To study game coordination mechanism for closed-loop supply chain in rural e-commerce

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Abstract. Focusing on problems such as resource waste, environmental pollution and reverse logistics difficulties, this study established a game model consisting of product manufacturers, rural e-commerce, consumers and government for closed-loop supply chain in rural e-commerce, analysed equilibrium strategies selection and stability of closed-loop supply chain under government’s reward and punishment strategies. The analytical results indicated that government’s reward and punishment strategies for enterprises were important factors affecting enterprise decision-making, and can effectively guide closed-loop supply chain to improve efficiency of reverse logistics utilization, increase recycling price of rural e-commerce, and improve total social welfare goal.

1. Introduction
With rapid development of Internet, rural e-commerce has become a new engine for rural economic development. But bottlenecks such as weak rural e-commerce circulation system and poor reverse logistics have restricted e-commerce into village. Therefore, we should fully consider unique conditions of rural area economy, put forward a suitable model for closed-loop supply chain in rural e-commerce, and achieve synergy of rural e-commerce and rural logistics. For rural supply chain, foreign researches mostly focus on rural logistics infrastructure construction, last mile cost, enterprise performance evaluation [1-3]. At present, researches on e-commerce logistics focus on e-commerce logistics transaction costs, logistics network planning, customer loyalty [4-5]. Few lucubrates complex relationships among various stakeholders in rural e-commerce products supply chain. This study clarified game behaviour and action strategies of stakeholders, built an evolution model consisting of product manufacturers, rural e-commerce, consumers and government based on dynamic game, analysed evolution of cooperative relationship and realization conditions of Nash equilibrium, and revealed relationship evolution mechanism for closed-loop supply chain in rural e-commerce.

2. Problems description and hypotheses
This study established a closed-loop supply chain model in rural e-commerce including different stakeholders, see Figure 1. Game subjects of the model are bounded rationality and take own-interests maximization as their own ultimate goals. The government’s interest is mainly reflected in how to improve social welfare, and encourage rural e-commerce enterprises to develop reverse logistics. For rural e-commerce enterprises, construction of closed-loop supply chain requires enormous investment...
of labour, resource and money. High investment and uncertainty return bring constraints. Customers as the end point of forward logistics and the starting point of reverse logistics need to pay environmental pollution costs. Therefore, government rewards and penalizes participation of dangerous goods manufacturers and customers in reverse logistics.

Figure 1. The model for closed-loop supply chain in rural e-commerce.

The hypotheses are as follows:

1) Product manufacturers and distribution enterprises are rational-economic man; they make decisions based on their own interests.

2) \( \theta \) represents product recovery rate.

3) Assuming product demand \( Q = a - bp \), \( a \) represents total market demand, \( b \) represents market demand price sensitivity coefficient, and \( p \) represents product sales price.

4) The product recycling return rate \( \varepsilon \) represents customer’s recycling willingness, which is affected by recovery price \( p_t \), and obeys uniform distribution. \( p_{\text{max}} \) represents customers’ expected recycling price. \( p_t < 0 \) represents that rural e-commerce pays cost to customer; \( p_t = 0 \) represents that rural e-commerce does not pay cost to customer; \( p_t < 0 \) represents that customer bears reverse logistics cost, and pays cost to rural e-commerce.

\[
\varepsilon = \begin{cases} 
0 & p_t \leq 0 \\
\frac{p_t}{p_{\text{max}}} & 0 < p_t < p_{\text{max}} \\
1 & p_t \geq p_{\text{max}}
\end{cases}
\] (1)

5) \( c_0 \) represents manufacturers’ unit production cost; \( c_1 \) represents unit cost of recycled products through reverse logistics that can be reused; \( c'_1 \) represents unit cost but not reusable.

6) \( c_2 \) represents unit sales cost of rural e-commerce. For reverse logistics, rural e-commerce needs to transfer products to manufacturers, \( c_2 \) represents unit operating cost of rural e-commerce, and \( 0 < c_2 < c_1 \).

7) Assuming that the government will implement dynamic incentives; parameter of government’s reward and punishment are represented by \( g \), \( 0 \leq g \leq 1 \). \( \alpha \) represents minimum reprocessing rate that product manufacturers should achieve; \( \beta \) represents minimum customer return rate.

Other parameters are follows:

- \( \pi_m \): Profits of product manufacturers.
- \( \Pi_{r} \): Profits of rural e-commerce.
- \( \sigma \): Product wholesale price of manufacturers.
- \( \varepsilon \): Recycling rate of products.
- \( \lambda \): Customers’ expected value for new products.
- \( F(\varepsilon) \): Customer utility function.
$\Pi$: Consumer surplus.
$Y$: Environmental benefits of marginal environment generated by product reverse logistics.
$N$: Pollution benefits of marginal environment generated by reverse logistics when products fail to be recycled.
$\pi_e$: Environment effects.
$\pi_g$: Government’s interests from participating in closed-loop supply chain.
$SW$: Total social welfare.

