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LRP-Based Design of Sustainable Recycling Network for Electric Vehicle Batteries

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Abstract: Driven by energy shortages and climate concerns, the electric vehicles are popular around the world with their energy-saving and environmentally friendly advantages. As electric vehicle batteries (EVBs) mainly use lithium batteries, and the batteries' performance decreases with the increase of charging times, a large number of batteries are entering the end-of-life (EoL) stage. Recycling and reuse of EVBs are effective ways to reduce environmental pollution and promote resources utilization and is now a top priority. Building a recycling network is the foundation of battery recycling. However, there are few studies on battery recycling networks and the construction of recycling networks is expensive, which impedes the sustainable development of electric vehicles. Based on this, recycling network design is critical for EVB recycling. This paper first analyzes three strategies to deal with used batteries: remanufacturing, reuse, and recycling materials. Secondly, an EVB recycling network model is developed with the objective of minimizing the total cost and carbon emissions. The model solves the problem of siting the centers in the network and the vehicle routing in the recycling process. Finally, the model was applied to GEM (a Chinese company dedicated to circular economy) and validated using a greedy algorithm. In addition, the results show that logistics costs and operating costs account for the majority of the recycling network total expense, at 48.45% and 31%, respectively. Therefore, if companies want to further reduce the cost of EVB recycling, they should reduce logistics costs and operating costs. In summary, this paper provides a decision-making approach for EVB recycling enterprises to carry out recycling and reuse, and offers advice on how to promote the sustainable economic and environmental development of the electric vehicle battery industry.

Keywords: electric vehicle battery; recycling network design; vehicle routing problem; greedy algorithm; carbon emission

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1. Introduction

One of the major causes of global warming is the emission of greenhouse gases into the atmosphere by humans. The transportation sector accounts for about 14% of total global CO_2 emissions, and more than 95% of transportation energy is associated with the burning of fossil fuels, which accelerates energy consumption and has a negative impact on the environment [1,2]. With the increasing problems of energy shortage and environmental pollution, electric vehicles (EVs) are becoming popular around the world due to their advantages of energy conservation and environmental protection [3]. Under the policy promotion of various countries, the development of the electric vehicle industry has become a global phenomenon. Some developed countries have already announced a total ban on the sales of combustion vehicles within the next 20 years. China has announced a complete ban on the sale of combustion vehicles by 2035 and a complete cessation on their use by 2050 [4]. In China, the accumulated sales of EVs are projected at five million units in 2025, reaching about 20% of total new vehicle sales [5]. Therefore, the development of electric vehicles is the general trend. The EVB is the most important component in an EV because it uses a simpler electric motor rather than a large internal combustion engine with many separate parts compared to a conventional car [6]. Lithium-ion batteries are widely used in the EVB market because of their advantage in terms of high specific energy, high efficiency, and long life [7]. Automotive power batteries are used under stringent conditions. The battery cannot be used in an electrical vehicle when the actual electrical energy capacity of the battery is less than 80% of the initial specified capacity [8]. The raw materials used to manufacture EVB, such as manganese, nickel, and cobalt, are harmful to the environment. They leach into soil and water sources when they are disposed of directly in landfills, thus causing irreversible damage to the ecological environment [9]. With the rapid growth of the electric vehicle market and the widespread application of lithium-ion batteries, a huge number of batteries are coming to their end-of-life. The global lithium battery recycling market is predicted to be worth $31 billion annually by 2040 [10]. Therefore, the proper disposal of end-of-life EVB with minimum impact on the environment and maximum utilization of resources is now the top priority.

The main methods of handling end-of-life EVB are disposal, recycling, and reuse [11]. Disposal is the discarding or landfilling of an end-of life EVB of poor quality. This generates a huge amount of waste, and contaminates soil and water with heavy metals and electrolytes, causing irreversible damage to the environment [12]. For lithium batteries, metals, such as cobalt, nickel, and lithium, and inorganic substances are transported beyond the landfill through the leachate of the landfill. The disposal of used batteries on the land has the potential to release toxic elements into the water supply [13]. This generates large amounts of waste and causes irreversible damage to human health and the environment. Recycling refers to the extraction and recovery of valuable materials from end-of-life EVB by physical or chemical means to bring them back into the value chain. This can partially alleviate the demand for raw materials for battery production, while greatly reducing the environmental impact of end-of-life EVB. The main components of EoL batteries that have a negative impact on the environment constitute 90% of the economic value of the batteries, including cobalt (39%), lithium (16%), copper (12%), graphite (10%), nickel (9%), aluminum (5%), and manganese (2%) [14]. Recycling EoL batteries enables the recycling of important metal recovery materials in power batteries, reduces the mining and waste of resources in total, and improves the efficiency of the use of resources, thus reducing the damage to the environment caused by the mining of metal raw materials. Reuse consists of two aspects: remanufacturing and repurposing. Remanufacturing refers to the replacement of a degraded part of the battery pack with a qualified component so that it can continue to be used in electric vehicles [15]. Repurposing refers to the reconfiguration of an EoL battery so that it can start its second life in a less stressful scenario, such as energy storage systems (ESS), peak shaving and load shifting, and electric ground vehicles [16]. It is more valuable to recycle EoL batteries than manufacture new ones [15]. Therefore, recycling and reuse are the most beneficial disposal options for sustainable development. Currently, repurposing is the main research direction for end-of-life EVB recycling. This is because after an EVB is used an EVs, the remaining capacity of the battery is 60–80% of the initial capacity, which can be reused in industries other than the automotive industry [17].

