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# Designing a Reverse Logistics Network Model for Waste Batteries

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**Abstract:** The logistics industry plays an important role in circular economy. Therefore, not only economic benefits, but also environmental protection factors have to be considered in reverse logistics. This paper uses the multi-objective 0-1 mixed integer programming to establish a reverse logistics network optimization model for waste batteries. The objective function is to minimize both, logistics costs and carbon dioxide emissions. The model considers the basic settings of reverse logistics (including recycling nodes, manufacturing, and processing nodes) and the material flow between different settings. In solving the model, Lingo 14.0 is used in this paper. An actual case of a waste battery reverse logistics enterprise verifies the effectiveness of the model in this paper. The results show that the application of this model can effectively improve the operating efficiency of waste battery reverse logistics enterprises.

**Keywords:** Circular economy; Supply chain; Reverse logistics; Network design; Integer programming

## 1. Introduction

With the development of circular economy, production companies and logistics companies are not only required to reduce economic costs, but also environmental pollution in the production process. With the continuous development of China’s electronic commerce, the number of waste batteries (WB) is also increasing. The design of a reverse logistics network for waste batteries is one of the important issues in reverse logistics research, including the establishment of regional recycling nodes and reproduction factories, as well as the flow of materials between nodes at different levels of the network according to the quantity and demand of used batteries. The recycling network for used batteries is shown in **Figure 1**.

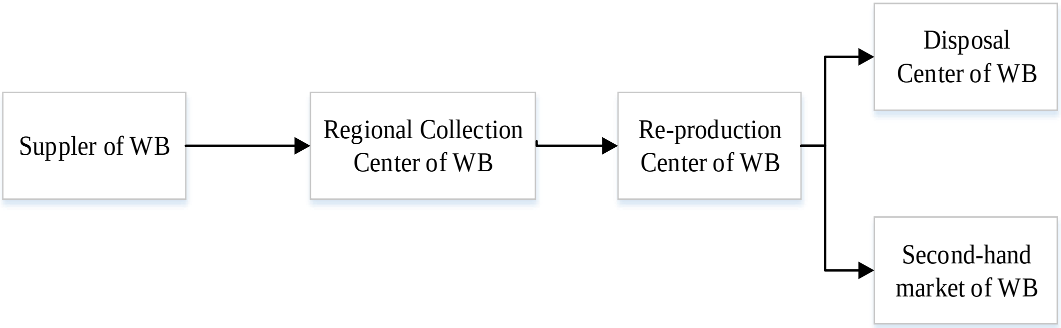

**Figure 1.** Reverse logistics network of used battery

Li and several other researchers analyzed the current situation of China’s waste battery recycling industry and the economy of recycling, as well as proposed several management measures [1]. A closed-loop supply chain network model aiming at the highest network profit was designed in a study [2]. The reverse logistics network problem under the uncertainty of customer demand and recovery was studied, and a two-stage stochastic programming model was proposed [3]. The uncertainty of parameters such as the recovery amount and recovery technology level of electric vehicle power battery was considered, and a reverse logistics network of electric vehicle power battery based on fuzzy multi-objective programming was designed with the goal of obtaining maximum total profit and effectuating minimum environmental impact [4]. In the process of reverse logistics, some products can be refurbished and reused. These products include glass [5], computers, mobile phones [6], medical equipment [7], empty bottles [8,9], solar cells [10], and other materials. Some products can be repaired, including refrigerators [11], modular products [12], electronic products [13], plastic bottles [14], gold products [15], laptops [16] and end-of-life vehicles (ELVs) [17]. Parts of products can be re-manufactured, such as waste electrical and electronic equipment (WEEE) [18-21].

At present, there are several studies on the design of waste battery reverse logistics network and material scheduling. Since the reverse logistics process of waste batteries is different from that of other products, the existing reverse logistics network cannot be applied directly to the reverse logistics of waste batteries. In addition, vehicle scheduling is rarely considered in current literatures on reverse logistics. In addition, vehicle scheduling is embedded in the designed waste battery reverse logistics network.

