Pricing and Marketing Effort Decisions in Closed-Loop Supply Chains with Dual Recycling Channel

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Abstract: In order to study the effects of recycling competition on the optimal strategies. We investigate a closed-loop supply chain (CLSC) with dual recycling channel, where the retailer and the third-party recycler competitively collect used products at the same time. Base on game theory, we derive the optimal strategies for both the decentralized and the centralized channel scenarios. Subsequently, we analyze the relationship of the optimal strategies and the average recovery price and the recycling competition coefficient. We also find that: the optimal retail price is monotonically increasing in the recycling competition coefficient and the average recovery price. In contrast to that the marketing effort and collection rates of the retailer and the third-party are monotonically decreasing. This paper enriches the research results of the closed-loop supply chain (CLSC) with dual recycling channel.

1. Introduction

With the development of science and technology, recycling and remanufacturing of waste products has developed rapidly in the past 20 years, thus the closed-loop supply chain (CLSC) gets a lot of attention in the industry and academia [1-2].

At present, many research achievements have been made in the closed-loop supply chain. Savaskan et al. analyzed the optimal strategies under different recycling bodies [3]. Savaskan et al. then extended this model to a closed-loop supply chain with one manufacturer and two retailers [4]. Huang et al. builds a closed-loop supply chain with dual recycling channel [5]. The cooperative and non-cooperative games are discussed, which provides the basis for decision makers to choose recycling channels. Shi et al. addressed the optimal production and the pricing strategies in a CLSC with uncertain demand and return [6].

However, none of the above literatures takes into account the effect of retailers' marketing efforts on product market demand. In practice, the retailer and the third-party recycler often recycle competitively at the same time, therefore this paper investigate a closed-loop supply chain (CLSC) with dual recycling channel, where the retailer and the third-party recycler competitively collect used products at the same time. On the other hand, the retailer can increase the sales of products by enhancing brand reputation and participating in promotions and advertising campaigns. In order to study the effects of recycling competition on the optimal strategies, we investigate a CLSC consisting of a manufacturer, a retailer and a third-party recycler, where in the reverse supply chain the retailer and the third party compete for collecting used products.

Based on the above literatures, we construct a closed-loop supply chain (CLSC) model with dual recycling channel, where the retailer and the third-party recycler competitively collect used products at the same time. Subsequently, we derive the optimal strategies for both the decentralized and the centralized channel scenarios. Moreover, we analyze the relationship of the optimal strategies and the average recovery price and the recycling competition coefficient.

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2. Symbol Description and Model Assumptions

In this paper, we study a CLSC with a manufacturer, a retailer and a third-party recycler. In the forward supply chain, the manufacturer can either directly use raw materials with the unit cost of production c_m, or recycle used products with the unit cost of remanufacturing c_r to produce a new product and sell it to the retailer with a wholesale price w. Then the retailer makes profits by selling with a retail price p to consumers. While in the reverse supply chain, the retailer and the third-party recycler competitively collect used products at the same average recovery price A. The manufacturer collects used products from them with different transfer prices b_R and b_T. The market demand is a linear function of the retail price and marketing effort.

$$D=\phi-\beta p+re \tag{1}$$

where □ is the market size, □ is the price elasticity demand, r is used to measure the impact of marketing effort on demand. The total marketing effort cost of the retail is expressed as $\eta e^2/2$, where□ □ □is the marketing cost coefficient [7]. The used product collection rate□ □ is introduced to reflect the collection effort and signify the reverse channel performance. In this paper, the collection rates of the retailer and the third-party recycler can be simplified as follows: $\tau_R=\sqrt{(I_R-\alpha I_T)/C_L}$ and $\tau_T=\sqrt{(I_T-\alpha I_R)/C_L}$, where C_L is a scalar parameter, which is the coefficient of exchange between the collection rate and the investment. □ is the recycling competition coefficient between the retailer and the third-party recycler. I_R, I_T denotes the investment of the retailer and the third-party on recycling channel, respectively.

Assumptions in this paper are similar to those in the literature [8].

(1)New products and remanufactured products are homogeneous, and the information is symmetric.

(2)Without loss of generality, $\Delta\ge b_R>A>0$, $\Delta\ge b_T>A>0$, where $\Delta=c_m-c_r$ is the unit cost savings by remanufacturing a product.