With the increase of battery end-of-life and the consequent problems of environmental pollution and resource waste, various countries have started to pay attention to the recycling of batteries. The European Union issued the Battery Directive (Directive 2006/66/EC) and the Waste Electrical and Electronic Equipment (WEEE) Directive (Directive 2012/19/EU), requiring manufacturers and distributors to recycle batteries free of charge and only with the best available technology [18]. The Ministry of Industry and Information Technology of China issued the Provisional Regulations on Traceability Management of Recycling and

Utilization of Power Batteries for New Energy Vehicles in July 2018, which stipulates that electric vehicle manufacturers must provide battery recycling services as required, with special emphasis on battery traceability management. Therefore, in response to government regulations, it is compulsory for electric vehicle manufacturers to actively participate in establishing recycling systems that will save raw materials, manufacturing costs, and energy consumption, thereby reducing their environmental impact.

Recycling networks are the key to end-of-life EVB recycling. A well-developed recycling network can effectively increase the recycling rate and reduce recycling costs. The objective of this paper is to plan an EVB recycling network by minimizing the total cost and carbon emission. EoL batteries can be divided into three categories according to their remaining capacity for their disposal strategy: remanufacturing, repurposing, and recycling. The total cost considered in this paper includes the construction cost of the centers, the operation cost of the centers, and the transportation cost between the centers. Carbon emissions include the carbon emissions generated from the construction of the centers, the handling of the batteries in the centers, and the transportation.

The paper is organized as follows. In Section 2, we give an overview of the research on the repurposing of vehicle batteries and the location routing problem. In Section 3, the research problem of this paper is stated and modeled. In Section 4, the proposed model is applied to the design of a battery recycling network in GEM. In Section 5, summarization and further research are presented.

2. Literature Review

2.1. Repurposing of EOL Vehicle Battery

Repurposing is the use of a product for a different purpose than the original [19]. Repurposed batteries can be used in areas such as energy balancing for renewable energy sources, such as solar or wind, peak-time energy shifting in smaller applications, such as homes or office buildings, and some low-speed vehicles [20]. Currently, second-life battery (SLB) systems are in their infancy. A second-life energy system from Nissan Leaf EVs is employed in the University of California, Davis. Rochester Institute of Technology and the University of California, San Diego have also conducted research projects on secondary batteries. Research and development projects are also conducted by industrial entities [21]. As the EVB market expands and the supply of EoL batteries increases, the application of repurposing will become more widespread. According to a study from Bloomberg New Energy Finance, the global market for EoL batteries could reach 26 GWh by 2025. This would represent one-third of the total end-of-life electric vehicles, about 47% of global lithium-ion battery supply in 2015 and 65% of global EVB demand in 2016 [22].

The repurposing of a huge number of batteries presents a great opportunity for the automotive industry as well as other industries. However, the economic and technical feasibility of repurposing EoL batteries still needs to be explored. Mathews et al. determined through modeling that utility scale solar-plus-storage systems are profitable if second-life batteries are sold at less than 60% of the price of new batteries [22]. Rallo et al. concludes from two case studies that while battery price is the most important factor in determining the economic viability of a stationary energy storage system (SESS) installation, battery aging plays a pivotal role in the economic results [23]. Song et al. suggests that for the current price of wind energy and lithium-ion batteries, it is not worth reusing batteries in the wind farms they studied, but that reused batteries could outperform new batteries in the future if the price of wind energy decreases much faster than the price of batteries [24]. Lee et al. stated that other factors such as depth of discharge (DOD) were found to severely affect the lifespan of second-life batteries. The right application and the right DOD need to be considered when implementing second-life batteries [25]. Therefore, when analyzing the technical and economic feasibility of second-life batteries, multiple factors such as the application scenario, health condition, and technical difficulty need to be considered.

In summary, the application of second-life batteries in different scenarios has attracted extensive research, and the reuse technology of batteries will become more mature. The current battery secondary use process is: (a) Collect batteries from consumers; (b) test the appearance and performance of the battery; (c) after maintenance and reorganization, use batteries of good quality for energy storage, household electricity, low-speed electric vehicles and other fields. Low quality batteries that cannot be reused should be disassembled and recycled for useable materials. This paper is based on this background to design the EVB recycling network.

2.2. Location Routing Problem (LRP)

The process of repurposing EoL batteries after recycling from consumers to dismantling centers is connected by reverse logistics. The transportation nodes and routes in reverse logistics make up the recycling network. Since transportation between nodes causes a large portion of the cost, the cost of recycling EoL batteries can be reduced by optimizing the recycling network. Drexl and Schneider define LRP as a mathematical optimization problem and should contain at least the following two interdependent decision subproblems: (a) Which facilities out of a finite or infinite set of potential ones should be used (for a certain purpose)? (b) Which vehicle routes should be built, i.e., which customer clusters should be formed and in which sequence should the customers in each cluster be visited by a vehicle from a given fleet (to perform a certain service) [26]?

