[1]Optimal design of electric vehicle battery recycling network - from the perspective of electric vehicle manufacturers

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HIGHLIGHTS

- A recycling network of Lithium-Ion batteries considering CO_2 emission is proposed.
- The factors affecting the cost and location optimization are analyzed.
- The carbon tax can influence the optimal network configuration.

ABSTRACT

Driven by the global campaign against climate change, the market of electric vehicles has boomed across the world in recent years. Since Lithium-Ion batteries are commonly used to power electric vehicles, a huge amount of batteries will soon reach their end-of-life; how to recycle them to reduce environmental pollution and promoting the sustainable development of the electric vehicle market has become an urgent challenge today. Implementation of the secondary reuse of used electric vehicle batteries is a valuable recycling strategy, However, there is a lack of research investigating electric vehicle batterie recycling network design at the enterprise level, which impedes the sustainable development of electric vehicles. Driven by this, this paper developed a model considering carbon emission for simulating the recycling of electric vehicle batteries. The proposed model takes into account three potential battery handling strategies (recycling, remanufacturing, and disposal) to processing used vehicle battery cells of different quality levels at different centers. A real case study from a Chinese electric vehicle manufacturer is presented, wherein a 5.6% decrease in total cost and a 22.1% reduction in CO_2 emission can be achieved. Moreover, the results of the scenario analysis show that transportation costs, carbon tax, and the number of used batteries, which can change both the configuration of the network, have been identified as three major factors affecting the optimal design of recycling networks. In addition, developing more economical recycling technology for electric vehicle manufacturers to further reduce the total cost of the recycling process is the main direction. In all, this research will provide foreign researchers with a perspective on Chinese companies in terms of electric vehicle battery recycling at the enterprise level, and promote economically and environmentally sustainable development in the electric vehicle battery industry.

Keywords: Electric vehicle; Battery recycling; Carbon emission; Network design

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1 Introduction

In recent years, the growing concern with environment and climate has promoted the fast development and deployment of Electric Vehicles (EVs). According to the International Energy Agency, the EV market is expected to expand to about 18,000,000 vehicles by the year 2020[1]. And particularly in China, the accumulated sales of EVs are projected at 5 million, which is almost 4 times the amount in 2015[2].Accompanying the large-scale adoption of electric vehicles, EV batteries (EVBs), which are a key component of EV, will be utilized in the next few years. At present, there are four main EVB technologies in use: lead-acid, nickel-metal hydride, lithium-ion (Li-ion), and nickel-nickel chloride [3]. Among them, lithium-ion batteries (LIBs) have unquestionable advantages in terms of raw material manufacturing, cost, extended cycle life, nickel metal and high specific capacity, so they have become the most widely used EVB in the market [4].Due to the booming EV market, the global Compound Annual Growth Rate of Lithium-ion batteries (the batteries most used as power sources in EVs) will grow by 36% from 2015 to 2020 [5].Along with the rapid growth of the EV market and the application of LIBs, a huge amount of batteries will soon reach their end-of-life. According to the China Automotive Technology and Research Centre, 120-170 thousand tons of used EVBs will need to be processed by 2020 [6]. It is well known that all materials used for making EVBs are extremely hazardous to both the environment and human health, and are able to permeate into the ground soil and thus water supplies when they are directly placed into landfills. For this reason, how to properly deal with so many used EVBs has become an urgent challenge today.

Currently, information is abundantly available concerning the Chevrolet Volt battery. The cost of manufacturing a new Chevrolet Volt battery is estimated to be $10,000 [7]. According to a report from the Argonne National Laboratory Center for Transportation, the breakdown of the manufacturing cost of an EV battery shows that material, labor, and overhead account for 80%, 10%, and 10%, respectively [8]. In order to lower battery costs, one potential way is to remanufacture from used batteries, since recycling materials from used EVBs is critical to saving on material costs. In the meantime, the increasing use of Lithium for EVBs is leading to the rapid depletion of Lithium, which implies an urgency to reduce the consumption of raw materials by recycling [9,10]. In addition, EV manufacturers need to take greater responsibility in battery recycling. For example, The Ministry of Industry and Information Technology of China (MIIT) promulgated *the Provisional Regulations on Traceability Management of Recycling and Utilization of Power Batteries for New Energy Vehicles* in July 2018, which clearly states that EV manufacturers must provide battery recycling service and promise to recycle in accordance with requirements, placing particular emphasis on the traceability management of batteries. In response to government regulations, it is mandatory for EV manufacturers to actively get involved in building recycling systems to reuse certain components, thereby yielding savings in raw materials, manufacturing costs, and energy consumption, leading to a reduction in environmental impact. Such a policy is very helpful to the conservation of raw materials, the lowering of manufacturing costs, and the reduction of energy consumption and environmental pollution risks.

Recycled lithium-ion batteries from electric vehicles could provide a valuable secondary source of materials [11]. It is also gratifying that, currently, more and more EV manufacturers have considered recycling used EV batteries. Nissan, Volkswagen, and BMW require their EV customers to return used batteries to licensed points or local authority battery collection schemes [12,13]. These returned used batteries are expected to be used as home energy storage instead of other energy storage equipment [14,15,16], considering the current price of lithium-ion batteries. In addition, Chevrolet has established an energy storage station using used EV batteries at the General Motors plant in Michigan [17]. In Europe, Tesla has begun recycling in cooperation with Umicore [18]. And the recycling of EVBs has been studied from various perspectives. For example, Georgimaschler et al [19] reviewed the recycling techniques for used batteries manufactured before 2012; Tang et al [20] investigated the social-economic-environmental impacts of recycling used EVBs under reward-penalty mechanisms; Liu et al [21] evaluated the latest technologies for used battery recycling and utilization; Qiao et al [22] compared Cradle-to-Gate greenhouse gas emissions of internal combustion engine vehicles and battery electric vehicles, and found that the production of EVBs causes an approximate 20% increase in greenhouse gas emissions; Hyung Kim et al [23] estimated the Cradle-to-Gate greenhouse gas emissions of an EV battery, and found it accounted for 45% of total emissions. Similar conclusions are also drawn in the research reported in [24]. To identify an effective way to reduce carbon emissions, Xiong et al [25] found that EV battery recycling and remanufacturing can reduce greenhouse gas emissions by 6.62% compared to manufacturing batteries from raw materials; Hao et al [26] analyzed electric vehicle (including EVB) recycling technology in China. The analysis results show that about 10% of lifecycle greenhouse gas emissions can be reduced by recycling. Ciez and Whitacre [27] compared the carbon emission situation of three recycling technologies (i.e. pyrometallurgical recycling, hydrometallurgical recycling, and direct cathode recycling), and found that direct cathode recycling has the potential to reduce emissions and is economically competitive.

In addition to the technologies adopted for disposing of used EVBs, the design of recycling networks also has a significant impact on costs or profits. A recycling network usually consists of: collection center, disassembly center, material recycling center, and waste disposal center. Because transportation between these centers causes costs and carbon emissions, there is no doubt that profits can be increased also by optimizing the design of the recycling network. To reach this purpose, Kannan et al. and Subulan et al. [28,29] proposed a closed-loop supply chain network to reduce the total cost of battery recycling and to recover valuable material from used EVBs; Li et al [30] also proposed a similar network for remanufacturing LIBs, and found that integrating remanufacture into LIB supply chains can help to increase profits; Gu et al [31] formulated optimal pricing strategies for manufacturers and remanufacturers, and studied the relationship between the rate of return, the rate of sorting, and the rate of recovery to optimize total profit in different periods.