(3) All strategies of the CLSC are considered in a single period.

(4) Agents of the CLSC are risk-neutral and the manufacturer is the market leader.

3. Decision Models

3.1 Centralized Model (C Model)

In the centralized model, the goal of all agents of CLSCs is to maximize system profits. The optimization model of the CLSC can be expressed as:

$$\max_{p,e,\tau_R,\tau_T}\ \pi_{SC}^{Cd}=\left(p-c_m+(\Delta-A)(\tau_R+\tau_T)\right)(\phi-\beta p+re)-\frac{\eta}{2}e^2-\frac{C_L\left(\tau_R^2+\tau_T^2\right)}{1-\alpha} \tag{2}$$

Lemma 1 If $\beta\eta-r^2>0$, $C_L\left(2\beta\eta-r^2\right)>\beta^2\eta(1-\alpha)(\Delta-A)^2+\beta\eta(1-\alpha)(\phi-\beta c_m)(\Delta-A)$, the profit function π_{SC}^{Cd} is strictly concave in p, e, τ_R and τ_T.

Simultaneous equations $\partial\pi_{SC}^{Cd}/\partial p=0$, $\partial\pi_{SC}^{Cd}/\partial e=0$, $\partial\pi_{SC}^{Cd}/\partial\tau_R=0$ and $\partial\pi_{SC}^{Cd}/\partial\tau_T=0$, we get Proposition 1.

Proposition 1 If $\beta\eta-r^2>0$, $C_L\left(2\beta\eta-r^2\right)>\beta^2\eta(1-\alpha)(\Delta-A)^2+\beta\eta(1-\alpha)(\phi-\beta c_m)(\Delta-A)$, in the centralized model, the optimal strategies are given by:

$$p^{Cd*}=\frac{C_L\left(\eta(\phi+\beta c_m)-r^2c_m\right)-\phi\eta\beta(1-\alpha)(\Delta-A)^2}{C_L\left(2\beta\eta-r^2\right)-\beta^2\eta(1-\alpha)(\Delta-A)^2},\ e^{Cd*}=\frac{C_Lr(\phi-\beta c_m)}{C_L\left(2\beta\eta-r^2\right)-\beta^2\eta(1-\alpha)(\Delta-A)^2},$$

$$\tau_R^{Cd*}=\frac{\beta\eta(1-\alpha)(\phi-\beta c_m)(\Delta-A)}{2C_L\left(2\beta\eta-r^2\right)-2\beta^2\eta(1-\alpha)(\Delta-A)^2},\ \tau_T^{Cd*}=\frac{\beta\eta(1-\alpha)(\phi-\beta c_m)(\Delta-A)}{2C_L\left(2\beta\eta-r^2\right)-2\beta^2\eta(1-\alpha)(\Delta-A)^2}.$$

Substituting p^{Cd*}, e^{Cd*}, τ_R^{Cd*} and τ_T^{Cd*} into equations (1) and (2), we obtain the market demand D^{Cd*} and π_{SC}^{Cd*}.

$$D^{Cd*} = \frac{C_L\beta\eta\left(\phi-\beta c_m\right)}{C_L\left(2\beta\eta-r^2\right)-\beta^2\eta\left(1-\alpha\right)\left(\Delta-A\right)^2},\ \pi_{SC}^{Cd*} = \frac{C_L\eta\left(\phi-\beta c_m\right)^2}{2C_L\left(2\beta\eta-r^2\right)-2\beta^2\eta\left(1-\alpha\right)\left(\Delta-A\right)^2}.$$

Corollary 1 The optimal retail price is monotonically increasing in α. In contrast to that the maximal profit of the CLSC, marketing effort, collection rates of the retailer and the third-party are monotonically decreasing in α.

Huang et al. (2013) derive the same result when the demand function assumes a simpler form of $D=\phi-\beta p$. Thus, this corollary confirms that our generalized demand function does not affect the trend of optimal strategies in α.

