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Study on the Equilibrium of the Closed Loop Supply Chain Network Considering the Quality of Old Products based on E-commerce Opening up the Second hand Market

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Abstract

Using variational inequalities to study the closed-loop supply chain network equilibrium under the participation of old products in the second-hand market opened up by network sellers. By considering the profit impact of the quality of old products at all levels of the closed-loop supply chain, it is found that the more old products a manufacturer recycles, the greater the profit they receive; The change in product quality coefficient has little impact on the recycling cost for online sellers when their products meet the recycling conditions. The more old products can be recycled, the more profits they will earn. And the higher the quality coefficient of second-hand products, the greater the positive impact of the supply chain under the participation of the second-hand market on online sellers and manufacturers.

Keywords

Supply Chain Network; Second Hand Market; Variational Inequality.

1. Introduction and Literature Review

In recent years, the proliferation of online retailers has significantly expanded consumer choice. Simultaneously, increasing consumer preferences and demands have led to a large number of still-functional products being left idle, giving rise to numerous online consumption formats for second-hand transactions, such as Preloved in the United States and Mercari in Japan. With the advancement of domestic e-commerce, trading models for used products have matured, evolving from local offline exchanges to cross-regional transactions via online platforms.This study examines various closed-loop supply chain models comprising manufacturers, retailers, second-hand traders, and consumers, while considering the role of product quality in shaping consumer decisions. Sales on second-hand platforms continue to grow as diverse products emerge. Consumers increasingly regard purchasing high-quality used products as a viable option.

Ranjbar et al. [1] investigated the impact of power structures on pricing and strategic decisions in recycling channels[2].Xu Limin et al. [3] examined competition and cooperation between manufacturers and remanufacturers under different models, considering uncertainty in remanufactured product output.Yao Fengmin et al. [4] studied pricing decisions in a closed-loop supply chain where retailers and third parties compete in recycling. Li et al. [5] incorporated recycling regulations and consumer green preferences to investigate manufacturers' optimal production and recycling strategies in a closed-loop supply chain..Gu[6] et al. [6] addressed the second-use of electric vehicle batteries and analyzed the influence of government subsidies on battery manufacturers' production and recycling decisions.Chen[7] et al. examined the conditions under which manufacturers recycle used products under various government regulations.

Regarding e-commerce platform-related supply chain decisions, Feng et al.[8] constructed a game-theoretic model in which consumers can independently buy or sell used products

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through second-hand platforms, and explored optimal decision-making.Wang et al.[9] considered heterogeneous government recycling policies and studied optimal recycling strategies. Wei et al. investigated online sales mode decisions for two competing manufacturers selling via e-commerce platforms, taking into account power structure, platform referral fees, and product substitutability.Zennyo[10] examined contract selection issues between two competing suppliers and a platform. Gong et al. [11] studied the selection of recycling models in a closed supply chain led by an e-commerce platform.Liu et al. [12] considered a closed-loop supply chain where manufacturers sell new products as well as remanufactured products through online channels, and determined optimal pricing. Liu Jiaguo et al.[13] analyzed pricing decisions under product quality differentiation. Wan Chenjie et al. [14] analyzed optimal decisions for second-hand market supply chains on idle-goods trading platforms. Savaskan[15] focused on optimal recycling channel choices from the manufacturer's perspective. Sun Jiayi et al.[16] focused on a competitive retailer environment and constructed recycling functions related to recycling prices. Chuang [17] studied manufacturer recycling channels for high-tech products from the perspective of product characteristics. Lu Ronghua et al. [18] examined recycling issues in closed-loop supply chains for electronic products.

From the above review, it is evident that recycling issues in e-commerce supply chains have drawn extensive attention, and many scholars have achieved notable results in closed-loop supply chain strategy. However, most decision-making studies on closed-loop supply chains have not considered the reintegration of recycled used products into the supply chain, where both manufacturers and online retailers participate simultaneously-acting as both producers and consumers. In light of existing literature, this paper constructs a closed-loop supply chain equilibrium model in which online retailers open second-hand markets and participate in both selling and recycling activities. By incorporating product quality considerations, we analyze how quality influences consumer behavior and overall supply chain decisions.

