

# Design of Reverse Logistics Network for Power Battery Considering Transportation Risk

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## ABSTRACT

In order to integrate the concept of sustainable development and safety into the management of power battery recycling, a sustainable reverse logistics network considering the balanced development of risk and cost is constructed. The model takes into account many uncertain factors, including the recovery amount, recovery price, transportation distance, treatment cost and so on, and uses fuzzy theory to transform it into a deterministic model. Finally, the validity of the model is analyzed by an example, and the sensitivity of the parameters is analyzed. The results show that the multi-objective decision-making model can effectively promote the coordinated development of risk and cost compared with the single-objective optimization model, and the change of risk and cost weight will lead to the corresponding change of its objective function, which provides a theoretical basis for the decision-making of risk and cost control of power battery reverse logistics network in the environment of limited information uncertainty.

## KEYWORDS

Retired power battery recycling; Risk control; Network optimization; Uncertain factors

## 1. INTRODUCTION

In recent years, with the rapid development of social economy, problems such as lack of resources, environmental pollution and climate change have become increasingly prominent, and countries have paid more and more attention to the development of electric vehicles. The development of electric vehicles will inevitably lead to the retirement of power batteries. As the ninth kind of dangerous goods, power battery has high energy density and is prone to natural and explosion accidents. In 2022 alone, more than 40 power batteries spontaneously ignited or exploded during transportation, posing a great risk to the lives and property of surrounding residents. According to the forecast of China Automotive Technology and Research Center, combined with the service life and retirement years of automotive power batteries, it is estimated that the annual retirement amount of power batteries will reach 3.5 million tons in 2030. Faced with such a large amount of decommissioning, if it cannot be effectively recycled, it will inevitably pose a great threat to the environment, economy and public health.

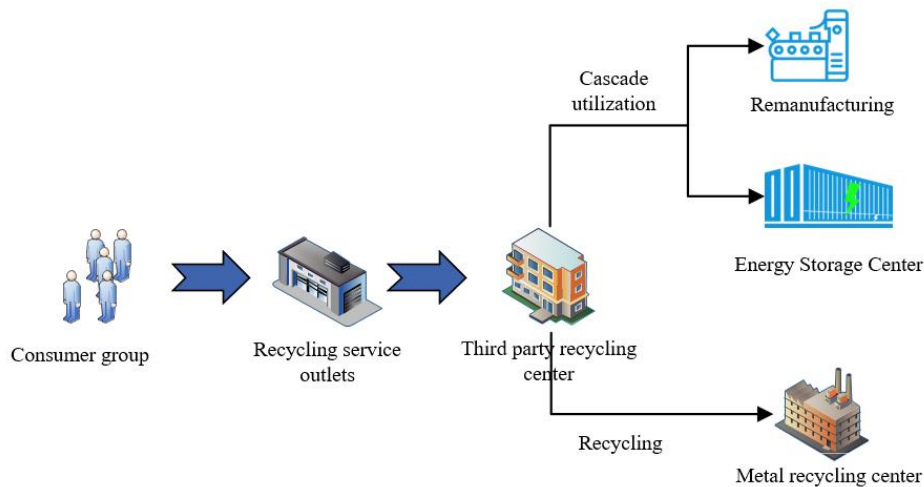
At present, there are a lot of literatures on the recycling of retired power batteries, such as the recycling mode [1-4], recycling system [5-6] and recycling policy [7-9]. However, there is little research on the optimization of reverse logistics network of retired power batteries. In the existing literature on recycling network, it mainly focuses on economic aspects, such as cost minimization [10-11], revenue maximization [12-13] and recycling risk [14]; Environmental aspects, such as minimizing carbon emissions [15-16]; Social aspects, such as social benefits [17]. Although the above literature discusses the optimization of reverse logistics network of power battery, it is not regarded as the transportation risk brought by the analysis and recovery of dangerous goods in the model.