In short, the recycling of car batteries can lead to more sustainable EVB production, which in turn supports the mass adoption of electric vehicles. However, there is not much literature relating to EV battery recycling network design, and there is a lack of research investigating EVB recycling at the enterprise level, which impedes the implementation of the secondary reuse of used EVBs. In fact, it is crucial that different handling strategies be adopted for different quality levels of used batteries for recycling network design; these strategies include, for example, recycling raw materials, remanufacturing battery cells, and landfill disposal. Although [28,29] have designed a closed-loop supply chain network for used batteries, unfortunately, their research rarely considers the differences between these used battery handling strategies, and their main consideration is to recycle and reuse raw materials from used batteries. Meanwhile, the design and optimization of recycling networks also has a significant impact on the reduction of carbon emissions, but to date, carbon tax, as an effective energy saving and emission reduction mechanism, has not been considered in the context of EVB recycling networks.

The purpose of this research is to fill this knowledge gap by developing a mathematical model to optimize recycling networks for EVBs. Unlike other models [20,28,29,30,31], the model proposed in this work considers three potential strategies to handle used batteries, including recycling, remanufacturing, and disposal (more information is given in Section 2.1). Used battery cells are classified according to quality, and are assigned to different processing centers in the recycling network. Moreover, to make the model more suitable for the development of the global low-carbon economy, carbon tax is also considered, to explore how the design of the EVB recycling network would be affected by the impact of carbon tax. The proposed recycling model is justified by a real case study of Chang'an Automobile (Group) Co., Ltd. (China). This research will bring guidance and decision-making to relevant companies at the enterprise level, that is, it supports EV manufacturers in reducing environmental burdens and total costs in the recycling network. Most importantly, this research will bring huge energy and environmental benefits to the electric vehicle industry, while also reducing the consumption of fossil fuels, and promote economically and environmentally sustainable development in the EVB industry. By conducting this research, the following three fundamental questions will be answered:

RQ1: How to design a recycling network model to reduce costs and carbon dioxide emissions?

RQ2: How do different factors affect the optimal location of facilities in the recycling network?

RQ3: How to further reduce costs to promote recycling of used batteries based on the designed recycling network model?

Accordingly, the rest of the paper is organized as follows. A mathematical model is developed and discussed in Section 2. A case study is conducted to validate the effectiveness of the proposed model in Section 3. Scenario analyses are performed in Section 4. The paper is finally ended in Section 5 with several important conclusions and a plan for future research.

2 Model of recycling network

2.1 Designing recycling network

This section introduces a model for EVB recycling networks considering carbon emissions. This model includes: collection centers, recycling and remanufacturing center, and waste disposal centers, as seen in Fig. 1. The proposed model will be able to determine the number of each type of center constructed in the recycling network, and the number of EVB batteries that should be transported from one center to another. The objective of the model is to minimize the total cost in an EVB recycling logistics network, which includes transportation costs, fixed costs, acquisition cost, cost for processing activities and environmental costs associated with carbon emissions. The environmental costs are measured by monitoring greenhouse gas emissions, such as the CO_2 generated by the transportation and disposal processes. The amount of carbon emissions is measured throughout the entire EVB recycling cycle, from the collection center to the reuse and waste disposal facilities. As illustrated in Fig. 1, the used EVBs stored at the collection center will be disassembled first; then their cells will be tested and categorized based on quality. Usually, the cells in a used battery can be roughly classified into the following 3 classes based on their capacity:

- Class 1 (L1) – capacity is higher than 80% of initial capacity;
- Class 2 (L2) – capacity is between 60% and 80% of initial capacity; and
- Class 3 (L3) – capacity is lower than 60% of initial capacity.

Based on the test results, different downstream processing strategies will be adopted for dealing with different qualities of cells, i.e.

- the L1-class cells will be transported to the remanufacturing plant and reassembled into new EVBs;
- the L2-class cells will be transported to the recycling plant, where some of the cells will be transported again to the remanufacturing plant and reused directly as batteries in other applications. The other L2-class cells in the recycling plant will be dissected, and only the reusable materials in them will be transported to the remanufacturing plant to make new battery cells;

- the L3-class cells and the waste from the remanufacturing plant and the recycling plant will be transported directly to the waste disposal center.

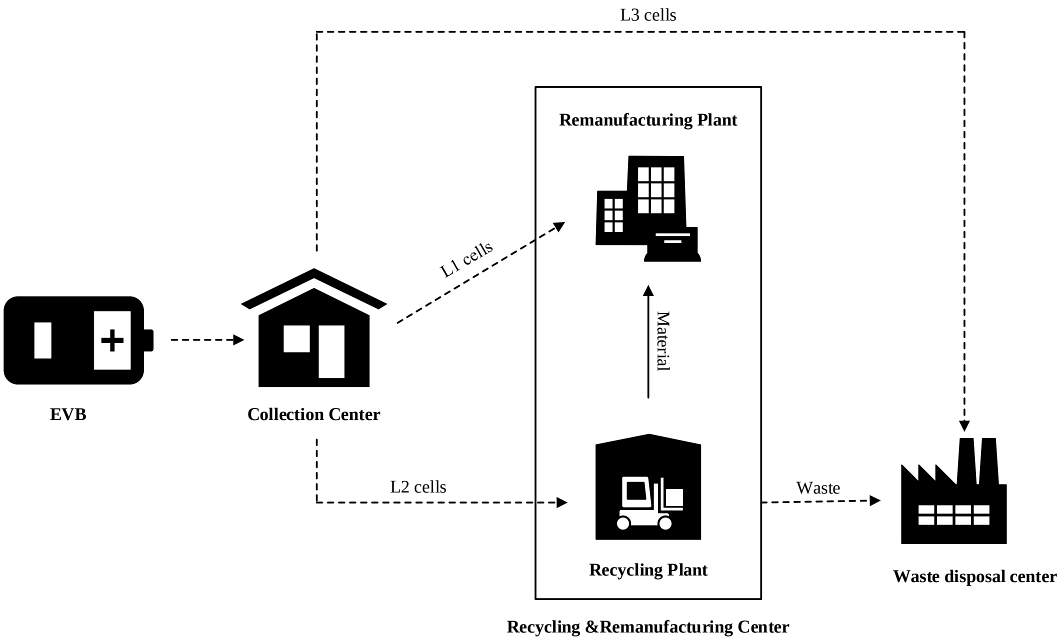

Fig. 1. EVB recycling network.

2.2 Main modeling assumptions

In order to simplify the model development, the following assumptions are introduced:

(1) $(Ni_xCo_yMn_{1-xy})O_2$ (NMC) is the most in-demand technology for EVBs, mainly due to its low self-heating rate and high energy density [32,33]. Therefore, all EVBs are assumed to be the same type.