According to the depth of research, LRP can be divided into deterministic LRP and uncertain LRP according to the degree of certainty of the problem, static LRP, dynamic LRP and periodic LRP according to the planning time span, and LRP without time window and LRP with time window according to the service time limit, etc. Hamidi proposed a heuristic algorithm using the Greedy Randomized Adaptive Search Procedure (GRASP) and two probabilistic tabu search strategies, intensification and diversification, to solve a complex multiproduct four-layer facility location routing problem with capacity constraints [27]. Prodhon proposed a hybrid evolutionary algorithm for solving large-scale periodic LRP instances with vehicle and warehouse capabilities which combines evolutionary local search (ELS) and a heuristic algorithm based on the randomized extended Clarke and Wright algorithm (RECWA) to generate feasible solutions [28]. Govindan introduced a two-echelon location routing problem with time windows (2E-LRPTW) for sustainable SCN design and optimization of perishable food SCNs with economic and environmental objectives. A new multi-objective hybrid algorithm MHPV, a hybrid of the multi-objective particle swarm optimization algorithm (MOPSO), and the adaptive multi-objective variable neighborhood search algorithm (AMOVNS), was proposed [29]. Nadizadeh studied the dynamic capacitated location routing problem with fuzzy demands. A hybrid heuristic algorithm (HHA) was proposed assuming that the customer's demand is a fuzzy variable [30]. It is summarized from the survey of the literature that there is more research on two-echelon LRP problems with capacity constraints and less research on multi-echelon LRP problems.

3. Modeling of Recycling Network

3.1. Description of the Recycling Network

Figure 1 depicts an EVB reclamation network. The network consists of four nodes: recycling center, EVB processing center, remanufacturing center, and waste disposal center. EoL batteries are collected by the recycling centers from customers and sent to the EVB processing centers. The EVB processing center is responsible for the initial testing of the battery. According to the remaining capacity, batteries are divided into three categories: T1 (remaining capacity more than 80%), T2 (Remaining capacity more than 60% and less than 80%), and T3 (remaining capacity less than 60%) [3]. Different treatment strategies are adopted for batteries with different health status. T1 (with intact packaging) cells are transported to remanufacturing center and reassembled into new EVBs; T2 cells are transported to a remanufacturing center where some of the cells will be reused directly as batteries in other applications. Other T2 (with packaging damage, etc.) cells are transported to waste disposal centers for deep disassembly, where reusable materials will be recycled to make new batteries. T3 cells are not suitable for reuse and will be transported to waste disposal center.

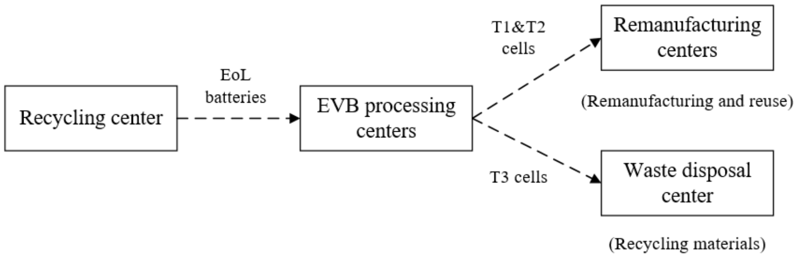


Figure 1. EVB recycling network.

The proposed model can determine the location of each center in the network, as well as the vehicle routing planning from the recycling center to the EVB disposal center, when the amount of recycling at each recycling center is known. The goal of the model is to minimize the total cost and CO_2 emissions of the EVB recycling network. The total cost of the EVB recycling network includes construction costs, operating costs, transportation costs, and remanufacturing costs. The total carbon emissions include carbon emissions from the construction of the center, processing at the center, and the transportation process. The proposed model is under the following assumptions:

- Assuming all EVBs are of the same type.
- It is assumed that the recovery period is one week.
- Assume that the centers have a useful life of N years. after N years, the estimated net residual value of the centers is 0.
- EVB processing centers have processing capacity limits and transport vehicles have load limits.
- EVB processing center, remanufacturing center, and waste disposal center locations to be determined. Possible center locations are known in advance.
- The cells will be subjected to multiple potential strategies (remanufacturing, repurposing and disposal) depending on the cell quality, where the number of cells corresponding to different strategies of disposal obeys a normal distribution.
- The distance between facility nodes using straight-line distance.
- Material recycling of waste EVB by pyrometallurgical recycling.

3.2. Proposed Model

3.2.1. Objective Function

Based on the above assumptions, a multi-objective model is developed to minimize the transportation cost and carbon emission of the whole recycling network.