In addition, in the existing power battery recycling network, the research in uncertain environment mostly focuses on the recycling quantity, which is to reduce the difficulty of solving. In fact, the recycling of power batteries is still in the early stage, and all kinds of information are limited. In the next few years, the number of retired batteries will increase substantially, and all kinds of facilities at all levels need to be improved. Therefore, it is more realistic to carry out research including more uncertain factors such as recovery price, treatment cost of facilities at all levels and transportation distance.

Therefore, by considering the cascade utilization characteristics of retired power batteries, this paper establishes a reverse logistics network that takes into account risks and costs and considers various uncertain factors. Finally, an example is analyzed to verify the effectiveness of the model, and the influence of the change of risk and cost weight on the design of retired power battery recycling network is analyzed.

## 2. PROBLEM DESCRIPTION

The decommissioned power battery recycling network generally includes consumer groups, recycling service outlets, third-party recycling centers, echelon utilization enterprises and recycling enterprises. The recycling process is shown in Fig. 1. Retired power batteries in consumers' hands are transported to a third-party recycling center through recycling service outlets, and the third-party recycling center disassembles the batteries into battery units, and carries out quality grade detection and classification. According to the degradation degree of battery performance, the battery is recycled and reused respectively.



**Figure 1.** Recycling process of retired power battery

### 2.1. Model Assumptions

For the convenience of research, the following assumptions are made:

- (1) Alternative addresses of known recycling service outlets, third-party recycling centers and echelon utilization enterprises.
- (2) The transportation risk of decommissioned power batteries is only related to the transportation quantity and the population density affected.
- (3) The recycling network cannot be transported by leaps and bounds, and the roads are interconnected, and the road conditions are normal (regardless of road congestion, etc.).
- (4) For the time being, the influence of social vehicles on retired power battery transport vehicles will not be considered.

## 2.2. Symbol Description

Parameters and variables are shown in Table 1:

**Table 1.** Description of model parameters and decision variables

|           | symbol  | meaning  |
|-----------|---|--|
| gather    | M   | Consumer, $m \in \{1, 2, \dots, M\}$   |
|           | N   | Recycling service outlets, $n \in \{1, 2, \dots, N\}$  |
|           | R   | Third-party recycling center, $r \in \{1, 2, \dots, R\}$   |
|           | A   | Remanufacturer, $a \in \{1, 2, \dots, A\}$   |
|           | B   | Energy storage center, $b \in \{1, 2, \dots, B\}$  |
|           | C   | Metal recycling center, $c \in \{1, 2, \dots, C\}$   |
| parameter | $\bar{F}$   | Fixed construction costs of recycling service outlets, third-party recycling centers, remanufacturers, energy storage centers and metal recycling centers: $\bar{F}_n, \bar{F}_r, \bar{F}_a, \bar{F}_b, \bar{F}_c$   |
|           | $\bar{O}$   | Unit processing cost of recycling service outlets, third-party recycling centers, remanufacturers, energy storage centers and metal recycling centers: $\bar{O}_n, \bar{O}_r, \bar{O}_a, \bar{O}_b, \bar{O}_c$   |
|           | $\bar{P}$   | Maximum processing capacity of recycling service outlets, third-party recycling centers, remanufacturers, energy storage centers and metal recycling centers: $\bar{p}_n, \bar{p}_r, \bar{p}_a, \bar{p}_b, \bar{p}_c$  |
|           | $\bar{D}$   | The distances between consumer groups, recycling service outlets, third-party recycling centers, remanufacturers, energy storage centers and metal recycling centers are: $\bar{D}_{mn}, \bar{D}_{nr}, \bar{D}_{ra}, \bar{D}_{rb}, \bar{D}_{rc}$                               |
|           | $\tilde{\rho}$  | Crowd density along the road between consumers, recycling service outlets, third-party recycling centers, remanufacturers, energy storage centers and metal recycling centers: $\tilde{\rho}_{mn}, \tilde{\rho}_{nr}, \tilde{\rho}_{ra}, \tilde{\rho}_{rb}, \tilde{\rho}_{rc}$ |
|           | $\tilde{U}_m$   | Weight of retired power batteries recovered by consumer group M  |
|           | $\tilde{T}$   | Recovery price per unit battery quality of recycling service outlets.  |
|           | $\tilde{X}$   | Recovery price per unit battery quality of recycling service outlets.  |
|           | $\theta$  | Consequences caused by accidents of decommissioned power batteries per unit weight   |
|           | $\omega$  | Probability of accidents of retired power batteries per unit weight  |
|           | $\sigma$  | The classification ratio of quality inspection of retired power batteries by the third-party recycling center is: $\sigma_1, \sigma_2, \sigma_3$   |
|           | decision variable   |  |
|           | $Y_n$   | 1, if the recycling service network n is opened, otherwise zero  |
| $Y_r$     | 1, if the third-party recycling center R is opened, otherwise zero  |  |
| $Y_a$     | 1, if the remanufacturer A is set up, otherwise zero  |  |
| $Y_b$     | 1, if the energy storage center B is set up, otherwise zero   |  |
| $Y_c$     | 1, if a metal recycling center is set up, otherwise zero  |  |
| $U_{cn}$  | An integer variable representing the weight of the battery transported from the consumer group c to the recycling service network n.                  |  |
| $U_{nr}$  | An integer variable that represents the weight of the battery transported from the recycling service network n to the third-party recycling center r. |  |
| $U_{ra}$  | An integer variable that represents the weight of the battery shipped from the third-party recycling center r to the remanufacturer a.                |  |
| $U_{rb}$  | Integer variable, indicating the quality of the battery transported to the energy storage center at the third-party recycling center r.               |  |
| $U_{rc}$  | Integer variable, which indicates the quality of the battery transported by the third-party recycling center r to the metal recycling center.         |  |

