Research on Coordination Model of Pharmaceutical Supply Chain under Carbon Emission Trading Policy

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Abstract

Objective To provide effective decision making for the subsidy policies given by the government to pharmaceutical enterprises and the coordination model adopted by pharmaceutical stakeholders under the carbon emission trading policy. **Methods** The Stackelberg model was used to discuss the optimal profits of each member and the whole supply chain under different decision-making models while considering the technical capacity of emission reduction and cost sharing contract. Based on this, the impact of the combined contract decision-making model on the technical efforts of drug manufacturers to reduce carbon emission, the profits of supply chain members and the overall profits of supply chain was investigated. **Results and Conclusion** Research has found that improving the research and development efforts of emission reduction technologies by pharmaceutical enterprises can increase drug sales and enhance the expected profits of pharmaceutical supply chain members. The members of the secondary pharmaceutical supply chain can achieve the optimal expected profit when reaching cooperation. Besides, when the cost sharing contract and quantity discount contract meet the constraint conditions, the combined contract decision model can perfectly coordinate the pharmaceutical supply chain, enabling supply chain members to achieve Pareto improvement and gradually reach Pareto optimum.

Keywords: carbon emission trading policy; pharmaceutical supply chain; R&D of emission reduction technology; contract model

In order to reduce the greenhouse effect, the United Nations Intergovernmental Panel on Climate Change formulated the Kyoto Protocol in 1997, proposing a carbon emission reduction mechanism (i.e. carbon emission trading policy), treating carbon dioxide emissions as a commodity and solving carbon emissions problems through market mechanisms [1]. In response to the policy, China launched the pilot work of carbon emission trading in seven cities including Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen in 2011 [2], and officially opened the national carbon emission trading market on July 16, 2021, which had a far-reaching impact on the production decisions of carbon emission dependent pharmaceutical enterprises [3].

1 Research background and literature review

Under the influence of carbon emission trading policy, drug manufacturers need to measure the relationship between carbon emission cost and

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production volume in the original production decision. Meanwhile, drug distributors need to decide whether to apportion carbon emission cost according to market demand. The carbon emission trading policy breaks the traditional interest distribution mode of the pharmaceutical supply chain. In order to prevent the supply chain from being interrupted due to the uneven distribution benefits among members of the pharmaceutical supply chain, it is of great significance to study a reasonable coordination model of the pharmaceutical supply chain and give certain incentive contracts to pharmaceutical manufacturers and drug distributors, which will improve the coordination and management ability of the supply chain and enhance the enthusiasm of supply chain members for emission reduction [4]. Therefore, under the background of carbon emission trading policy, selecting appropriate incentive contracts and designing effective pharmaceutical supply chain coordination strategies have become an urgent problem to be solved in the pharmaceutical supply chain.

Scholars at home and abroad have put forward their opinions and suggestions in response to the above issues. Liu, et al. [5] found that while achieving carbon emissions targets, consumer preferences for low-carbon products could benefit both supply chain members and pharmaceutical enterprises. Bai, et al. [6] believed that reasonable investment in emission reduction technologies could effectively increase the profits of supply chain members under certain cost sharing conditions. Yu, et al. [7] constructed an investment game model and found that cost subsidies and cost sharing contracts under the carbon emission trading system had a certain promoting effect on emission reduction investment by pharmaceutical enterprises. Hou, et al. [8] used differential game theory and dynamic optimization methods to explore the investment decision-making of dynamic emission reduction technology, pointing out that under the carbon emission trading system, cost sharing contracts had a certain regulatory effect on enterprises' emission reduction investment and profits, which continuously increased over time. Meanwhile, supply chain contracts had always been a hot topic of discussion among management scholars and experts, among which the most common supply chain contracts include wholesale price contracts [9], repurchase contracts [10], and quantity discount contracts [11]. Ogier M, et al. [12] explored how to use quantity discount contracts to coordinate a supply chain composed of one manufacturer and multiple independent retailers, and the results showed that quantity discount contracts could effectively achieve optimal supply chain profits in a decentralized decision-making model. Cui [13] constructed a three-stage closed-loop supply chain quantity discount contract coordination model for retailer price competition and determined the optimal pricing strategy and profit for the enterprise under this model. Zhao, et al. [14] found that quantity discount contracts could successfully coordinate a cooperative competitive supply chain consisting of a supplier and a duopoly manufacturer producing alternative products. Although the above research pointed out that enterprises could effectively reduce their emission reduction costs by using incentive contracts to enhance their technology capabilities of emission reduction, most studies were based on supply chains with good compliance and no oligopoly industries. In this case, a single contract can indeed successfully coordinate the supply chain, but medical supply chains often have poor compliance, and pharmaceutical enterprises are oligopoly enterprises, playing the role of "leaders" in the supply chain. Having the power to choose downstream supply chain members often makes it difficult to successfully coordinate the pharmaceutical supply chain with a single contract. Therefore, based on the hypothesis that pharmaceutical enterprise was the "leader", a secondary supply chain consisting of a pharmaceutical production enterprise and a pharmaceutical trading enterprise was constructed. The Stackelberg model was used to discuss the optimal profits of each member of the supply chain and the overall supply chain under cooperative and decentralized decision-making models while considering the technology capabilities of emission reduction and cost sharing contracts. And on this basis, the impact of quantity discount contracts and cost sharing contracts on the technology efforts of emission reduction, supply chain member profits, and overall supply chain profits of pharmaceutical production enterprises was explored.

