

# Study on Recycling Decisions of Recycling Dismantlers of Used Power Batteries Under the Influence of Recycling Efforts

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**Abstract:** In this study, a closed-loop supply chain consisting of a waste power battery recycler and a power battery manufacturer will be constructed on this basis. The function models under different decision-making modes are constructed with profit maximization as the objective function, and the simulation analysis discusses how the power battery manufacturer should set the purchase price of the raw materials obtained from the dismantling and processing of the waste power battery recycling dismantler, as well as how the waste power battery recycling dismantler should make decisions on the extent of its own efforts under the scenario where the waste power battery recycling dismantler is recycling only its efforts.

**Keywords:** Power battery, Recycling efforts, Recycling decision.

## 1. Introduction

In recent years, with the popularization of new energy vehicles, the demand for power batteries has been rising, which also indicates that the number of retired used power batteries will gradually increase. However, the current recycling process of waste power batteries has not been perfected, resulting in most of the waste batteries failing to enter the dismantling enterprise for processing according to the norms, thus triggering the waste of resources and environmental pollution and other issues. Waste power battery recycling and dismantling business has the ability to recycle and preliminary dismantling and processing of waste power batteries, by which the recycling can make the resources in waste power batteries can be effectively utilized. However, due to the small scale of recycling of waste power battery recycling dismantlers, the dismantling and processing capacity is relatively elementary, which can not cope with the current situation of more and more waste power batteries. Therefore, waste power battery recyclers and dismantlers should invest in recycling efforts to expand the scale of recycling, and invest in dismantling and processing efforts to improve dismantling and processing technology, in order to realize the standardized recycling of waste power batteries and the recycling of resources.

This study will construct a closed-loop supply chain composed of a waste power battery recycler and a power battery manufacturer on this basis. The function models under different decision-making modes are constructed with profit maximization as the objective function, and the simulation analysis discusses how the power battery manufacturer should set the purchase price of raw materials obtained from the dismantling and processing of the waste power battery recycling dismantler under the scenario that the waste power battery recycling dismantler puts in its recycling efforts and how the waste power battery recycling dismantler should decide the extent of its own efforts.

## 2. Literature Review

In the current research on recycling decision-making Parsaeifar<sup>[1]</sup> et al. study and discuss how it makes ordering and pricing decisions on the basis of profit optimization by constructing a closed-loop supply chain involving a manufacturer and multiple suppliers and retailers. Cheng<sup>[2]</sup> et al. establish a recycling decision-making for improving the recycling rate of end-of-life products by using BP neural network optimized by adaptive genetic algorithm. Zhao<sup>[3]</sup> and others constructed a closed-loop supply chain model consisting of different remanufacturing entities and third-party recyclers, and studied the recycling decision-making of their different remanufacturing modes. Yi et al.<sup>[4]</sup> similarly added a third-party recycler to the supply chain members, and constructed a closed-loop supply chain model with a dual recycling channel in which the third-party recycler recycles with the retailer to discuss the optimal recycling decision-making based on profit maximization. maximization basis to discuss their optimal decisions. In the domestic research on recycling decision-making, Fei Wei<sup>[5]</sup> studies and discusses the recycling decision-making of different recycling subjects in the supply chain when they carry out recycling. Feng Zhongwei<sup>[6]</sup> and others discussed the recycling decision of power battery manufacturers in terms of the choice of competing perspectives. Lu Yingjin<sup>[7]</sup> et al. modeled the decision-making problem of the dual-channel recycling structure of a closed-loop supply chain consisting of manufacturers, retailers, and third parties, and introduced a two-part pricing contract mechanism to coordinate the supply chain in order to improve the decision-making level of the supply chain as a whole. Yao Fengmin<sup>[8]</sup> et al. study the recycling decision problem considering manufacturers and retailers based on the EPR system.

Recycling efforts refer to a range of efforts invested in recycling activities, including, but not limited to, the promotion of recycling education, the expansion of recycling networks, and the optimization of recycling processes. These efforts are widely used in a variety of fields, such as garbage

recycling, packaging recycling, appliance recycling, steel recycling, and power battery recycling. Through these measures, public awareness of recycling has not only been enhanced, but also recycling efficiency and resource reuse have been improved. Li Feng<sup>[9]</sup> et al. concluded that garbage recycling efforts positively affect consumers' purchase intention. A study by Ji Chunyi et al<sup>[10]</sup> discussed the positive impact of recycling efforts on logistics packaging and found that packaging waste can be reduced and logistics costs can be lowered by optimizing the recycling process. A study by Worksop<sup>[11]</sup> et al. discussed the positive impact of recycling efforts on parts recycling and noted that by improving recycling technologies and management processes, companies can recycle used parts more efficiently, thereby reducing production costs and supporting sustainable production. Qin Li<sup>[12]</sup> et al. investigated the positive impact of recycling efforts on the recycling of electronic and electrical appliances, and that by enhancing recycling efforts the recycling rate of consumer electronics products can be significantly increased and the environmental impact of these products can be mitigated. Together, these findings suggest that enhancing and expanding recycling efforts can not only increase material recycling rates, but can also have a positive impact at the social and economic levels, facilitating the transition to more sustainable consumption and production patterns.

