Research on the pricing of the double-competition closed-loop supply chain with uncertain recycling quantity

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Abstract. In order to solve the uncertainty impact of recycled products on pricing decision-making and financial intervention policy in double competition closed-loop supply chain, a pricing decision-making model is built by using the game theory and MATLAB numerical simulation. The model analyses and verifies the impact of the uncertain quantity upon the competition intensity, sale and recycling prices, supply chain node companies’ profits and social welfare, recovery rate of the closed-loop supply chain from four dimensions. The research results show that the recycling and repurchase prices are increasing when the quantity of recycled products shows significant fluctuation. The profit of social welfare and sellers are increasing, but manufacturer’s profit is decreasing, which means the uncertainty on recovery quantity directly affects the manufacturers, who play a leading role in implementing remanufacturing.

1. Introduction

The construction of a sustainable green ecological circular economy meets the requirement of social progress, and the closed-loop supply chain is an important carrier of the sustainable development of a green ecological circular economy. The research on the closed-loop supply chain system has become a major subject for developing a green ecological circular economy, and the selection of fiscal intervention strategies and closed-loop supply chain pricing decisions under government regulation are the core issues of the research in this field.

Some researches on the pricing decision-making of closed-loop supply chain had been made. For example, Xing Guangjun[1], Cheng Faxin[2], etc. studied the optimal pricing decisions of closed-loop supply chains by considering consumer’s green preference. Their study shows that: there is a positive correlation between product pricing and consumer’s green preference; under the centralized decision-making mode, comparing with the decentralized decision-making mode, the retail price of green products is far lower while the recovery rate of waste products is much higher. Gao Honghong [3] analyzed the impact of consumer’s market change on pricing decisions in the context of the buyer's market. Their studies show that the stronger consumer’s preference for second-hand goods could result in a better quality of waste products. but lower Closed-loop supply chain profit; Zhao Jing[4], based on consumers’ different preferences for traditional retail channels and online direct sale channels as well as different channel operating costs, researched the retailers who sell new products and recycle obsolete products and the manufacturers who open up online direct sale channels. In addition, some
scholars studied the closed-loop supply chain pricing decisions from different perspectives. For example, Min Huang[5] studied the closed-loop supply chain competition under the coexistence of three recycling channels; George[6] and others used a system dynamics method to study the impact of recycling competition on re-manufacturing; Jiuh-Biing Sheu[7] studied the cooperation relationship when there is competition in the reverse supply chain; Tolga Aydinliyim[8] studied the management of recycling competition. Regarding the competition in closed-loop supply chains, most studies have focused on recycling competition in reverse supply chains, but the studies on dual competition are rarely reported in related literature. Luis J[9]'s research shows that the uncertainty of recycling quantity is related to the quantity and quality of reverse supply chain products which are directly affected by consumers and recyclers. Li Xiang[10] studied the closed-loop supply chain consisting of distributors and re-manufacturers, which shows that recycling price can influence the quantity of waste products and the recycling quantity changes in a random manner. The researchers, who used game theory and optimization theory to obtain the optimal decision under the decentralized and centralized supply chain system, proved that the lower remanufacturing quantity and recycling price in the decentralized system further lead to the higher selling price. Wang Daoping[11] found that the higher the expectation of recovery quantity, the greater the reduction of the unit carbon emission. Existing studies on the uncertainty of the recovered quantity have revealed the root cause of the uncertainty of the recovered quantity and the impact of the uncertainty of the recovered quantity on the objective functions such as pricing decision and expected profit. However, above mentioned studies also have certain limitations. For example, on the one hand, the wide impact of recycling rate and social welfare are not involved. On the other hand, considering the changes in the business environment of the closed-loop supply chain, the research on the uncertainty of recycling volume in a complex environment needs to be further conducted.

Based on existing studies, this paper takes the double competition closed-loop supply chain as the research object, explores the government financial intervention strategy and pricing decision-making mechanism by using the method of Game Theory and MATLAB numerical simulation in the case of uncertain recovery quantity and discusses the impact of the recovery quantity uncertainty on the double competition of the closed-loop supply chain.