Equation (1) represents the minimum total cost of the network.

$$TC = \min(C_1 + C_2 + C_3) \tag{1}$$

C_1 refers to the fixed cost of the facility spread evenly over each week.

$$C_1 = \frac{1}{52N}\Big(\sum_{j\in J} y_j c_j + \sum_{k\in K} z_k c_k\Big) \tag{2}$$

C_2 refers to the transportation costs of the recycling network.

$$C_2 = \sum_{i\in I}\sum_{j\in J}\sum_{n\in N} \alpha q_i y_j x_{ij}^n d_{ij} + \sum_{j\in J}\sum_{k\in K} \beta(Q_1 + Q_2) z_k d_{jk} + \sum_{j\in J}\sum_{l\in L} \gamma Q_3 d_{jl} \tag{3}$$

C_3 refers to the operating costs of each center. Operating costs refer to the costs required to maintain the center's normal operations, which include the salaries of employing staff, equipment maintenance costs, utilities, and other daily expenses

$$C_3 = \sum_{j \in J} y_j D_j + \sum_{k \in K} z_k M_k \tag{4}$$

Equation (5) represents the minimum carbon emission of the whole network.

$$TE = \min(\mathrm{E}_F + \mathrm{E}_P + \mathrm{E}_T) \tag{5}$$

E_F indicates the carbon emissions generated by the construction of centers.

$$E_F = \frac{1}{52N}(\sum_{j \in J} y_j e_j + \sum_{k \in K} z_k e_k) \tag{6}$$

E_P indicates the carbon emissions of the EVB due to processing at each center.

$$E_P = \sum_{i \in I} \sum_{j \in J} \sum_{n \in N} q_i y_j x_{ij}^n e_{Pj} + \sum_{k \in K} z_k e_{Pk}(Q_1 + Q_2) + e_{Pl} Q_3 \tag{7}$$

E_T indicates the carbon emissions generated by EVB during transportation.

$$E_T = \sum_{i \in I} \sum_{j \in J} \sum_{n \in N} e_t q_i y_j x_{ij}^n d_{ij} + \sum_{j \in J} \sum_{k \in K} e_t (Q_1 + Q_2) z_k d_{jk} + \sum_{j \in J} \sum_{l \in L} e_t Q_3 d_{jl} \tag{8}$$

3.2.2. Constraints

1. Capacity constraints. There is a limit to the capacity of the EVB processing center and the load capacity of the transport vehicle. The constraints (9) indicate the capacity constraints of the EVB processing center, represented by P_j. The load capacity of the vehicles is limited. The constraints (10) indicate the load capacity constraints of transport vehicles, represented by cap.

$$P_j \le \sum_{i \in I} \sum_{n \in N} q_i x_{ij}^n \tag{9}$$

$$\sum_{i \in V} \sum_{j \in V} q_i x_{ij}^n \le cap \tag{10}$$

2. Uniqueness constraint. Constraint (11) refers to each recycling center being manned by only one transport vehicle. Constraint (12) refers that an EVB processing center must build if it serves a recycling center. Constraints (13) indicate the number of centers constraint. The number of both remanufacturing center and waste treatment center in the network is only 1.

$$\sum_{n \in N} \sum_{j \in J} x_{ij}^n = 1, \ (\forall i \in I) \tag{11}$$

$$\sum_{n \in N} \sum_{i \in I} x_{ij}^n \le y_j, \ (\forall j \in J) \tag{12}$$

$$\sum_{k \in K} z_k = 1 \tag{13}$$

3. Other constraints. Constraint (14) is a path continuity constraint, which indicates that a vehicle arriving at any center must leave that center. Constraint (15) is a flow conservation constraint, indicating that the number of batteries shipped from the

recycling center is the same as the number of batteries shipped to the EVB processing center.

$$\sum_{j \in V} x_{ij}^{n} - \sum_{j \in V} x_{ij}^{n} = 0, \ (\forall i \in V, \ \forall n \in N) \tag{14}$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{n \in N} q_i x_{ij}^{n} = \sum_{i \in I} q_i \tag{15}$$

4. Decision variables constraints. Constraints (16) are related to the corresponding decision variables.

$$x_{ij}^{n}, y_j, z_k \in \{0, 1\} \tag{16}$$

3.3. Method

The location routing problem is divided into two problems, the location allocation problem and the vehicle routing problem. To solve the above problem, a two-stage heuristic algorithm is proposed in this paper. The first stage solves the facility location problem and the second stage solves the vehicle routing problem.

Firstly, the clustering algorithm based on greedy strategy is used to solve the location allocation problem of the EVB processing center. The following two principles need to be followed when making the allocation. (a) Closest. The EVB processing center that is close to the recycling center is given priority until the total recycling volume exceeds the center's maximum processing capacity. Adjustments are then made based on capacity. (b) The minimum number of facilities is required. The cost of constructing an EVB processing center is high and concentrated, and too many facilities can put financial pressure on the company. Therefore, the minimum number of facilities is required to meet the demand. The Greedy Algorithm is a very common algorithm and has become the basic idea of many optimization algorithms. The basic idea of clustering analysis is to judge whether it is the same clustering by the distance between two points according to the principle of distance priority, and then cluster recycling centers into several clusters. Secondly is vehicle route planning with genetic algorithms. When applying the method to the problem proposed in this paper, the following steps are included.

1. Initial clustering.

Recycling centers are assigned to the nearest EVB processing center according to the distance priority principle.

2. Determine the minimum number of EVB processing center.

Based on the total amount of recycling in the recycling center, the lowest number of facilities is determined based on the idea of greedy algorithm, while the minimum number P of different combinations of facilities are obtained. Priority is given to facilities with many aggregation nodes and high capacity when combining facilities. M denotes the total number of facilities meeting the conditions and N denotes the minimum number of facilities. Therefore, there are site selection options.

3. Secondary clustering.

Based on different combinations of facilities, each of the initially clusters are divided again, with the main division based on distance priority and capacity constraints. After completing the LAP phase of the problem, we enter the VRP phase of the solution problem.

