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Research article

The optimization of an EV decommissioned battery recycling network: A third-party approach

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ABSTRACT

In this paper, we solve the urgent problem to construct a recycling network of decommissioned batteries of Electric Vehicles (EVs) and clarify the recycling entities that will be responsible for its reverse logistics (RL) process. We consider the third-party recycling entities to develop a recycling network and conduct a case-study of Xi'an, a key industry of EVs in China to provide a reference for the government and enterprises to develop recycling plans. We scientifically optimize our recycling network, which will have a significant impact on the environmental and economic benefits of electric vehicles (EVs) in Xi'an in the future. Specifically, we consider the costs of transportation, construction, operation, recycling, packaging, and emission, as well as the profits achieved through sales revenue and subsidy offerings. We collect the actual data of potential facility locations in Xi'an, predict the quantity of decommissioned batteries in the future, and develop a fuzzy-based model to solve the optimal results of battery traveling path and distribution in the recycling process network. Our results show that with the rapid growth of the number of decommissioned batteries, third-party revenues will reach about 53.08 billion by 2035. When the facilities split the recycling process load appropriately, the network has increase in revenue while the utilization rate of facilities will decrease. We expect that splitting will be a major trend in the future development of recycling network in Xi'an. Finally, a sensitivity analysis finds that with the environmentally conscious and safe operation of recycling, the negative impact on the third-party enterprises' revenue will be small. Our proposed methodology can serve as a critical framework for other cities and governments to plan their recycling networks and formulate regulations, reflecting on the realistic projection of the scale of decommissioned batteries of EVs and the potential siting and sizing of the recycling facilities.

1. Introduction

Driven by the winds of industrialization and urbanization, the transportation sector produces a significant portion of the total volume of greenhouse gasses emitted globally (Sikder et al., 2022a,b). To reduce the carbon footprint of the transportation sector, governments around the world have implemented a series of policy initiatives that seek to stimulate the production and consumption of electric vehicles (EVs) (Wang et al., 2022, 2024). Over the last five years the worldwide sales of NEV (New Energy Vehicles) have increased from 2 million in 2018 to more than 10 million in 2022, a 2.5%–14% increase in market share, from which EVs made up a significant majority (IEA, 2022). As both a major producer and seller of such vehicles, China sold 6.887 million EVs, including both Battery EVs (BEVs) and Plug-in Hybrid EVs (PHEVs), in 2022, representing 60% of the global NEV market share (IEA, 2023).

However, the rapid adoption of EVs will not solve the climate change quandary by itself (Hu et al., 2023). Key to the problem is the charge capacity of the EV batteries, which falls to 80% of optimal levels over three to five years (Pražanová et al., 2022). Moreover, at the end of their life cycle, the EV batteries must still then be recycled and/or disposed of (L. Zhang et al., 2021). While the rapid adoption of EVs may help fight climate change by reducing of emissions, the problems around battery production and recycling present their own significant concerns. In China alone, it has been estimated that the volume of batteries recycled

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in 2023, 2024, and 2025 will be 540,000 tons, 600,000 tons and 1.2 million tons respectively, before reaching some 3.001 million tons in 2030 (IIGF, 2023). If the amount of waste decommissioned batteries cannot be properly disposed of, its electrolytes and heavy metals will directly affect the environment and even endanger human health (Wang et al., 2020). There is therefore an urgent need to develop a clear battery management plan that not only deals with increased EV demand but also effectively manages the recycling and disposal of batteries at the end of their lifecycle.

Decommissioned batteries are not worthless, with the raw materials used in battery production available for future use. For example, the LFP batteries and NCM batteries, commonly used in EVs, containing many valuable metals like lithium (Li), nickel (Ni), cobalt (Co), copper (Cu), manganese (Mn), aluminum (Al) and graphite (Wang et al., 2023). As such, the valuable metals found in high-quality batteries can be reused as a basis for other forms of battery production (Martins et al., 2021). It is not only conducive to environmental protection, but also can effectively alleviate the shortage of Ni and Co in China (Sikder et al., 2022a; Wang et al., 2021). For example, in China, many decommissioned batteries are used in mobile charging piles, low-speed EVs, AGV power supplies, streetlamp energy storage, uninterruptible power systems (UPS) and power grid suppliers (Yu et al., 2022), or it can be used in buildings to facilitate meeting household energy needs (Yan et al., 2023) and contribute to the progress of decarbonizing buildings (M. Zhang et al., 2023; Zou et al., 2023). In the future, more decommissioned batteries will enter above facilities through echelon utilization (Shafique et al., 2022), or continue to be put into battery production to achieve resource circulation (Wang et al., 2020a) Given such developments, the environmental and socio-economic problems caused by decommissioned batteries have received greater public and academic attention in recent times.