When modeling a function of recycling effort, it is critical to identify which participants need to invest in recycling effort. Current research covers multiple subjects, including manufacturers, retailers, recyclers, and e-commerce platforms. A study by Li Fang<sup>[13]</sup> et al. explored how manufacturers should adjust their recycling effort levels to optimize resource recovery efficiency under different recycling models. It was found that the recycling effort invested by manufacturers had a significant effect on increasing product recycling rates and reducing environmental impacts. Ji Chunyi<sup>[10]</sup> and others, on the other hand, considered how e-commerce platforms should influence the recycling model by investing recycling efforts from the perspective of e-commerce platforms, and compared the profitability under centralized versus decentralized decision-making environments, and designed a supply chain coordination mechanism based on cost sharing in order to improve the recycling efficiency and economic benefits of the entire supply chain. Wang Yongchao<sup>[14]</sup>, on the other hand, focused on third-party recyclers and explored how third-party recyclers can improve the coordination of the reverse supply chain by increasing recycling efforts, and his study concluded that the increase in recycling efforts of third-party recyclers affects the overall coordination of the supply chain. Ding Bin<sup>[15]</sup>, on the other hand, discusses how manufacturers, when investing recycling efforts, should rationally allocate these efforts to achieve optimal profits in the supply chain. His study discusses a proportional allocation mechanism to maximize the benefits of the entire supply chain through rational allocation of resources. Wang Xiuyan<sup>[16]</sup> et al. discuss the decision-making problem when these two roles undertake recycling efforts from the perspectives of recyclers and recycling processors, respectively. In addition, waste power battery recycling and dismantling vendors differ from ordinary recyclers in terms of cost composition due to the fact that they have both recycling and dismantling and processing capabilities. There are relatively few studies in this area, so this paper will focus on the decision-making model of this

type of recycling dismantler after putting in recycling efforts. Through in-depth analysis, this paper will explore the recycling decision-making from the perspective of waste power battery recyclers and dismantlers after they have invested in recycling efforts, in order to optimize the recycling and treatment process of waste power batteries, and to achieve the enhancement of both environmental and economic benefits.

In the current study, recycling effort is considered to be an important factor influencing the recycling decision of used power batteries, which influences the recycling decision by affecting the recycling quantity and thus the recycling decision. Savaskan<sup>[17]</sup> et al. and Atasu<sup>[18]</sup> et al. considered recycling effort to have a single effect on the recycling quantity. Ma Deqing<sup>[19]</sup> et al. consider the study of recycling decision of retailers with fair news giving under the premise that recycling effort affects recycling quantity, Wang Wenbin<sup>[20]</sup> et al. discuss how closed-loop supply chain incentives should be formulated to encourage recyclers to recycle under the premise that recycling effort affects recycling quantity, and Qin Yanhua<sup>[21]</sup> et al. consider that the price of recycling and recycling effort how the closed-loop supply chain should develop a supply chain coordination strategy when the recycling price and recycling effort affect the recycling quantity at the same time. Since the recyclers and dismantlers of used power batteries are the recipients of the recycling market price of used power batteries, the model construction in this paper will be based on the above studies to discuss the situation where the recycling quantity is only affected by recycling efforts, and through the construction of the model to analyze how the recycling decision-making of the recyclers and dismantlers of used power batteries can maximize the profit of the members of the closed-loop supply chain in the case where they put in the recycling efforts.

### 3. Basic Assumptions and Modeling

#### 3.1. Raise a question

Consider a closed-loop supply chain consisting of a used power battery recycler and dismantler (BR) and a power battery manufacturer (BM), where BR dismantles used batteries and minimally processes them to produce the raw materials required by BM, and BM purchases the raw materials and then produces the batteries for sale. In the supply chain, BM is the dominant player with pricing power, and based on the price set by BM, BR determines its own level of recycling efforts, including the number of recycling outlets, the number of employees it employs, and recycling publicity, thus determining the amount of recycling to be done.

#### 3.2. Underlying assumption

Assumption 1: The raw materials obtained from BR dismantling and processing meet only the minimum requirements for direct remanufacturing by BM.

Assumption 2: Assuming that the only recycling effort invested at this point is the amount of recycling effort, and that the amount of BR recycled is influenced by the level of recycling effort.  $Q_r = Q_0 + \gamma e$ ,  $Q_r$  is the number of recyclables obtained by BR

Assumption 3: Assuming that the quantity of market demand for remanufactured power batteries is  $D$ , (BM's production capacity is  $D$ , and it can sell all of them at the market price of the batteries) and that the quantity of market demand is sufficient.  $D \geq Q_r$ .