4. Initial route arrangement.

Select one of facility combinations. After the minimum number of vehicles is determined, the route is arranged and the result is taken as the initial population of genetic algorithm.

5. Vehicle routing arrangement.

Based on the current number of vehicles, genetic algorithm is used to arrange the best route and calculate the current lowest cost.

6. Preservation of minimum costs and routing arrangements.

Route arrangement and cost calculation after increasing the number of vehicles. Compare the best solution for different vehicle numbers and save the lowest cost and route for this combination.

7. Traverse over all.

Go back to step 4, select the next combination from combinations, and proceed to Step 5 and Step 6 until all combinations have been traversed. Save the optimal solution of all schemes.

8. Comprehensive comparison.

Compare the best cost of different combinations and select the best combination scheme. Output the optimal route of the scheme. End.

The core flow of the method is shown in Figure 2.

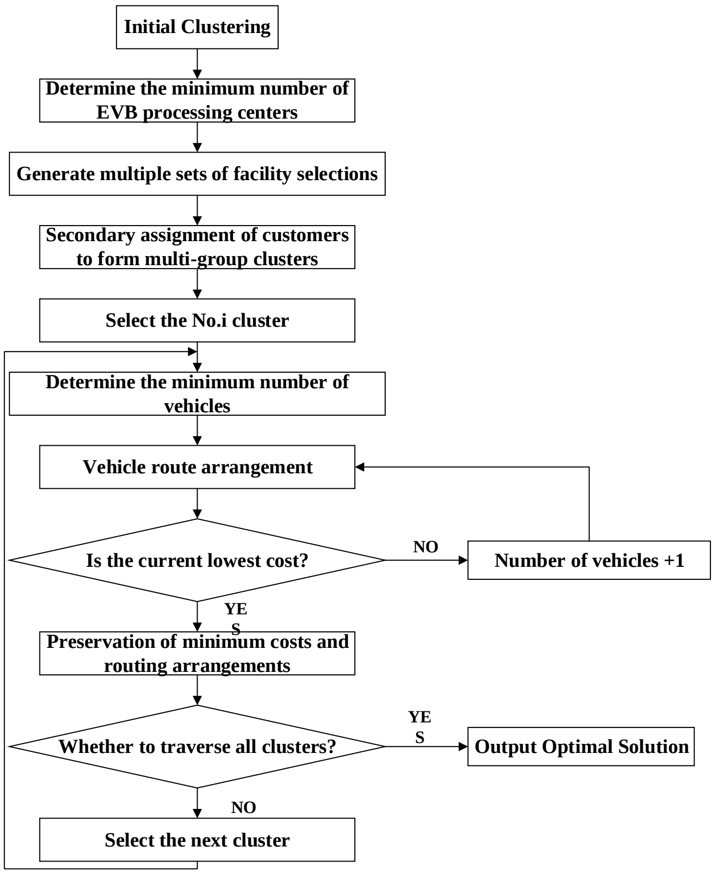


Figure 2. Core steps of the method.

4. Results

4.1. Problem Description

GEM is a leading company in EVB recycling and reuse. It is committed to building a nationwide recycling network system with primary terminal recycling, secondary recycling storage and transportation, tertiary disassembly and stepped utilization, and quaternary remanufacturing. GEM connects with major domestic automobile remanufacturers and battery remanufacturers to recycle electric vehicle batteries in order to overcome the key technology of battery-stepped utilization and realize a green recycling value chain. GEM wants to establish a recycling network in a region where there are known to be 40 recycling points, 10 alternative EVB disposal centers, three alternative remanufacturing centers, and one waste disposal center. Recycling centers are generally 4S shops and end-of-life vehicle recycling and dismantling enterprises, which are responsible for recycling EVBs from customers. The EVB processing center is responsible for the initial dismantling and testing of recycled EVBs and dividing the battery cells into three classes according to their remaining capacity. The candidate EVB processing centers were selected from the recycling centers. The remanufacturing center accepts T1 and T2 batteries, and the T3 batteries are accepted by waste disposal centers. Different treatment strategies are adopted for different classes of battery cells, as mentioned in the previous section. Therefore, it is necessary to select the appropriate facility location among the alternative centers and plan their vehicle routing schemes between recycling centers and EVB disposal centers.

4.2. Input Data

Table 1 gives the current annual number of EVB recoveries in different centers from which we calculated the weekly recoveries. The number of cells at different levels were obtained according to hypothesis 4. The capacity and associated costs of each candidate EVB processing center are given in Table 2. The costs associated with the remanufacturing center and waste treatment center are shown in Table 3. The other parameters in the model are given in Table 4. Since batteries are dangerous goods, they should be transported in professional packaging. The resulting cost is included in the unit shipping cost.

Table 1. Recycling volume of each recycling center.

Recycling Center	Annual Recycling	Weekly Recycling	T1 (>80%)	T2 (60–80%)	T3 (<60%)
1	470	39	6	24	9
2	235	21	3	13	5
3	321	27	4	11	6
4	180	15	2	9	4
5	197	16	2	10	4
...	...	...	...	...	...
40	132	11	2	6	3

Table 2. Relevant parameters of EVB processing center.