1.1. Global efforts to recycle decommissioned batteries

Many governments around the world are concerned about global energy demand and low-carbon issues (Chen et al., 2023), especially in household electric appliances or batteries (Xiang et al., 2023). They have attempted to develop a sustainable system for recovering and potentially disposing of decommissioned batteries. For example, the European Union (EU) has proposed new battery regulations under the Circular Economy Action Plan and the European Green Deal (European Commission, 2020). The USA and Canada have also implemented co-regulatory or voluntary product stewardship schemes to manage battery recycling (Call2Recycle Canada, 2017; Call2Recycle USA, 2017). Similarly, Japan and South Korea, who are considered the largest manufacturers and distributors of batteries in the world, have implemented a series of legislative measures to ensure the resources used in their production are better managed (METI, 2021). From the perspective of recycling modes, these countries have their own characteristics. The United States is one of the first countries in the world to adopt a third-party recycling mode. The BCI (Battery Council International) acts as the third-party enterprise, which is responsible for battery recycling in every state. It also refines the classification process, specifications, and knowledge popularization of battery recycling (Kahhat et al., 2008). In addition, European countries pay attention to the implementation of the extended producer responsibility system and advocate industrial alliances (Turner et al., 2016). Japan began battery recycling as early as 1994, and proposed the 4 R (reuse, resell, refabricate, recycle) concept to support the echelon utilization of decommissioned batteries (Fujita et al., 2021). Battery recycling in South Korea is still in its early stages, but it is worth noting that South Korea has cooperated extensively with China. Such consultations led to the signing of a memorandum between Grammy and the Pohang municipal government and ECOPRO in October 2019, which seeks to promote NEV battery echelon utilization and recycling projects (GEM Co., Ltd, 2019).

Therefore, in response to the rapid growth in demand for EVs and their decommissioned batteries, the Chinese government issued the "*Interim Measures for the Management of the Recycling and Utilization of NEV Power Batteries*" as early as 2018, which clearly stipulates that automobile manufacturers have the main responsibility for recycling decommissioned batteries and promoting the construction of their recycling networks (MIIT, 2018). Also, via the "*Industry Specification Conditions for the Comprehensive Utilization of Waste Power Batteries for NEVs*", which was released in 2019, an attempt has been made to regulate and explain the layout and site selection, technology, process, energy consumption and other aspects of battery and EV manufacturers (MIIT, 2019). In 2020, the State Council formulated and released the "*NEV Industry Development Plan (2021–2035)*". This initiative emphasizes the role that manufacturers play in the selection of NEV technical routes and the construction of production service systems (MIIT, 2020). In 2021, the Xi'an Municipal Government issued the "*Implementation Opinions on Accelerating the High-quality Development of the New Energy Vehicle Industry*". This policy has two key components. Firstly, it seeks to promote the fuel cell project applications, which helps to accelerate the pace of growth across the industry. Secondly, it seeks to improve not only the daily supervision and management system of NEV manufacturers and their products, but also the safety management systems of operating vehicles, and battery recalls (Xi'an Municipal Government, 2021).

In summary, around the world, many countries and governments have sought to improve their battery recycling systems, policies, and regulations. However, despite growing EV demand and policies to encourage the more sustainable management of EV battery waste, China has not yet formed an effective and systematic decommissioned EV battery recycling system (MIIT, 2022). In fact, in China, many organizations have long been engaged in the battery recycling business, such as BYD, Grammy, and CATL. In addition, many other small companies have independently carried out small-scale battery recycling. In both instances, these organizations usually have independent recycling capabilities but lack state-authorized recycling qualifications. A lack of network-wide analysis may lead to low levels of efficiency across the decommissioned battery reverse logistics and recycling market. Therefore, there is an urgent need for a scientific pilot study that provides a solution to the EV battery recycling problem. There is still great potential for developing a plan that effectively coordinates existing recycling networks and resources in a manner that efficiently manages waste materials and the battery recycling process.