Assumption 4: The cost of recycling effort is affected by the level of recycling effort, assuming that the cost of recycling effort<sup>[22]</sup> is quadratic  $C_n = \frac{ke^2}{2}$ ,  $k$  is the cost coefficient of recovery effort,  $k > 0$ , and  $e$  is the level of recovery effort,  $e > 0$ .

Assumption 5: BM has a fixed production capacity and always produces at that size.

Assumption 6: BM's unit remanufacturing cost for remanufacturing using raw materials purchased in the market is  $C_z$  and BM's unit remanufacturing cost for remanufacturing using raw materials purchased at BR is  $C_v$  with  $C_z > C_v$

Assumption 7: Inventory costs for BR and BM are excluded for modeling purposes.

### 3.3. Description of symbols

Description of symbols: as shown in Table 1-3

**Table 1.** Description of supply chain member symbols

| Supply chain members | Description of symbols                  |
|----------------------|---|
| <b>BR</b>            | Used power battery recycling dismantler |
| <b>BM</b>            | Power Battery Manufacturers             |

**Table 2.** Description of parameter symbols

| parameter symbol           | Description of symbols  |
|----------------------------|---|
| <b>D</b>                   | $D$ is the market demand for remanufactured power batteries   |
| <b><math>Q_0</math></b>    | $Q_0$ is the quantity of used power battery that BR can recycle when the recycling price is 0           |
| <b><math>\gamma</math></b> | $\gamma$ is the sensitivity coefficient of recycling effort   |
| <b><math>k</math></b>      | $k$ is the cost coefficient of recycling effort   |
| <b><math>C_z</math></b>    | BM's unit remanufacturing cost for remanufacturing using raw materials purchased from the market        |
| <b><math>C_v</math></b>    | Unit remanufacturing cost of remanufacturing by BM using raw materials purchased at BR                  |
| <b><math>c_d</math></b>    | Unit dismantling and processing cost of raw materials obtained by BR through dismantling and processing |
| <b><math>p_p</math></b>    | Purchase price of standard raw materials purchased from the market by BM                                |
| <b><math>p_s</math></b>    | Sales price of remanufactured power batteries   |
| <b><math>p_r</math></b>    | Unit recycling price of used power battery  |

**Table 3.** Description of decision variable symbols

| Decision Variables      | Symbol Description   |
|-------------------------|--|
| <b><math>p_m</math></b> | Unit selling price of raw materials obtained from dismantling and processing |
| <b><math>Q_r</math></b> | the recycling quantity of used power batteries recycled by BR                |
| <b><math>e</math></b>   | $e$ is the level of recycling effort invested by BR                          |

### 3.4. Model building

Cost function for BR = cost of recycling + cost of dismantling and processing + cost of recycling effort = (quantity recycled \* price of recycling + quantity recycled \* cost of dismantling + cost of recycling effort)

$$C_r = Q_r * (p_r + c_d) + \frac{ke^2}{2}$$

Revenue function for BR = Revenue from raw material sales = Quantity recovered \* Raw material purchase price

$$S_r = Q_r * p_m$$

Profit function of BR = Revenue function of BR - Cost function of BR

$$\Pi_r = S_r - C_r = Q_r * (p_m - p_r - c_d) - \frac{ke^2}{2}$$

Cost function for BM = cost of raw material purchased at BR + cost of standard raw material purchased in the market + cost of remanufacturing = (quantity recovered \* price of raw material purchased + (quantity demanded - quantity recovered) \* price of standard raw material purchased + cost of remanufacturing \* quantity demanded)

$$C_m = Q_r * p_m + (D - Q_r) * p_p + D * C_z$$

Revenue function for BM = Revenue from sales of power batteries + Revenue from remanufacturing cost savings = (Sales price of power batteries \* Quantity demanded + (Cost of remanufacturing - Cost of remanufacturing per unit of remanufacturing using raw materials purchased at BR) \* Quantity recycled)

$$S_m = D * p_s + (C_z - C_v) * Q_r$$

Profit function of BM = Revenue function of BM - Cost function of BM

$$\begin{aligned} \Pi_m &= S_m - C_m = D * p_s + (C_z - C_v) * Q_r - Q_r * p_m \\ &\quad - (D - Q_r) * p_p - D * C_z \\ &= D * (p_s - p_p - C_z) + Q_r * (C_z - C_v - p_m + p_p) \end{aligned}$$

### 4. Model Calculation

(1) Model solution under decentralized decision making

The order of the game at this point is that BM sets the price  $p_m$  of raw materials obtained from BR's disassembly and processing, and BR decides the level of recycling effort  $e$  based on the price  $p_m$  of raw materials.