2. Double-competition closed-loop supply chain model with uncertain recycling quantity

Closed-loop supply chain, in its operation process, presents the dual competition phenomenon, namely retailer and third-party recycler recycling competition, new product and remanufactured product sale competition. Both retailers and third-party recyclers have uncertainties about the quantity of recycled products in the recycling process. By setting up a disturbance of the recycled quantity, this paper studies the uncertainty of the recycled quantity and the change law of dual competition.

2.1. Symbol definition

The definition of the parameter symbols used in this research is shown in Table 1.

| Symbol | Definition |
|--------|------------|
| $w_i$ | Wholesale price per unit product ($i=1,2$, respectively for new products and remanufactured products) |
| $\beta_i$ | Retail price per unit product ($i=1,2$, respectively for new products and remanufactured products) |
| $Q_i$ | Market demand for product quantity ($i=1,2$, respectively for new products and remanufactured products) |
| $c_r$ | Production cost of remanufactured products |
| $\rho_i$ | Production cost saved by unit product recycling, $\Delta = c_r - c_i$ |
| $D_j$ | Quantity recovered ($j=R,T$, respectively Retailers and third-party Recyclers) |
| $\Gamma$ | Profit |
| $b_m$ | Manufacturer's recovery price |
| $b_j$ | Recycler unit product recycling price ($j=R,T$, respectively Retailers and third-party Recyclers) |
Among the above symbols, the decision variables are: government subsidy amount per unit product \( \delta \), 
wholesale price per unit product \( w_i \), retail price per unit product \( p_i \), repurchase price and recovery price per unit product \( b \) and \( b_j \). In the forward supply chain, manufacturers sell new products and remanufactured products to retailers at wholesale price \( w_1 \) and \( w_2 \), respectively, and retailers sell new products and remanufactured products to consumers at retail price \( p_1 \) and \( p_2 \), respectively. In the reverse supply chain, manufacturers repurchase waste products at recovery price \( b \) from retailers and third-party recyclers. Green products are produced from raw materials at unit cost \( c_m \), or useful components are extracted and recycled at unit cost \( c_r \) and used to make green products. Due to their own interests, the two recyclers play a game of recycling waste products. The competition between recyclers, recyclers’ recycling decisions, the choice of brand new products and remanufactured products in market sales and financial intervention strategies, as well as pricing decisions, will affect the interests of the supply chain node companies. The uncertainty of the quantity of recycled product will lead to fluctuations in recycling price and remanufacturing cost. The relationship of decision variables in a closed-loop supply chain is shown in Figure 1.

![Figure 1. Relationship of decision variables in a closed-loop supply chain](image)

### 2.2. Model assumptions

In order to make the research more scientific and targeted, the following relevant assumptions are established for the specific situations of waste electronic product industry:

**Hypothesis 1:** The information about the market among the members of the closed-loop supply chain is symmetrical and risk-neutral. In non-cooperative situations, manufacturers, retailers, and third-party recyclers are rationally pursuing their own maximum profits [12].

**Hypothesis 2:** There is a quality difference between new and remanufactured products. In other words, the market deals with the two types of products differently. The market demands for new and remanufactured products are related to the sale price and affected by the sale price of the other party. There is no functional difference between remanufactured products and new products. To some extent, they can replace each other, but consumers have different Willingness to Pay (WTP) towards new products and remanufactured products. Therefore, they are priced differently by both manufacturers and retailers. Retailers purchase new and remanufactured products at wholesale prices \( w_1 \) and \( w_2 \) from manufacturers, respectively, and sell them at retail prices \( p_1 \) and \( p_2 \) separately (\( w_1 > w_2 > 0, \quad p_1 > p_2 > 0 \)). The new product and remanufactured product are related to each other through the Bertrand Duopoly Model of price competition, from which the demand function between the new product and remanufactured product can be expressed as:

\[
Q_i(p_i, p_j) = a - p_i - \theta(p_j - p_i), \quad i, j = 1, 2, i \neq j.
\]
where, \( a > 0 \) represents the market size of new and remanufactured products, and the value range of \( \theta \) is \((0, 1)\), which represents the substitution coefficient between new products and remanufactured products. The demand function for new and remanufactured products expresses that when new product price fall or remanufactured product price increase, the demand for new products increases, and vice versa. Therefore, the quantity of sales can be expressed as a function of price behavior.