(2) All centers have disposal capacity constraints;

(3) The possible locations of centers are known in advance;

(4) Cells in EVBs will be processed with multiple potential strategies (remanufacturing, recycling, and disposal) based on the cells' quality; where the number of cells processed (corresponding to the different strategies) follows Normal Distribution [17];

(5) The geographical location of each facility, and the distance between each facility, are determined by each facility's latitude and longitude, and accordingly straight-line distance is considered between centers;

(6) Based on the IPCC (Intergovernmental Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories, only the CO_2 emissions from the EVB recycling network are considered [34];

2.3 Proposed model

Based on the above assumptions, a mixed integer programming problem model is formulated to optimize the locations of the EVB recycling network, minimizing the total cost of the entire recycling network as shown in Eq. (1)-(3).

$$\min F = F_{operation} + F_{CO_2 emission} \tag{1}$$

Where

$$F_{operation} = f_{AC} + f_{FC} + f_{PC} + f_{TC} \tag{2}$$

$$F_{CO_2 emission} = f_{FEC} + f_{TEC} \tag{3}$$

As indicated in (1), the recycling cost comprises two parts, i.e. operation costs and CO_2 emission costs. Since all used batteries have to be recycled, based on [16,17], EV battery recycling and remanufacturing can reduce greenhouse gas emissions compared to manufacturing batteries from raw materials. In addition, the operation of the EVB recycling network will generate corresponding costs and carbon emissions, but these can be reduced by optimizing the design of the recycling network.

The former is the sum of acquisition cost f_{AC}, fixed cost f_{FC}, processing cost f_{PC} and transportation cost f_{TC}; the latter is the sum of the costs incurred in the processing and transportation processes, which are denoted by f_{FEC} and f_{TEC}, respectively.

2.3.1 Operation costs

The acquisition cost means that in order to promote the recycling of used batteries, subsidies could be offered to consumers. The acquisition cost of collection centers from the consumer market is calculated by Eq. (4).

$$f_{AC} = \sum_i \sum_u QB_i \bullet r_u \bullet \alpha_u \tag{4}$$

where

QB_i - quantity of used batteries returned to collection center i

r_μ- acquisition cost for used EVBs at different quality levels (L1/L2/L3)

α_μ - percentage of batteries at different quality levels (L1/L2/L3)

For the recycling and remanufacturing centers in the recycling network, the total fixed cost is described by Eq. (5).

$$f_{FC} = \sum_i x_i FC_i + \sum_j x_j FC_j + \sum_k x_k FC_k \tag{5}$$

where

FC_j, FC_j, and FC_j - fixed cost of collection center i, recycling and remanufacturing center j and waste disposal center k, respectively

$\boldsymbol{x_i}$ - binary decision variable equal to 1 if collection center j is open and 0 otherwise

$\boldsymbol{x_j}$ - binary decision variable equal to 1 if recycling and remanufacturing center j is open and 0 otherwise

$\boldsymbol{x_k}$ - binary decision variable equal to 1 if waste disposal center j is open and 0 otherwise

The processing cost of each center is mainly composed of three parts, i.e. the cost of detection and disassembly in the collection center, the production cost in the recycling and remanufacturing centers, and the processing cost in the waste disposal center. This can be f_{PC} formulated in Eq. (6).

$$f_{PC} = \sum_i pcc_i \bullet QB_i + \sum_i \sum_j pcr_j \bullet QCR_{ij} + \sum_i \sum_j pcm_j \bullet QCM_{ij} + \sum_i \sum_k pcw_i \bullet QCW_{ik} \tag{6}$$

where

QCR_{ij} - quantity of cells flowed between collection center i and recycling plant j

QCM_{ij} - quantity of cells flowed between collection center i and remanufacturing plant j

QCW_{ik} - quantity of cells flowed between collection center i and waste disposal center k

pcc_i - processing cost of collection center i

pcr_j - processing cost of recycling plant

pcm_j - *processing cost of remanufacturing plant*

pcw_k - *processing cost of waste disposal center k*

The transported products mainly include battery cells and waste from recycling and remanufacturing processes. The transportation cost from one node to another is formulated in Eq. (7).

$$f_{TC} = \sum_i \sum_j D_{ij} \cdot tcc \cdot QCR_{ij} + \sum_i \sum_j D_{ij} \cdot tcc \cdot QCM_{ij} + \sum_i \sum_k D_{ik} \cdot tcc \cdot QCW_{ik} + \sum_j \sum_k D_{jk} \cdot tcw \cdot QW_{jk} \tag{7}$$

where

tcc - transportation cost of one cell

tcw- transportation cost per unit waste

2.3.2 CO_2 emission costs

The respective costs of CO_2 emissions from processing used battery cells in the collection center, the recycling and remanufacturing plant, and the waste treatment center can be estimated by Eq. (8).

$$f_{FEC} = \sum_i p_{ct} \cdot fec_i \cdot QB_i + \sum_i \sum_j p_{ct} \cdot fer_j \cdot QCR_{ij} + \sum_i \sum_j p_{ct} \cdot fem_j \cdot QCM_{ij} + \sum_i \sum_k p_{ct} \cdot few_k \cdot QCW_{ik} \tag{8}$$

where

fec_i - *CO_2 emissions in collection center i*

fer_j - *CO_2 emissions in recycling plant*

fem_j - *CO_2 emissions in remanufacturing plant*

few_k - *CO_2 emissions in waste disposal center k*

p_{ct} - *carbon tax of unit carbon emission*

Meanwhile, the carbon emission cost of the transportation process, including transporting battery cells and waste, is shown in Eq. (9).

$$f_{TEC} = \sum_i \sum_j p_{ct} \cdot D_{ij} \cdot te \cdot QCR_{ij} + \sum_i \sum_j p_{ct} \cdot D_{ij} \cdot te \cdot QCM_{ij} \cdot \omega + \sum_i \sum_k p_{ct} \cdot D_{jk} \cdot te \cdot QCW_{ik} \cdot \omega + \sum_j \sum_k p_{ct} \cdot D_{jk} \cdot te \cdot QW_{jk} \cdot \omega \tag{9}$$

where

ω - *number of goods per container*

t_e - *CO_2 emissions of shipping one container of products per kilometer*

2.3.3 Constraints

To solve the model, the following constraints are considered.

2.3.3.1 Mass balance

$$bc \cdot \sum_i QB_i = \sum_i \sum_j QCR_{ij} + \sum_i \sum_j QCM_{ij} + \sum_i \sum_k QCW_{ik} \quad \forall i \in I, j \in J, k \in K \tag{10}$$

$$\sum_j \sum_k QW_{jk} = \sum_i \sum_j QCR_{ij} \cdot w_b \cdot \varphi + \sum_i \sum_j QCM_{ij} \cdot w_b \cdot \varphi \quad \forall i \in I, j \in J, k \in K \tag{11}$$

where

w_b *- the weight per cell(kg)*

bc *- number of cells included in an EVB*

φ - The mass of cells will change after being processed in the recycling center, which will directly affect the cost of transport and the carbon emissions costs. Therefore, the mass ratio of the outflowed waste from recycling and remanufacturing center to the disposal center is φ [35].