2. Modeling Supply Chain Equilibrium with Used-Product Quality

(1) Problem Statement and Model Development

This paper considers a closed-loop supply chain composed of manufacturers, online retailers, and consumers, and explores the scenario in which online retailers simultaneously open second-hand markets and participate in the closed-loop supply chain. Let i denote a manufacturer $i=1,\ldots M$ so there are M manufacturers; let j denote an online retailer $j=1,\ldots N$ so there are N online retailers; let k denote a consumer market,, $k=1,\ldots Q$ so there are Q consumer markets; Non-cooperative competition exists across all echelons. At the manufacturer level, multiple manufacturers compete with each other. In this model, manufacturers use both virgin and recycled materials to produce new products, which are then sold to online retailers, with each manufacturer maximizing its own profit, leading to a manufacturer-level equilibrium.; Next, multiple online retailers, acting as intermediaries between manufacturers and consumers, also engage in non-cooperative competition and reach a market equilibrium, denoted by the superscript *; Finally, consumers in the demand markets make choices by comparing offerings from multiple online retailers, thereby reaching a demand-market equilibrium, which ultimately brings the entire e-commerce supply chain to equilibrium.

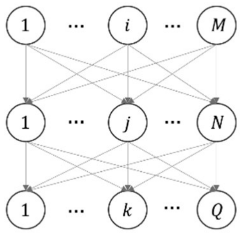

Figure 1. Supply Chain Network Model

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(2)Profit Models and Variational Inequalities for the Supply Chain

1) Manufacturer Optimality Conditions and Variational Inequality

m manufacturers compete with one another. Manufacturer i determines the transaction quantity and endogenous price with online retailer j, bearing production costs and transaction costs with online retailers. Let q_{ij} denote the transaction quantity between manufacturer i and online retailer j, and let Q be the column vector of all q_{ij}, with Q∈R^{mn}{+}; let ρ{ij} denote the transaction price between manufacturer i and online retailer j. The per-unit production cost using virgin materials is c_i^v, and using recycled materials is c_i^r, where θ denotes the quality coefficient of used products. Higher used-product quality reduces the cost of producing new products. Products manufactured from recycled and virgin materials are assumed to be of identical quality [18] and can both be sold in the market. Let $\sum_{j=1}^{N}\omega\beta c_{ij}q_{ij}$ represent the cost savings from using recycled materials $\sum_{j=1}^{N}t\beta q_{ij}\rho_{ij}$ denote the commission paid by the manufacturer to retailers for recycling β represent the proportion of used products the manufacturer recycles from online retailers; t denote the commission rate for recycling from online retailers; $\sum_{j=1}^{N}f_{ij}\left(A_1\right)$ be the manufacturer's transaction cost; $\sum_{j=1}^{N}\left(\rho_{ij}-c_{ij}\right)q_{ij}$ denote the manufacturer's revenue net of costs. Based on the above assumptions, the profit function of manufacturer i is given by:

$$\begin{aligned}&Max\pi_M=\sum_{j=1}^{N}\left(\rho_{ij}-c_{ij}\right)q_{ij}+\sum_{j=1}^{N}\omega\beta q_{ij}c_{ij}\\&-\sum_{j=1}^{N}t\beta q_{ij}\rho_{ij}-\sum_{j=1}^{N}f_{ij}\left(A_1\right)\\&\quad st.\ \ q_{ij}\geq 0\end{aligned} \tag{1}$$