Assumption 3: Assume that the unit production cost of the new product is \( c_m \), the production cost of the remanufactured product is \( c_r \), and \( 0 \leq c_r \leq c_m \), and that the production of a unit remanufactured product can save the production cost \( \Delta \) [13].

Hypothesis 4: All node companies in the closed-loop supply chain are willing to cooperate with each other as a whole, which means \( p_i > w_i > 0, w_i \geq \Delta \geq b > c_i \).

Hypothesis 5: Build a recycling function according to the sales function, and then the retailer recycling function can be expressed as \( D_r(b_x, b_y) = \beta (b_y - b_x) \) and the third-party recycler recycling function can be expressed as \( D_r(b_x, b_y) = \beta (b_y - b_x) \), where \( k > 0 \) represents the recycling market size and \( 0 < \beta < 1 \) represents the consumer's sensitivity coefficient to the difference between the retailer's and the third-party recycler's recycling prices. Although the total recovery function \( D = D_x + D_y = k b_x \) seems to be a function of \( b_x \), due to competition, the total recovery function is a function of the recovery price of both parties, which is \( D(b_x, b_y) \).

Hypothesis 6: The quantity of waste products repurchased by the manufacturer is random \( \tilde{q}(b, \varepsilon) \), and affected by the repurchase price, and let \( \tilde{q}(b, \varepsilon) = D(b)\varepsilon \). The random disturbance \( \varepsilon \) describes the impact of the external environment (such as sale market conditions and relevant government policies) on the waste product recycling market normally. Assume that \( \varepsilon \), is defined within the interval \([A, B]\) with the mean value of 1 and the variance of \( \sigma^2 \), and the distribution function and density function are \( F(\varepsilon) \) and \( f(\varepsilon) \), respectively.

Assumption 7: Assume that the recycled products are manufacturable, which means the uncertainty or difference in the quality of the recycled products is not considered. In reality, to optimize inventory, many companies manufacture the products based on placed orders, which means remanufacturing waste products after the demand is realized [14].

Hypothesis 8: In a closed-loop supply chain system, it is assumed that manufacturers, sellers, and third-party recyclers are risk-neutral and fully rational. In other words, decisions are made to maximize their expected profits. There is a Stackelberg relationship between upstream manufacturer, downstream seller and the third-party recycler. The manufacturer is the leader of the game, and the seller, the third-party recycler and the government are the followers [15].

Hypothesis 9: In the process of recycling by retailers and third-party recyclers, the unit cost of labor, storage and transportation required for each recycled product can be considered together with the repurchase price or recycling price [16].

Based on the above assumptions, the function of expected profit and social welfare expectation can be expressed as:

\[
\begin{align*}
\Max\mathcal{E}(\Pi_M) & = E((p_1 - w_1)Q_1 + (p_2 - w_2)Q_2 + (b - b_x)D_R) \\
\Max\mathcal{E}(\Pi_T) & = E((b - b_y)D_T) \\
\Max\mathcal{E}(SW) & = E(\Pi_M) + E(\Pi_R) + E(\Pi_T) - \delta(D_R + D_T)
\end{align*}
\]

3. Calculation and analysis of the optimal decision solution

The inverse induction method is adopted to calculate the solution of the model. The closed-loop supply chain dominated by the manufacturer will determine the impact of the uncertainty of the
recycling quantity on the decision of the closed-loop supply chain. Therefore, $\varepsilon$ is regarded as an independent variable and the expected value of the optimal solution is a function of $\varepsilon$.

**Stage 3 decision**
Manufacturers first determine their own optimal strategies $w_1, w_2, b$ to maximize their own profits, and then sellers and the third parties determine their optimal strategies, respectively. For a given $b$, the expected profit of a third-party recycler is: $E(\Pi_T) = (b - b_x)D_x(b_x)\varepsilon_T$. Since the mathematical expectation of $\varepsilon_T$ is 1, we can get $E(\Pi_T) = (b - b_x)\beta b_x^2$. The results show that the relationship between the optimal expected profit of the third party recycler and the repurchase price is a quadratic function, and the third-party recycler’s optimal recycling price is linear with the manufacturer’s repurchase price. Therefore, the manufacturer must set a repurchase price. Similarly, according to the retailer’s profit expectations: $E(\Pi_R) = E((p_1 - w_1)Q_1 + (p_2 - w_2)Q_2 + (b - b_x)D_x(b_x)\varepsilon_x)$ the mathematical expectation of $\varepsilon_R$ is 1, and then by substituting the expression $D_x(b_x)$ into the model and calculating through $\frac{\partial E(\Pi_R)}{\partial b_x} = 0$ and $\frac{\partial E(\Pi_R)}{\partial p_1} = 0$, we can get:

$$
p^*_1 = \frac{a + w_1}{2}, \quad p^*_2 = \frac{a + w_2}{2},$$

$$
b^*_r = \frac{6b(k + \beta)}{8(k + \beta)^2 - 2}, \quad b^*_p = b \frac{2(k + \beta) + 1}{4(k + \beta) - 1}$$

$$D_x(b_x, b) = b(k \frac{2(k + \beta) + 1}{4(k + \beta) - 1} - \beta \frac{(k + \beta) - 1}{4(k + \beta) - 1})$$

$D_x(b_x, b) = \beta b \frac{(k + \beta) - 1}{4(k + \beta) - 1}$

**Stage 2 decision**
It is assumed that manufacturer’s production capacity is fixed and the manufacturer can complete the production of new and remanufactured products on $Q_1 + Q_2$ quantity; when the quantity of recycled waste products is larger than its maximum production quantity, namely $b_1^* \geq Q_1 + Q_2$, the manufacturer

$$q(b, \varepsilon) \geq Q_1 + Q_2,$$

the manufacturer does not need to use new raw materials to produce. All are remanufactured with waste products. In addition, the manufacturer can obtain residual value $h$ from unused waste products. However, when the quantity of recycled waste products is less than its maximum production quantity, namely $q(b, \varepsilon) < Q_1 + Q_2$, part of the manufacturer's production is made from new raw materials and part of it is remanufactured with waste products, so the manufacturer's profit function is:

$$z = \frac{Q_1 + Q_2}{D_x + D_T},$$

From equation (4), the manufacturer's expected profit is:

$$\max \mathbb{E}(\Pi_R) = (w_1 - c_w - h(Q_1' + Q_2') + (\Delta + \delta + w_2 - c_r)(Q_1' + Q_2') + (\Delta + \delta + w_2 - c_r) \int f(\varepsilon) d\varepsilon + \int (h - b)(D_x' + D_T') f(\varepsilon) d\varepsilon$$
Calculate the optimal solution of
\[
\begin{align*}
\mathbf{w}_1^* \\
\mathbf{w}_2^* \\
b^*
\end{align*}
\]
through

\[
\begin{align*}
\frac{\partial E(\Pi_x)}{\partial b} &= 0, \\
\frac{\partial E(\Pi_x)}{\partial w_i} &= 0, \\
\frac{\partial E(\Pi_u)}{\partial n_i} &= 0
\end{align*}
\]

With

\[
\begin{align*}
b^* &= \frac{b^* (8(k + \beta) - 2)}{6(k + \beta)} \\
\end{align*}
\]

and

\[
\begin{align*}
\int_0^1 (h - b)(D_x + D_f) f(\varepsilon)d\varepsilon = (h - b)kh\frac{2(k + \beta) + 1}{4(k + \beta) + 1}\int_0^1 f(\varepsilon)d\varepsilon,
\end{align*}
\]

the optimal solution can be calculated. Although it’s analytical solution is difficult to calculate, it is easy to calculate it’s numerical optimal solution, with which further analysis can be made through numerical simulation.

**Stage 1 decision**

For the government, the optimal amount of financial subsidy is also calculated by

\[
SW = \Pi_x + \Pi_y + \delta(D_x + D_f),
\]

and the results of the first two stages are substituted into the social welfare function to calculate the optimal solution and get

\[
\frac{\partial SW}{\partial \delta} = 0.
\]

It is also difficult to find its analytical solution, so further analysis will be made through numerical simulation.