EVB Processing Center	Processing Capacity	Fixed Cost	Operation Cost
1	250	260	29
2	208	230	20
3	140	185	18
4	146	190	16
5	150	196	17
6	151	200	18
7	148	180	16
8	175	170	20
9	160	167	19
10	140	180	13

Table 3. Parameters related to remanufacturing centers.

	Fixed Cost	Operation Cost
Remanufacture center 1	150	12
Remanufacture center 2	150	12
Remanufacture center 3	135	12

Table 4. Relevant parameters of EVB processing center.

Parameters	Operation Cost
Load capacity of the vehicle cap	50
Unit transportation cost α	0.18
Unit transportation cost β	0.16
Unit transportation cost γ	0.20
Service life of the facility N	15
Carbon emissions from building a center $e_j,\ e_k$	570 [31]
Carbon emissions in EVB processing center e_{Pj}	2.43 [5]
Carbon emissions in remanufacture center e_{Pk}	31 [5]
Carbon emissions in waste disposal center e_{Pl}	204 [32]
Unit carbon emissions of EVB transportation e_t	7.03 [33]

4.3. Optimized Design Results

1. Allocation of EVB processing center

Step 1: Initial clustering.

The distances between 40 recycling centers and 10 candidate EVB processing centers were calculated, and each recycling center was assigned to the nearest EVB processing center according to the distance priority principle. The results of initial clustering are shown in Table 5.

Table 5. Initial clustering results.

EVB Processing Center	Recycling Center	Recycling Volume
1	1, 2, 3, 7, 15, 19, 22, 24, 27	184
2	5	16
3	6, 11, 23, 30, 31	84
4	8, 17, 18	52
5	9, 25, 33	46
6	10, 35	30
7	12, 13, 28, 29, 34, 36	101
8	14, 16, 37, 39	74
9	4, 21, 32	47
10	20, 26, 38, 40	56

Step 2: Determine the minimum number of EVB processing centers and location plan.

From the initial clustering results, most of the recycling centers are gathered in the EVB processing centers 1, 3, and 7. Under the condition that the capacity is satisfied, the facilities with more initial clustered recycling centers are given priority, and the location selection scheme of the EVB processing centers is determined. The optimal location of the remanufacturing center is then selected based on the cost minimization principle. There are three final location plans, as shown in Table 6.

Table 6. Possible location schemes.

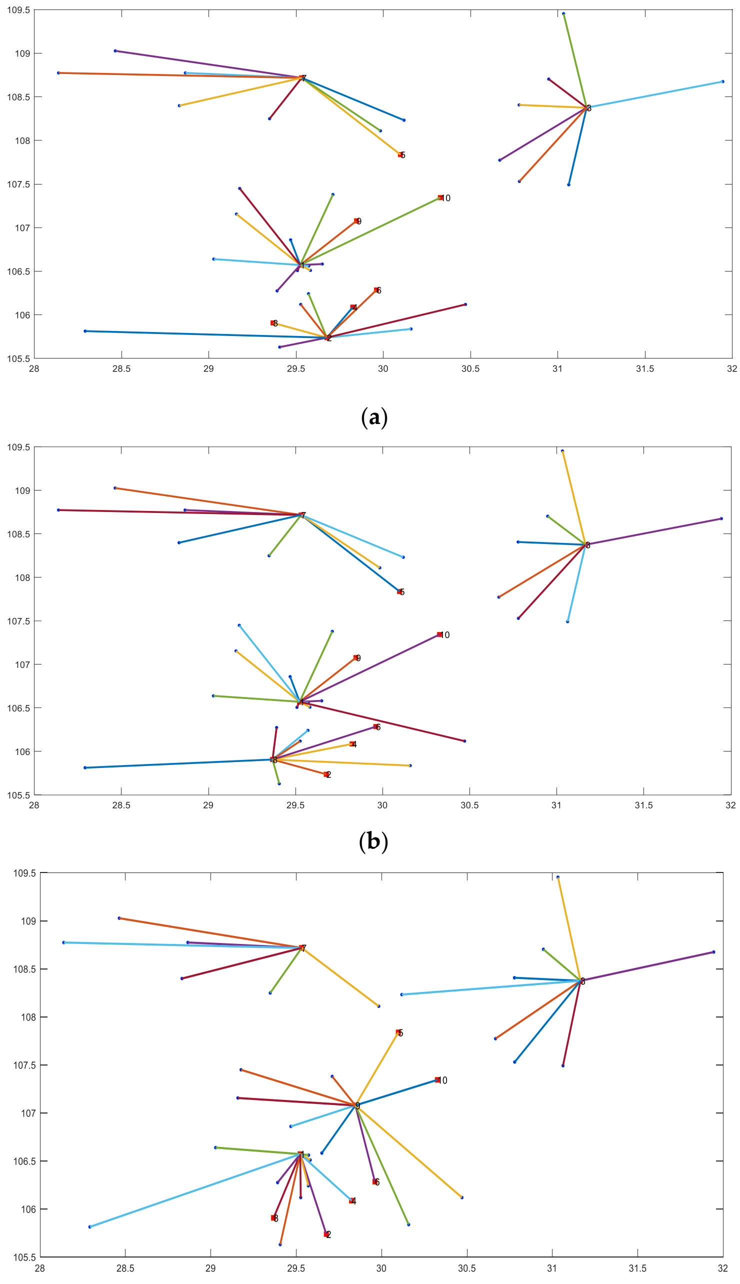
EVB Processing Center										Remanufacturing Center		
1	2	3	4	5	6	7	8	9	10	1	2	3
1	1	1	0	0	0	1	0	0	0	0	1	0
1	0	1	0	0	0	1	1	0	0	0	1	0
1	0	1	0	0	0	1	0	1	0	0	1	0

Step 3: Secondary clustering.