2 Problem description and basic assumptions

2.1 Problem description

Suppose a complete pharmaceutical supply chain consists of a drug manufacturer (M) and a drug distributor (R). Under the influence of the carbon emission trading policy, the profits of drug manufacturers are affected by the R&D capability of emission reduction technologies, and the profits of drug distributors are affected by the cost sharing contract as well as the R&D capability of emission reduction technologies, refer to Fig. 1 for specific impact trends.

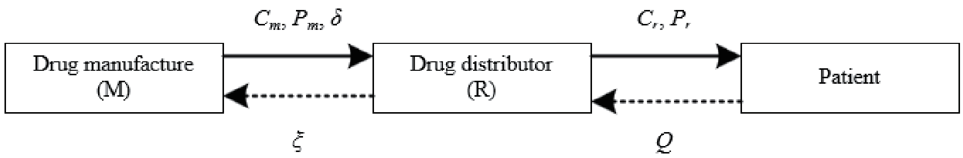

Fig. 1 Supply chain composition and impact trends

Symbol description:

C_m: Unit production cost of drug manufacturers;

P_m: Unit sales price of drug manufacturers;

δ: Distribution proportion of quantity discount contracts between drug manufacturers and drug distributors;

ξ: Distribution proportion of cost sharing contract between drug manufacturers and drug distributors;

C_r: Unit sales cost of drug distributors;

P_r: Pricing per unit product by drug distributors based on sales cost and market demand;

Π_L: Expected profits of drug distributors;

Π_{L1}: Expected profits of drug distributors that do not participate in the cost sharing contract;

Π_s: Expected profits of drug manufacturers;

Π_{s1}: Expected profits of drug manufacturers not participating in cost sharing contracts;

Π_{Lq}: Expected profit of pharmaceutical enterprises under combined contract model;

Π_{sq}: Expected profits of drug manufacturers under the combined contract model;

d_{z1}: Unit added product pricing without cost sharing contract under cooperative decision model;

Q_{z1}: Total medical demand without participating in cost sharing contract under cooperative decision model;

Π_{z1}: Total expected profit of pharmaceutical supply chain without participating in cost sharing contract under cooperative decision model;

$e_{z,\ f,\ q}$: Effort degree of emission reduction technology under different decision models;

$d_{z,\ f,\ q}$: Pricing of unit added products under different decision models;

$\Pi_{z,\ f,\ q}$: Total expected profit of pharmaceutical supply chain under different decision models;

$Q_{z,\ f,\ q}$: Total medical demand under different decision models;

Z represents the cooperative decision model, f represents the decentralized decision model, q represents the combined contract cooperation model, and * represents the optimal parameters.

Considering the carbon emission trading policy, it is assumed that the total medical demand in the market is:

$$Q = a + \lambda e - \omega d\,(1 - \xi)$$

Where a is the basic demand of the market, e is the effort of drug manufacturers to improve emission reduction technology, λ is the sensitivity of demand to the technology capacity of emission reduction, d is the unit product pricing increased by drug manufacturer to reduce the impact of the decline in total demand caused by the R&D of emission reduction technology by drug distributor, and ω is the elasticity index of pricing per unit product for demand. Among these, a, λ, $\omega > 0$, and they are constants, while e, $d \geq 0$.

2.2 Basic assumptions

(1) It is assumed that both drug manufacturers and drug distributors aim at maximizing profits, and the decision makers are rational people without any risk preference.

(2) There are patients with low-carbon preference in the market, and the higher the emission reduction technology level of drug manufacturers, the more their products are loved by patients with low-carbon preference, and the higher the demand. However, patients will also prefer other products due to the increase in product pricing of drug distributors, resulting in a decrease in demand, and vice versa.

(3) The cost of participating in the cost sharing contract is greater than the cost of reducing the total medical demand due to not participating in the cost sharing contract. Therefore, under the decentralized decision-making model, drug distributors are often reluctant to participate in the cost sharing contract.

(4) Emission reduction cost is a quadratic function of emission reduction effort, i.e. $G = \mu e^2/2$. Where G is the emission reduction cost of the drug manufacturer, μ is the cost price of improving emission reduction capacity, e is the effort of drug manufacturers to improve emission reduction technology, $\mu > 0$, and it is a constant.

(5) The unit product cost and unit product pricing of drug manufacturers and drug distributors conform to the general market law, that is, $P_r > C_r + P_m$, $P_m > C_m$, and the unit product cost of drug manufacturing enterprises is greater than that of drug distributing enterprises, that is, $C_m > C_r$.