### 2.3. Model Building

In this paper, the accident probability adopts the formula [18] of dangerous goods accident rate per mile/vehicle in 2001 of the Federal Motor Transport Safety Administration of the United States, namely:

$$\omega = 3.19922 * 10^{-7} * \frac{distance}{1.609344} = 1.987903 * 10^{-7} * distance \quad (1)$$

At this time, the distance unit is converted from the original mile to km.

Assuming that the accident scope is circular and the radius of the accident scope is 1km, the accident consequences are as follows:

$$\theta = \pi * 1^2 * \rho \quad (2)$$

The transportation risk Q is:

$$Q = \omega * \theta * \rho * \tilde{D} \quad (3)$$

With the goal of minimizing the total transportation risk and total network cost of reverse logistics of power batteries, a fuzzy multi-objective programming model I is constructed, as shown below:

$$Z1 = 1.987903 * 10^{-7} * \pi * \left( \sum_m \sum_n U_{mn} \tilde{D}_{mn} \tilde{\rho}_{mn} + \sum_n \sum_r U_{nr} \tilde{D}_{nr} \tilde{\rho}_{nr} + \sum_r \sum_a U_{ra} \tilde{D}_{ra} \tilde{\rho}_{ra} + \sum_r \sum_b U_{rb} \tilde{D}_{rb} \tilde{\rho}_{rb} + \sum_r \sum_c U_{rc} \tilde{D}_{rc} \tilde{\rho}_{rc} \right) \quad (4)$$

$$Z2 = \tilde{X} \left( \sum_m \sum_n \tilde{D}_{mn} U_{mn} + \sum_n \sum_r \tilde{D}_{nr} U_{nr} + \sum_r \sum_a \tilde{D}_{ra} U_{ra} + \sum_r \sum_b \tilde{D}_{rb} U_{rb} + \sum_r \sum_c \tilde{D}_{rc} U_{rc} \right) + \sum_n \tilde{F}_n Y_n + \sum_r \tilde{F}_r Y_r + \sum_a \tilde{F}_a Y_a + \sum_b \tilde{F}_b Y_b + \sum_c \tilde{F}_c Y_c + T \sum_m \sum_n U_{mn} + \sum_m \sum_n \tilde{O}_n U_{mn} + \sum_n \sum_r \tilde{O}_r U_{nr} + \sum_r \sum_a \tilde{O}_a U_{ra} + \sum_r \sum_b \tilde{O}_b U_{rb} + \sum_r \sum_c \tilde{O}_c U_{rc} \quad (5)$$

s.t.