### 4. Numerical sensitivity analysis

In this paper, Matlab numerical simulation is adopted to conduct numerical sensitivity analysis, of which the main procedures are: first, with a fixed competition coefficient \(\theta\) and \(\beta\), the change rule of the quantity coefficient of recycled product \(\varepsilon\) to the financial intervention strategy, pricing decision, expected profit, social welfare expectation and recovery rate of the supply chain node enterprises are obtained through numerical sensitivity analysis; Then, the change rules of financial intervention strategy, pricing decision, expected profit, social welfare expectation value and recovery rate of the closed-loop to the supply chain node enterprises under the uncertainty of the quantity of recovered products are obtained; Finally, according to a certain value of the calculation, find the influence rule of the variation coefficient of the recycled product \(\varepsilon\) on the recycling competition coefficient \(\beta\), and obtain the influence rule of the uncertainty of the recycled product quantity on the recycling competition. In order to simplify the calculation, set double competition parameters \(\theta = 0.6, \beta = 0.6, h = 3\), and discuss the change rule of recovery quantity \(\varepsilon\) in the range of [5, 20], as shown in Table 2.

| Parameters \(a\) | Preset value | \(c_a\) | Preset value | \(b_0\) | Preset value |
|------------------|--------------|---------|--------------|---------|--------------|
| 80               | 6            | 50      | 6            | 6       |              |
4.1. Changes in wholesale price and retail price

According to Figure 2 and figure 3, the wholesale price and retail price display a decreasing trend in the face of increasing volatility of product recycling market, and when the volatility of recycled quantity increases to a certain amount, the price relationship between the sale price of the original new product and that of the remanufactured product will be broken, and the sale price of new product will decrease rapidly, while the decrease of the sale price of remanufactured product will slow down, This is because when the number of recycled products increases, manufacturers will mainly use recycled products as the source materials, so the sale price will fluctuate accordingly.

The economic theory analysis of the change law of the quantity of recycled product is [17] when the amount of recycled product is very high, the economic way is to completely remanufacture without any waste; when the amount of recycled product is very low, the economic way is not to remanufacture but completely waste; partial remanufacturing is the least economic way and should be avoided. The quantity of recycled products should be large enough so as to enable the remanufacture to have certain scale and form industrialization, only by which enterprises can gain profit. Therefore, the closed-loop supply chain can be called sustainable supply chain only when the quantity of recycled product decreases and remanufactured product maintains a relatively stable sale price and certain quantity and occupies a certain position in the entire social market.

Enlightenment from management can be obtained from the above conclusions: Due to the different consumers’ Willingness to Pay (WTP) and the influence of the change of recycled product quantity, the wholesale price and retail price of new products and remanufactured products fluctuate, so the sale quantity and profit of new products and remanufactured products in the closed-loop supply chain market become the basis for manufacturers to control the price; In addition, when the quality of remanufactured product reaches or approaches that of the new product, remanufactured product still needs coordination or necessary policy support to obtain market recognition.

4.2. Changes in recycling price and repurchase price

Figure 4 and figure 5 show that when the market volatility of the product recycling market increases, retailers and third-party recyclers are the first to know the change of market risk. In order to obtain
benefits and reduce risks, it is necessary to encourage the recycling of waste products by improving the recycling price of waste product. The third-party recycler’s recycling price is always lower than the retailer's recycling price, because the third-party recycler’s profit mainly comes from the difference between the recycling price and the manufacturer’s repurchase price. On the premise that the repurchase price is determined by the manufacturer, in order to obtain the maximum profit, the third-party recycler can only increase the recycling volume by reducing the recycling price. The increase of the recycling price increases manufacturer’s production cost, which in turn leads to the increase of retail price and decrease of market demand. Consequently, manufacturers' profit is directly affected by the changes.

The change law of the recycling price and the repurchase price reflects the practice of risk transfer in the closed-loop supply chain economic practice when retailers and third-party recyclers face the increase of recycling quantity, which leads to the adverse changes in the recycling price and the loss of profits. From the above conclusions, management enlightenment can be obtained: the third-party recycler is always at a disadvantage position in recycling activities. In order to prevent companies with professional recycling and dismantling technologies from losing the market, necessary coordination and subsidy measures should be in place to keep and boost the third-party recycler’s vitality. Particularly, in the case of the continuous increase of the waste product quantity, the professional recycling and dismantling enterprises are needed. Therefore, maintaining the vitality of a closed-loop supply chain with professional recycling and dismantling companies, such as third-party recyclers, is one of the key issues for building a virtuous cycle of the closed-loop supply chain.