Constraints (10-11) represent the mass equilibrium of the recycling and remanufacturing centers and waste disposal centers, respectively.

2.3.3.2. Capacity constraints

The collection capacity of the collection center, the recycling capacity of the recycling plant, and the remanufacturing capacity of the remanufacturing plant are limited. Constraints (12-14) indicate the capacity restriction constraints of the collection center, the recycling and remanufacturing centers, and the waste disposal centers, represented by I_i, J_j, and K_k, respectively.

$$\sum_i QB_i \le \sum_i I_i x_i \quad \forall i \in I \tag{12}$$

$$\sum_i \sum_j QCR_{ij} + \sum_i \sum_j QCM_{ij} \le \sum_j J_j x_j \quad \forall i \in I, j \in J \tag{13}$$

$$\frac{\sum_i \sum_k w_b \cdot QC_{ik}}{bc} + \sum_j \sum_k QW_{jk} \le \sum_k K_k x_k \quad \forall i \in I, j \in J, k \in K \tag{14}$$

2.3.3.3. Decision variables constraints

$$QB_i, QCR_{ij}, QCM_{ij}, QW_{jk} \ge 0 \tag{15}$$

$$x_i, x_j, x_k \in \{0,1\} \tag{16}$$

Constraints (15-16) are related to the binary and non-negativity restrictions on the corresponding decision variables.

3 Case Study

3.1 Description of Current network

Chang'an Automobile (Group) Co., Ltd. (Chang'an) is a manufacturer of EVs and therefore is responsible for recycling used power batteries. Chang'an has established an EVB recycling network, including: eight collection centers, which are responsible for providing services for detecting and dismantling used batteries; one recycling and remanufacturing center; and two waste disposal centers. These are shown in Fig. 2, in which green, blue, and black dashed lines represent the material flows of L1 & L2 cells, L3 cells, and waste produced in the recycling and remanufactured process, respectively. I, J, and K are used to indicate the collection centers, recycling and remanufacturing centers, and waste disposal centers, respectively. Because EV battery recycling and reuse mainly include the recycling of raw materials from used batteries and the remanufacturing of used batteries, the operation of the recycling network is organized according to the location of the recycling and remanufacturing center.

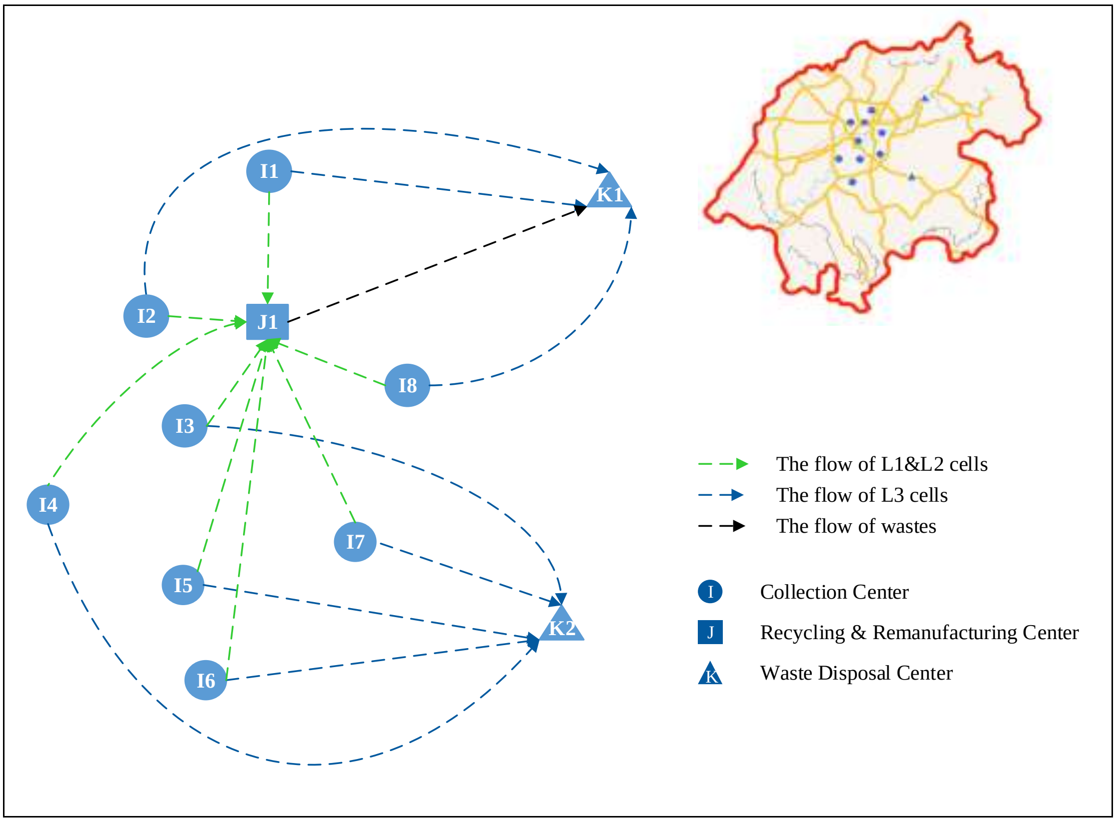

Fig. 2. The current recycling network of EVBs in Chang'an.

3.2 Input data

The current numbers of used EVBs handled in different centers are summarized in Table 1. Due to lacking information, the quantities of the cells at different levels are obtained based on assumption 4. The specifications of an EVB are given in Table 2.

Tables 1. The flows cells at different centers.

Collection center	No. of used EVBs for Chang'an	Recycling and remanufacturing centers		To Waste disposal centers (L3 cells)
		To Recycling Plant (L2 cells)	To Remanufacturing Plant (L1 cells)	
I1	420	62	260	98
I2	351	54	217	80
I3	684	107	421	157
I4	539	82	333	124
I5	574	83	360	132
I6	637	97	391	149
I7	314	48	184	82
I8	720	117	421	164

Table 2. EVB parameters.

Weight (kg)	the weight per cell (kg)	Cells within an EVB	Capacity (kWh)
365	3.5	96	52.56

The other costs needed by the calculation are presented in Table 3.

Table 3. Cost parameters.

Parameter classification	Value
Fixed cost ($/center)	[250,000–650,000] [29]
Processing cost in collection center ($/cell)	8.3 [36]
Processing cost in recycling plant($/cell)	20.5 [36]
Processing cost in remanufacturing plant($/cell)	62.3 [36]
Processing cost in waste disposal center($/cell)	0.08 [36]
Unit transportation cost ($/cell · km)	0.08 [27]
Unit transportation cost ($/waste · km)	0.012 [27]
Acquisition cost for L1/L2/L3 batteries ($/battery)	(850, 220, 0) [23]
The price of carbon tax ($/ton)	44 [37]

Different recycling technologies result in different carbon emissions [24]. In this study, hydrometallurgical recycling is considered. The corresponding emission data are shown in Table 4. Moreover, based on the results of [38], for transportation by trucks (Load: 9.0 ton/truck), the normal fuel consumption is about 0.33 l/km, which implies a carbon emission density of 0.00249 kg CO_2/(ton·km), based on the carbon emission density of diesel, 0.06805 kg CO_2/l [39].