1.2. Literature review

Reverse logistics is the process of planning, implementing and controlling the efficient, effective inbound flow and storage of secondary goods and related information, opposite to the traditional supply chain directions for the purpose of recovering value and proper disposal (Fleischmann et al., 2001). From a reverse logistics (RL) perspective (Wang et al., 2022), the key aspect of recycling an EV decommissioned battery is generating profit from any value that may remain (Hao et al., 2017). Studies have shown that by improving the efficiency of the RL network, EV decommissioned batteries can promote green development and social benefits (Tang et al., 2019), which has in turn garnered significant interest from many countries around the world (Biçe and Batun, 2021).

The last few decades have seen many researchers explore the RL of batteries. For example, from an international perspective, Yender (1998) documented the challenges of battery recycling, such as the participation of end-users, the cost efficiency of recycling batteries and battery sorting. Schultmann et al. (2003) developed a hybrid approach to establishing a closed-loop supply chain for used batteries that combines an optimization model for planning a reverse-supply network. Shi et al. (2012) analyzed the RL processes of used batteries, including collection, transportation, storage, and sorting, loading/unloading, recycling, and final disposal. For our study, RL refers to the decommissioned batteries that flow from the end of the supply chain to third-party enterprises and includes their transportation, recycling, collection, disassembly, and remanufacturing. The optimal solutions sought from the process include environmental protection, resource utilization, supply chain coordination and a wide range of economic benefits.

This RL study for EV decommissioned batteries can be divided into three research categories: 1) the recycling situation and future developments; 2) the analysis of recycling modes; 3) the construction of the RL recycling network (Gan and He, 2013). Some examples for each thematic area are now discussed with gaps within the literature also identified.

As part of a current and future assessment of recycling batteries in India, Kumar et al. (2021) presented the three most important challenges facing the sustainable supply chain of EV batteries, namely, ineffective recycling and reuse of batteries, disposal of batteries, and insufficient charging infrastructure. In other works, Islam et al. (2022) investigated the consumers' perspective on waste battery collection and recycling behaviors in Australia and analyzed their implications for developing recycling schemes. While, Kastanaki et al. (2023) forecasted the amounts and capacity of batteries directed to remanufacturing, reuse, and recycling in the EU-27 as a whole, as well as more specific focuses on Germany and France and emphasized the importance of future investments in recycling infrastructure. The articles on this topic generally use *qualitative analysis* as a means of assessing, from a circular economy perspective, the recycling behavior and willingness of countries, enterprises, or consumers. Qualitative methodologies are also used during the early stages of RL analyses; however, such approaches fail to capture the significant volumes of data that are now available, such as the number of decommissioned batteries, the amount of carbon emissions, and the costs and/or profits of the organizations involves. As a consequence, many authors have sought to provide deeper analyses on battery recycling modes and their subsequent networks using big data approaches.

To analyze the recycling modes, Q. Zhang et al. (2021) constructed a Stackelberg model with battery manufacturers, automobile manufacturers and third-party recycling enterprises as the main recycling subjects. From this analysis, they obtained a series of optimal decision and profit layers for three recycling modes. Hao et al. (2021) constructed a recycling cost model and compared four recycling modes. They proposed that the third-party recycling mode is more efficient. Moreover, as the number of decommissioned batteries increases, the third-party outsourcing mode is more competitive than the recycling systems utilized by the OEMs. Tang et al. (2018) proposed a reward-penalty mechanism and tested its impact on battery recycling using the Stackelberg game theory. They found that competition between manufacturers and retailers in the recycling channels has some advantages. Sun et al. (2022) constructed three battery recycling modes and used the Stackelberg game to discuss the selection of recycling channels.

Many authors focus on the uncertainty of recycling networks and consider environmental protection and/or profit generation as their objectives. To study the construction of the RL recycling network, Kuşakcı et al. (2019) found the issue of uncertainty to be an important construct when assessing the recycling network. Trochu et al. (2020) explored the environmental policy demands and carbon emission uncertainties to develop and model a robust RL network. Xiao et al. (2022) focused on the uncertainty of the disassembly sequence of EV decommissioned batteries to offer a dynamic and optimized process for manufacturers. Mu et al. (2023) explored the optimal layout of a sustainable RL network for EV decommissioned battery recycling and emphasized the important role that uncertainty plays. However, they fail to analyze the performance of the third-party mode, even though their recycling network is based on third-party logistics enterprises. Ma and Liu (2021) proposed a four-level battery recycling network, including collection warehouses, storage warehouses, transit hubs, echelon utilization enterprises and other nodes. Alamerew and Brissaud (2020) proposed a MILP model for the battery recycling network and optimized it by using a heuristic algorithm. Li et al. (2023) considers the full or partial cooperation of different EV manufacturers, revealing the effectiveness of the location decision made by a facility. In doing so, they also provide support for the types of decisions made during the EV waste battery recycling and production processes. However, in fact, across-network cooperation may also exist between battery manufactures, third-party recyclers and car recyclers. Rosenberg et al. (2023) conducted a German-based OEM case study in which they examined the impact that a growing number of end-of-life batteries can have. They found that it is necessary to extend the scale of existing recycling facilities or choose to establish additional production facilities to drive higher levels of profitability. Despite such a focus, they fail to consider important environmental factors. In fact, the effectiveness of network design is closely related to the actual recycling situation and local policy requirements. For example, Australia is characterized by many large and sparsely populated areas and the collection and transportation of batteries is a critical issue in achieving efficiency (King and Boxall, 2019).