3 Building decision model to get the solution

3.1 Cooperative decision model

In the cooperative decision-making model, drug manufacturers and drug distributors, as a whole, both aim at maximizing the overall profits of the supply chain. At this point, the expected profit of the whole supply chain can be expressed as：

$$\Pi_z = (P_r + d - C_m - C_r)(a + \lambda e - \omega d(1 - \xi)) - \mu e^2/2(1 - \xi) - \xi\mu e^2/2 \quad (1)$$

Calculating the second-order partial derivative of e by formula (1) $\frac{\partial^2 \Pi z}{\partial^2 e} = -\mu < 0$. It proves Π_z is a strictly concave function of e, that is, there is a maximum point. When $\frac{\partial \Pi z}{\partial e} = (P_r + d - C_m - C_r)\lambda - \mu e = 0$, the optimal emission reduction effort of drug manufacturers is:

$$e_z^* = (P_r + d - C_m - C_r)\lambda/\mu \quad (2)$$

Calculating the second-order partial derivative of d by formula (1), we obtain $\frac{\partial^2 \Pi z}{\partial^2 d} = -2\omega(1 - \xi) < 0$. It proves Π_z is a strictly concave function of d. When $\frac{\partial \Pi z}{\partial d} = a + \lambda e + (C_m + C_r - P_r - 2d)\omega(1 - \xi) = 0$, the optimal product price added by the drug manufacturers as:

$$d_z^* = \frac{Cm + Cr - Pr}{2} + \frac{a + \lambda e}{2\omega(1 - \xi)} \quad (3)$$

By substituting formula (3) into the previously set total medicine demand Q, the optimal medicine order quantity under the cooperative decision-making mode can be obtained:

$$Q_z^* = \frac{a + \lambda e}{2} - \frac{\omega(1 - \xi)(Cm + Cr - Pr)}{2} \quad (4)$$

Substituting formula (3) and (4) into formula (1) can obtain the optimal profit of the pharmaceutical supply chain under the cooperative decision-making mode:

$$\Pi_z^* = \frac{(a + \lambda e + (Pr - Cm - Cr)\omega(1 - \xi))^2}{4\omega(1 - \xi)} - \frac{\mu e^2}{2} \quad (5)$$

3.2 Decentralized decision model

Under the decentralized decision-making model, all members of the pharmaceutical supply chain aim to maximize their own interests. The drug distributors do not participate in the cost sharing contract, and the drug manufacturers need to bear the cost of improving emission reduction technology separately, so $\xi = 0$. It is assumed that the drug manufacturer is an oligopoly enterprise, it is the “leader” of the pharmaceutical supply chain because it can master the priority pricing power and the pharmaceutical supply volume. Besides, the drug distributor is the “follower” of the pharmaceutical supply chain because it cannot take the initiative and its strength is relatively weak. This assumption conforms to the Stackelberg model and can be solved by reverse derivation.

The expected profit of the drug distributors is:

$$\Pi_L = (P_r + d - P_m - C_r)(a + \lambda e - \omega d(1-\xi)) - \xi\mu e^2/2 \quad (6)$$

In order to pursue the maximum profit, the cost sharing ratio ξ is 0, that is

$$\Pi_{L1} = (P_r + d - P_m - C_r)(a + \lambda e - \omega d) \quad (7)$$

The expected profit of the drug manufacturers:

$$\Pi_s = (P_m - C_m)(a + \lambda e - \omega d(1-\xi)) - \mu e^2/2(1-\xi) \quad (8)$$

Since the drug distributors do not participate in cost sharing, the actual expected profit of the drug manufacturers is:

$$\Pi_{s1} = (P_m - C_m)(a + \lambda e - \omega d) - \mu e^2/2 \quad (9)$$

Under the decentralized decision-making model, the overall profit of the pharmaceutical supply chain is:

$$\Pi_f = \Pi_{L1} + \Pi_{s1} \quad (10)$$

Calculating the second-order partial derivative of d by formula (7) , we can get $\frac{\partial \Pi^2_{L1}}{\partial^2 d} = -2\omega < 0$. It proves Π_{L1} is a strictly concave function of d. When $\frac{\partial \Pi_{L1}}{\partial d} = \omega(P_m + C_r - P_r - d) + a + \lambda e = 0$, the optimal growth product pricing under decentralized decision-making mode can be obtained as:

$$d_f^* = \frac{\omega(Pm + Cr - Pr) + a + \lambda e}{2\omega} \quad (11)$$

By substituting formula (11) into the previously set total medicine demand Q, the quantity of optimal medicine order under the decentralized decision-making mode can be obtained:

$$Q_f^* = \frac{a + \lambda e - \omega(Pm + Cr - Pr)}{2} \quad (12)$$

Theorem 1:

A certain amount of investment in emission reduction technologies will increase the expected profits of drug manufacturers, but excessive investment in emission reduction technologies will reduce the expected profits. The total drug orders in the market and the expected profits of drug distributors will increase with the investment of emission reduction technology by drug manufacturers.

Certification:

It is easy to substitute formula (12) into formula (9):

$$\Pi_{s1} = (P_m - C_m)\frac{a + \lambda e - \omega(Pm + Cr - P)}{2} - \mu e^2/2 \quad (13)$$

Calculating the second-order partial derivative of e by equation (13), we can obtain $\frac{\partial^2 \Pi_{s1}}{\partial^2 e} = -\mu < 0$. It proves Π_{s1} is a strictly concave function of e, which has a maximum point. When $\frac{\partial \Pi_{s1}}{\partial e} = \lambda(P_m - C_m) - \mu e = 0$, the maximum value point can be obtained:

$$e_f^* = \frac{\lambda(Pm - Cm)}{\mu} \quad (14)$$

Calculating the partial derivative of e by equation (12), we can obtain $\frac{\partial Q_f^*}{\partial e} = \lambda > 0$. It proves Q is a monotonically increasing function of e.