Based on the profit functions of BM and BR and the order of the game between them, reverse induction is applied to solve the problem.

Solution: under decentralized decision making, BR and BM need to maximize their own profits respectively.

At this time, the function of BR's maximized profit  $\Pi_r$  is:

$$\begin{aligned} \Pi_r &= Q_r * (p_m - p_r - c_d) - \frac{ke^2}{2} \\ &= (Q_0 + \gamma e) * (p_m - p_r - c_d) - \frac{ke^2}{2} \end{aligned}$$

Applying the inverse induction method for the solution, it is first necessary to solve for the decision variable  $e$  of BR, which is obtained after the first-order derivation of  $e$  with respect to  $\Pi_r$ :

$$\frac{\partial \Pi_r}{\partial e} = \gamma * (p_m - p_r - c_d) - ke$$

Then find the second order partial derivative of  $\Pi_r$  with respect to  $e$ ,  $\frac{\partial^2 \Pi_r}{\partial e^2} = -k < 0$  When  $\frac{\partial \Pi_r}{\partial e} = 0$ , there exists a unique equilibrium solution of  $\Pi_r$  with respect to  $e$ .

At this point, let the first-order partial derivative of the recycling effort  $e$  be equal to 0, i.e.

$$\frac{\partial \Pi_r}{\partial e} = \gamma * (p_m - p_r - c_d) - ke = 0$$

Find the response function for the level of recycling effort  $e$ :

$$e = \frac{\gamma * (p_m - p_r - c_d)}{k}$$

At this point the number of recoveries  $Q_r$  is:

$$Q_r = Q_0 + \gamma e = Q_0 + \frac{\gamma^2 * (p_m - p_r - c_d)}{k}$$

At this point the reaction function  $e$  is brought into the profit function of BM. At this point the profit function of BM:

$$\begin{aligned} \Pi_m &= D * (p_s - p_p - c_z) + Q_r * (c_z - c_v - p_m + p_p) \\ &= D * (p_s - p_p - c_z) + Q_0 * (c_z - c_v - p_m + p_p) \\ &\quad + \frac{\gamma^2 * (p_m - p_r - c_d) * (c_z - c_v - p_m + p_p)}{k} \end{aligned}$$

This is obtained after first order derivation of  $p_m$  with respect to  $\Pi_m$ :

$$\frac{\partial \Pi_m}{\partial p_m} = -Q_0 + \frac{\gamma^2 (c_z - c_v + p_p + p_r + c_d) - 2\gamma^2 * p_m}{k}$$

It is obtained by continuing the second order partial derivation for  $p_m$ :

$$\frac{\partial^2 \Pi_m}{\partial p_m^2} = \frac{-2\gamma^2}{k}, \quad \frac{-2\gamma^2}{k} < 0$$

It can be known that  $\Pi_m$  is a strictly concave function with respect to  $p_m$ , at this time, make  $\frac{\partial \Pi_m}{\partial p_m} = 0$ , you can get the optimal raw material purchase price  $p_m$

$$p_m = \frac{-kQ_0 + \gamma^2 (c_z - c_v + p_p + p_r + c_d)}{2\gamma^2}$$

Bringing  $p_m$  into the reaction function, at this point the BR inputs the optimal level of recycling effort  $e$  is:

$$e = \frac{-kQ_0 + \gamma^2 (c_z + p_p - c_v - p_r - c_d)}{2\gamma k}$$

The optimal number of recoveries  $Q_r$  at this point is:

$$Q_r = \frac{kQ_0 + \gamma^2 (c_z - c_v + p_p - p_r - c_d)}{2k}$$

The optimal profit function for BR at this point:

$$\begin{aligned} \Pi_r &= Q_r * (p_m - p_r - c_d) - \frac{ke^2}{2} \\ &= \frac{\gamma^4 (c_z - c_v + p_p - p_r - c_d)^2 - 3k^2 Q_0^2 + 2kQ_0 \gamma^2 (c_z + p_p - c_v - p_r - c_d)}{8k\gamma^2} \end{aligned}$$

The optimal profit function for BM at this point:

$$\begin{aligned} \Pi_m &= D * (p_s - p_p - c_z) + Q_r * (c_z - c_v - p_m + p_p) \\ &= D * (p_s - p_p - c_z) \\ &\quad + \frac{k^2 Q_0^2 + \gamma^4 (c_z - c_v + p_p - p_r - c_d)^2 + 2kQ_0 \gamma^2 (c_z + p_p - c_v - p_r - c_d)}{4k\gamma^2} \end{aligned}$$