3. Model construction and solution

3.1. Model construction

Considering government’s dynamic reward and punishment strategies, producer profits formula of rural e-commerce closed-loop supply chain is as follows:

$$\pi_n = (\sigma - c_o)Q + (c_o - c_i)Qe - c_i Q(1-\epsilon) - Q\tilde{p}_m + (\epsilon - \alpha)Q\sigma g$$

(2)

In the formula (2), \((\sigma - c_o)Q\) represents wholesale profits of product manufacturers; \((c_o - c_i)Qe\) represents cost reduction of product reuse in reverse logistics; \(c_i Q(1-\epsilon)\) represents processing cost of recycled product; \(Q\tilde{p}_m\) represents cost paid by product manufacturers to rural e-commerce; \((\epsilon - \alpha)Q\sigma g\) represents government’s reward and punishment amount for product manufacturers. The profits formula of rural e-commerce is:

$$\pi_L = (p - \sigma - c_i)Q + (p_m - p_i - c_s)Q\tilde{p}$$

(3)

In the formula (3), \((p - \sigma - c_i)Q\) represents sales profits of rural e-commerce; \((p_m - p_i - c_s)Q\tilde{p}\) represents profits of rural e-commerce in reverse logistics. The consumer utility formula is:

$$F(\tilde{p}) = \lambda - p + p_i \tilde{p} + (\tilde{p} - \beta)gp$$

(4)

In the formula (4), \((\lambda - p)\) represents the excess when customer’s expected price exceeds sales price; \(p_i \tilde{p}\) represents customer’s revenue from reverse logistics; \((\tilde{p} - \beta)gp\) represents government’s reward and punishment amount to customer. Consumer surplus represents the difference between consumer’s revenue and actual cost in reverse logistics. The consumer residual formula is:

$$\Pi = \int \int F(\tilde{p})d\tilde{p} = (\lambda - p)Q + \frac{1}{2} p_i Q + (\frac{1}{2} - \beta)gp Q$$

(5)

In the formula (5), \((\lambda - p)Q\) represents total difference between expected price and selling price when all customers purchase product; \(\frac{1}{2} p_i Q\) represents total income of all customers participating in reverse logistics; \((\frac{1}{2} - \beta)gp Q\) represents total amount of government rewards and punishments for customers.

The formula of environmental benefits is:

$$\pi_e = Q e Y - (1 - \epsilon)QN$$

(6)

In the formula (6), \(Q e Y\) represents environmental benefits of reverse logistics in closed-loop supply chain; \((1 - \epsilon)QN\) represents pollution benefits. The formula of government’s interests is:

$$\pi_g = (\alpha - \epsilon)g + (\beta - \frac{1}{2})gp Q$$

(7)

In the formula (7), \((\alpha - \epsilon)g\) represents environmental benefits of reverse logistics; \((\beta - \frac{1}{2})gp Q\) represents total amount of government rewards and punishments for customers. Total social welfare is benefits of all stakeholders, see formula (8).
\[ SW = \pi_m + \pi_L + \Pi + \pi_e + \pi_g \] (8)

### 3.2. Model solution

The formula (2) and formula (3) form Stackelberg game model. Manufacturers as the leader of Stackelberg game, decide price paid to rural e-commerce; rural e-commerce as Stackelberg game followers, set product prices according to manufacturer’s strategies to maximize their own profits. The model is solved by inverse induction method. Firstly, the formula (2) is derived.

\[
d\pi_L/d\pi = (p_m - 2p_1 - c_1)\alpha - (a - bp)/p_{max} \tag{9}
\]

\[
d^2\pi_L/d\pi^2 = -(a - bp)/p_{max} \tag{10}
\]

\[(a - bp) > 0, \quad p_{max} > 0, \quad d^2\pi_L/d\pi^2 < 0, \quad \text{the rural e-commerce income formula has a largest value.}\]

When \(d\pi_L/d\pi = 0\), it can be obtained:

\[ p_1^* = (p_m - c_1)/2 \tag{11}\]

The formula (2) is derived by inverse induction method.

\[
d\pi_m/d\pi = (a - bp)[(c_0 - c_1 + c_1' + \sigma g)\varepsilon + c_3 - c_1]/2p_{max} \tag{12}
\]

\[
d^2\pi_m/d\pi^2 = (bp - a)/2p_{max} \tag{13}
\]

\[(a - bp) > 0, \quad p_{max} > 0, \quad d^2\pi_m/d\pi^2 > 0, \quad \text{the producer income formula has a maximum value.}\]

