda_R^2 > 0)$, the supplier has the highest wholesale price when they have fairness concerns, followed by the retailer with fairness concerns and the risk-neutral situation; If the retailer's fairness concern is small, that is $\lambda_R < \lambda_R^3$ $(\lambda_R^2 > 0)$, the supplier has the highest wholesale price when the retailer has fairness concerns, followed by the supplier with fairness concerns and the risk-neutral situation. Case ①–④ are shown in Figure 3.

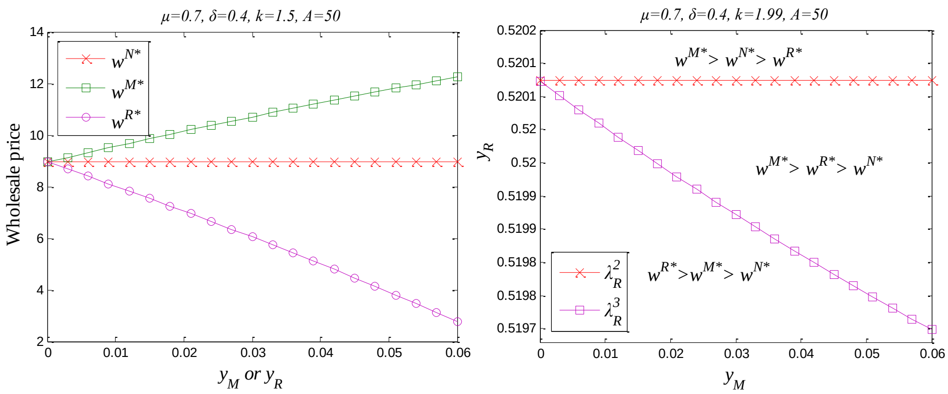

Figure 3. The effect of λ_M and λ_R on wholesale price in the three cases

From the model solution results in Section 3, we obtain:

$$e^{N*} - e^{M*} = \frac{2A\lambda_M \delta^2[4\delta^2(1-k)(1+2\lambda_M)+\mu^2(2-k)(2+k+3k\lambda_M)]}{\Delta_0[4(3-k)\delta^2-\mu^2(k-2)^2]} \tag{41}$$

$$e^{N*} - e^{R*} = \frac{\begin{pmatrix} 2A\lambda_R[2\delta^2\mu^2(2-k+4\lambda_R-k\lambda_R) \\ +\mu^4(2-k)(k-4-6\lambda_R+k\lambda_R)-4\delta^4(1+\lambda_R)] \end{pmatrix}}{\Delta_1[4(3-k)\delta^2-\mu^2(k-2)^2]} \tag{42}$$

$$e^{M*} - e^{R*} = \frac{\begin{pmatrix} A\Delta_1(1+\lambda_M)[\delta^2(2+4\lambda_M)+\mu^2(k-2)(1+\lambda_M)] \\ -A\Delta_0(1+\lambda_R)[2\delta^2(1+\lambda_R)+\mu^2(k-2-4\lambda_R+k\lambda_R)] \end{pmatrix}}{\Delta_1[4(3-k)\delta^2-\mu^2(k-2)^2]} \tag{43}$$

Based on Equations (41)–(43), Proposition 5 is obtained.

Proposition 5. ① When $k < k^0$, $e^{M*} > e^{N*} > e^{R*}$; ② when $\lambda_R > \lambda_R^4\ (k > k^0)$, $e^{N*} > e^{M*} > e^{R*}$; ③ when $\lambda_R^4 > \lambda_R > \lambda_R^5(k > k^0)$, $e^{N*} > e^{R*} > e^{M*}$; ④ when $\lambda_R < \lambda_R^5(k > k^0)$, $e^{R*} > e^{N*} > e^{M*}$.

$$k^0 = \frac{3\mu^2-4\delta^2+\sqrt{16\delta^4+9\mu^4}}{3\mu^2} \tag{44}$$

$$\lambda_R^4 = \frac{4\delta^4-2\mu^2\delta^2(2-k)+\mu^4(8-6k+k^2)}{2\mu^2\delta^2(4-k)-4\delta^4-\mu^4(12-8k+k^2)} \tag{45}$$

λ_R^5 satisfies $$\begin{aligned} &A\Delta_1(1+\lambda_M)[\delta^2(2+4\lambda_M)+\mu^2(k-2)(1+\lambda_M)] \\ &-A\Delta_0(1+\lambda_R)[2\delta^2(1+\lambda_R)+\mu^2(k-2-4\lambda_R+k\lambda_R)]=0 \end{aligned} \tag{46}$$