Calculating the partial derivative of e by equation (7), we can obtain $\frac{\partial \Pi_{L1}}{e} = \lambda(P_r + d - P_m - C_r)$. According to hypothesis (5) $P_r > P_m + C_r$, it is easy to get $P_r + d > P_m + C_r$, that is, $P_r + d - P_m - C_r > 0$. Therefore, Π_{L1} is a monotonically increasing function of e. According to the above analysis, it can be inferred that the expected profit of drug manufacturers increases with the increase of research and discovery capability of emission reduction technology (e) and it reaches a maximum value when $e = e_f^*$. Later, the expected profit of drug manufacturers decreases because the cost of input of emission reduction technology capability is greater than the generated profit. The total pharmaceutical orders and the expected profits of drug distributors will increase with the improvement of research and discovery capacity of emission reduction technology.

Theorem 2:

When all members of the pharmaceutical supply chain do not participate in the cost sharing contract, the decision variables under the cooperative decision model are better than those under the decentralized decision model, that is $Q_{z1}^* > Q_f^*$, $d_{z1}^* < d_f^*$, and $\Pi_{z1}^* > \Pi_f^*$, $e_z^* > e_f^*$.

Certification:

When the drug distributors do not participate in the cost sharing contract, the optimal decision variables under the cooperative decision-making mode are the following.

Referring to formula (2), the optimal emission reduction effort e^* under the cooperative decision model is not affected by the cost sharing contract, so it does not change.

d^* from formula (3) has been changed into the following.

$$d_{z1}^* = \frac{Cm + Cr - Pr}{2} + \frac{a + \lambda e}{2\omega} \quad (15)$$

Q_z^* from formula (4) has been changed into the following.

$$Q_{z1}^* = \frac{a + \lambda e}{2} - \frac{\omega(Cm + Cr - Pr)}{2} \quad (16)$$

Π_z^* from formula (5) has been changed into the following.

$$\Pi_{z1}^* = \frac{(a + \lambda e + (Pr - Cm - Cr)\omega)^2}{4\omega} - \frac{\mu e^2}{2} \quad (17)$$

Because the drug manufacturers in the decentralized decision-making model do not participate in any cost sharing contract, which has no impact on the decentralized decision-making model, all parameters remain unchanged.

Comparison of optimal unit growth product pricing under two decision models by difference method is made.

$$d_{z1}^* - d_f^* = \frac{Cm - Pm}{2} \quad (18)$$

According to hypothesis (5), it can be seen that equation (18) is less than 0, that is, the pricing of products added by the optimal unit in the decentralized decision model is greater than that of products added by the optimal unit in the cooperative decision model.

Similarly, the total demand can be proved.

$$Q_{z1}^* - Q_f^* = \frac{\omega(Pm - Cm)}{2} \quad (19)$$

According to hypothesis (5), it can be seen that equation (19) is greater than 0, that is, the optimal total medical demand under the cooperative decision model is greater than the optimal total medical demand under the decentralized decision model.

Similarly, it can be proved that the effort of emission reduction technology is:

$$e_z^* - e_f^* = \frac{\lambda(Pr + d - Cr - Pm)}{\mu} \quad (20)$$

According to hypothesis (5), it can be seen that equation (20) is greater than 0, that is, the technology effort of optimal emission reduction under the cooperative decision model is greater than that under the decentralized decision model.

By substituting equation (11) (12) (14) into equation (7) (9), the optimal profit of each member of the pharmaceutical supply chain under the decentralized decision-making model is:

$$\Pi_{L1}^* = \frac{(\omega(Pr - Pm - Cr) + a + \lambda e_f^*)^2}{4\omega} \quad (21)$$

$$\Pi_{s1}^* = (P_m - C_m)\frac{a + \lambda e_f^* - \omega(Pm + Cr - Pr)}{2} - \frac{\mu e_f^{*2}}{2} \quad (22)$$

Substituting equation (21) (22) into equation (10), we can obtain the optimal total profit of the pharmaceutical supply chain under the decentralized decision model:

$$\Pi_f^* = \frac{(\omega(Pr - Pm - Cr) + a + \lambda e_f^*)^2}{4\omega} + (P_m - C_m)\frac{a + \lambda e_f^* - \omega(Pm + Cr - Pr)}{2} - \frac{\mu e_f^{*2}}{2} \quad (23)$$

Comparison of total profit under two decision models by difference method is made.

$$\Pi_{z1}^* - \Pi_f^* = \frac{(a + \lambda e)(Cm - Cr)}{2} + \frac{\omega(Pm - Cm)^2}{2} \quad (24)$$

According to hypothesis (5), it can be seen that equation (24) is greater than 0, that is, without considering the cost sharing contract, the total profit under the cooperative decision-making model of the pharmaceutical supply chain is greater than that under the decentralized decision-making model.

Theorem 3:

Although the cost sharing contract can optimize the relevant parameters of the cooperative decision-making model to a certain extent, which can reduce the optimal unit, increase product pricing, increase the optimal total medical demand and the optimal total expected profit, it does not change the parameters of the decentralized decision-making model. It increases the gap between cooperative decision model and decentralized decision model. Besides, it does not substantially coordinate the pharmaceutical supply chain.

Certification:

If we make equation (3) smaller than equation (11), we can obtain the following formula.

$$\frac{Cm+Cr-\Pr}{2}+\frac{a+\lambda e}{2\omega(1-\xi)}<\frac{\omega(Pm+Cr-Pr)+a+\lambda e}{2\omega}$$

$$\xi>\frac{\omega(Pm-Cm)}{a+\lambda e+\omega(Pm-Cm)} \tag{25}$$

When current cost allocation proportion ξ is greater than the above parameters, $d_z^* < d_f^*$.