## (2) Model solving under centralized decision making

Under centralized decision making, the overall profit optimization of the closed-loop supply chain needs to be achieved, when the total profit of the supply chain is:

$$\begin{aligned} \Pi_{r,m} &= \Pi_r + \Pi_m \\ &= Q_r * (p_m - p_r - c_d) - \frac{ke^2}{2} + D * (p_s - p_p - c_z) + Q_r \\ &\quad * (c_z - c_v - p_m + p_p) \\ &= D * (p_s - p_p - c_z) + (Q_0 + \gamma e) \\ &\quad * (-p_r - c_d + c_z - c_v + p_p) - \frac{ke^2}{2} \end{aligned}$$

At this point, the supply chain members jointly make a decision on the level of recycling effort  $e$ . A first-order derivation of  $e$  with respect to  $\Pi_{r,m}$  yields

$$\frac{\partial \Pi_{r,m}}{\partial e} = \gamma * (-p_r - c_d + c_z - c_v + p_p) - ke$$

Then find the second-order partial derivative of  $\Pi_{r,m}$  with respect to  $e$ ,  $\frac{\partial^2 \Pi_{r,m}}{\partial e^2} = -k < 0$  and there exists a unique equilibrium solution of  $\Pi_{r,m}$  with respect to  $e$ , such that a one-sectional partial derivative of the recycling effort  $e$  is equal to 0, i.e.

$$\frac{\partial \Pi_{r,m}}{\partial e} = \gamma * (-p_r - c_d + c_z - c_v + p_p) - ke = 0$$

The optimal level of recycling effort can be obtained  $e$ :

$$e = \frac{\gamma * (-p_r - c_d + c_z - c_v + p_p)}{k}$$

The optimal number of recoveries  $Q_r$  at this point is:

$$Q_r = Q_0 + \gamma e = \frac{kQ_0 + \gamma^2 * (-p_r - c_d + c_z - c_v + p_p)}{k}$$

At this point the total supply chain profit  $\Pi_{r,m}$  is:

$$\begin{aligned} \Pi_{r,m} &= D * (p_s - p_p - c_z) + (Q_0 + \gamma e) \\ &\quad * (-p_r - c_d + c_z - c_v + p_p) - \frac{ke^2}{2} \\ &= D * (p_s - p_p - c_z) \\ &\quad + \frac{2kQ_0 * (-p_r - c_d + c_z - c_v + p_p) + \gamma^2 * (-p_r - c_d + c_z - c_v + p_p)^2}{2k} \end{aligned}$$

## 5. Parametric Analysis

In order to compare the decentralized decision-making and centralized decision-making, the optimal profit of each member of the supply chain, this paper will be brought into the parameters for preliminary calculations, the relevant parameters are assumed as follows, as shown in Table 4.

Table 4. Parameter assignment

| Parameter Symbol | Parameter Assignment |
|------------------|----------------------|
| $D$              | 500                  |
| $Q_0$            | 100                  |
| $\gamma$         | 10                   |
| $k$              | 5                    |
| $c_z$            | 25                   |
| $c_v$            | 15                   |
| $c_d$            | 10                   |
| $p_p$            | 20                   |
| $p_s$            | 50                   |
| $p_r$            | 10                   |

(1) Comparative analysis under decentralized and centralized decision making

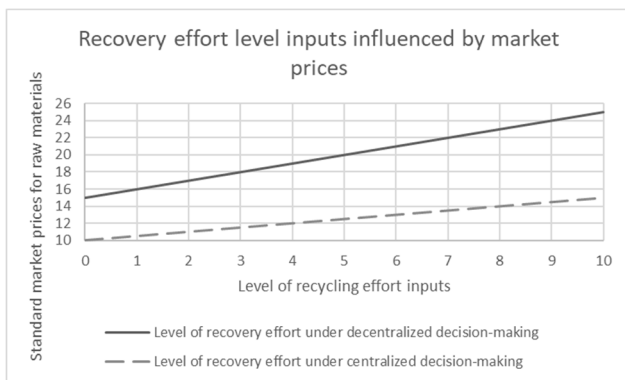
The above values are brought into the function model constructed by decentralized decision making. When BM buys the raw materials obtained from disassembly and processing from BR at the optimal price per unit  $p_m = 22.5$ , BR's optimal recycling effort  $e = 5$ , and the optimal number of used power batteries to be recycled  $Q_r$  is 150 units. At this time, the profit of BR is \$312.5 and the profit of BM is \$3625. Bringing the above values into the function model constructed by centralized decision making, the optimal recycling effort in the closed-loop supply chain is  $e = 5$ , the optimal recycling quantity  $Q_r$  is 300, and the optimal profit is \$4500.

By comparing the profits under decentralized decision-making and centralized decision-making, it can be found that under centralized decision-making, the supply chain members

need to invest more recycling efforts and can recycle more quantity of used power batteries, and the overall profit of the supply chain is larger than the overall profit under decentralized decision-making. This shows that the centralized decision-making of each member in a closed-loop supply chain is better than the separate decision-making of each member.