Table 4. Unit emission parameters.

Parameters	Values
CO_2 emissions in collection centers (CO_2 kg/cell)	2.43 [24]
CO_2 emissions in recycling plants (CO_2 kg/cell)	8.55 [40,41]
CO_2 emissions in remanufacturing plants (CO_2 kg/cell)	31.03 [21,42]
CO_2 emissions in waste disposal centers (CO_2 kg/cell)	0.35 [40,42]

3.3 Optimization of the studied case

In order to verify the effectiveness of the proposed model, the current Chang'an automobile battery recycling network is firstly optimized. A genetic algorithm (GA) is used to solve the model for the case study. For the GA, the crossover probability and mutation probability are 0.6 and 0.05, and the number of iterations is 100. The optimized recycling network is shown in Fig. 3, and the cost savings are shown in Fig. 4.

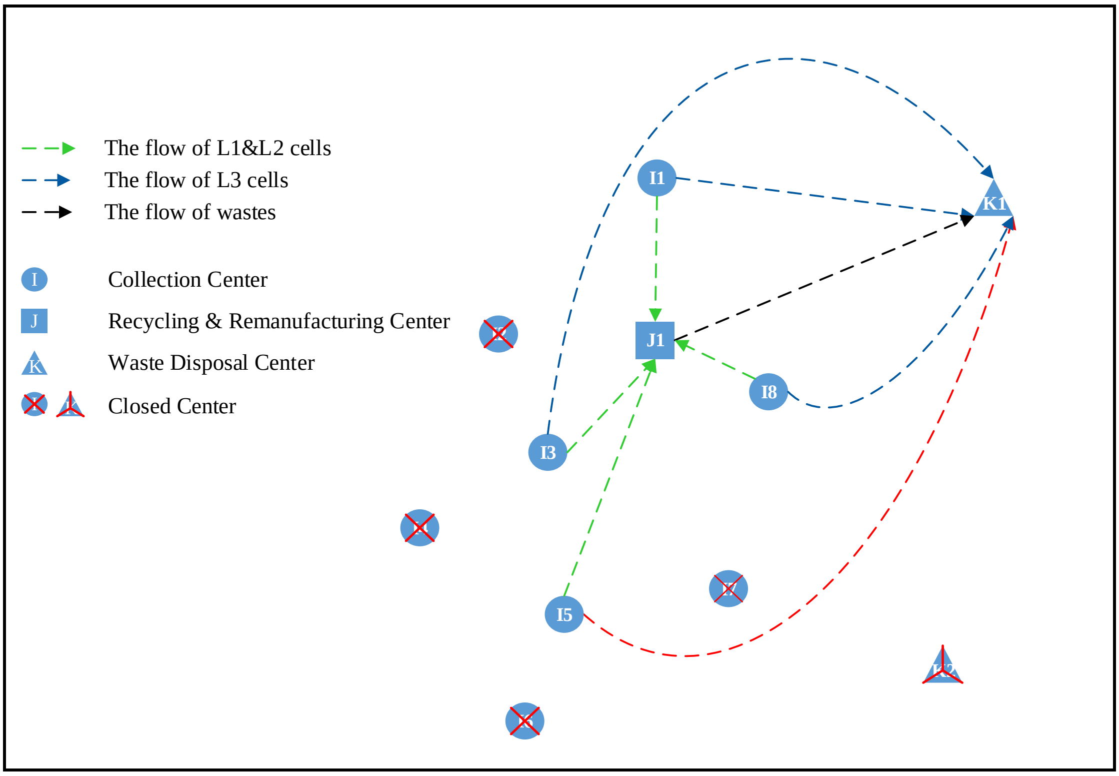

Fig. 3. The recycling network after optimization.

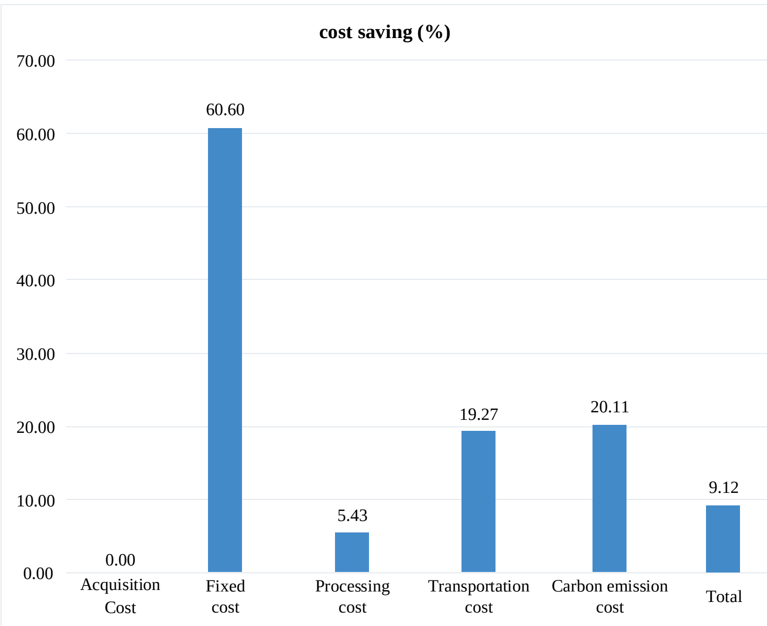

Fig. 4. The cost savings after optimization.

As seen from Fig. 3 and Fig. 4, the optimized network reduced the number of collection centers and waste disposal centers. Correspondingly, the transportation routes between centers have also been changed, which can result in a reduction of the total costs of the current Chang'an EVB recycling network. Moreover, carbon emissions can be effectively reduced by 21%.

To meet the requirements of the booming market, Chang'an is planning to build one more recycling and remanufacturing center in the current recycling network. According to city planning, there are 3 alternative addresses available to build the new recycling and remanufacturing center. They are also marked in Fig. 5, where blue solids represent existing centers, and red solids represents potential locations for the new centers. In addition, it is worth noting that J1, J2 and J4 are all in Yubei District, while J3 is in Jiangbei District in the administrative division of Chongqing. In order to identify the best choice among these options, thereby achieving the lowest cost and carbon emissions, the model developed in Section 2 is applied to optimize the network.

The proposed model is adopted to achieve the following goals: (1) determine the location of the new recycling and remanufacturing center; (2) optimize the transport routes of the recycling network. In order to minimize the total cost of the recycling network, some collection centers may be closed; and (3) comprehensively understand the impact of key factors on the location-allocation and operating cost of the EVB recycling network.