$$\sum_n U_{mn} \geq \tilde{U}_m, \quad \forall m \quad (6)$$

$$\sum_m U_{mn} = \sum_r U_{nr}, \quad \forall n \quad (7)$$

$$\sum_n U_{nr} = \sum_a U_{ra} + \sum_b U_{rb} + \sum_c U_{rc}, \quad \forall r \quad (8)$$

$$\sum_a U_{ra} = \sigma_1 \sum_n U_{nr}, \quad \forall r \quad (9)$$

$$\sum_b U_{rb} = \sigma_2 \sum_n U_{nr}, \quad \forall r \quad (10)$$

$$\sum_c U_{rc} = \sigma_3 \sum_n U_{nr}, \forall r \quad (11)$$

$$\sum_m U_{mn} \leq \tilde{P}_n Y_n, \forall n \quad (12)$$

$$\sum_n U_{nr} \leq \tilde{P}_r Y_r, \forall r \quad (13)$$

$$\sum_r U_{ra} \leq \tilde{P}_a Y_a, \forall a \quad (14)$$

$$\sum_r U_{rb} \leq \tilde{P}_b Y_b, \forall b \quad (15)$$

$$\sum_r U_{rc} \leq \tilde{P}_c Y_c, \forall c \quad (16)$$

$$U_{mn}, U_{nr}, U_{ra}, U_{rb}, U_{rc} \geq 0 \text{ and is an integer}, \forall m, n, r, a, b, c \quad (17)$$

$$Y_n, Y_r, Y_a, Y_b, Y_c \in \{0,1\}, \forall n, r, a, b, c \quad (18)$$

Where Formula (4) is the total risk objective function; Formula (5) is the total cost objective function; Formula (6) indicates that the total amount of transportation from consumer groups to recycling service outlets is not greater than the total amount of recycled decommissioned power batteries; Formula (7) indicates that all power batteries recovered by consumers are transported to a third-party recycling center; Formula (8) indicates that all the power batteries of the third-party recycling center flow to the echelon utilization enterprise; Equations (9)-(11) represent the relationship between the recovery amount of the echelon utilization enterprise and the total yield of the power battery; Equations (12)-(16) represent the constraints of facility handling capacity, and equations (17)-(18) represent the constraints of decision variables.

## 2.4. Fuzzy Model Transformation

There are uncertain parameters in model I, which need to be converted into equivalent definite parameters for the convenience of calculation. Let  $\tilde{\varepsilon} = (\varepsilon^1, \varepsilon^2, \varepsilon^3)$  is a triangular fuzzy number, and  $\varepsilon^1 \leq \varepsilon^2 \leq \varepsilon^3$ , confidence level is  $\alpha$ . Assuming that it is a triangular fuzzy number and the confidence level is  $\alpha$ , the fuzzy model I is transformed into a deterministic model II by deblurring:

$$\begin{aligned} Z1 = & 1.987903 * 10^{-7} * \pi * \left( \sum_m \sum_n U_{mn} \frac{D_{mn}^1 + 2D_{mn}^2 + D_{mn}^3}{4} \frac{\rho_{mn}^1 + 2\rho_{mn}^2 + \rho_{mn}^3}{4} + \right. \\ & \sum_n \sum_r U_{nr} \frac{D_{nr}^1 + 2D_{nr}^2 + D_{nr}^3}{4} \frac{\rho_{nr}^1 + 2\rho_{nr}^2 + \rho_{nr}^3}{4} + \sum_r \sum_a U_{ra} \frac{D_{ra}^1 + 2D_{ra}^2 + D_{ra}^3}{4} \frac{\rho_{ra}^1 + 2\rho_{ra}^2 + \rho_{ra}^3}{4} \\ & \left. + \sum_r \sum_b U_{rb} \frac{D_{rb}^1 + 2D_{rb}^2 + D_{rb}^3}{4} \frac{\rho_{rb}^1 + 2\rho_{rb}^2 + \rho_{rb}^3}{4} + \sum_r \sum_c U_{rc} \frac{D_{rc}^1 + 2D_{rc}^2 + D_{rc}^3}{4} \frac{\rho_{rc}^1 + 2\rho_{rc}^2 + \rho_{rc}^3}{4} \right) \end{aligned} \quad (19)$$