From the literature, we find that the design of the recycling network involves two important aspects, the first is the recycling mode, the determination of the responsible entity, and the second is the scientific network design. Specifically, in terms of recycling mode, the recycling systems of decommissioned EV batteries are developed using three approaches: (1) the end-of-life battery operation of automobile OEMs; (2) the alliance operation; and (3) the third-party outsourcing operation. Since most of the research on recycling modes uses the Stackelberg model to analyze pricing, subsidies, taxes, etc. From the perspective of game theory, few authors can visually describe the cost, profit or carbon emission gap between different modes. In addition, only a few authors set their recycling modes before network design optimization. For the purposes of this study, we employ third-party outsourcing methods. In terms of network design, we have made further modifications. This is reflected in 1) retaining a centralized hub and adopting a comprehensive and muti-functional battery processing center, which has less cost investment and lower building consumables than splitting it into multiple factory facilities with different functions. At the same time, we use sensitivity analysis to fully test whether this modification could meet the recycling needs of Xi'an City. 2) Propose the reasonable disposal of body frames. We believe that in addition to batteries, body frames of EVs are also important recyclable resources, if both battery retirement and EV scrapping are met at the same time, the body frames can circulate into the resource recycling market and batteries enter the RL process. These modifications promote further optimization of resource allocation. Based on this, we propose the three important contributions to the literature as follows.

First, using actual data from Xi'an city in China, our study examines in significant detail the existing and potential future scale of EV adoption in the city. We also examine the scale of battery recycling, as well as the government policy preferences associated with constructing a recycling network model for decommissioned batteries. As such, our research provides a series of instructive guidelines for best practice.

Second, we study the configuration and optimization of the decommissioned battery recycling network, outsourced to third-party recycling entities. There is still little discussion on this mode despite the clear advantages of the third-party outsourcing method, such as its practical applicability and simpler recycling procedures.

Third, our study provides a sensitivity analysis of important factors such as facility capacity, environmental impact and safety. In particular, we analyze, in the case of Xi'an, whether it is more efficient to expand production facilities, or split some key recycling locations as the scale of decommissioned batteries grows.

To conduct this research, we explore the following three significant research questions.

Research question 1. Is the recycling network design scientific enough to satisfy recycling demands, promote third-party enterprises to get more profits and reduce carbon emission at the same time?

Research question 2. Construction costs account for a larger part of the total cost. How to scale the current recycling network to maximize facility utilization while demonstrating future trends in facility construction?

Research question 3. How do safety and environmental factors influence revenues?

The rest of this paper is organized as follows. Section 2 describes the research problem and assumptions. Section 3 introduces the methodologies we use in research, mainly including the recycling network configuration and optimization model. Section 4 presents the research results. We discuss the research implications and develop the future work in Section 5.

2. Problem description

Our research attempt to solve the problem of finding the optimal state of a recycling network using a third-party outsourcing approach for the city of Xi'an, China. As part of this, we seek to ascertain the recycling mode and network design.

2.1. City of study

This study seeks to develop a realistic network solution for recycling batteries in Xi'an, China. As one of the most economically developed cities in China, Xi'an represents the core component of the Guanzhong Plain urban agglomeration that was approved by the State Council. To develop green and more sustainable forms of transportation, Xi'an has carried out a number of large-scale urban transportation infrastructure projects and has introduced many policies that seek to incentivize the popularization and adoption of EVs (Wang et al., 2022). By the end of 2022, the number of EVs in Xi'an had reached 227,500, which account for about 5% of the total number of EVs in China. It is worth noting that Xi'an is also seeking to accelerate the development of a high-quality EV industry by building a national first-class EV industrial base by 2025, which aims to have about 500,000 EVs on the road in the city by 2025 (Xi'an Municipal Government, 2022). The pretext and mature production and sales environment in Xi'an City renders it an ideal research target.