3.2 Decentralized Model (d Model)

In the decentralized model, all agents of the CLSC are independent decision makers. Each of them aims to maximize its own profit. According to the problem description and hypothesis, we can get the two followers' problems are given by

$$\max_{p,e,\tau_R}\ \pi_R^{Dd} = \left(p-w+\left(b_R-A\right)\tau_R\right)\left(\phi-\beta p+re\right)-\frac{\eta}{2}e^2-\frac{C_L\left(\alpha\tau_T^2+\tau_R^2\right)}{1-\alpha^2} \tag{3}$$

$$\max_{\tau_T}\ \pi_T^{Dd} = \left(b_T-A\right)\tau_T\left(\phi-\beta p+re\right)-\frac{C_L\left(\alpha\tau_R^2+\tau_T^2\right)}{1-\alpha^2} \tag{4}$$

Similar to centralized model, the Hessian matrix of π_R^{Dd} is

$$H\left(p,e,\tau_R\right)=\begin{bmatrix} -2\beta & r & -\beta\left(b_R-A\right) \\ r & -\eta & rb_R \\ -\beta\left(b_R-A\right) & rb_R & -\dfrac{2C_L}{1-\alpha^2} \end{bmatrix}$$

It is obvious that $\partial^2\pi_R^{Dd}/\partial p^2=-2\beta<0$. if $\beta\eta-r^2>0$, we have $\left|H_2\left(p,e,\tau_R\right)\right|=2\beta\eta-r^2>0$. Because $0\le\alpha<1$, if $2C_L\left(2\beta\eta-r^2\right)>\beta^2\eta\left(\Delta-A\right)^2$, thus $\left|H_3\left(p,e,\tau_R\right)\right|<-\left(2C_L\left(2\beta\eta-r^2\right)-\beta^2\eta\left(\Delta-A\right)^2\right)\Big/\left(1-\alpha^2\right)<0$.

Taking the second-order derivatives of π_T^{Dd} with respect to τ_T, we have $\partial^2\pi_T/\partial\tau_T^2=-2C_L\Big/\left(1-\alpha^2\right)<0$, thus, simultaneous equations $\partial\pi_R^{Dd}/\partial p=0$, $\partial\pi_R^{Dd}/\partial e=0$, $\partial\pi_R^{Dd}/\partial\tau_R=0$ and $\partial\pi_T^{Dd}/\partial\tau_T=0$, we have

$$p^{Dd*}\left(w,b_R,b_T\right)=\frac{2C_L\eta\left(\phi+\beta w\right)-2C_Lr^2w-\phi\beta\eta\left(1-\alpha^2\right)b_R^2}{2C_L\left(2\beta\eta-r^2\right)-\beta^2\eta\left(1-\alpha^2\right)b_R^2},$$

$$e^{Dd*}\left(w,b_R,b_T\right)=\frac{2C_Lr\left(\phi-\beta w\right)}{2C_L\left(2\beta\eta-r^2\right)-\beta^2\eta\left(1-\alpha^2\right)b_R^2},$$

$$\tau_R^{Dd*}\left(w,b_R,b_T\right)=\frac{\beta\eta\left(1-\alpha^2\right)\left(\phi-\beta w\right)b_R}{2C_L\left(2\beta\eta-r^2\right)-\beta^2\eta\left(1-\alpha^2\right)b_R^2},$$

$$\tau_T^{Dd*}\left(w,b_R,b_T\right)=\frac{\beta\eta\left(1-\alpha^2\right)\left(\phi-\beta w\right)b_T}{2C_L\left(2\beta\eta-r^2\right)-\beta^2\eta\left(1-\alpha^2\right)b_R^2}.$$

For a given p, e, τ_R and τ_T, the manufacturer's problem is given by

$$\max_{w,b_R,b_T}\ \pi_M^{Dd}=\left(w-c_m+\left(\Delta-b_R\right)\tau_R+\left(\Delta-b_T\right)\tau_T\right)\left(\phi-\beta p+re\right) \tag{5}$$

Substituting $p^{Dd*}\left(w,b_R,b_T\right)$, $e^{Dd*}\left(w,b_R,b_T\right)$, $\tau_R^{Dd*}\left(w,b_R,b_T\right)$ and $\tau_T^{Dd*}\left(w,b_R,b_T\right)$ into equations (5), we get

$$\max_{w,b_R,b_T}\ \pi_M^{Dd}=\left(w-c_m+\frac{\beta\eta\left(1-\alpha^2\right)\left(\phi-\beta w\right)Y}{X}\right)\frac{2C_L\beta\eta\left(\phi-\beta w\right)}{X}\tag{6}$$

where $X=2C_L\left(2\beta\eta-r^2\right)-\beta^2\eta\left(1-\alpha^2\right)b_R^2$, $Y=b_R\left(\Delta-b_R\right)+b_T\left(\Delta-b_T\right)$.