Since manufacturers at the same level engage in non-cooperative competition, and production and transaction costs are continuously differentiable convex functions, the equilibrium conditions for all manufacturers can be expressed as the following variational inequality:

$$\begin{aligned}&\sum_{i=1}^{M}\sum_{j=1}^{N}\left[\frac{\partial f_{ij}\left(A_1^*\right)}{\partial q_{ij}}+\left(1-\omega\beta\right)\frac{\partial c_i\left(A_1^*\right)}{\partial q_{ij}}-\left(1-t\beta\right)\rho_{ij}^*\right]\\&\times\left[q_{ij}-q_{ij}^*\right]\geq 0,\forall A_1\ \in R_+^{MN}\end{aligned} \tag{2}$$

2) Optimality Conditions for Online Retailers with Second-Hand Markets and Variational Inequalit

N online retailers j compete with one another. Retailer j can obtain products from manufacturer i and sell them to consumers. Let q_{jk} denote the transaction quantity between online retailer j and consumer market k and let A_2 be the column vector of all with $A_2\in R_+^{NQ}$; ; let ρ_{jk} denote the selling price from retailer j o consumer k; Online retailer j also collects used products from consumers k for quality assessment If the used-product quality coefficient ω falls below a threshold, the product cannot be resold; instead, the retailer transfers it to manufacturers for a commission. If ω meets the threshold, the product can be resold to consumers, generating a commission for the retailer.Let θq_{jk} $(0<\theta<1)$ denote the quantity of used products recycled from consumer market k by retailer j, with recycling price $\mu\rho_{jk}$ $(0<\mu<1)$

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The retailer's holding cost is $c_j(A_1)$, and the cost of reselling products to consumers is $f_{jk}(A_2)$ Based on the above assumptions, the profit function of online retailer j that operates a second-hand market is:

$$\begin{aligned} Max\pi_N &= \sum_{k=1}^{Q}\sum_{j=1}^{N}(1-\theta\mu)q_{jk}\rho_{jk} + \sum_{i=1}^{M}\sum_{j=1}^{N}t\beta q_{ij}\rho_{ij} \\ &-\sum_{i=1}^{M}\sum_{j=1}^{N}q_{ij}\rho_{ij} - \sum_{j=1}^{N}f_{jk}(A_2) - \sum_{j=1}^{N}c_j(A_1) \\ &st.\ \ \theta\sum_{k=1}^{Q}q_{jk} \ge \beta\sum_{i=1}^{M}q_{ij} \end{aligned} \tag{3}$$

Assuming all relevant cost functions are continuously differentiable and convex, and given that all manufacturers are in non-cooperative competition, the simultaneous optimality conditions for all retailers can be expressed as the following variational inequality, i.e., the solution satisfies:

$$\begin{aligned} &\sum_{i=1}^{M}\sum_{j=1}^{N}\left[\frac{\partial c_j(A_1^*)}{\partial q_{ij}} + (1-t\beta)\rho^*_{ij} - \gamma_1^*\right]\times\left[q_{ij} - q^*_{ij}\right] \\ &+\sum_{j=1}^{N}\sum_{k=1}^{Q}\left[\frac{\partial f_{jk}(A_2^*)}{\partial q_{jk}} + (\theta\mu-1)\rho^*_{jk} - \gamma_1^*\right]\times\left[q_{jk} - q^*_{jk}\right] \\ &\sum_{j=1}^{N}\left[\beta\sum_{i=1}^{M}q^*_{ij} - \theta\sum_{k=1}^{Q}q^*_{jk}\right]\times\left[\gamma_2 - \gamma_2^*\right] \ge 0, \\ &\forall(A_1, A_2, \gamma_1, \gamma_2) \in R_+^{MN+NQ+2N} \end{aligned} \tag{4}$$

In the above, γ_1,γ_2 denotes the Lagrange multiplier associated with the online retailer's constraints.