From Proposition 5, if the parameters (δ, μ, k) meet $k < k^0$, the supplier has the highest green technology effort when it has fairness concerns, followed by the risk-neutral situation and then the retailer's fairness concern situation; if the retailer's fairness concern is high and $k > k^0$, that is, $\lambda_R > \lambda_R^4\ (k > k^0)$, the supplier has the highest green technology effort input in the risk-neutral situation, followed by the supplier with fairness concerns and then the retailer's fairness concern situation; if the retailer's fairness concern is general and $k > k^0$, that is, $\lambda_R^4 > \lambda_R > \lambda_R^5(k > k^0)$, the supplier has the highest green technology effort input in the risk-neutral situation, followed by the retailer's fairness concern and supplier's fairness concern situations. Case ①–④ are shown in Figure 4.

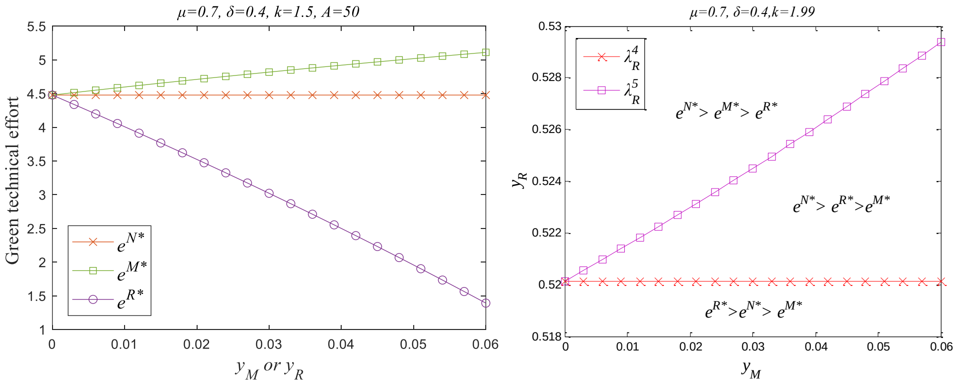

Figure 4. The effect of λ_M and λ_R on green technology effort in the three cases

From the model solution results in Section 3, we can obtain:

$$p^{M*} - p^{R*} = \frac{\begin{pmatrix} 2A\Delta_1\delta^2(1+2\lambda_M)[5+k(\lambda_M-1)+3\lambda_M]+\mu^2(k-2)(1+\lambda_M)^2-2A\Delta_0 \\ [\delta^2(1+\lambda_R)(5-k+7\lambda_R-k\lambda_R)+\mu^2(k-2-9\lambda_R+3k\lambda_R-9\lambda_R^2+2k\lambda_R^2)] \end{pmatrix}}{\Delta_0\Delta_1} \tag{47}$$

$$p^{N*} - p^{M*} = \frac{2A\delta^2\lambda_M[\mu^2(2-k)(2+k+k^2+2\lambda_M-k\lambda_M+3k^2\lambda_M)-4\delta^2(k-1)^2(1+2\lambda_M)]}{\Delta_0[4(3-k)\delta^2-\mu^2(k-2)^2]} \tag{48}$$

$$p^{N*} - p^{R*} = \frac{\begin{pmatrix} 2A\lambda_R\{4\delta^2(1-k)(1+\lambda_R)-2\mu^2\delta^2[2\lambda_R+k^2(1+\lambda_R) \\ -2k(1+2\lambda_R)]+\mu^4(2-k)[(k^2-2)(1+\lambda_R)-k(3+5\lambda_R)]\} \end{pmatrix}}{\Delta_1[4(3-k)\delta^2-\mu^2(k-2)^2]} \tag{49}$$

Due to the complexity of Equations (47)–(49), the theoretical solution cannot be obtained. Therefore, we use the numerical simulation method, combining Equations (47)–(49) and Figure 5 to obtain Proposition 6.

Proposition 6. The retailer has the highest retail price in the risk-neutral situation, followed by the supplier's fairness concern and the retailer's fairness concern situations, that is, $p^{N*} > p^{M*} > p^{R*}$.