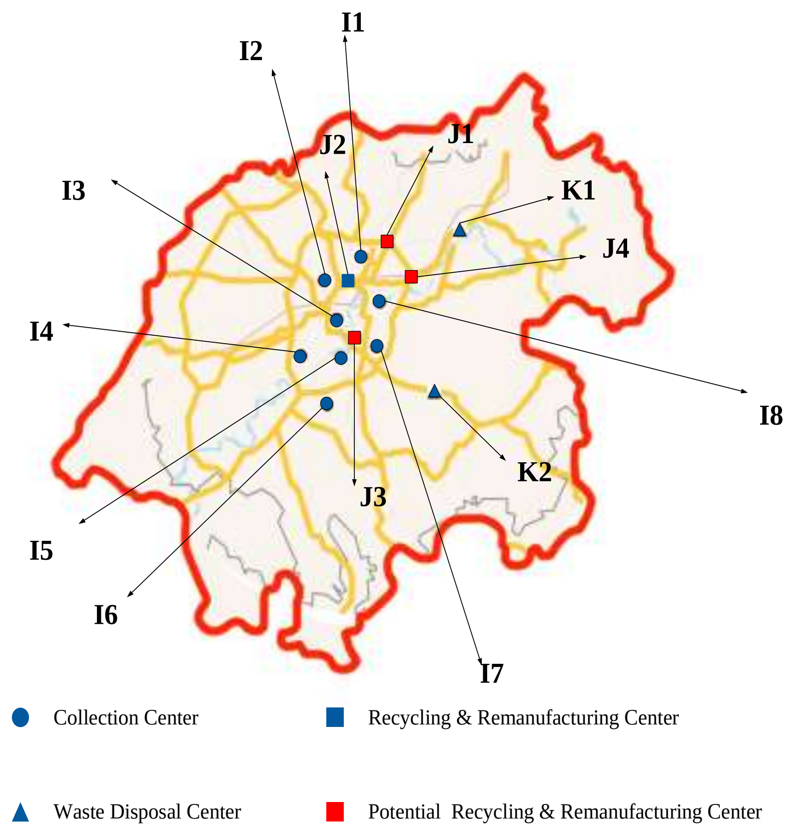

Fig. 5. The distribution of facilities.

The new network design to optimize the location of the new recycling and remanufacturing center for EVB recycling is shown in Fig. 6. The black and red dashed lines represent existing and proposed transport routes, respectively, and the closed centers have been marked. Moreover, a comparison of the costs of existing and proposed networks is shown in Fig. 7. The corresponding costs per unit of battery recycling are shown in Fig. 8.

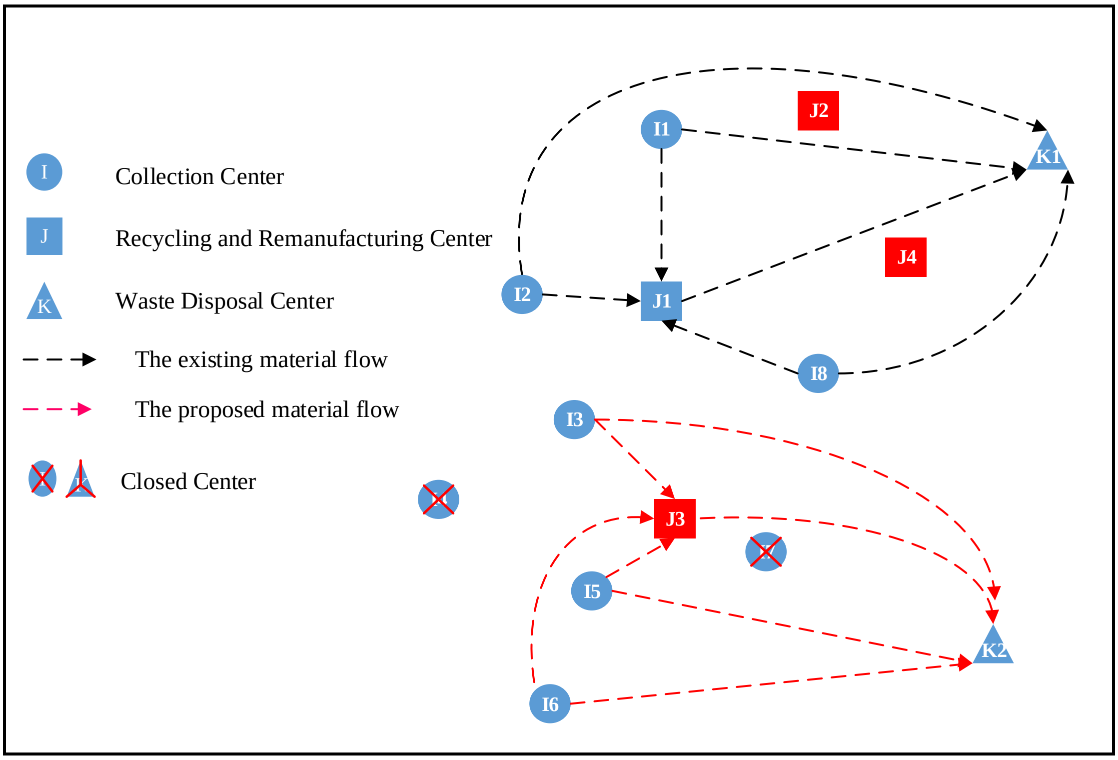

Fig. 6. The recycling network after determining location of new opened center.

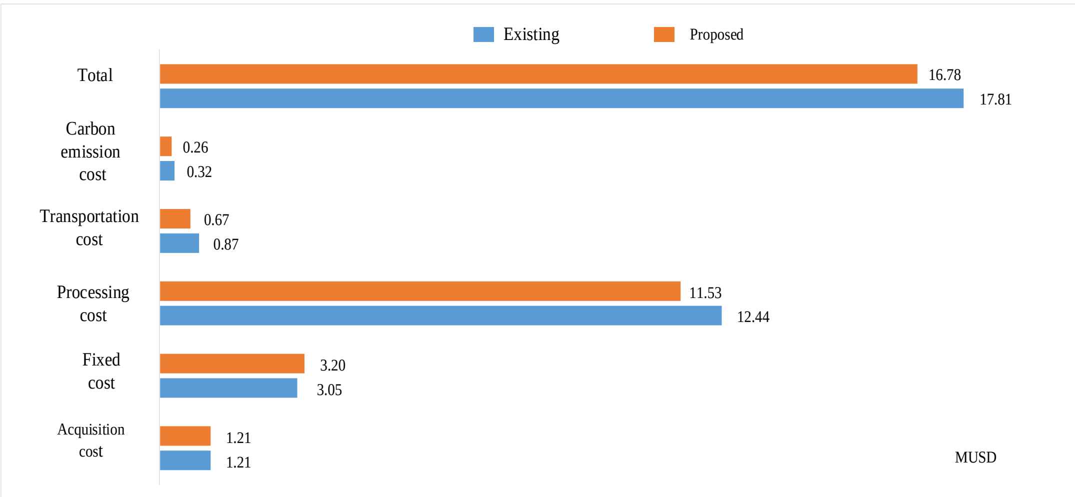

Fig. 7. The various cost comparison of existing and proposed.