2.2. Recycling network with third-party outsourcing

Comparing the recycling of EVB (Electric Vehicle Battery) to different recycling subjects (S. Zhang et al., 2023), we find that the third-party recycling approach is suitable for the mature and highly developed EVB industry in Xi'an. The scale effect of centralizing the recycling of batteries will gradually become prominent with the continuous expansion of the EV market. Therefore, a third-party outsourcing approach provides a more suitable mechanism for achieving large-scale recycling, when compared to the government-led recycling programs or the self-operated recycling program of the automobile OEMs. It is important to note that the third-party enterprises involved must be authorized by the government in China (Govindan et al., 2019). To represent the third-party outsourcing of recycling the batteries, we consider several components across the recycling network, such as automobile sales and service dealerships, centralized hubs, processing centers, resource recycle markets and energy storage markets; refer to Fig. 1.

The automobile sales and service dealerships that are operated and managed by the car manufacturers represent the first component of the recycling process. The next recycling facility of the car sales and service dealership is the centralized hub, which is operated by the battery recycling businesses, and the battery processing center is managed by third-party enterprises, which represent the core facility of the decommissioned battery recycling network.

The specific process is as follows: First, the independent dealers or car sales service dealerships (with recycling-related after-sales service functions) under the car businesses obtain the decommissioned EV batteries (trade-in or scrapped) from the users and send them to the centralized hubs (generally an enterprise with EV recycling or scrapping qualifications).

Second, the vehicles are dismantled, the batteries are extracted, collected, tested, classified, and packaged in the centralized hub. The hubs are operated and managed by the battery recycling enterprises. The disassembled body frames are handled by the EV recycling firms.

Third, the batteries are transferred to the battery processing center. It takes on the responsibility of battery dismantling and metal extraction. This requires professional equipment, advanced technology and high-end talents, which is in contrast to centralized hub that only

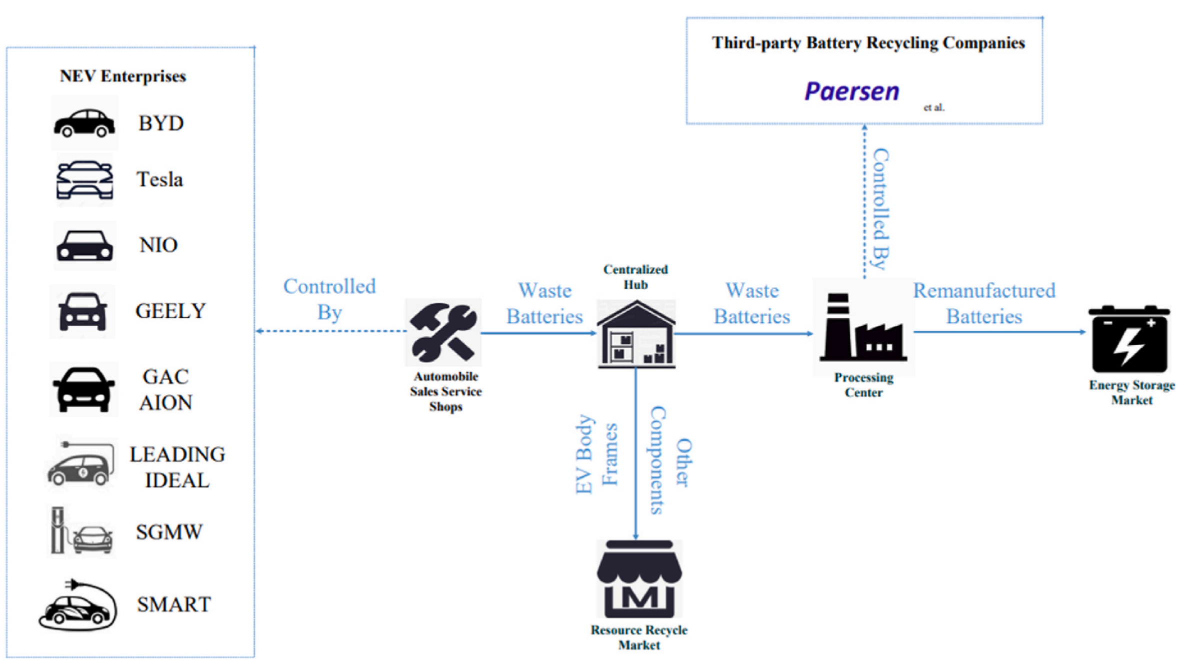

Fig. 1. Components of third-party recycling network of EV decommissioned batteries.

undertake simple tasks such as sorting and packaging. This highlights the core role the battery processing center plays across the entire recycling network. We assume that the center is operated and managed by third-party enterprises, integrating many functions, such as battery classification, dismantling, remanufacturing, extraction of raw metal material, and the disposal of waste. According to their different qualities, decommissioned batteries with a capacity of more than 80% will be transferred to and sold in secondary energy storage markets (Geng et al., 2022).