(2) Analysis of the impact of changes in the purchase prices of standard raw materials in the market on the level of recycling efforts put in by recyclers and dismantlers of used power batteries

With all other parameters held constant, it can be seen from Figure 1. Under both decentralized and centralized decision making, the level of recycling effort input of the waste power battery recycling dismantler increases with the increase in the standard price of raw materials in the market. Under decentralized decision making, when the purchase price of raw materials in the market is equal to the unit remanufacturing cost of BM using raw materials purchased from BR for remanufacturing, the level of recycling effort input  $e = 0$ . Under centralized decision making, when the purchase price of raw materials in the market is equal to the unit dismantling processing cost of raw materials obtained from BR for dismantling processing, the level of recycling effort input  $e = 0$ . In both cases, the waste power battery recycling dismantlers will not choose to increase the quantity of recyclables recovered by increasing their own recycling effort input and thus increasing the quantity of recyclables recovered.



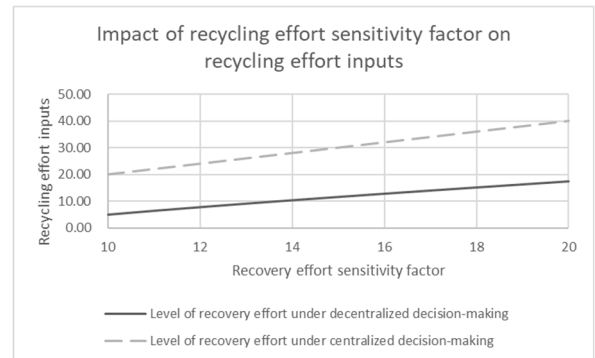
**Figure 1** Recovery effort inputs under the influence of market prices

It can be seen that when the market standard raw material price decreases to a certain extent, waste power battery recycling dismantlers will no longer be willing to invest in recycling efforts. Whereas, when the market standard price rises, waste power battery recycling dismantlers will be willing to invest more recycling efforts to recycle in large quantities.

(3) Impact of recycling effort sensitivity coefficients on the level of recycling effort invested by recyclers and dismantlers of used power batteries

With other parameters held constant, assuming  $\gamma \in (10,20)$ , as known from Fig. 2. Under decentralized decision-making and centralized decision-making, the recycling effort input level of waste power battery recycling dismantlers increases with the increase of the recycling effort sensitivity coefficient. Meanwhile, as known from the figure, under the same recycling effort sensitivity coefficient, centralized decision-making is more willing to invest recycling effort to participate in recycling behavior compared to decentralized

decision-making.

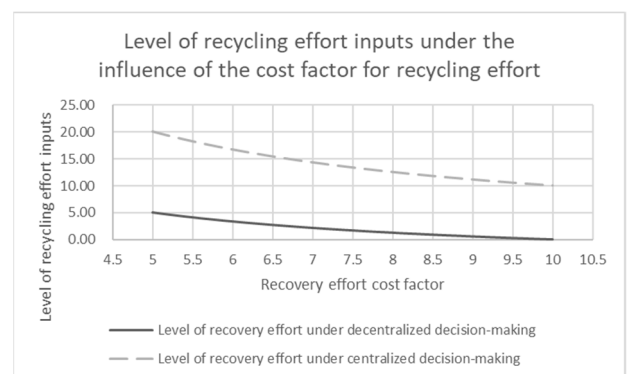


**Figure 2** Impact of recycling effort sensitivity factor on recycling effort inputs

The sensitivity factor of recycling efforts is influenced by social environmental protection propaganda and national environmental protection requirements. With the improvement of social environmental protection requirements, consumers' environmental protection awareness increases, and they are willing to deliver used power batteries to recyclers and dismantlers with formal dismantling and processing capabilities, thus increasing the number of recycling dismantlers. At the same time, the increase of consumers' environmental awareness makes them acceptance of remanufactured power batteries, which increases the demand for remanufactured power batteries, and promotes the recycling and dismantling business to increase the degree of recycling efforts, and recycle a greater number of used power batteries. Therefore, the state should strengthen the education of environmental protection awareness, guide consumers to choose formal recycling and dismantling channels, and realize the recycling of waste power battery resources.

(4) Impact of recycling effort cost coefficients on the level of recycling effort invested by recyclers and dismantlers of used power batteries

With other parameters held constant, assuming  $k \in (5,10)$ , as known from Fig. 3. Under both decentralized and centralized decision making, the recycling effort input level of waste power battery recycling dismantlers decreases with the increase of the recycling effort cost coefficient.



**Figure 3.** Impact of recovery effort cost coefficients on recovery effort inputs

The cost coefficient of recycling effort is related to the innovation of enterprise management. If waste power battery recycling dismantlers can standardize the management of the recycling process, the cost sensitivity coefficient of their recycling efforts will be reduced and the level of recycling

effort input will increase, which will affect the recycling quantity of waste power batteries. Therefore, used power battery recyclers and dismantlers need to be encouraged to strictly standardize their internal process management.