When \(d\pi_m/d\pi = 0\), it can be obtained:

\[ p_m^* = [(c_0 - c_1 + c_1' + \sigma g)\varepsilon + c_3 - c_1']/2 \tag{14}\]

\[ p_m^* = [(c_0 - c_1 + c_1' + \sigma g)\varepsilon - c_3 - c_1']/4 \tag{15}\]

Substituting the formula (14) and formula (15) into the producer income formula, the rural e-commerce income formula and the consumer residual formula, it can be obtained:

\[ \pi_m^* = (\sigma - c_0)Q + (c_0 - c_1)Q\bar{\varepsilon} - c_0'Q\bar{\varepsilon}(1 - \varepsilon) - Q\bar{\varepsilon}'[(c_0 - c_1 + c_1' + \sigma g)\varepsilon + c_3 - c_1']/2 + (\bar{\varepsilon} - \alpha)Q\sigma g \tag{16}\]

\[ \pi_L^* = (p - \sigma - c_2)Q + [(c_0 - c_1 + c_1' + \sigma g)\varepsilon + c_3 - c_1']/4 - Q\bar{\varepsilon} \tag{17}\]

\[ \Pi' = (\lambda - p)Q + Q((c_0 - c_1 + c_1' + \sigma g)\varepsilon - c_3 - c_1')/8 + (1/2 - \beta)gpQ \tag{18}\]

Deriving \(g\) of the formula (14) and formula (15), we can obtain \(dp_m^*/dg = \sigma\varepsilon/2, \quad dp_1^*/dg = \sigma\varepsilon/4\). Because \(dp_m^*/dg > dp_1^*/dg > 0, \quad dp_m^*/dg - dp_1^*/dg = \sigma\varepsilon/4\). Then Deriving \(g\) of the formula (18), we can obtain:

\[ d\Pi'/dg = (a - bp)[(4 - 8\beta)p + \sigma\varepsilon]/8 \tag{19}\]

In the formula (19), \(a - bp > 0, \quad p > 0, \quad \sigma > 0, \quad \varepsilon > 0; \quad \text{when} \quad 0 < \beta < 1/2 < (\sigma\varepsilon/8p) + 1/2, \quad d\Pi'/dg > 0, \quad \Pi' \quad \text{is an increasing function of} \quad g \quad \text{. Instead, when} \quad (\sigma\varepsilon/8p) + 1/2 < \beta < 1, \quad d\Pi'/dg < 0, \quad \Pi' \quad \text{is a decreasing function of} \quad g \quad \text{. Substituting the formula (14) and formula (15) into the total social welfare formula, it can be obtained:}

\[ SW' = (\sigma - c_0)Q + (c_0 - c_1)Q\bar{\varepsilon} - c_0'Q\bar{\varepsilon}(1 - \varepsilon) - Q\bar{\varepsilon}'[(c_0 - c_1 + c_1' + \sigma g)\varepsilon + c_3 - c_1']/2 + (\bar{\varepsilon} - \alpha)Q\sigma g + (p - \sigma - c_2)Q + [(c_0 - c_1 + c_1' + \sigma g)\varepsilon + 3c_3 - c_1']/4 - Q\bar{\varepsilon} + (\lambda - p)Q + Q((c_0 - c_1 + c_1' + \sigma g)\varepsilon - c_3 - c_1')/8 + (1/2 - \beta)gpQ + Q\bar{\varepsilon}Y - (1 - \bar{\varepsilon})QN \tag{20}\]

Deriving \(g\) in the formula (20):
\[ \frac{dSW^*}{dg} = \left( Q \sigma e / 8 p_{\text{max}} \right) \left( (c_0 - c_1 + c_1 - c_1' + \sigma g) e - c_1 - c_1' + 2Y + 2N + p_{\text{max}} \right) \tag{21} \]

\[ d^2SW^* / dg^2 = -Q \sigma^2 e^2 / 8 p_{\text{max}} \tag{22} \]

In the formula (20), \( a - bp > 0 \), \( \sigma > 0 \), \( e > 0 \), \( p_{\text{max}} > 0 \), so \( d^2SW^* / dg^2 = -Q \sigma^2 e^2 / 8 p_{\text{max}} < 0 \); when \( dSW^* / dg = 0 \), \( SW^* \) has a largest value. The government’s optimal reward and punishment parameter is \( g^* \).

\[ g^* = \left[ (c_0 - c_1)e + (e - 1)c_1' - c_1 + 2Y + 2N \right] / \sigma e \tag{23} \]

4. Case analyses
This study used specific numerical examples and MATLAB software to test effectiveness of the model. The parameters are assumed as follows: \( a = 200 \), \( b = 2 \), \( \sigma = 18 \), \( c_0 = 8.4 \), \( c_1 = 4.4 \), \( e = 60\% \), \( c_1' = 2 \), \( p = 22 \), \( c_2 = 1.2 \), \( c_3 = 3.6 \), \( \alpha = 20\% \), \( \lambda = 40 \), \( p_{\text{max}} = 6 \).