In each combination case, secondary clustering of EVB processing centers and recycling centers is carried out, and the clustering results obtained are shown in Table 7 and Figure 3.

Table 7. Secondary clustering results for each scheme.

Scheme	EVB Processing Center	Recycling Center	Recycling Volume
1	1	1, 2, 3, 4, 7, 15, 19, 21, 22, 24, 26, 27, 32	244
	2	5, 8, 10, 14, 16, 17, 18, 35, 37, 39	172
	3	6, 11, 20, 23, 30, 31, 38, 40	127
	7	9, 12, 13, 25, 28, 29, 33, 34, 36	147
2	1	1, 2, 3, 4, 7, 15, 19, 21, 22, 26, 27, 32, 35	241
	3	6, 11, 20, 23, 30, 31, 38, 40	127
	7	9, 12, 13, 25, 28, 29, 33, 34, 36	147
	8	5, 8, 10, 14, 16, 17, 18, 24, 37, 39	175
3	1	1, 2, 5, 7, 8, 14, 15, 16, 17, 24, 27, 37, 39	246
	3	6, 11, 20, 23, 30, 31, 33, 38, 40	139
	7	12, 13, 25, 28, 29, 34, 36	138
	9	3, 4, 8, 10, 18, 19, 21, 22, 26, 32, 35	138



(**a**) (**b**) (**c**)

Figure 3. (**a**) Secondary clustering of scheme 1; (**b**) secondary clustering of scheme 2; (**c**) secondary clustering of scheme 3.

2. Vehicle routing plan

Based on the determined schemes in the location plan, the route arrangement of each scheme is carried out successively, and the optimal route arrangement decision of each location scheme of the whole network is finally obtained. The cost and carbon emission of each scheme is shown in Table 8.

Table 8. Cost breakdown of each scheme.

Scheme	C_1	C_2	C_3	TC	TE
1	56,944.44	120,194.37	79,166.67	256,305.48	10.7785
2	52,499.99	123,772.80	79,166.67	255,439.46	10.7508
3	52,333.33	130,720.81	78,333.33	261,387.47	10.8992

Therefore, scheme 2 is taken as the final option. In this scheme, recycling outlets X1, X6, X13, and X14 were selected as EVB processing centers by numbering them E1, E3, E7, and E8. It performs detection and classification work and has the function of a recycling center. The alternative remanufacturing center R2 are selected. Batteries from recycling centers X2, X3, X4, X7, X15, X19, X21, X22, X26, X27, X32, and X35 will be shipped to EVB processing center E1. Batteries from recycling centers X11, X20, X23, X30, X31, X38, and X40 will be shipped to EVB processing center E3. Batteries from recycling centers X9, X12, X25, X28, X29, X33, X34, and X36 will be shipped to EVB processing center E7. Batteries from recycling outlets X5, X8, X10, X16, X17, X18, X24, X37, and X39 will be shipped to EVB processing center E8. After being tested at the EVB processing center, the batteries are sorted according to their remaining capacity and shipped to the remanufacturing center R2 and the waste recycling center W1. The optimal vehicle routing scheme is shown in Table 9 and Figure 4.

Table 9. Optimal scheme for vehicle path planning.

EVB Processing Center	Routing
1	E1 → 2 → 3 → E1 E1 → 4 → 32 → 22 → E1 E1 → 35 → 26 → 21 → E1 E1 → 15 → 27 → 19 → E1 E1 → 7 → E1
3	E3 → 11 → E3 E3 → 20 → 40 → 38 → E1 E3 → 31 → 23 → 30 → E3
7	E7 → 12 → 34 → 28 → E7 E7 → 25 → 9 → 33 → E7 E7 → 29 → 36 → E7
8	E8 → 8 → 10 → 18 → E8 E8 → 16 → 5 → E8 E8 → 39 → 17 → 24 → E8 E8 → 37 → E8