## 2. Mathematical model

### 2.1. Parameters

$A$ : Set of suppliers of WB
$C$ : Set of regional collection centers of WB
$R$ : Set of re-production centers of WB
$D$ : Set of disposal centers of WB
$H$ : Set of second-hand markets of WB
$V$ : Set of WB vehicles used
$S_a$ : Number of waste batteries provided by customer $a$
$F_v$ : Rental or acquisition cost of vehicle $v$
$M_v$ : Cost of vehicle $v$ driving unit mileage
$CO_V$ : Carbon dioxide emission per unit mileage of vehicle $v$
$DIS_{cr}$ : Mileage from regional collection center $c$ to re-production center $r$
$DIS_{rd}$ : Mileage from to re-production center $r$ to disposal center $d$
$DIS_{rh}$ : Mileage from to re-production center $r$ to second-hand market $h$
$F_c$ : Fixed cost of regional collection center $c$
$V_c$ : Variable cost of regional collection center $c$
$F_{\mathrm{r}}$ : Fixed cost of re-production center $r$
$V_r$ : Variable cost of re-production center $f$
$CK_c$ : Capacity limits of vehicle $c$
$UL_c$ : Upper limit of processing capacity for regional collection center $c$
$UL_r$ : Upper limit of processing capacity for re-production center $r$
$M$ : A positive number large enough
$Q_h$ : Requirements of waster batteries from second-hand market $h$
$Q_d$ : Requirements of waster batteries from disposal center $d$

### 2.2. Decision variables

$xx_e$ : If facility *e* operates, then $xx_e = 1$, or else $x_{ee} = 0$.

$xx_{ac}$ : If supplier *a* is distributed to regional collection center *c*, then $xx_{ac} = 1$, or else $xx_{ac} = 0$.

$yy_v$ : If vehicle *v* is available in logistics operations, then $yy_v = 1$, or else $yy_v = 0$.

$z_{cr}^v$ : If vehicle *v* picks up materials at regional collection center *c* and then ships them to re-production center *r*, then $z_{cr}^v = 1$, otherwise, $z_{cr}^v = 0$.

$z_{rh}^v$ : If vehicle *v* picks up materials at re-production center *r* and then ships them to second-hand market *h*, then $z_{rh}^v = 1$, otherwise, $z_{rh}^v = 0$.

$z_{rd}^v$ : If vehicle *v* picks up materials at re-production center *r* and then ships them to disposal center *d*, then $z_{rd}^v = 1$, otherwise, $z_{rd}^v = 0$.

$qq_{cr}^v$ : Number of waste batteries picked up by vehicle *v* at regional collection center *c* and shipped to re-production center *r*.

$qq_{rd}^v$ : Number of waste batteries picked up by vehicle *v* at re-production collection center *r* and shipped to disposal center *d*.

$qq_{rh}^v$ : Number of waste batteries picked up by vehicle *v* at re-production collection center *r* and shipped to second-hand market *h*.

### 2.3. Objective function

$$MinZ_1 = CV + CF \tag{1}$$

Objective function 1 minimizes the total logistics cost. The total logistics cost is the fixed/variable cost of vehicles and various facilities.

$$CV = \sum_c \sum_r \sum_v DIS_{cr} M_v qq_{cr}^v + \sum_r \sum_d \sum_v DIS_{rd} M_v qq_{rd}^v + \sum_r \sum_h \sum_v DIS_{rh} M_v qq_{rh}^v + \sum_v F_v yy_v \tag{2}$$

*CV* represents the total cost of transportation, which includes the fixed cost of vehicle use and the variable cost of vehicle transportation between different nodes in the reverse logistics network.

$$CF = \sum_c F_c xx_c + \sum_a \sum_c V_c S_a xx_{ac} + \sum_r F_r xx_r + \sum_c \sum_r \sum_v V_c qq_{cr}^v \tag{3}$$

*CF* is the sum of the fixed cost and operating cost of the facility (including all regional collection centers and re-production centers), in which the operating cost is linear with the volume handled by the facility.

$$MinZ_2 = \sum_c \sum_r \sum_v DIS_{cr} CO_v qq_{cr}^v + \sum_r \sum_d \sum_v DIS_{rd} CO_v qq_{rd}^v + \sum_r \sum_h \sum_v DIS_{rh} CO_v qq_{rh}^v \tag{4}$$

Objective function 2 reflects that carbon emissions are minimized throughout the logistics process.