(5) The effect of recovery effort sensitivity coefficients and recovery effort cost coefficients on raw material purchase prices, recovered quantities, and profits under different decisions

Assume  $\gamma \in (10,20), k \in (5,10)$  with all other parameters held constant.

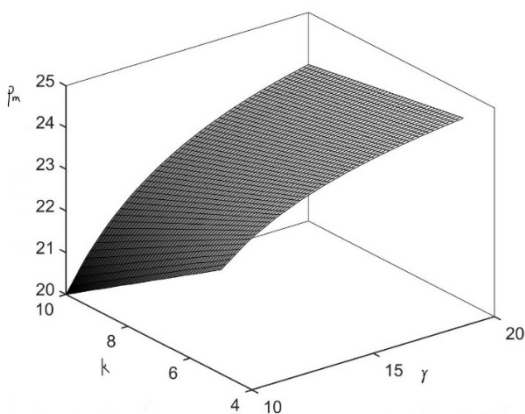
Under decentralized decision making, the effects of the recycling effort sensitivity coefficient  $\gamma$  and the recycling effort cost coefficient  $k$  on the raw material prices set by BM are shown in Figure 4. The effects of recycling effort sensitivity coefficient  $\gamma$  and recycling effort cost coefficient  $k$  on the quantity of BR recycled are shown in Fig. 5. The effect of recycling effort sensitivity coefficient  $\gamma$  and recycling effort cost coefficient  $k$  on BR profit is shown in Fig. 6.

The effect of recycling effort sensitivity coefficient  $\gamma$  and recycling effort cost coefficient  $k$  on the quantity of supply chain recycling under centralized decision-making is shown in Fig. 7. The effect of recycling effort sensitivity coefficient  $\gamma$  and recycling effort cost coefficient  $k$  on the overall supply chain profit is shown in Fig. 8.

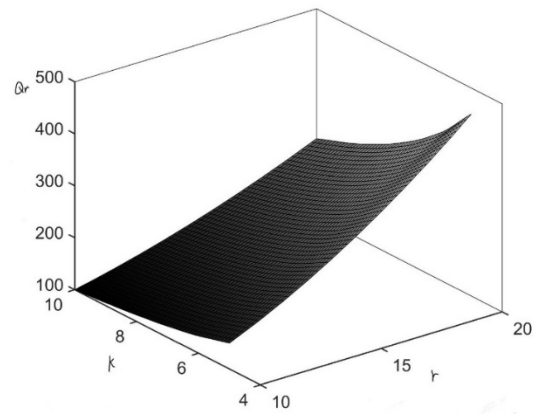
The variable case assumes that  $\gamma \in (10,20), k \in (5,10)$ .

Under decentralized decision making, the effects of the recycling effort sensitivity coefficient  $\gamma$  and the recycling effort cost coefficient  $k$  on the raw material prices set by BM are shown in Figure 4. The effects of recycling effort sensitivity coefficient  $\gamma$  and recycling effort cost coefficient  $k$  on the quantity of BR recycled are shown in Fig. 5. The effect of recycling effort sensitivity coefficient  $\gamma$  and recycling effort cost coefficient  $k$  on BR profit is shown in Fig. 6.

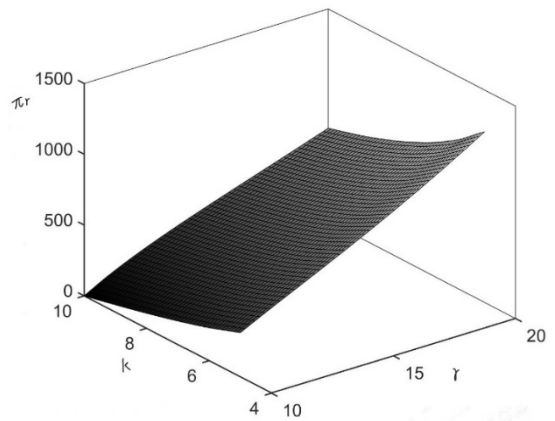
The effect of recycling effort sensitivity coefficient  $\gamma$  and recycling effort cost coefficient  $k$  on the quantity of supply chain recycling under centralized decision-making is shown in Fig. 7. The effect of recycling effort sensitivity coefficient  $\gamma$  and recycling effort cost coefficient  $k$  on the overall supply chain profit is shown in Fig. 8.