If we make equation (4) greater than equation (12), we can obtain the following formula.

$$\frac{a+\lambda e}{2}-\frac{\omega(1-\xi)(Cm+Cr-Pr)}{2}>\frac{a+\lambda e-\omega(Pm+Cr-Pr)}{2}$$

$$\xi<\frac{Pm-Cm}{Pr-Cm-Cr} \tag{26}$$

When current cost allocation proportion ξ is greater than the above parameters, $Q_z^* > Q_f^*$.

If we make equation (5) greater than equation (23), we can obtain the following formula.

$\Pi_z^* > \Pi_f^*$;

$$\xi<\frac{-b+\sqrt{b^2-8\omega^2(Pr-Cm-Cr)^2(Pm^2+Cm^2-2CmPr)}}{2\omega^2(Pr-Cm-Cr)^2} \tag{27}$$

$$b=\omega^2(-P_r^2-C_r^2-2C_m^2-P_m^2-3C_mC_r+2C_rP_r+4C_mP_r)+(a+\lambda e)^2$$

When current cost allocation proportion ξ is less than the above parameters. $\Pi_z^* > \Pi_f^*$.

Referring to equation (11), (12), (23) at the same time, it can be seen that the cost allocation contract cannot optimize the parameters under the decentralized decision contract.

3.3 Cost allocation and quantity discount combined contract coordination model

According to Theorem 3, the cost sharing contract cannot effectively coordinate the pharmaceutical supply chain, and the double marginal effect still exists in the decentralized decision-making model. Therefore, the quantity discount contract is introduced on the basis of the cost sharing contract to reduce the double marginal effect and achieve the purpose of coordinating the pharmaceutical supply chain.

When the drug manufacturers are willing to take part in the quantity discount contract, the contract parameters are δ. Because drug manufacturers participate in the quantity discount contract, drug distributors are willing to participate in the cost sharing contract under the decentralized decision-making model.

Expected profits of drug distributors:

$$\Pi_L=(P_r+d+\delta(a+\lambda e-\omega d(1-\xi))-P_m-C_r)(a+\lambda e-\omega d(1-\xi))-\xi\mu e^2/2 \tag{28}$$

Expected profits of drug manufacturers:

$$\Pi_s=(P_m-C_m-\delta(a+\lambda e-\omega d(1-\xi)))(a+\lambda e-\omega d(1-\xi))-\frac{(1-\xi)\mu e^2}{2} \tag{29}$$

Calculating the second-order partial derivative of d by formula (28), so $= 2\omega^2\delta(1-\xi) - 2\omega(1-\xi) < 0$, which proves Π_L is a strictly concave function of d. When $= (a+\lambda e) - 2\omega d(1-\xi) - (a+\lambda e)\omega\delta(1-\xi) + 2\omega^2\delta d(1-\xi)^2 - \omega(1-\xi)(P_r - P_m - C_r) = 0$, the optimal growth product pricing under the combined contract decision model can be obtained as:

$$d_q^*=\frac{\delta(a+\lambda e)+Pr-Pm-Cr}{2(\omega\delta-1)}-\frac{a+\lambda e}{2\omega(1-\xi)(\omega\delta-1)} \tag{30}$$

Substituting equation (30) into the set total medical demand, the optimal total medical demand under the combined contract decision model is:

$$Q_q^*=\frac{a+\lambda e+2(a+\lambda e)(\omega\delta-1)-\omega(1-\xi)(\delta(a+\lambda e)+Pr-Pm-Cr)}{2(\omega\delta-1)} \tag{31}$$

Calculating the second-order partial derivative of e by formula (29), then $\frac{\partial^2\Pi_s}{\partial^2 e} = -\delta\lambda^2 - (1-\xi)\mu < 0$, which proves that Π_{s1} is a strictly concave function of e, and it has a maximum point. When $\frac{\partial\Pi_s}{\partial e} = \lambda(P_m - C_m - 2\delta(a-\omega d)(1-\xi)) - (1-\xi)\mu e - 2\lambda^2 e = 0$, the optimal effort degree of emission reduction technology under the combined contract decision model can be obtained:

$$e_q^*=\frac{\lambda(Pm-Cm-2\delta(a-\omega d(1-\xi))}{2\lambda^2+(1-\xi)\mu} \tag{32}$$

Substitute equation (30) (31) (32) into equation (28) and (29), the optimal profit of each member of the pharmaceutical supply chain under the combined contract decision model is:

$$\Pi_{Lq}^*=(P_r+\frac{\delta(a+\lambda e)+\Pr-Pm-Cr}{2(\omega\delta-1)}-\frac{a+\lambda e}{2\omega(1-\xi)(\omega\delta-1)}+\delta\frac{a+\lambda e+2(a+\lambda e)(\omega\delta-1)-\omega(1-\xi)(\delta(a+\lambda e)+Pr-Pm-Cr)}{2(\omega\delta-1)}-P_m-C_r)\frac{a+\lambda e+2(a+\lambda e)(\omega\delta-1)-\omega(1-\xi)(\delta(a+\lambda e)+Pr-Pm-Cr)}{2(\omega\delta-1)}-\xi\mu e^2/2 \tag{33}$$

$$\Pi_{sq}{*}=\left(P_m-C_m-\frac{a+\lambda e+2(a+\lambda e)(\omega\delta-1)-\omega(1-\xi)(\delta(a+\lambda e)+Pr-Pm-Cr)}{2(\omega\delta-1)}\right)\frac{a+\lambda e+2(a+\lambda e)(\omega\delta-1)-\omega(1-\xi)(\delta(a+\lambda e)+Pr-Pm-Cr)}{2(\omega\delta-1)}-\frac{(1-\xi)\mu e^2}{2} \quad (34)$$

Then, the optimal total profit of the pharmaceutical supply chain under the combined contract decision model is:

$$\Pi_q{*}=\Pi_{Lq}{*}+\Pi_{sq}{*} \quad (35)$$

Theorem 4:

The quantity discount ratio δ and cost allocation ratio ξ makes the optimal total expected profit under the combined contract decision model equal to that under the cooperative decision model.