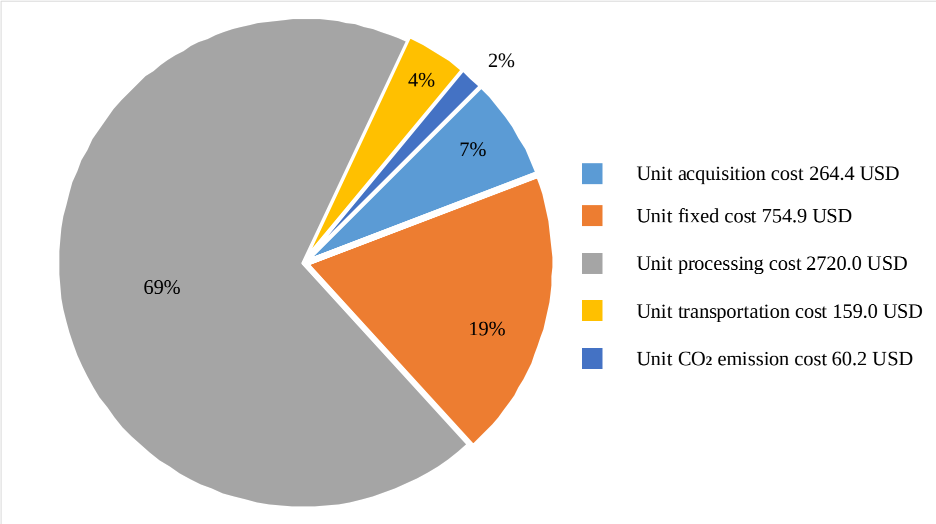

Fig. 8. Cost breakdown: per unit of battery recycling.

From Fig. 6, it can be seen that J3 was selected as the best address of the new recycling and remanufacturing center. In addition, it was found that, compared to the previous recycling network, the optimized network is divided into two parts. The operation of the first part is centered on J2, while the operation of the second part is centered on J3. Moreover, as the operation of the new center will inevitably increase fixed costs, the optimization results recommended that existing collection centers I4 and I7 be closed to reduce the costs of the whole recycling network.

Compared to the costs of the previous network, as shown in Fig. 7, the new network can achieve a reduction of the total cost by 5.60%. The transportation cost showed the biggest drop (reduced by 22.79%), followed by the carbon emission cost (reduced by 21.1%). The processing cost represented the biggest share in the total cost; even though it was reduced by 7.3%, it showed the most obvious impact. These data prove that the developed model does work in optimizing the design of the recycling network.

From Fig. 8, the cost per unit battery is 3958.4 USD in the recycling network; this is much lower than the cost of manufacturing a new battery ($10,000) [7,8]. Meanwhile, the battery cells produced by the recycling and remanufacturing process can be reassembled in new batteries, thereby further reducing the cost of raw materials purchased by enterprises in the process of producing new batteries. In addition, the cost of a unit battery is based on the current recycling amount of used batteries and cost parameters. As more and more used batteries are recycled, and recycling technology develops, the value will change. Therefore, the optimization in this paper mainly involves transportation costs and carbon emissions generated during transportation.

4 Scenarios analysis

According to the cost equations in the objective function, many factors are found to affect the design and the operating cost of the network, such as the number of used batteries, carbon tax, unit transportation cost and unit processing cost. We expect that as transportation costs and carbon taxes change, in order to reduce carbon emissions, EV manufacturers will significantly differ from the baseline situation in the location and allocation of facilities in the recycling network. In addition, changes in processing costs will not affect the design of recycling network locations. In order to further understand the impacts, five scenarios are considered in the research:

- **Scenario 1 (S1)** represents the reference scenario, with all inputs at the current level;
- **Scenario 2 (S2)** considers an increase of used EVB by 30%, in which the increased number of used

batteries does not exceed the processing capacity of the current opened center;

- **Scenario 3 (S3)** considers changes to carbon tax, assuming an increase of carbon tax by 50%;
- **Scenario 4 (S4)** considers changes to transportation cost, assuming an increase of fuel price by 50%;
- **Scenario 5 (S5)** studies the impact of processing cost, assuming that advances in technology have reduced unit processing costs by 25%.

The optimal designs of the network under different scenarios are illustrated in Fig. 9; the total cost and cost breakdown are shown in Fig. 10 ; and the number of batteries handled in each center is shown in Table 5. The results clearly show that the effects of processing cost and carbon tax on location optimization were mild, and that the effects of the number of used batteries and fuel price can change the optimal location of the EVB recycling network.

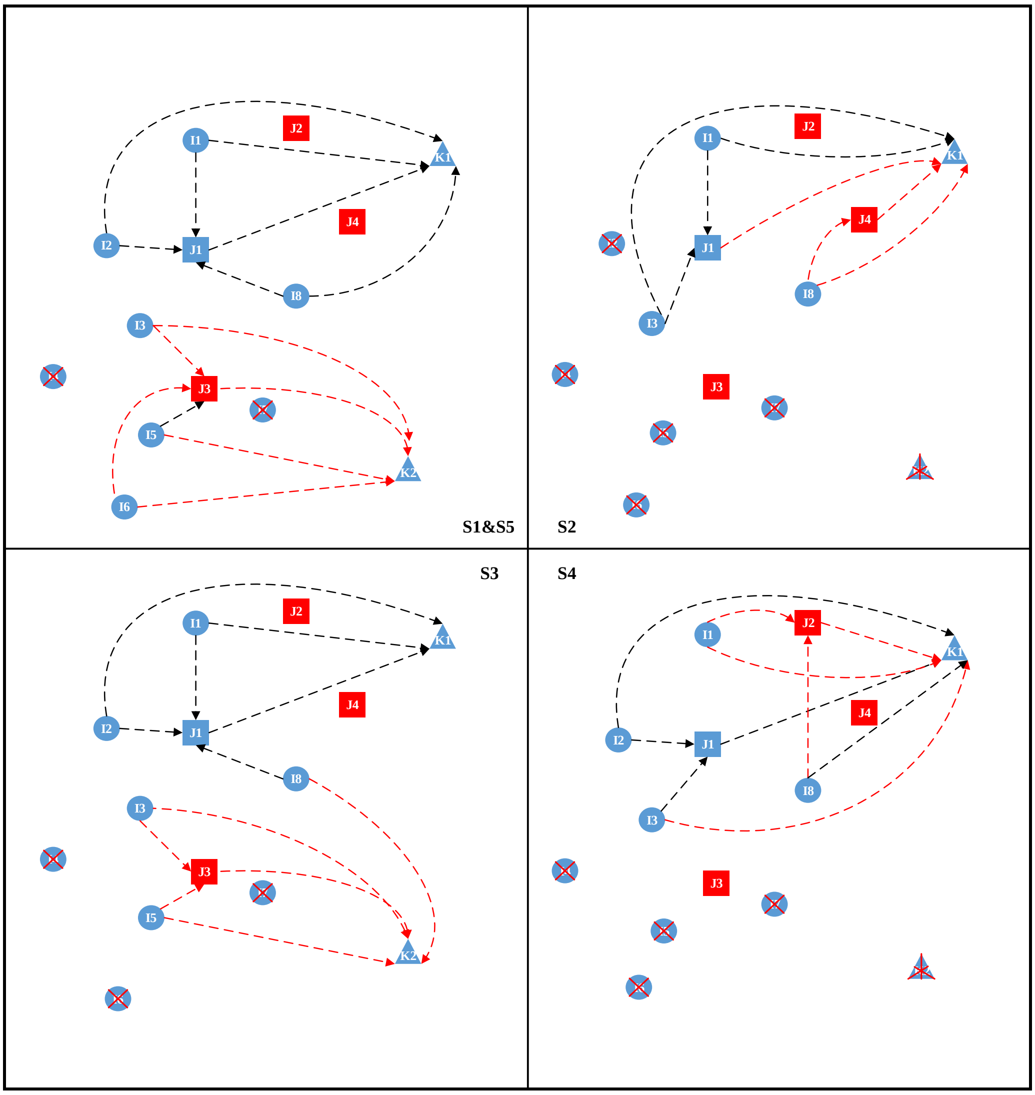

Fig. 9. The recycling network of S1-S5.