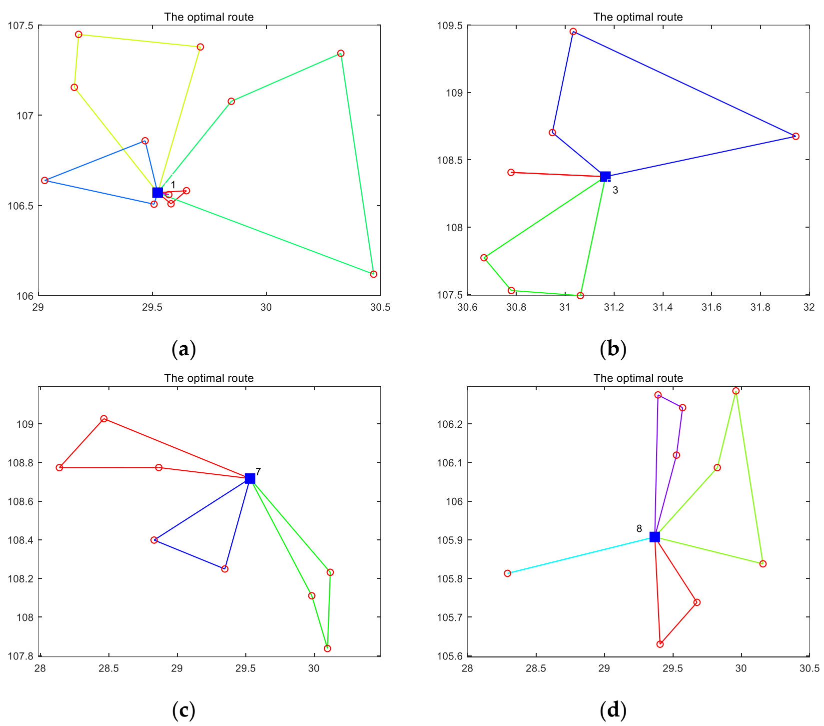


Figure 4. (**a**) Route planning of EVB processing center 1 in scheme 2; (**b**) route planning of EVB processing center 3 in scheme 2; (**c**) route planning of EVB processing center 7 in scheme 2; (**d**) route planning of EVB processing center 8 in scheme 2.

5. Conclusions

In response to the urgent need to establish a comprehensive recycling network, an optimization model considering the health condition of EVB is established. The model refines the recycling problem, considers the vehicle path problem, and realizes the optimal design of the EVB recycling network. The model is also validated by taking GEM enterprise as an example. The cost breakdown of the example results shows that logistics costs account for the majority of the recycling network, with operational costs coming in second. Taking the optimal planning result as an example, the logistics cost is 48.45% of the total cost and the operation cost is 31% of the total cost. Therefore, in order to reduce the cost of EVB recycling, reducing logistics costs and operating costs are the most effective strategy. For reducing logistics costs, the following directions can be considered: (1) Select the appropriate vehicle for transportation. The purchase of transport vehicles is a significant expense. It is most economical only when the actual capacity of the vehicle is close to the rated capacity. This point is also considered in general route planning. Therefore, transport vehicles should be equipped according to the projected recycling volume in the region to avoid wasting resources due to high empty load rates. (2) Rationalization of transportation. In the actual transportation process, in the departure or return of vehicles for empty transport, roundabout transport, repeat transport, and other unreasonable transport methods will lead to additional costs and consumption, greatly increasing the cost of logistics and transport. (3) Optimize the layout of network nodes. This is the top priority of recycling network planning. Changes in node location and capacity can have a huge impact on the global impact of the recycling network. Therefore, setting the right network nodes greatly reduces the logistics costs in the recycling process. For reducing operating costs, the following directions can be considered: (1) Technology innovation in testing the EoL batteries. The testing of EoL batteries is a current hotspot and presents difficulties. It is related to the enthusiasm of enterprises and consumers for battery recycling and the promotion of reuse. The testing of used batteries can accurately estimate the remaining value of batteries and make the trading of used batteries more transparent. The test results will indicate which disposal strategy and which scenario the used battery is suitable for. It contributes to the safe recycling of used batteries. However, current methods of battery testing are expensive and difficult, which increases the cost of battery recycling. (2) Improve management. Improve the professionalism and technical ability of employees. Improved management systems can effectively reduce the operating costs within the company. (3) Improve information technology. Adopting advanced information technology and attaching importance to information synergy in all links of recycling can also reduce the operating costs in the recycling process to a certain extent. For further study, additional factors can be considered that can be helpful in making decisions about EVB recycling, for example, the design of an appropriate recycling cycle. An appropriate recycling center consolidates the resources in the recycling network and maximizes the utilization of available resources.

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Nomenclature

N	Service life of the facility
c_j	Fixed costs of building EVB processing center j
c_k	Fixed costs of building remanufacturing center k
α	Unit transportation cost between recycling center and EVB processing center
β	Unit transportation cost between EVB processing center and remanufacturing center
γ	Unit transportation cost between EVB processing center and waste disposal center
q_i	Recycling volume of recycling center i
d_{ij}	Distance between center i and center j. where $i,j \in V$, and $V = I \cup J$
d_{jk}	Distance between EVB processing center j and remanufacturing center k
d_{jl}	Distance between EVB processing center j and waste disposal center l
Q_i	The quantity of battery $T_i(i = 1,2,3)$
D_j	Testing costs for EVB processing center j.
M_k	Remanufacturing costs for remanufacturing center k
x_{ij}^n	Decision variables. The transport tasks of center i and center j are completed by vehicle n is 1, otherwise 0. where $i,j \in V$ and $V = I \cup J$
y_j	Decision variables. EVB processing center j enable is 1, otherwise 0
z_k	Decision variables. Remanufacturing center k enable is 1, otherwise 0
e_j, e_k	Carbon emissions from the construction of the EVB processing center j and remanufacturing center k
e_{Pj}	Unit carbon emissions from battery testing at EVB processing center j
e_{Pk}	Carbon emissions from remanufacturing of each battery
e_t	Carbon emissions per kilometer generated during EVB transport

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