Certification:

Referring to the research methods of Zhang, et al. [4], when the parameters $e_z{*}=e_q{*}$, we can obtain the following formula:

$$\delta=\frac{(Pm-Cm)}{2(a-\omega d(1-\xi))}-\frac{(2\lambda^2+(1-\xi)\mu)(Pr+d-Cm-Cr)}{2(a-\omega d(1-\xi))\mu} \quad (36)$$

When parameters $d_z{*}=d_q{*}$, we can obtain the following formula:

$$\xi=\frac{Pr-Pm-Cr+(Pr-Cm-Cr)(\omega\delta-1)}{\delta(a+\lambda e)+Pr-Pm-Cr+(Pr-Cm-Cr)(\omega\delta-1)} \quad (37)$$

When quantity discount proportion δ and cost allocation proportion ξ are the above parameters, $\Pi_z{*}=\Pi_q{*}$.

Theorem 5:

Under the premise of considering the cost allocation contract, the introduction of quantity discount contract can effectively change the situation that the cost allocation contract in Theorem 3 cannot effectively coordinate the pharmaceutical supply chain. Besides, it can make each member of the supply chain achieve Pareto improvement.

Certification:

When formula (33) > formula (21), we can obtain:

$$\Pi_{Lq}{*}>\Pi_{L1}{*} \quad (38)$$

When formula (34) > formula (22), we can obtain:

$$\Pi_{sq}{*}>\Pi_{s1}{*} \quad (39)$$

When we put equations (38) and (39) together, we can obtain:

$$\xi>1-\frac{(a+2ac)(\delta a+b+2bc+\delta a+\delta^2c)+a(\delta a+b)+\mu e^2c-(\omega b+a)^2c/2\omega}{a(a+2ac)+\delta\omega^2(\delta a+b)^2+2\delta\omega(\delta a+b)(a+2ac)+\omega(\delta a+b)(2b+\delta a+b)+\mu e^2c} \quad (40)$$

$$\xi<\frac{(Pm-Cm)\left(ac+4ac^2+\omega bc\right)-\mu e^2c}{\omega^2\delta(\delta a+b)^2+(\delta+1)\omega\delta(a+2ac)(\delta a+b)-2c\omega(Pm-Cm)(\delta a+b)-\mu e^2c} \quad (41)$$

$a=(a+\lambda e)$, $b=(P_r-P_m-C_r)$, $c=(\omega\delta-1)$

When we add formula (38) to formula (39), we can get $\Pi_q{*}>\Pi_f{*}$. It means when ξ is within the above range, the optimal total expected profit under the combined contract model is greater than that under the decentralized contract model, which reduces the double marginal effect and effectively coordinates the pharmaceutical supply chain. With the continuous optimization of cost sharing ratio and quantity discount ratio, it is bound to increase the expected profits of drug manufacturers and drug distributors, realizing the Pareto improvement of pharmaceutical supply chain members.

4 Empirical analysis and simulation

Based on the market sales of a drug, the following parameters are assumed according to the specific situation: the unit product price of the drug manufacturers (p_m) is 10, the unit product price of the drug distributors (p_r) is 14, the unit product cost of the drug manufacturers (C_m) is 4, the unit product cost of the drug distributors (C_r) is 3, the basic market demand (a) is 100, and the elasticity index of the demand to the unit product price (ω) is 1.5, sensitivity of demand to emission reduction technology capacity (λ) is 3.5, the unit product price increased by drug distributors (d) is 10, and the emission reduction cost of drug manufacturing enterprises (μ) is 8. According to the relevant parameters, the analysis results of the example are as follows.

In order to verify theorem 1, sensitivity analysis of e is carried out under the decentralized decision-making model, and the results are shown in Fig. 2 and Fig. 3.