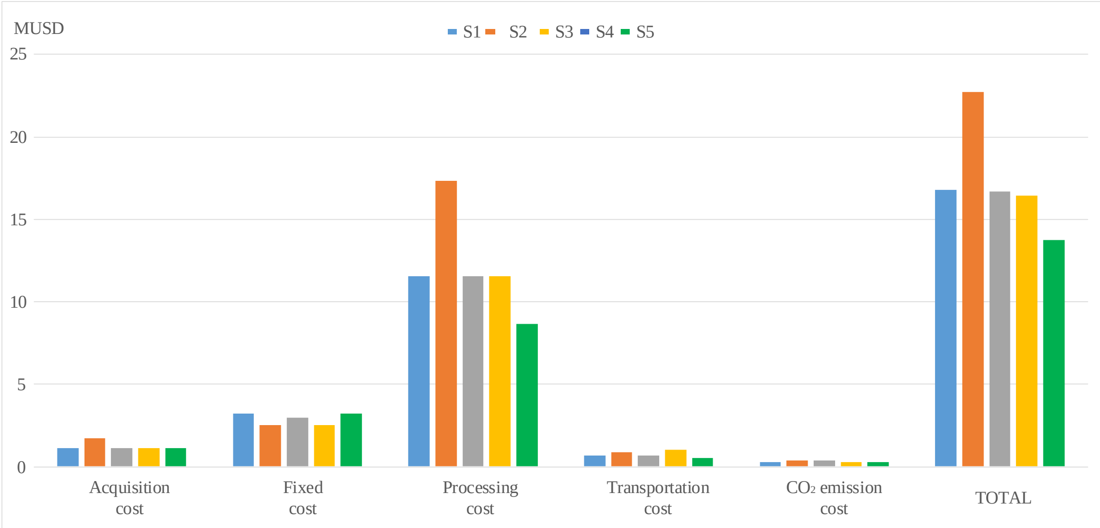

Fig. 10. The costs breakdown of S1-S5.

Tables 5. The number of handled batteries of S1-5 at different centers.

Scenarios		**S1**	**S2**	**S3**	**S4**	**S5**
Collection centers	I1	945	1911	420	1461	945
	I2	486	×	723	867	486
	I3	819	1747	1191	1335	819
	I4	×	×	×	×	×
	I5	866	×	946	×	866
	I6	637	×	×	×	637
	I7	×	1091	×	×	×
	I8	877	1619	1092	1236	877
Recycling and remanufacturing centers	J1	1253	2012	1325	1824	1253
	J2	×	×	×	1442	×
	J3	2014	×	1928	×	2014
	J4	×	2249	×	×	×
Waste disposal centers	K1	337	1249	375	971	337
	K2	635	×	609	×	635

From the results of S2, as shown in Fig. 9, the optimal location of the recycling and remanufacturing center has been changed, from J3 to J4. The closed centers and the transport routes were also different from S1.

Increased amount of used batteries will lead to increased costs in the recycling network; therefore, several existing centers (I2, I4, I5-I6, and K2) will be closed in the optimized recycling network to reduce costs. In the optimized network, both the new and existing recycling and remanufacturing centers J4 and J2 were the core of the operation of the EVB recycling network. Compared with S1, the recycling network was more centralized in S2.

According to S3, changes in carbon tax can also clearly affect the optimal design of the recycling network. Fig. 9 shows that J3 will be selected for the new center. Since carbon emissions occur mainly during transportation of goods between the centers, and during processing in each of them, identifying the shortest route for transportation through optimization became more important when the carbon tax was increased by 50%. In order to offset the fixed costs due to the opening of new recycling and remanufacturing centers J3, while minimizing the carbon emissions generated, the existing collection centers I4, I6 and I7 were closed in the optimized network, which was different from the other scenarios.

In S4, the optimal location of the recycling and remanufacturing center has been changed from J3 to J2. Meanwhile, as the increased cost of fuel prices mainly affects the transportation routes, the closed collection centers and waste disposal centers as well as the transport routes were also different from S1. According to Fig. 10, increasing fuel price can clearly increase the transport cost. But its impact on carbon tax was not obvious, due to the optimized routes.

5 Conclusion and future work

Due to the urgent need for the recycling of used electrical vehicle batteries, this work developed a model which considers three used battery potential handling strategies (recycling, remanufacturing, and disposal). This includes the waste battery disposal strategies of most domestic and foreign companies, and is generally representative. Different quality levels for the used battery cells are considered in model, and are used to assign processing jobs to different centers within the network for the design optimization of battery recycling networks. This research can provide planning and decision-making methodology for electric vehicle manufacturers for recycling and secondary reuse at the enterprise level. To reduce the costs and carbon dioxide emissions of the entire network, the developed model has been applied to a real case study, based on the network of Chang'an electric vehicle manufacturer. And the results obtained are summarized as follows：

(i) The proposed model can effectively optimize the design of recycling networks. Compared to the current layout of the network, the total cost can be reduced by 5.6%, and CO_2 emissions can be reduced by 21.1% after optimization. The model can also be used to select optimal locations when additional centers are planned.

(ii) Transportation costs, carbon tax, and the number of used electric vehicle batteries have been identified as three major factors affecting the optimal design of the recycling network. Scenario analyses reveal that variations in the key factors can change both the configuration of the network and the total cost. From the perspective of total cost, processing cost has the most obvious impact; meanwhile, carbon tax has the least impact.

(iii) Although processing cost accounts for the largest proportion of the total cost, changes in processing cost will not affect network optimization. Therefore, for electric vehicle manufacturers, it is possible to further reduce the total cost of the recycling network by improving recycling technology.

In fact, different types of batteries from different manufacturers can use the same recycling network for secondary use of used batteries. It is worth noting that the results will also vary from case to case due to the different actual conditions of different companies and regions. For example, adopt different recycling processes or areas with very high carbon tax. Therefore, relevant companies should refer to the scenarios analysis in this article and combine their environment to analyze, in order to accurately determine the number of facilities and transportation routes in the recycling network.

In the next step, the research reported above can be further deepened by considering more factors to achieve broader insights into the recycling and reusing of used electric vehicle batteries. For example, the model could consider the impact of different transportation methods and the types of used batteries on the total cost and the corresponding carbon emissions of the recycling network, thereby making the model more accurately simulate the operation of an actual battery recycling network. In addition, besides carbon emissions, other environmental pollutants (e.g. PM2.5 or other gaseous pollutants) generated during the electric vehicle battery recycling process could be also considered in the model. That would enable the model to provide a more reliable prediction of the impact of the recycling of used EVBs on the environment.

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