2.3. Assumptions

This study examines the recycling process of decommissioned batteries. It in turn reflects the realistic constraints of designing a recycling network by making the following assumptions.

(1) Since most of the current EV batteries in Xi'an are LFP batteries, this study constructs a single-product, single-cycle recycling network according to the standards of LFP batteries. Currently, the EV brands in Xi'an mainly include NIO, Geely, BYD and Tesla. Among them, BYD, Tesla and Geely use LFP batteries in EVs, and NIO uses NCM batteries. However, the inner cells of the NCM batteries are still mainly conducted using the LFP batteries.
(2) The unit transportation costs of the decommissioned batteries and their components are assumed to be fixed and are expressed in terms of the unit transportation cost of the decommissioned batteries.
(3) Independent dealers or automobile sales service dealerships can only transport the decommissioned batteries to qualified centralized hubs and cannot directly transport them to the battery processing centers or energy storage markets.
(4) The decommissioned batteries can only circulate between different types of facilities in the network and cannot circulate them among the same type of facilities. For example, they can circulate them from the centralized hubs to the battery processing center, however they are unable to circulate them from battery processing center 1 to battery processing center 2.
(5) In circulation from the car sales and service dealership to the centralized hub and from the centralized hub to the battery processing center, there is no battery loss.
(6) Every centralized hub and battery processing center are known and have capacity limitations, such as storage and processing efficiency.
(7) The recycling quantity (X_j) and quality of decommissioned batteries are known.
(8) The time consumed by the recycling process of the decommissioned batteries is not included in the total cost the recycling price of LFP is fixed, and the secondary selling price in the energy storage market is fixed.
(9) During transportation, we only consider the impact of the decommissioned battery flow and the distance on transportation cost without considering the traffic condition. Within each facility, the unit operation cost is fixed and does not depend on the processing time.
(10) We assume that in context of the battery processing center, all decommissioned batteries need to be processed here. Only part of remanufactured batteries can circulate to the energy storage market, and the proportion of these batteries is uncertain.

3. Methodology

In this section, we describe the context of the recycling network problem. We also derive the MILP model from a fuzzy approach to consider the uncertainties in recycling. Finally, we explain the case study of Xi'an city in terms of its data acquirement, data processing, model validation, and by conducting a sensitivity analysis.

3.1. Context of the recycling network

In this study, the recycling network problem maximizes the profit of a recycling network by optimizing the flow of the decommissioned batteries that must go through various processing locations. The recycling network is a directed graph consisting of locations such as sales and service dealerships, centralized hubs, battery processing centers, and energy storage markets. Each battery unit visits each station once in a specific order. It starts at the sales and service dealership, the centralized center, the battery processing center, and finally arrives at the energy storage market. Each battery unit has a fixed transportation cost to visit each station. We conserve the number of batteries in the network, but during the collection stage the network is affected by uncertainties, such as a consumer's willingness to recycle the batteries. Only a small portion of the batteries can enter the RL network. During the processing stage, due to the quality differences that exist among the batteries, only a subset of batteries can be used in the energy storage market, while other battery units may be completely disassembled, lost or wasted. We use triangular fuzzy numbers to describe these uncertainties. We do not consider time factors such as travel time, processing time, storage time and loading and unloading time.

3.2. Recycling network optimization model

In the following, we describe the variables, the parameters, the objective function, and the constraints used to optimize the battery recycling network. The variables and parameters used in this study are listed in Table 1.