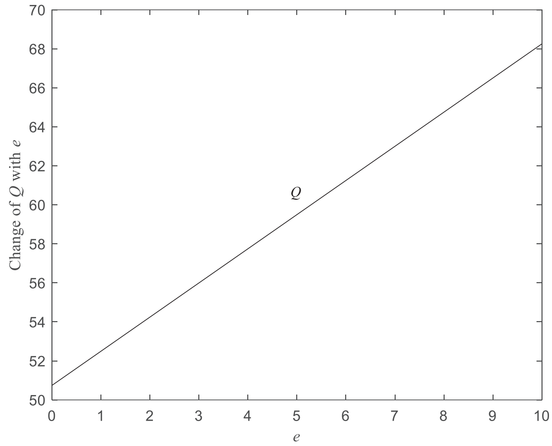

Fig. 2 Impact of *e* on total pharmaceutical demand in the market

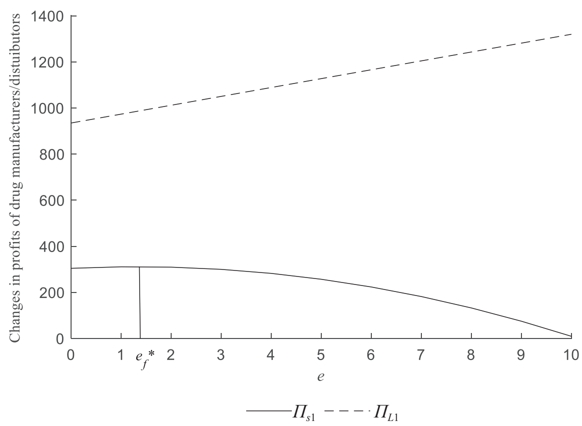

Fig. 3 Impact of *e* on profits of drug manufacturers distributors

It can be seen from Fig. 2 that the total drug order quantity Q in the market increases with the increase of efforts e of drug manufacturers to improve emission reduction technology, and there is no decreasing trend. It can be seen from Fig. 3 that the expected profit of drug distributors Π_{L1} increases with the increase of e, which has no decreasing trend. Meanwhile, drug manufacturers expect profits Π_{s1} first increases with the increase of e, and reaches the maximum value at e_f*, but when it is greater than e_f*, its expected profit decreases with the increase of e. So, Theorem 1 holds.

In order to verify theorem 2, the parameters are substituted into the calculation results, and the results are shown in Table 1.

Table 1 Difference results of variables under different decision models

Variables	$d_f^* - d_{z1}^*$	$Q_{z1}^* - Q_f^*$	$e_z^* - e_f^*$	$\Pi_{z1}^* - \Pi_f^*$
Difference calculation result	3	4.5	4.8	81.6

It can be seen from Table 1 that the difference calculation results are greater than 0, that is, the decision variables under the cooperative decision model are better than those under the decentralized decision model. So, theorem 2 holds.In order to verify Theorem 3, sensitivity analysis is performed on the . The results are shown in Fig. 4, 5 and 6.

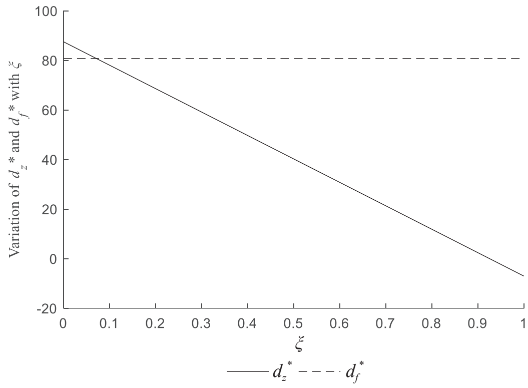

Fig. 4 Impact of on different decision models on increasing unit product pricing of drug distributors

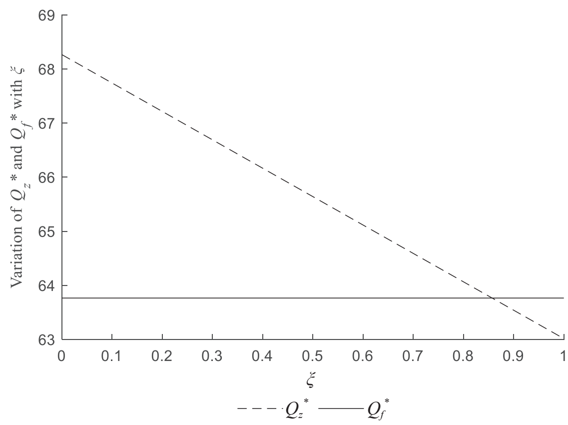

Fig. 5 Impact of on total medical demand under different decision models

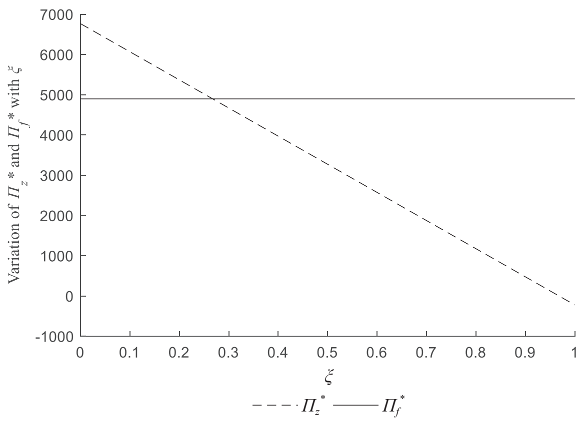

Fig. 6 Impact of on total expected profit of pharmaceutical supply chain under different decision models

It can be seen from Fig. 4 that the unit product pricing d_z* of drug distributors in the cooperative decision-making model decreases with the increase of ξ, while d_f* in the decentralized decision-making model does not change with the increase of ξ. It can be seen from Fig. 5 that the total medical demand Q_z* in the cooperative decision model increases with the decrease of ξ, while Q_f* in the decentralized decision model does not change with the decrease of . It can be seen from Fig. 6 that the total expected profit of the pharmaceutical supply chain under the cooperative decision model Π_z* increases with the decrease of ξ, while in the decentralized decision model Π_f* does not change with the decrease of ξ. So, Theorem 3 holds.