$$\begin{aligned}
Z2 = & \frac{X^1 + 2X^2 + X^3}{4} \left( \sum_m \sum_n \frac{D_{mn}^1 + 2D_{mn}^2 + D_{mn}^3}{4} U_{mn} + \sum_n \sum_r \frac{D_{nr}^1 + 2D_{nr}^2 + D_{nr}^3}{4} U_{nr} + \right. \\
& \sum_r \sum_a \frac{D_{ra}^1 + 2D_{ra}^2 + D_{ra}^3}{4} U_{ra} + \sum_r \sum_b \frac{D_{rb}^1 + 2D_{rb}^2 + D_{rb}^3}{4} U_{rb} + \sum_r \sum_c \frac{D_{rc}^1 + 2D_{rc}^2 + D_{rc}^3}{4} U_{rc} \left. \right) + \\
& \sum_n \frac{F_n^1 + 2F_n^2 + F_n^3}{4} Y_n + \sum_r \frac{F_r^1 + 2F_r^2 + F_r^3}{4} Y_r + \sum_a \frac{F_a^1 + 2F_a^2 + F_a^3}{4} Y_a + \sum_b \frac{F_b^1 + 2F_b^2 + F_b^3}{4} Y_b + \\
& \sum_c \frac{F_c^1 + 2F_c^2 + F_c^3}{4} Y_c + \frac{T^1 + 2T^2 + T^3}{4} \sum_m \sum_n U_{mn} + \sum_m \sum_n \frac{O_n^1 + 2O_n^2 + O_n^3}{4} U_{mn} + \sum_n \sum_r \frac{O_r^1 + 2O_r^2 + O_r^3}{4} U_{nr} \\
& + \sum_r \sum_a \frac{O_a^1 + 2O_a^2 + O_a^3}{4} U_{ra} + \sum_r \sum_b \frac{O_b^1 + 2O_b^2 + O_b^3}{4} U_{rb} + \sum_r \sum_c \frac{O_c^1 + 2O_c^2 + O_c^3}{4} U_{rc}
\end{aligned} \tag{20}$$

s.t.

$$\sum_n U_{mn} \geq \alpha_1 \left( \frac{U_m^3 + U_m^2}{2} \right) + (1 - \alpha_1) \left( \frac{U_m^1 + U_m^2}{2} \right), \quad \forall m \tag{21}$$

$$\sum_m U_{mn} \leq [\alpha_3 \left( \frac{P_n^1 + P_n^2}{2} \right) + (1 - \alpha_3) \left( \frac{P_n^3 + P_n^2}{2} \right)] Y_n, \quad \forall n \tag{22}$$

$$\sum_n U_{nr} \leq [\alpha_4 \left( \frac{P_r^1 + P_r^2}{2} \right) + (1 - \alpha_4) \left( \frac{P_r^3 + P_r^2}{2} \right)] Y_r, \quad \forall r \tag{23}$$

$$\sum_r U_{ra} \leq [\alpha_5 \left( \frac{P_a^1 + P_a^2}{2} \right) + (1 - \alpha_5) \left( \frac{P_a^3 + P_a^2}{2} \right)] Y_a, \quad \forall a \tag{24}$$

$$\sum_r U_{rb} \leq [\alpha_6 \left( \frac{P_b^1 + P_b^2}{2} \right) + (1 - \alpha_6) \left( \frac{P_b^3 + P_b^2}{2} \right)] Y_b, \quad \forall b \tag{25}$$

$$\sum_r U_{rc} \leq [\alpha_7 \left( \frac{P_c^1 + P_c^2}{2} \right) + (1 - \alpha_7) \left( \frac{P_c^3 + P_c^2}{2} \right)] Y_c, \quad \forall c \tag{26}$$

And the constraints (7)-(11), (17)-(18) in model I.