**Figure 4** Impact of recycling effort inputs on the price of purchased raw materials

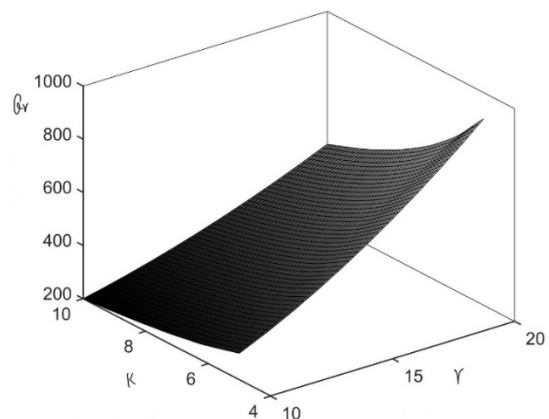


**Figure 5** Impact of recycling effort inputs on recycled quantities

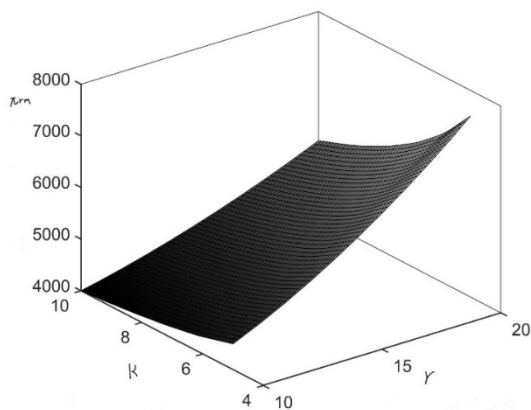


**Figure 6** Impact of recycling effort inputs on the profitability of recycling dismantlers

As can be seen from Figures 4, 5 and 6, under decentralized decision-making, the recycling effort cost coefficient and the recycling effort sensitivity coefficient simultaneously affect the raw material procurement price, the quantity of used power batteries recycled and the overall profit of used power battery recyclers and dismantlers. The higher the recycling effort sensitivity coefficient, the lower the recycling effort cost coefficient, the higher the raw material procurement price pricing of power batteries, the higher the quantity of used power batteries recycled, and the higher the overall profit of used power battery recyclers.



**Figure 7** Impact of recycling effort inputs on recycled quantities



**Figure 8** Impact of recycling effort inputs on overall supply chain profitability

As can be seen from Figures 7 and 8, under centralized decision-making, the closed-loop supply chain will become a whole and make decisions on recycling behaviors together. At this time, the recycling effort cost coefficient and the recycling effort sensitivity coefficient affect both the quantity of used power battery recycling and the overall profit of the closed-loop supply chain. The higher the recycling effort sensitivity coefficient is, the lower the recycling effort cost coefficient is, the higher the quantity of used power battery recycling is, and the higher the overall profit of the closed-loop supply chain is.

Comparing the overall profits under decentralized and centralized decision-making suggests that individual members of a closed-loop supply chain should centralize their decision-making, and that shared responsibility for effort will result in greater profits. Under decentralized decision-making, each member may only consider maximizing its own interests, leading to waste of resources and inefficiency, thus affecting the overall profit. In contrast, centralized decision-making can coordinate each link, optimize resource allocation, and improve overall efficiency, thus maximizing profits in a closed-loop supply chain. In addition to the centralization of decision-making among members, the state should also strengthen the guidance of consumer behavior, through policies and regulations and publicity and education to guide consumers to reduce the casual disposal of waste power batteries and promote recycling. This can reduce the emissions of waste power batteries and reduce environmental pollution, while expanding the scale of the recycling market and providing more recycling resources for waste power battery recycling and dismantling vendors. In addition, waste power battery recycling dismantlers should also regulate their own recycling behavior management, establish a sound recycling and dismantling process and environmental protection measures to ensure the protection of the environment and personnel safety in the dismantling process, and improve the quality and reuse rate of recycled products. This will not only help to improve corporate image and market competitiveness, but also contribute to the sustainable development of the entire closed-loop supply chain.

## 6. Summary and Outlook

### Acknowledgment

This chapter compares the results of decentralized and centralized decision making by constructing a model and

performing parametric simulation analysis. It is found that centralized decision-making can more easily lead to higher profits in a closed-loop supply chain. In addition, the recycling effort input is affected by the price of standard raw materials in the market, and when the price of standard raw materials in the market decreases to a certain extent, the waste power battery recycling and dismantling vendors will be reluctant to carry out recycling efforts. In addition, the recycling effort positively affects the recycling quantity and overall profit after the waste power battery recycling dismantler puts in recycling effort. The recycling effort is also affected by the recycling effort sensitivity factor and the recycling effort cost factor, in which the recycling effort sensitivity factor is related to the social environmental protection awareness, and the recycling effort cost factor is related to the management innovation of the waste power battery recycling dismantlers.

In summary, the society needs to strengthen the publicity of environmental protection awareness, the government needs to guide consumers to regulate the recycling behavior, and at the same time, the waste power battery recycling and dismantling merchants also need to carry out management innovation and regulate their own recycling process. The research results in this chapter provide important references for decision-making in the closed-loop supply chain, and also put forward specific suggestions for environmental awareness and management innovation in related fields.

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