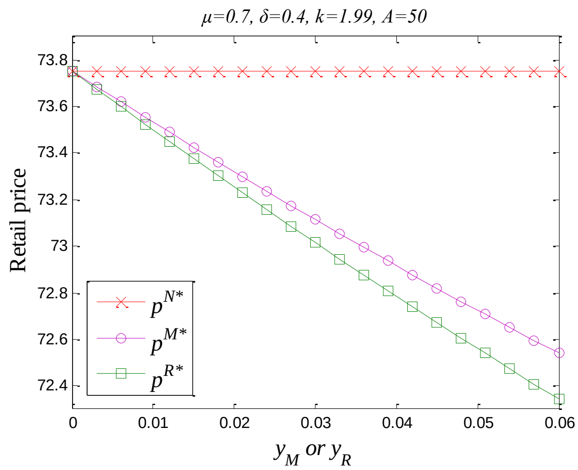

Figure 5. The effect of λ_M and λ_R on retail price in the three cases

From the model solution results in Section 3, we obtain:

$$\pi_M^{N*}-\pi_M^{M*}=\frac{\begin{pmatrix}A^2\Delta_0^2[4\delta^4-\mu^4(2-k)^2]-A^2(1+\lambda_M)[4(3-k)\delta^2-\mu^2(k-2)^2]^2\\ \{4\delta^4(1+2\lambda_M)[1+5\lambda_M+2(1+k)\lambda_M^2]-\mu^4(k-2)^2(1+\lambda_M)^3\}\end{pmatrix}}{\Delta_0^2[4(3-k)\delta^2-\mu^2(k-2)^2]} \tag{50}$$

$$\pi_M^{N*}-\pi_M^{R*}=\frac{\begin{pmatrix}A^2\Delta_1^2[4\delta^4-\mu^4(2-k)^2]-A^2(1+\lambda_R)^2[4(3-k)\delta^2-\mu^2(k-2)^2]^2\\ [2\delta^2(1+\lambda_R)+\mu^2(2-k-k\lambda_R)][2\delta^2(1+\lambda_R)-\mu^2(2-k-k\lambda_R+4\lambda_R)]\end{pmatrix}}{\Delta_1^2[4(3-k)\delta^2-\mu^2(k-2)^2]^2} \tag{51}$$

$$\pi_M^{M*}-\pi_M^{R*}=\frac{\begin{pmatrix}A^2\Delta_1^2(1+\lambda_M)\{4\delta^4(1+2\lambda_M)[1+5\lambda_M+2(1+k)\lambda_M^2]-\mu^4(k-2)^2(1+\lambda_M)^3\}\\ -A^2\Delta_0^2(1+\lambda_R)^2[2\delta^2(1+\lambda_R)+\mu^2(2-k-k\lambda_R)][2\delta^2(1+\lambda_R)-\mu^2(2-k-k\lambda_R+4\lambda_R)]\end{pmatrix}}{\Delta_0^2\Delta_1^2} \tag{52}$$

$$\pi_R^{N*}-\pi_R^{M*}=\frac{4\lambda_M A^2\delta^4(2+\lambda_M+k\lambda_M)}{[4(3-k)\delta^2-\mu^2(k-2)^2]\Delta_0} \tag{53}$$

$$\pi_R^{N*}-\pi_R^{R*}=\frac{\begin{pmatrix}A^2\delta^2\Delta_1^2-A^2(1+\lambda_R)[4(3-k)\delta^2-\mu^2(k-2)^2]\{4\delta^4(1+\lambda_R)^2(3-k+5\lambda_R-k\lambda_R)-\delta^2\mu^2\\ (1+\lambda_R)[4+32\lambda_R+44\lambda_R^2+k^2(1+\lambda_R)^2-4k(1+4\lambda_R+3\lambda_R^2)]+4\lambda_R^2\mu^4(3-k+5\lambda_R-k\lambda_R)\}\end{pmatrix}}{\Delta_1^2[4(3-k)\delta^2-\mu^2(k-2)^2]} \tag{54}$$

$$\pi_R^{M*}-\pi_R^{R*}=\frac{\begin{pmatrix}A^2\delta^2\Delta_1^2(1+\lambda_M)^2-A^2\Delta_0(1+\lambda_R)\{4\delta^4(1+\lambda_R)^2(3-k+5\lambda_R-k\lambda_R)-\delta^2\mu^2(1+\lambda_R)\\ [4+32\lambda_R+44\lambda_R^2+k^2(1+\lambda_R)^2-4k(1+4\lambda_R+3\lambda_R^2)]+4\lambda_R^2\mu^4(3-k+5\lambda_R-k\lambda_R)\}\end{pmatrix}}{\Delta_1^2\Delta_0} \tag{55}$$

Due to the complexity of the model in the above equation, solving for the theoretical solution is rendered impossible. Therefore, numerical simulation is used to solve the problem, and Proposition 7 is obtained as follows.