We want to maximize our objective function, Z, the profit of the entire recycling network, including transportation cost C_t, operating cost C_o, fixed construction cost C_c, recycling cost C_r, carbon emission cost C_e, packaging cost C_p, sales revenue R, and government subsidy S, are defined in Equation [1].

$$Z = R + S - \left(C_t + C_o + C_c + C_r + C_e + C_p\right) \quad [1]$$

We briefly describe each component in the objective function. The transportation cost C_t is defined by the transportation and circulation of the decommissioned batteries and their parts within the network, as shownin Equation [2].

$$C_t = T_e\left[\sum_j\sum_l D_{jl}Q_{jl} + \sum_l\sum_k D_{lk}Q_{lk} + \sum_k\sum_s D_{ks}Q_{ks}\right] \quad [2]$$

The operation cost C_o refers to the cost of storage, classification, and commissioning and processing of the decommissioned batteries in the network facilities, as shown in Equation [3].

$$C_o = \sum_j\sum_l CO_l Q_{jl} + \sum_l\sum_k CO_k Q_{lk} \quad [3]$$

The construction cost C_c refers to the construction cost of building the facilities and the equipment of centralized hubs and battery processing centers, as shown in Equation [4]. Note that the construction cost is predicted as the battery recycling scale and the recycling capacity of the facilities are also predicted.

$$C_c = \sum_l F_l N_l + \sum_k F_k N_k \quad [4]$$

The recycling cost C_r refers to the recycling fee that needs to be paid to the automobile enterprises to obtain the decommissioned batteries from them, as shown in Equation [5].

$$C_r = \sum_j\sum_l Q_{jl}P_e \quad [5]$$

The carbon emission cost C_e refers to the carbon tax incurred during the transportation of the decommissioned batteries, as shown in Equation [6].

Table 1
Nomenclature.

Variable	Definition
J	Automobile sales service dealership in the recycling area, $j = \{1,\ldots,J\}$
L	Centralized hub node, $l = \{1,\ldots,L\}$
K	Battery processing center node, $k = \{1,\ldots,K\}$
S	Energy Storage Market node, $s = \{1,\ldots,S\}$
P_e	Unit recycling cost of EV decommissioned batteries
R_e	Unit selling price of decommissioned batteries in the Energy Storage Market
S_e	Unit subsidy given by the government to decommissioned batteries
X_j	The number of units of decommissioned batteries acquired in the recycling areas (unit)
X_{jli}	The lower bound value of X_j
X_{jmi}	The median bound value of X_j
X_{jri}	The upper bound value of X_j
T_e	Unit transportation cost of decommissioned batteries (*yuan*)
U_e	Unit carbon tax cost for decommissioned battery transportation (yuan)
V_e	Unit packaging cost of decommissioned batteries (*yuan*)
N_l	The number of centralized hub L
N_k	The number of battery processing center K
N_s	The number of energy storage market S
Y_l	The binary number of centralized hub L
Y_k	The binary number of battery processing center K
Y_s	The binary number of energy storage market S
CO_l	Unit operation cost of centralized hub L (*yuan*)
CO_k	Unit operating cost of battery processing center K (*yuan*)
F_l	Unit construction cost of centralized hub L (*yuan*)
F_k	Unit construction cost of battery processing center K (*yuan*)
M_l	Storage capacity of centralized hub L (unit)
M_k	Storage capacity of battery processing center K (unit)
M_s	Storage capacity of energy storage market S (unit)
D_{jl}	Distance from automobile sales service dealership in the recycling area j to the centralized hub l (km)
D_{lk}	Distance from the centralized hub l to the battery processing center k (km)
D_{ks}	Distance from the battery processing center k to the energy storage market s (km)
ω_{ks}	Flow rate of batteries from processing center k to the energy storage market s
ω_{ksli}	The lower bound value of ω_{ks}
ω_{ksmi}	The median bound value of ω_{ks}
ω_{ksri}	The upper bound value of ω_{ks}
Q_{jl}	The number of batteries from automobile sales service dealership in the recycling area j to the centralized hub l (unit)
Q_{lk}	The number of batteries from centralized hub l to battery processing center k (unit)
Q_{ks}	The number of batteries from battery processing center k to the energy storage market s (unit)

$$C_e = U_e\left[\sum_j\sum_l D_{jl}Q_{jl} + \sum_l\sum_k D_{lk}Q_{lk} + \sum_k\sum_s D_{ks}Q_{ks}\right] \quad [6]$$

The packaging cost C_p is the cost of the materials used to pack the decommissioned batteries before transportation, as shown in Equation [7].

$$C_p = V_e\left[\sum_j\sum_l D_{jl}Q_{jl} + \sum_l\sum_k D_{lk}Q_{lk} + \sum_k\sum_s D_{ks}Q_{ks}\right] \quad [7]$$

The sales revenue R is obtained after recycling the decommissioned batteries, when the batteries are sold from the battery processing centers to the energy storage markets, as shown in Equation [8].

$$R = \sum_k\sum_s Q_{ks}R_e \quad [8]$$

The subsidy S refers to the compensation issued by the government for recycling EV decommissioned batteries, as shown in Equation [9].

$$S = \sum_j\sum_l Q_{jl}S_e \quad [9]$$

The constraints of the recycling network model built for this study mainly include the flow balance, the capacity constraints, as well as the domain of the decision variables to non-negative binary values.