## 2.5. Multi-objective Optimization Solution

The above multi-objective programming model gives the objective functions of risk and cost. In the model, risk and cost are contradictory, and their importance is different in different situations, and the scope and unit of each goal are different, so the simple linear weighting method is unreasonable. To this end, we first consider eliminating the two target units, and set  $\gamma$  as the weight value of the risk target and  $\eta$  as the weight value of the cost target, so that the numerical range of each weight is standardized as the  $[0, 1]$  interval, namely:

$$\min Z = \gamma \frac{Z1}{Z1^*} + \eta \frac{Z2}{Z2^*} \tag{27}$$

Where  $Z1^*$  and  $Z2^*$  respectively represent the minimum risk value of a single risk objective and the minimum cost value of a single cost objective.

### 3. EXPERIMENTAL ANALYSIS

#### 3.1. Description of an Example

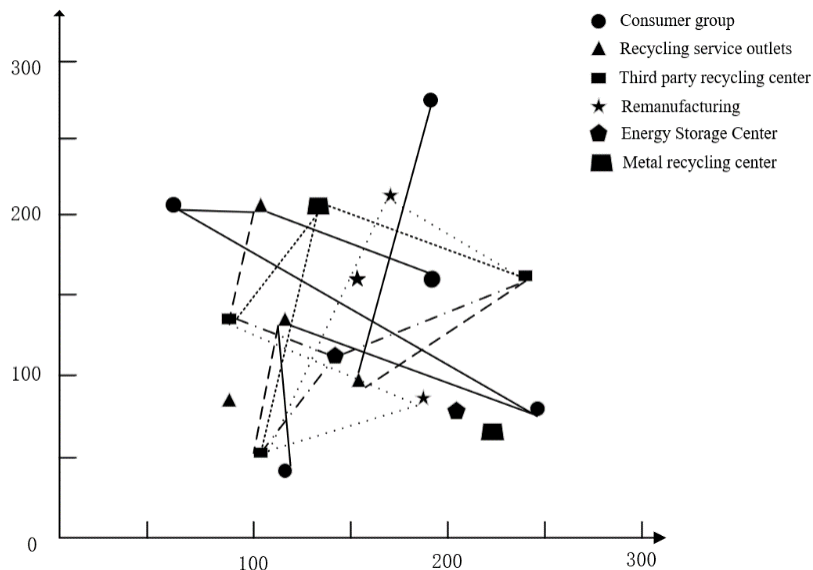
There are five consumer points randomly generated by simulation software, four candidate recycling service outlets, three candidate third-party recycling centers, three remanufacturers, two energy storage centers and two metal recycling centers. In addition, let  $\alpha=0.9$ ,  $\gamma=0.9$  and  $\eta=0.1$ ,  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$  be 0.5, 0.3 and 0.2, respectively. See Table 2 for the parameter settings.

**Table 2.** Parameter Settings

| parameter | distributed function | parameter   | distributed function |
|-----------|----------------------|-------------|----------------------|
| $F_n$     | U(60000, 100000)     | $P_c$       | U(4500, 8000)        |
| $F_r$     | U(200000, 400000)    | $D_{mn}$    | U(2, 20)             |
| $F_a$     | U(200000, 300000)    | $D_{nr}$    | U(50, 300)           |
| $F_b$     | U(180000, 290000)    | $D_{ra}$    | U(100, 400)          |
| $F_c$     | U(100000, 180000)    | $D_{rb}$    | U(150, 300)          |
| $O_n$     | U(90, 140)           | $D_{rc}$    | U(100, 500)          |
| $O_r$     | U(200, 500)          | $\rho_{cn}$ | U(20000, 40000)      |
| $O_a$     | U(150, 400)          | $\rho_{nr}$ | U(15000, 30000)      |
| $O_b$     | U(120, 200)          | $\rho_{ra}$ | U(10000, 20000)      |
| $O_c$     | U(80, 130)           | $\rho_{rb}$ | U(12000, 26000)      |
| $P_n$     | U(3000, 4700)        | $\rho_{rc}$ | U(12000, 20600)      |
| $P_r$     | U(4000, 6200)        | $U_c$       | U(15000, 30000)      |
| $P_a$     | U(3000, 5100)        | $T$         | U(20000, 50000)      |
| $P_b$     | U(4100, 6500)        | $X$         | U(1.5, 4)            |
| $P_r$     | U(4000, 6200)        |             |                      |