To verify theorem 4, the set parameters are taken into the formula to get the results, and the results are shown in Fig. 7.

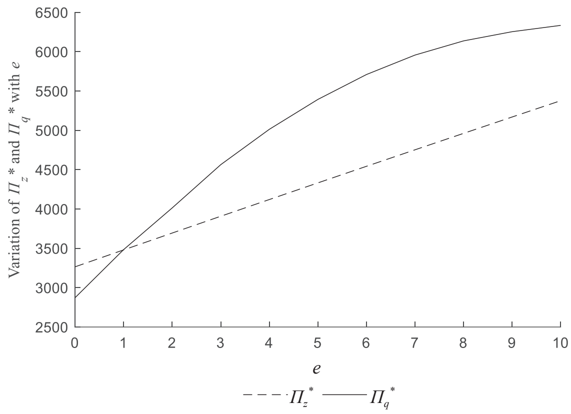

Fig. 7 Impact of *e* on the total expected profit of pharmaceutical supply chain under cooperative/combined contract decision model

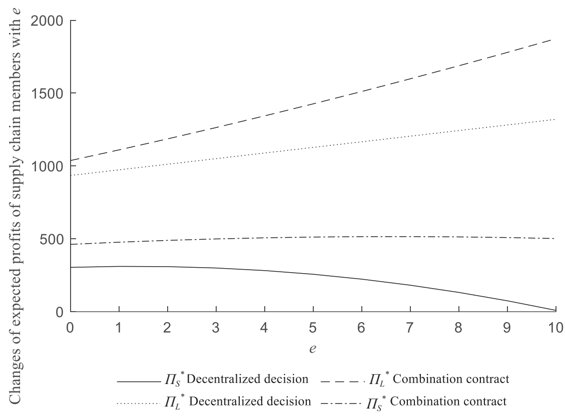

Fig. 8 Impact of e on the expected profit of supply chain members under decentralized/combined contract decision model

It can be seen from Fig. 8, with the continuous increase of *e*, the expected profits of each member of the supply chain under the combined contract decision model are greater than those under the decentralized decision model, and the slope of the profit function under the combined contract decision model is higher than that under the decentralized decision model. So, Theorem 5 holds.

5 Conclusion

This paper constructs a two-level pharmaceutical supply chain composed of a drug manufacturer and a drug distributor. The model takes into account the impact of drug manufacturers' participation in research and discovery of emission reduction technology on the expected profits of each member of the supply chain and the whole supply chain under the background of carbon quota trading policy. Then we discuss the possibility of drug distributors' participation in cost sharing of emission reduction technology. On the premise that the cost allocation contract cannot coordinate the model, the quantity discount contract is introduced. It is found that the combined contract decision model can perfectly coordinate the pharmaceutical supply chain and achieve the Pareto improvement of the supply chain members. Through research and analysis, this paper draws the following conclusions.

(1) Drug manufacturers' efforts to improve research of emission reduction technologies can attract more low-carbon preference patients to buy and use their drugs, which increases drug sales and enhances the expected profits of pharmaceutical supply chain members. Drug manufacturers should actively respond to the call of the government, establish a good corporate image of carbon emission reduction, increase efforts in research and development of carbon emission reduction technologies, which can contribute to China's carbon emission neutralization in 2060.

(2) The members of the secondary pharmaceutical supply chain can achieve the optimal expected profit and the lowest drug price when they reach cooperation. Compared with drug manufacturers, drug distributors are in a weak position. When drug manufacturers reduce drug supply, drug distributors can only maintain expected profits by increasing drug prices. If cooperation is reached, drug manufacturers can reduce part of the research costs of emission reduction technologies, while drug distributors can obtain sufficient supply, thus reducing drug prices.

(3) When the cost allocation contract and quantity discount contract meet the constraints, the combined contract decision model can effectively coordinate the pharmaceutical supply chain, reduce the "double marginal effect", and make the supply chain members achieve Pareto improvement. At the same time, when the drug distributors propose cost sharing, the drug manufacturers should also consider whether to give a certain quantity discount to the drugs. If the drug distributors only unilaterally execute the contract, the cooperation may be terminated at any time for the sake of vested interests. However, the drug manufacturers give a certain quantity discount contract, which can make the cooperation among the supply chain members more stable, and gradually achieve Pareto improvement, so as to achieve a win-win goal.

Through the research, we can learn that under the background of carbon quota trading policy, the drug manufacturers in the "leader" position play a decisive role in the emission reduction of the pharmaceutical supply chain. Therefore, the government should improve the initiative of pharmaceutical production enterprises in reducing emissions under the background of carbon quota trading policies, timely give corresponding incentives and subsidies, increase support for emission reduction of drug manufacturers, and implement the reward and punishment system to regulate the carbon emission behavior of drug manufacturers, which will finally achieve China's carbon neutrality goal in 2060. In addition, we innovatively introduce the cost allocation contract into the cooperative decision model and decentralized decision model and consider the possibility of supply chain members executing the cost allocation contract on the premise of ensuring the expected profit. However, this paper still has some shortcomings. Firstly, in most cases, multi-level agents are responsible for the transportation and sale of drugs in the pharmaceutical supply chain, but this paper does not consider this factor. Secondly, in general, there is no absolute drug monopoly. There are often multiple supply chains for a drug. However, this paper only discusses one supply chain. Therefore, several pharmaceutical supply chains should be discussed in the future research.

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