### 2.4. Constraints

Constraints (5) to (19):

$$\sum_c xx_c \geq 1 \tag{5}$$

$$\sum_r xx_r \geq 1 \tag{6}$$

$$\sum_c x_{ac} = 1 \qquad \forall a \in A \tag{7}$$

$$\sum_a xx_{ac} \leq Nxx_c \qquad \forall c \in C \tag{8}$$

$$\sum_a S_a xx_{ac} = \sum_v \sum_r qq^v_{cr} \qquad \forall c \in C \tag{9}$$

$$\sum_a S_a xx_{ac} \leq UL_c xx_c \qquad \forall c \in C \tag{10}$$

$$z^v_{cr} \leq yy_v \qquad \forall v \in V, c \in C, r \in R \tag{11}$$

$$qq^v_{cr} \leq CK_c \times z^v_{cr} \qquad \forall v \in V, c \in C, r \in R \tag{12}$$

$$\sum_c \sum_v qq^v_{cr} \leq UL_r xx_r \qquad \forall r \in R \tag{13}$$

$$\sum_v \sum_c qq^v_{cr} = \sum_v \sum_c qq^v_{rd} + \sum_v \sum_h qq^v_{rh} \qquad \forall r \in R \tag{14}$$

$$\sum_v \sum_d qq^v_{rd} + \sum_v \sum_h qq^v_{rh} = \sum_h Q_h \sum_d Q_d \tag{15}$$

$$z^v_{rh} + z^v_{rd} \leq y_v \qquad \forall v \in V, r \in R, h \in H, d \in D \tag{16}$$

$$qq^v_{rd} \leq CK_c \times z^v_{rd} \qquad \forall v \in V, r \in R, d \in D \tag{17}$$

$$qq^v_{rh} \leq CK_c \times z^v_{rh} \qquad \forall v \in V, r \in R, h \in H \tag{18}$$

$$qq^v_{cr}, qq^v_{rh}, qq^v_{rd} \geq 0 \qquad \forall v \in V, r \in R, d \in D, c \in C, h \in H \tag{19}$$

Constraint (5) represents the requirement for the establishment number of regional collection centers. Constraint (6) represents the requirement for the establishment number of re-production centers. Constraint (7) represents that for a supplier, it can be dispatched to one and only one regional collection center. Constraint (8) shows that a customer can only be assigned to a regional collection center on the condition that the regional collection center is operated. Constraint (9) shows that for any regional collection center, all incoming waste batteries have to be shipped out. Constraint (10) shows the processing capacity for any regional collection center. Constraint (11) indicates the necessary premise for the vehicle to be used during transportation from the regional collection center to the re-production center. Constraint (12) represents the volume limit from the regional collection center to the re-production center for any vehicle. Constraint (13) refers to the upper limit of the processing capacity of any re-production center. Constraint (14) shows that the waste batteries shipped into any manufacturing center must be shipped out to second-hand markets and disposal centers. Constraint (15) indicates that the number of used batteries shipped from any manufacturing center to second-hand markets or disposal centers is equal to their demands, respectively. Constraint (16) reflects the necessary conditions for the use of vehicles for transportation from re-production centers to second-hand markets or disposal centers. Constraint (17) reflects the transport capacity limit from re-production centers to second-hand markets. Constraint (18) reflects the transport capacity limit from re-production centers to disposal centers. Constraint (19) indicates the variables are non-negative.