For a given b_R, the Hessian matrix of π_M^{Dd} is

$$H\left(w,b_T\right)=\begin{bmatrix}\dfrac{4C_L\beta^2\eta\left(\beta^2\eta\left(1-\alpha^2\right)Y-X\right)}{X^2} & \dfrac{-4C_L\beta^3\eta^2\left(1-\alpha^2\right)\left(\phi-\beta w\right)\left(\Delta+A-2b_T\right)}{X^2}\\ \dfrac{-4C_L\beta^3\eta^2\left(1-\alpha^2\right)\left(\phi-\beta w\right)\left(\Delta+A-2b_T\right)}{X^2} & \dfrac{-4C_L\beta^2\eta^2\left(1-\alpha^2\right)^2\left(\phi-\beta w\right)^2}{X^2}\end{bmatrix}$$

When $C_L\left(2\beta\eta-r^2\right)>\beta^2\eta\left(1-\alpha\right)\left(\Delta-A\right)^2+\beta\eta\left(1-\alpha\right)\left(\phi-\beta c_m\right)\left(\Delta-A\right)$ holds, because $0\le\alpha<1$, it is obvious that $\beta^2\eta\left(1-\alpha^2\right)Y-X<\left(3\beta^2\eta\left(1-\alpha^2\right)\left(\Delta-A\right)^2-4C_L\left(2\beta\eta-r^2\right)\right)\big/2<0$, then $\partial^2\pi_M^{Dd}/\partial w^2<0$, in addition, $X-\beta^2\eta\left(\left(1-\alpha^2\right)Y+\left(\Delta-2b_T\right)^2\right)>0$, thus $\left|H\left(w,b_T\right)\right|>0$, which means that the function π_M^{Dd} is strictly concave in w and b_T. Simultaneous equations $\partial\pi_M^{Dd}/\partial w=0$ and $\partial\pi_M^{Dd}/\partial b_T=0$, we get Proposition 2.

Proposition 2 If $\beta\eta-r^2>0$, $C_L\left(2\beta\eta-r^2\right)>\beta^2\eta\left(1-\alpha\right)\left(\Delta-A\right)^2+\beta\eta\left(1-\alpha\right)\left(\phi-\beta c_m\right)\left(\Delta-A\right)$, in the decentralized model, the optimal wholesale price w^{Dd*} and the transfer prices b_T^{Dd*} are given by

$$w^{Dd*}=\frac{4C_L\left(2\beta\eta-r^2\right)\left(\phi+\beta c_m\right)-\beta^2\eta\left(1-\alpha^2\right)\left(2\beta c_m\left(b_R-A\right)^2+\phi\left(\Delta^2+4\Delta b_R-6\Delta A-2b_R^2+3A^2\right)\right)}{8C_L\beta\left(2\beta\eta-r^2\right)-\beta^3\eta\left(1-\alpha^2\right)\left(\Delta-A\right)\left(\Delta+4b_R-5A\right)},$$

$$b_T^{Dd*}=\frac{\Delta+A}{2}.$$

Observation 1 Because the manufacturer's profit increases in b_R, thus, the optimal transfer price b_R should be set at $b_R^{Dd*}=\Delta$ in the decentralized model.

Substituting w^{Dd*}, b_R^{Dd*} and b_T^{Dd*} into $p^{Dd*}\left(w,b_R,b_T\right)$, $e^{Dd*}\left(w,b_R,b_T\right)$, $\tau_R^{Dd*}\left(w,b_R,b_T\right)$ and $\tau_T^{Dd*}\left(w,b_R,b_T\right)$, we get Proposition 3.