#### 3.2. Solution Analysis

Combined with the actual situation, the model is solved, and the global optimal solution is obtained as  $Z1=33409.32$ ,  $Z2=62665780$ . The model site selection scheme is shown in Fig 2. Obviously, the model built in this paper can simulate the reverse logistics network of retired power batteries under risk supervision.



**Figure 2.** reverse logistics site selection scheme for decommissioned power batteries

### 3.3. Multi-objective Optimization Analysis

In order to test the validity of the model and change the risk weight in the model,  $\gamma$  was set to 0.1, 0.3, 0.5, 0.7 and 0.9 respectively, and five groups of experiments were carried out. Fig 3 shows the changes of risks and costs in five groups of experiments. Obviously, when decision makers give different weights to risks, risks and costs have different optimal values, and the improvement of one goal is likely to cause the deterioration of another goal. Further analysis of the experimental results shows that with the increase of risk weight, the road with lower population density is more likely to be selected, but this method often means higher cost. Therefore, in the actual situation, decision makers can choose the appropriate weight value according to the degree of attention to risks and costs.

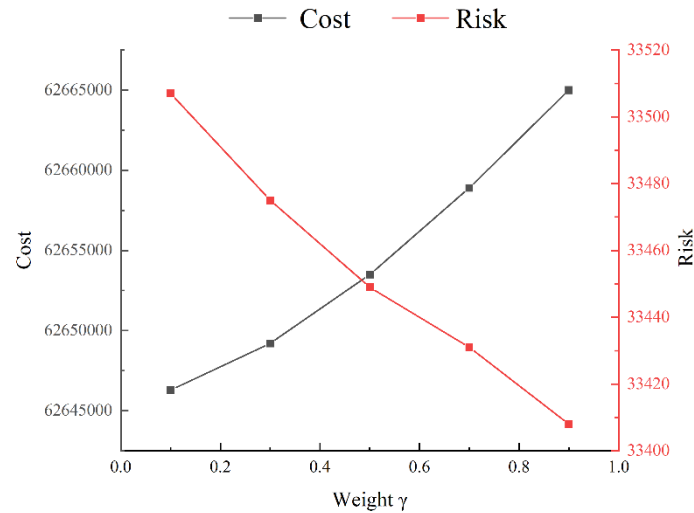


Figure 3. Trend diagram of cost and risk changing with weight

## 4. CONCLUDING REMARKS

The main results are as follows: (1) In this paper, when the retired power battery is recycled, a multi-objective model is established with the goal of minimizing transportation risk and network cost, and the multi-objective is transformed into a single objective by adopting a single risk and cost goal. Finally, the risk weight is set to make the decision more in line with the actual situation.

(2) Starting from the high uncertainty in the early stage of the recycling of retired power batteries, the logistics network optimization model is established considering various uncertain factors such as recycling quantity, recycling price, transportation distance, processing cost, etc., and the model is transformed into certainty by using triangular fuzzy, which is more in line with the actual situation and improves the accuracy of the recycling network decision.

(3) The correctness of the mathematical model is verified by an actual example. An example shows that the solution of the model is feasible, and it can solve the network problem with high uncertainty in the initial stage of the actual decommissioned power battery recycling. The sensitivity analysis of the weight is carried out, and different conclusions are drawn under different weight decisions, so as to realize the scientific selection of recycling facilities.

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