Proposition 7. ① The supplier has the highest expected profit when they have fairness concerns, followed by the risk-neutral situation and the retailer's fairness concern situation, that is, $\pi_M^{M*} > \pi_M^{N*} > \pi_M^{R*}$; ② the retailer has the highest expected profit in the risk-neutral situation, followed by the situations wherein the retailer and the supplier have fairness concerns, respectively, that is, $\pi_R^{N*} > \pi_R^{R*} > \pi_R^{M*}$. As shown in Figure 6.

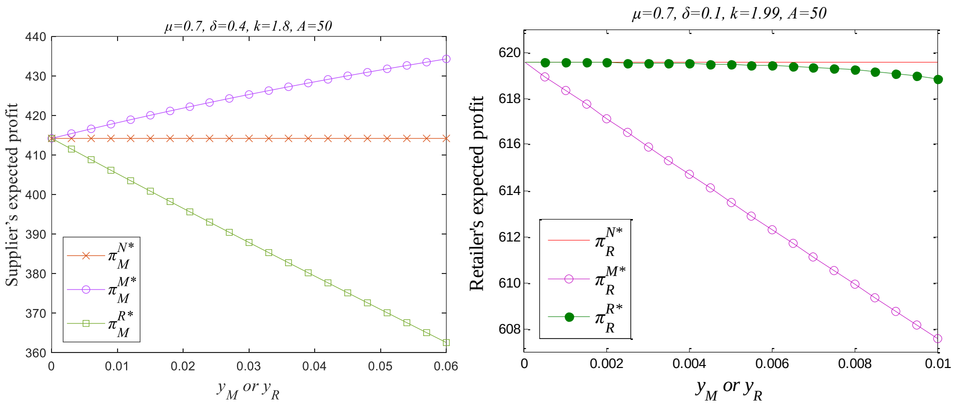

Figure 6. The effect of λ_M and λ_R on supplier's expected profit in the three cases

5. Conclusions

This study considers a two-level supply chain model consisting of a single follower supplier and a single dominant retailer. The supplier's output faces uncertainty and is affected by the green technology effort. The market price of the product is affected by the actual output and green technology effort. Three cases have been considered: the supplier with fairness concerns, the retailer with fairness concerns, and the risk-neutral situation. In this study, the influence of fairness concerns on the decision-making and expected profit of supply chain enterprises has been analysed. The decision-making and expected profit in the three cases were also compared. We conclude the following:

(1) The supplier has the highest expected profit when it has fairness concerns, followed by the risk-neutral situation and finally the retailer's fairness concern situation. The retailer has the highest expected profit in the risk-neutral

situation, followed by the retailer’s fairness concern and the supplier’s fairness concern situations.

(2) The retailer has the highest retail price in the risk-neutral situation, followed by the supplier’s fairness concern and the retailer’s fairness concern situations.

(3) If the parameters (δ, μ, k) satisfy $\lambda_R^0 < 0$ and $\lambda_R^2 < 0$, or the retailer has high fairness concerns, the highest order quantity and wholesale price are seen for the supplier with fairness concerns, followed by the risk-neutral situation and the retailer’s fairness concern situation; if the retailer's fairness concern is general, the order quantity and wholesale price are the highest when the supplier has fairness concerns, followed by the retailer’s fairness concern situation and the risk-neutral situation; if the retailer's fairness concern is small, the order quantity and wholesale price are the highest when the retailer has fairness concerns, followed by the supplier’s fairness concern situation and the risk-neutral situation.

(4) If the parameter k satisfies $k < k^0$, the green technology effort is the greatest in the supplier’s fairness concern situation, followed by the risk-neutral situation and the retailer’s fairness concern situation; if the retailer’s fairness concern is high, the green technology effort is the greatest in the risk-neutral situation, followed by the supplier’s fairness concern and the retailer fairness concern situations; if the retailer's fairness concern is general, the highest green technology effort is observed in the risk-neutral situation, followed by the retailer’s fairness concern situation and the supplier’s fairness concern situation; if the retailer's fairness concern is small, the green technology effort is greatest when the retailer has fairness concerns, followed by the risk-neutral situation and that of the supplier having fairness concerns.

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