4.3. Changes in expected profit and social welfare

Figure 6, figure 7, and figure 8 show that encouraging the recycling of waste products will increase the quantity of recycled products and reduce the manufacturing cost. However, the continuous decrease of the manufacturer’s profit and constant increase of the recycler’s profit mean, that the recycler successfully transferred the risk to the manufacturer.

Figure 9 shows that increasing the recycling price of waste products can encourage recycling activity in the market. The increase in the quantity of recycling leads to a decline in wholesale price and a
reduction in sale price of sellers. On the other hand, for sellers, in order to improve service level and meet market demand, the reduction of sale price will inevitably lead to an increase of the quantity ordered.

When the recycling quantity is uncertain, the change in the expected profit of the supply chain node enterprises reflects the risk transferred by both recyclers to the manufacturer. Therefore, the increase of the recycling quantity will result in the increment of recycler’s profit but the reduction of manufacturer’s profit, namely manufacturer taking all risks. This phenomenon will reduce the manufacturer’s enthusiasm to produce remanufactured products and hinder a virtuous circular economy. Therefore, it is necessary to study the control scheme of supply chain risk transfer, and encourage manufacturers who play a leading role in the closed-loop supply chain to remanufacture.

4.4. Changes of recovery with the recovery quantity and competition

Figure 10 shows that the recovery rate increases with the increase of the recovery quantity. When recovery quantity increases significantly, the competition between recyclers is no longer a significant influencing factor. This phenomenon also fully demonstrates that when the whole society's awareness of environmental protection increases, leading to the increase of recovery quantity, the recovery rate will see a remarkable growth, and thus, a virtuous circle of economic situation is formed. In addition, the change rule of recovery rate caused by the change of recovery quantity can also prove the economic theory demonstrated in Figure 2 and Figure 3[18].

4.5. The change law of manufacturer's expected profit with recycling quantity and competition

Figure 11 and Figure 12 show the change law of the manufacturer’s profit with the recycling parties’ competition coefficients and recycling quantities. To be specific, as the recycling competition strengthens, manufacturer’s profit increases; within a certain range of recycling quantity, manufacturer's profit increase, but out of the above range limits, manufacturer's profit will show a downward trend. In addition, conclusion can be drawn from the analysis and comparison of Figure 11 and Figure 12, when the quantity of recycled products is greater than the sale quantity, the manufacturer's profit is greater than the profit he/she earns when the quantity of recycled products is less than the sale quantity. The economic explanation of this phenomenon is that when the quantity of
recycled products is greater than the sale quantity, the recycled products can meet the manufacturer's production capacity because remanufacture is mainly conducted from recycled products, which leads to the increment of the manufacturer's profit. This phenomenon also proves that the circular economy will bring greater profit to manufacturers [19].

5. Summary
This paper studies the change law of closed-loop supply chain decision variables with uncertain recovery quantities under dual competition and builds a manufacturer-dominated dual-competition closed-loop supply chain financial intervention strategy and pricing decision model. The game theory method and Matlab numerical simulation are used to solve the problem. The analysis and comparison of the change laws of wholesale and retail price expectations, recycling and repurchase price expectations, closed-loop supply chain node enterprise profit and social welfare expectations, as well as recovery rate expectations, show that when the quantity of recycled products fluctuates greatly, remanufacturer’s recycling price and repurchase price will also increase; in the closed-loop supply chain with uncertain recycling quantity, the uncertainty of recycling quantity directly affects the enthusiasm of manufacturers who play a leading role in remanufacturing. In addition, when the recycling rate increases significantly, the recycling rate will no longer be the main factor affecting the recyclers’ profit. Combining the above results with economic theoretical analysis, we can draw the following conclusions: When the recycling quantity of closed-loop supply chain is uncertain under dual competition, supply chain node companies would adjust the recycling price to transfer and control market risks. Therefore, only when the quantity of recycled products is sufficient enough to enable the remanufacturing companies to keep a certain business scale and form industrialization, the remanufacturing and recycling companies can really gain profit and, in order to improve social welfare, the government can promote the remanufacturing through financial subsidies. Only in this way, a virtuous economic cycle system can be built in a closed-loop supply chain which also becomes a continuous supply chain[20].

This paper will provide theoretical basis for government fiscal intervention policy formulation and closed-loop supply chain recycling, offer guidance for supply chain companies to avoid the risk resulted from uncertain recycling quantities and further improve the theory of supply chain management.

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