3) Consumer Competitive Behavior and Variational Inequality

In each demand market, let k denote the transaction cost between demand market $c_k(A_2)$ and online retailers,which determines the price consumers are willing to pay for products and the recycling price for used products. Let ρ_k be the recycling price in demand market Q and d_k denote the quantity demanded in demand market k which typically depends on the demand price in that consumer market. Consumers incur costs when purchasing products from online retailers. Following the user-optimal choice behavior in network equilibrium, the user-optimal equilibrium conditions are:

$$\rho_k^* + c_k(A_2^*)\begin{cases} = \rho_k^* & q_k^* \ge 0 \\ \ge \rho_k^* & q_k^* = 0 \end{cases} \tag{5}$$

$$d_k\begin{cases} = \sum_{j=1}^{N}q_{jk}^* & \rho_k^* > 0 \\ \le \sum_{j=1}^{N}q_{jk}^* & \rho_k^* = 0 \end{cases} \tag{6}$$

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The above inequality indicates that, for consumers in the demand market, the product selling price offered by the online retailer plus the transaction cost must not exceed the consumers' demand price.If the equilibrium price consumers are willing to pay for the product is positive, then the quantity purchased from retailers will exactly equal the demand in that consumer market.In the reverse supply chain, consumers are the source of used products. That is, when online retailers offer a reasonable recycling price, consumers will sell their used products back to the retailers

$$b_k^R + c_{ij}^R\left(q_{jk}^R\right)\begin{cases}\geq \rho_{jk} & q_{jk}^* = 0\\ = \rho_{jk} & q_{jk}^* > 0\end{cases}$$
$$s.t\sum_{j=1}^{N}\sum_{k=1}^{Q} q_{jk}^R \leq b\sum_{j=1}^{N}\sum_{k=1}^{Q} q_{jk} \tag{7}$$

where b is the recyclable coefficient of products in the consumer market.

If all transaction and demand functions are convex and continuous, then the simultaneous optimality conditions for all consumer markets are equivalent to the solution of the following variational inequality problem, i.e., the solution satisfies:

$$\begin{aligned}&\sum_{j=1}^{N}\sum_{k=1}^{Q}\left[\rho_{jk}^* + c_k - \rho_k^* - b\gamma_k\right]\times\left[q_{jk} - q_{jk}^*\right]\\&+\sum_{k=1}^{Q}\left[\sum_{j=1}^{N} q_{jk} - d_k\right]\times\left[\rho_k - \rho_k^*\right]\\&+\sum_{j=1}^{N}\sum_{k=1}^{Q}\left[\rho_{jk}^{R*} + c_{jk} - b\gamma_k\right]\times\left[q_{jk} - q_{jk}^*\right]\\&+\sum_{j=1}^{N}\left[bq_{jk}^* - q_{jk}^{R*}\right]\times\left[\gamma_k - \gamma_k^*\right]\geq 0\end{aligned} \tag{8}$$

4) Supply Chain Network Optimality and Variational Inequality

When manufacturers, online retailers, and consumer markets are simultaneously in equilibrium-i.e., when conditions (2), (4), and (8) hold simultaneously-the supply chain network reaches equilibrium.By the additivity property of variational inequalities and eliminating endogenous price variables, we obtain the supply chain network equilibrium:

$$\begin{aligned}&\sum_{i=1}^{M}\sum_{j=1}^{N}\left[\frac{\partial f_{ij}\left(A_1^*\right)}{\partial q_{ij}} + (1-\omega\beta)\frac{\partial c_i\left(A_1^*\right)}{\partial q_{ij}} - (1-t\beta)\rho_{ij}^*\right]\times\left[q_{ij} - q_{ij}^*\right]\\&+\sum_{i=1}^{M}\sum_{j=1}^{N}\left[\frac{\partial c_j\left(A_1^*\right)}{\partial q_{ij}} + (1-t\beta)\rho^*_{ij} - \gamma_1^*\right]\times\left[q_{ij} - q^*_{ij}\right]\\&+\sum_{j=1}^{N}\left[\beta\sum_{i=1}^{M} q^*_{ij} - \theta\sum_{k=1}^{Q} q^*_{jk}\right]\times\left[\gamma_2 - \gamma_2^*\right]\\&+\sum_{j=1}^{N}\sum_{k=1}^{Q}\left[\frac{\partial f_{jk}\left(A_2^*\right)}{\partial q_{jk}} + (\theta\mu - 1)\rho^*_{jk} - \gamma_1^*\right]\times\left[q_{jk} - q^*_{jk}\right]\\&+\sum_{j=1}^{N}\sum_{k=1}^{Q}\left[\rho_{jk}^* + c_k - \rho_k^* - b\gamma_k\right]\times\left[q_{jk} - q_{jk}^*\right]\\&+\sum_{k=1}^{Q}\left[\sum_{j=1}^{N} q_{jk} - d_k\right]\times\left[\rho_k - \rho_k^*\right]\\&+\sum_{j=1}^{N}\sum_{k=1}^{Q}\left[\rho_{jk}^{R*} + c_{jk} - b\gamma_k\right]\times\left[q_{jk} - q_{jk}^*\right]\\&+\sum_{j=1}^{N}\left[bq_{jk}^* - q_{jk}^{R*}\right]\times\left[\gamma_k - \gamma_k^*\right]\geq 0\\&\forall\left(A_1, A_2, \gamma_1, \gamma_2, \gamma_k\right)\in R_+^{MN+NQ+2N+Q}\end{aligned} \tag{9}$$

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The above expression is the equilibrium variational inequality for the entire supply chain network. In the next section, we validate this variational inequality through numerical examples.

3. Numerical Example

When solving supply chain problems using variational inequalities, the solution set may exhibit slight deviations. As shown in [19], if the feasible set is compact, the variational inequality has at least one solution.In this section, we employ the modified projection algorithm to verify the model's validity and specifically analyze the impact of return compensationThe numerical example considers a network equilibrium with 2 Based on data from the literature, we assume the following cost functions and parameter values:

(1) Manufacturer production cost functions

$$c_1(q_{i1}) = 2.5q_{i1}^2 + q_{i1}q_{i2} + 2q_{i1} - 0.5q_i$$
$$c_2(q_{i2}) = 2.5q_{i2}^2 + q_{i1}q_{i2} + 2q_{i2} - 0.5q_i$$

(2) Manufacturer-online retailer transaction cost functions

$$c_{11}(q_{11}) = 0.5q_{i11}^2 + q_{i11} \quad c_{12}(q_{12}) = 0.5q_{i12}^2 + q_{i12}$$
$$c_{21}(q_{21}) = 1.5q_{i21}^2 + q_{i21} \quad c_{22}(q_{22}) = 0.5q_{i22}^2 + q_{i22}$$

(3) Online retailer holding cost functions $c_{j1}(Q_1^*) = 0.4(q_{i11}^2 + q_{i21}^2) \quad c_{j2}(Q_1^*) = 0.4(q_{i12}^2 + q_{i22}^2)$

(4) Online retailer-consumer transaction cost functions

$$f_{11}(q_{j11}) = q_{j11}^2 + q_{j11} \quad f_{12}(q_{j12}) = q_{j12}^2 + q_{j12}$$
$$f_{21}(q_{j21}) = 0.5q_{j21}^2 + 2q_{j21} \quad f_{22}(q_{j22}) = 0.5q_{j22}^2 + 2q_{j22}$$

(5) Demand functions for consumer-market transactions

$$d_1 = -2\rho_{k1} - 2\rho_{k2} + 1000 \quad d_2 = -2\rho_{k2} - 2\rho_{k1} + 1000$$

We implement the modified projection algorithm in MATLAB, substituting the above cost functions into the network equilibrium conditions to obtain the equilibrium decisions and profits for each decision-maker, as well as the overall supply chain network equilibrium.We first solve the numerical example using the modified projection algorithm in $Matlab2016b$ with step size 0.01,and precision $\varepsilon = 0.001$.Initial transaction quantities are set to 16 and initial online transaction prices to 20 The iterative results are shown below:

Table 1. Algorithmic Results

A_1^*	A_2^*	ρ_{ij}	ρ_{jk}
14.805	26.832	23.24	24.61
14.809	27.542	23.38	24.43
13.604	28.013	23.27	24.34
13.607	24.346	26.37	24.07