4.1. Decision-making analysis of closed-loop supply chain in rural e-commerce
Through case analyses, the optimal decision of introducing government reward and punishment mechanism to closed-loop supply chain in rural e-commerce is confirmed, as shown in table 1.

| Parameters of government reward and punishment \( g \) | \( 0.00 \) | \( 0.10 \) | \( 0.20 \) | \( 0.30 \) | \( 0.40 \) | \( 0.50 \) | \( 0.60 \) | \( 0.70 \) | \( 0.80 \) | \( 0.90 \) | \( 1.00 \) |
|---------------------------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Transfer price \( p_m^* \)                        | 2.6      | 3.14     | 3.68     | 4.22     | 4.76     | 5.3      | 5.84     | 6.38     | 6.92     | 7.46     | 8        |
| Recovery price \( p_i^* \)                        | -1.4     | -1.13    | -0.86    | -0.59    | -0.32    | -0.05    | 0.22     | 0.49     | 0.76     | 1.03     | 1.3      |
| Production profits \( \pi_m^* \)                  | 1534     | 145      | 1383     | 1263     | 1173     | 114      | 1114     | 109      | 1085     | 6        | 6        |
| E-commerce profits \( \pi_i^* \)                  | 455      | 444      | 436      | 432      | 432      | 436      | 443      | 455      | 470      | 488      | 511      |

Figure 2. Trend chart for the difference between transfer price and recovery price.

It can be seen from Table 1 that with increase of government’s reward and punishment parameters, transfer price of reverse logistics and recovery price of rural e-commerce corporations will increase; while profits of product manufacturers will show a decreasing trend, but still keep higher; rural e-commerce profits are first reduced and then increased. When government rewards and punishments are low, economic benefits of reverse recycling products are lower, and prices paid by product manufacturers are lower, so that recovery price of rural e-commerce is higher than reverse transfer price of manufacturers; rural e-commerce as a “rational person” no longer participates in closed-loop supply chain, so reverse recycling price paid is negative, and customers need to bear expenses to participate in reverse logistics, which leads to failure of manufacturer’s recycling product. When actual utilization rate of producer is less than minimum re-utilization rate, the government will impose
penalties on the unfinished part, so as government’s reward and punishment parameters increase, producer’s income decreases. We can see from Figure 1 that with increase of government reward and punishment parameters, the difference between transfer price and recovery price becomes larger, and higher than recovery cost of rural e-commerce, so rural e-commerce tends to pay higher recovery price to increase revenue; enthusiasm of customers to participate in logistics is higher.

4.2. Analysis of environmental benefits and social welfare
Substituting parameters of closed-loop supply chain into the formula (22) and formula (23), it can be obtained:

\[
dS W^* / dg^2 = -379 < 0, \quad g^* = 0.19(Y + N) - 0.19, \quad d^2 SW^* / dg^2 \text{ has a maximum at } g^*.
\]

Due to \(0 < g^* < 1\), \(1 - Y < N < 6.26 - Y\) and \(0 < Y < 6.26\). When reverse logistics is not constructed, marginal cost of environmental damage is \([1 - Y, 6.26 - Y]\), \(0 < Y < 6.26\), the government needs to formulate reward and punishment strategies to encourage stakeholders to participate in supply chain construction. When reverse logistics was built failed, supply chain system cannot optimize total social welfare by itself. When the government introduces reward and punishment strategies, total social welfare will be higher than that when it was not introduced, and there is the best government reward and punishment in the interval, which optimizes total social welfare and promotes environmental logistics.

5. Conclusions
In view of different interests of stakeholders for closed-loop supply chain system in rural e-commerce, this study discussed the government’s participation in formulation of reward and punishment strategies to achieve optimal social welfare, and response of product manufacturers and rural e-commerce to government participation strategies. The following conclusions are drawn through analysis: the government reward and punishment strategies can guide manufacturers, rural e-commerce and consumers of closed-loop supply chain in rural e-commerce to participate in reverse logistics. Applying government’s reward and punishment strategies to closed-loop supply chain system can significantly change rural e-commerce reverse logistics dilemma, arouse product manufacturers’ initiative, encourage rural e-commerce to increase reverse prices, and enhance customers’ awareness of participating in reverse logistics.

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