Proposition 3 If $\beta\eta-r^2>0$, $C_L\left(2\beta\eta-r^2\right)>\beta^2\eta\left(1-\alpha\right)\left(\Delta-A\right)^2+\beta\eta\left(1-\alpha\right)\left(\phi-\beta c_m\right)\left(\Delta-A\right)$, in the decentralized model, the optimal retail price, marketing effort, collection rates of the retailer and the third-party are given by

$$p^{Dd*}=\frac{4C_L\left(\phi\left(3\beta\eta-r^2\right)+\beta c_m\left(\beta\eta-r^2\right)\right)-5\phi\beta^2\eta\left(1-\alpha^2\right)\left(\Delta-A\right)^2}{8C_L\beta\left(2\beta\eta-r^2\right)-5\beta^3\eta\left(1-\alpha^2\right)\left(\Delta-A\right)^2},$$

$$e^{Dd*}=\frac{4C_Lr\left(\phi-\beta c_m\right)}{8C_L\left(2\beta\eta-r^2\right)-5\beta^2\eta\left(1-\alpha^2\right)\left(\Delta-A\right)^2},\quad \tau_R^{Dd*}=\frac{2\beta\eta\left(1-\alpha^2\right)\left(\phi-\beta c_m\right)\left(\Delta-A\right)}{8C_L\left(2\beta\eta-r^2\right)-5\beta^2\eta\left(1-\alpha^2\right)\left(\Delta-A\right)^2},$$

$$\tau_T^{Dd*}=\frac{\beta\eta\left(1-\alpha^2\right)\left(\phi-\beta c_m\right)\left(\Delta-A\right)}{8C_L\left(2\beta\eta-r^2\right)-5\beta^2\eta\left(1-\alpha^2\right)\left(\Delta-A\right)^2}.$$

Substituting w^{Dd*}, p^{Dd*}, e^{Dd*}, τ_R^{Dd*} and τ_T^{Dd*} into equations (1) and (3)-(5), we obtain the market demand D^{Dd*} and the profits of all the members. $D^{Dd*}=\frac{4C_L\beta\eta(\phi-\beta c_m)}{8C_L(2\beta\eta-r^2)-5\beta^2\eta(1-\alpha^2)(\Delta-A)^2}$,

$\pi_M^{Dd*}=\frac{2C_L\eta(\phi-\beta c_m)^2}{8C_L(2\beta\eta-r^2)-5\beta^2\eta(1-\alpha^2)(\Delta-A)^2}$, $\pi_R^{Dd*}=\frac{C_L\eta\left(8C_L(2\beta\eta-r^2)-\beta^2\eta(1-\alpha^2)(4+\alpha)(\Delta-A)^2\right)(\phi-\beta c_m)^2}{\left(8C_L(2\beta\eta-r^2)-5\beta^2\eta(1-\alpha^2)(\Delta-A)^2\right)^2}$,

$\pi_T^{Dd*}=\frac{C_L\beta^2\eta^2(1-4\alpha)(1-\alpha^2)(\phi-\beta c_m)^2(\Delta-A)^2}{\left(8C_L(2\beta\eta-r^2)-5\beta^2\eta(1-\alpha^2)(\Delta-A)^2\right)^2}$, $\pi_{SC}^{Dd*}=\frac{C_L\eta\left(24C_L(2\beta\eta-r^2)-\beta^2\eta(5\alpha+13)(1-\alpha^2)(\Delta-A)^2\right)(\phi-\beta c_m)^2}{\left(8C_L(2\beta\eta-r^2)-5\beta^2\eta(1-\alpha^2)(\Delta-A)^2\right)^2}$.

Observation 2 If $\alpha > 0.25$, the third-party recycler will give up recycling.

Proof Because the third-party recycler's profit is affected by *α*, it's obvious that, if $\alpha > 0.25$, $\pi_T^{Dd*} < 0$.

Similar to centralized model, from proposition 3 we derive corollary 2.

Corollary 2 The optimal retail price is monotonically increasing in *α*. In contrast to that the maximal profit of the manufacturer, marketing effort, collection rates of the retailer and the third-party are monotonically decreasing in *α*.

4. Strategies Comparison and Analysis

In this section, we compare our results between decentralized and the centralized model. Moreover, we analyze the relationship between the optimal strategies and the average recovery price. Based on the results summarized in proposition 1 and 3, some interesting observations can be found.

Proposition 4 (1) $p^{Cd*} < p^{Dd*}$, (2) $e^{Cd*} > e^{Dd*}$, (3) $\tau_R^{Cd*} > \tau_R^{Dd*}$, $\tau_T^{Cd*} > \tau_T^{Dd*}$.

Proposition 4 confirms that the centralized mode is better than decentralized mode and dual recycling channel. That's to say the retail price of centralized mode is lower that of decentralized mode, the marketing effort of centralized mode is higher that of decentralized mode, both of the retailer and the third-party recycler make more efforts to recycle used products.