## 3. Solution

Transforming multi-objective programming into single objective programming:

$$MinZ = \lambda_1 Z_1 + \lambda_2 Z_2 \qquad (\lambda_1, \lambda_2 \geq 0, \lambda_1 + \lambda_2 = 1) \tag{20}$$

## 4. Numerical example

The case of Zhejiang Tianhe Logistics Company, whose main business is recycling, processing, and treatment of waste batteries, is taken as an example in this paper for analysis. The company has eight customers, four regional collection centers, two re-production centers, two disposal centers, and two second-hand markets. The purchase cost of each vehicle is 15 yuan, and the driving cost per kilometer is two yuan. The fixed operating cost of each regional collection center is 120 yuan, and the cost of handling each ton of waste batteries is 10 yuan. The setup cost of each re-production center is 150 yuan, and the cost of handling each ton of waste batteries is 12 yuan. The capacity of each vehicle is limited to six tons. The quantity of used batteries provided by each supplier is 40 tons. The capacity of each regional collection center and re-production center is limited to 100 tons and 180 tons, respectively. The demand for used batteries in each second-hand market and reprocessing center is 150 tons and 50 tons, respectively. The distance between each regional collection center and each re-production center is shown in **Table 1**. The carbon emissions per kilometer of a vehicle is 40 grams.

**Table 1.** Distance between regional collection centers and re-production centers (unit: kilometers)

| | **Regional collection center 1** | **Regional collection center 2** | **Regional collection center 3** | **Regional collection Center 4** |
|---|---|---|---|---|
| **Re-production center 1** | 98 | 92 | 89 | 92 |
| **Re-production center 2** | 89 | 88 | 79 | 87 |

The distances from re-production centers to second-hand markets are shown in **Table 2**.

**Table 2.** Distances between re-productions centers and disposal centers or second-hand markets (unit: kilometers)

| | Disposal center 1 | Disposal center 2 | Second-hand market 1 | Second-hand market 2 |
|---|---|---|---|---|
| **Re-production center 1** | 101 | 91 | 93 | 95 |
| **Re-production center 2** | 103 | 92 | 94 | 89 |

The total logistics cost $Z_1$ is 87,653 yuan, including the transportation cost (*CV)* of 51,278 yuan and the sum of fixed cost and variable cost (*CF*) of facilities of 36,375 yuan. Due to the processing capacity limitation of each fixed facility, all regional collection centers and re-production centers are put into operation. The transportation scheme with the lowest t cost is selected on the premise of meeting the processing capacity of facilities. For example, in the transportation from regional collection center 2 to each re-production center, priority is given to the transportation to production center 2, because the freight of this route is the most economical. The total carbon emission is 23,765 grams. Under the condition of taking different values of $\lambda_1$ and $\lambda_2$, the total logistics cost and carbon emission are shown in **Table 3**.

**Table 3.** Change of carbon emission ($Z_2$) and total logistics cost ($Z_1$) (carbon emission unit: gram; cost unit: yuan)

| | $\lambda_1 = 0.6, \lambda_2 = 0.4$ | $\lambda_1 = 0.55, \lambda_2 = 0.45$ | $\lambda_1 = 0.5, \lambda_2 = 0.5$ |
|---|---|---|---|
| $Z_2$ | 52360 | 53987 | 55035 |
| $Z_1$ | 22875 | 21976 | 20776 |

As can be seen from **Table 3**, with the continuous increase of $\lambda_2$, carbon emissions decrease, while logistics costs increase. Reverse logistics enterprises should timely adjust the value of carbon emission according to the requirements, so as to reduce the total logistics cost under the condition of ensuring that the carbon emission does not exceed the standard requirements.

## 5. Conclusion

The design of reverse logistics network for waste batteries is one of the important aspects in reverse supply chain research. In this paper, the multi-objective 0-1 mixed integer programming is used to establish a waste battery reverse logistics network. The objective of the model is to optimize the total logistics cost and carbon emission. The constraints consider the setting of logistics nodes and the scheduling of vehicles between logistics nodes. The example shows that the application of this model can effectively save logistics costs and reduce carbon emissions for reverse logistics enterprises.

## Disclosure statement

The authors declare no conflict of interest.

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