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Table 2. Impact of Increasing Used-Product Quality Coefficient on Each Echelon

ω	0.2	0.3	0.5	0.6	0.7
A_1^*	112.20	123.06	140.02	154.91	165.86
A_2^*	116.91	120.56	136.10	146.41	157.81
q_{jk}^*	554.35	602.80	674.19	722.21	786.05
π_M	452.02	551.51	680.92	797.81	920.96
π_N	434.31	512.46	678.02	716.90	878.73

From Table 1, the iterative algorithm yields the sales quantities and prices across echelons in the basic closed-loop supply chain network. Table 2 shows the impact of the used-product quality coefficient on all supply chain echelons. As the quality of recycled products increases, online retailers collect more used products, and with relatively stable recycling costs, their profits rise.

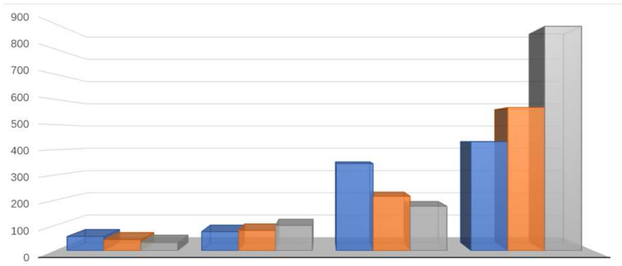

Figure 2. Impact of Used-Product Quality Coefficient on the Supply Chain

From Figure 2, we observe the effects of the used-product quality coefficient θ on the specific collection quantities at each echelon, as well as on manufacturer cost savings and online retailer profit increases. Clearly, as θ increases, online retailers intensify recycling efforts and obtain higher profits, whereas manufacturers experience a decline in collected quantities and thus lower cost savings from recycled materials.

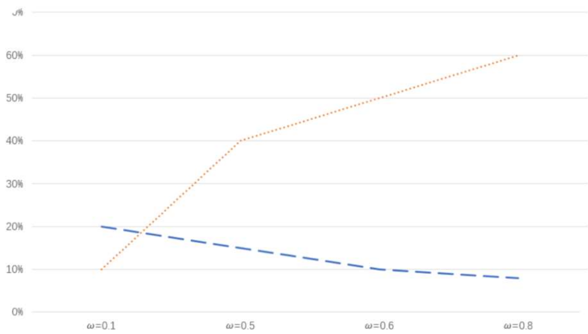

Figure 3. Profitability of Recycling Used Products by Quality

From Figure 3, we find that the used-product quality coefficient θ affects the profit margins of manufacturers and online retailers differently. In this supply chain, online retailers hold a dominant position in recycling used products. As θ increases, manufacturers' profit margin from recycling declines, while online retailers' profit margin from recycling increases.Evidently, as ω increases, online retailers gain more benefits from the supply chain than manufacturers do.

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4. Conclusion

This paper employs variational inequality and equilibrium theory to study a closed-loop supply chain composed of manufacturers and online retailers that operate second-hand platforms. We formulate the equilibrium conditions for each echelon using variational inequalities and validate the results via numerical simulations in MATLAB.The numerical results support the following conclusions:

(1) For online retailers, opening second-hand markets consistently generates additional profits. By establishing a retailer-led sales chain, fluctuations in the quality coefficient of used products-provided they meet recyclability conditions-have little effect on recycling costs. Leveraging channel convenience, online retailers are better positioned to proactively promote the recycling and resale of used products.

(2) For manufacturers, recycling used products can reduce production costs without compromising product quality, thereby increasing profits. For consumers in demand markets, reselling second-hand goods represents a form of resource reuse, turning waste into value, saving resources, and making the entire supply chain more efficient and beneficial. Future research can extend this work by allowing manufacturers or third-party platforms to compete in the recycling supply chain, or by examining the impact of subsidy or compensation mechanisms on the supply chain during the recycling proces.

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