Proposition 5 (1) $\partial p^{Cd*}/\partial A > 0$, $\partial p^{Dd*}/\partial A > 0$, (2) $\partial e^{Cd*}/\partial A < 0$, $\partial e^{Dd*}/\partial A < 0$, (3) $\partial\tau_R^{Cd*}/\partial A = \partial\tau_T^{Cd*}/\partial A < 0$, $\partial\tau_R^{Dd*}/\partial A < 0$, $\partial\tau_T^{Dd*}/\partial A < 0$.

Proposition 5 confirms that the optimal retail price is monotonically increasing with the average recovery price. In contrast to that the marketing effort, collection rates of the retailer and the third-party recycler are monotonically decreasing with the average recovery price in the centralized mode and the decentralized mode.

5. Numerical Simulation

Next, numerical studies are carried out to further verify the validity of the obtained results and better understand the obtained propositions. Let $\phi = 300$, $C_L = 3100$, $\beta = 2$, $r = 1$, $c_m = 50$, $\Delta = 35$, $\eta = 10$, $\alpha \in [0, 0.99]$, $A \in [0, 10]$, Figures 1–4 validate Proposition 4-5 and Corollary 1-2.

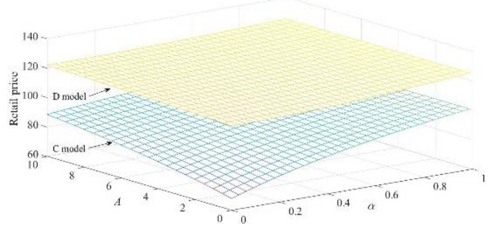

Figure 1 The relationship of retail price and the recovery price and the competition coefficient

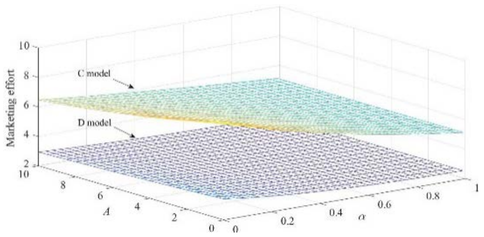

Figure 2 The relationship of marketing effort and the recovery price and the competition coefficient

Figure 1 shows that the optimal retail price of centralized mode is lower that of decentralized mode and the optimal price is monotonically increasing in the recycling competition coefficient α or the average recovery price A. Furthermore, the gap is narrowing along as α or A increases between centralized mode and decentralized mode. Figure 2 shows that the optimal marketing effort of centralized mode is higher that of decentralized mode and the optimal marketing effort is strictly decreasing in the recycling competition coefficient α or the average recovery price A. Furthermore, the gap is also narrowing along as α or A increases between centralized mode and decentralized mode. Figure 3-4 show that the collection rates of the retailer and the third-party in the centralized mode and decentralized mode, respectively. It's obvious that collection rates of the retailer and the third-party are strictly decreasing in the recycling competition coefficient α or the average recovery price A. When $\alpha > 0.8$, the collection rate of the retailer is almost the same between centralized mode and decentralized mode. When $\alpha > 0.9$, the collection rate of the third-party is also almost the same between centralized mode and decentralized mode. Figure 3-4 also demonstrate that, the recycling competition coefficient is more sensitive to the collection rate than the average recovery price.

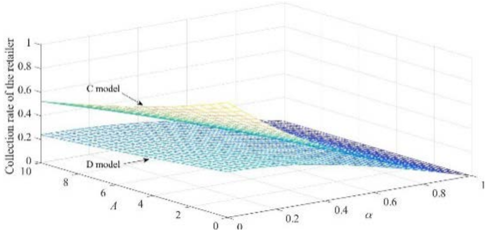

Figure 3 The relationship of the collection rate of the retail and the recovery price and the competition coefficient

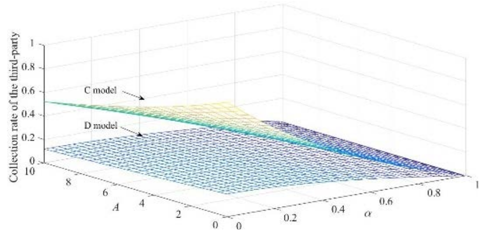

Figure 4 The relationship of the collection rate of the third-party and the recovery price and the competition coefficient

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