The network flow balance ensures that the inflow and outflow of the decommissioned batteries or their raw materials at any node in the recycling network are conserved. The constraint is expressed in Equation [10–12].

$$\sum_j X_j = \sum_j\sum_l Q_{jl} \quad [10]$$

$$\sum_j\sum_l Q_{jl} = \sum_l\sum_k Q_{lk} \quad [11]$$

$$\sum_k\sum_s Q_{ks} = \omega_{ks}\sum_l\sum_k Q_{lk} \quad [12]$$

The capacity constraints ensure that the number of decommissioned batteries and their raw materials flowing to each node cannot exceed the storage capacity of that node, as shown in Equation [13–15].

$$\sum_j\sum_l Q_{jl} \le \sum_l M_l \quad [13]$$

$$\sum_l\sum_k Q_{lk} \le \sum_k M_k \quad [14]$$

$$\sum_k\sum_s Q_{ks} \le \sum_s M_s \quad [15]$$

In addition, we define constraints for the binary and non-negativity of decision variablesin Equation [16–17].

$$Y_l, Y_k, Y_s \in \{0, 1\} \quad [16]$$

$$X_j, Q_{jl}, Q_{lk}, Q_{ks} \ge 0 \quad [17]$$

Taking into consideration several uncertain factors such as the disposal cost, recycling time, and the treatment method of the EV decommissioned batteries, these issues can be treated as marginal or extended influencing factors (Rajaeifar et al., 2022). Therefore, the model constructed for our research considers the uncertain conditions in the recycling quantity and quality of the decommissioned EV batteries. Our model draws on Yang et al. (2022) to fuzz the recycling quantity and quality of the decommissioned batteries and introduce a triangular fuzzy function to transform uncertain conditions into deterministic conditions. According to the theory of fuzzy programming, the confidence level of the objective function must be greater than or equal to α, and the confidence level of the constraints must be greater than or equal to β, given as:

	$\max_x f$	
Such that	$P(f(x,\theta) \le \widehat{f}) \ge \alpha$ $P(g_{j(x,\theta)} \le 0) \ge \beta$	$\forall j$

The fuzzy parameters are X_j and ω_{ks}. According to the above formula and fuzzy parameters, the constraints can be modified slightly. First, we add a new constraint about the objective functionin Equation [18].

$$P(Z \le z) \ge \alpha_1 \quad [18]$$

Also, we can replace the constraints in Equations [10] and [12] with Equations [19] and [20], respectively, asshown in Equation [19–20].

$$P\left(\sum_j X_j = \sum_j\sum_l Q_{jl}\right) \ge \beta_1 \quad [19]$$

$$P\left(\sum_k\sum_s Q_{ks} = \omega_{ks}\sum_l\sum_k Q_{lk}\right) \ge \beta_2 \quad [20]$$

The fuzzy variables in the network model can be represented by triangular fuzzy numbers (l_i, m_i, r_i), where the recycling amount of EVBs is expressed as $(X_{jli}, X_{jmi}, X_{jri})$, and the recycling quality of EVBs is expressed as $(\omega_{ksli}, \omega_{ksmi}, \omega_{ksri})$. Therefore, the objective function containing fuzzy variables can be defuzzed and converted into a deterministic equivalence class, and the specific model is shown below, replacing the original objective function Equation [1] with Equation [21],

$$Z' = R' + S - \left(C_t' + C_o + C_c + C_r + C_e' + C_p'\right) \quad [21]$$

Where some components with the uncertain components are updated in Equation [22–25]

$$R' = [(1-\alpha_1)\omega_{ksli} + \alpha_1\omega_{ksmi}]\sum_l\sum_k Q_{lk}R_e \quad [22]$$

$$C_t' = T_e\left[\sum_j\sum_l D_{jl}Q_{jl} + \sum_l\sum_k D_{lk}Q_{lk} + [(1-\alpha_1)\omega_{ksli} + \alpha_1\omega_{ksmi}]\sum_l\sum_k Q_{lk}D_{ks}\right] \quad [23]$$

$$C_e' = U_e\left[\sum_j\sum_l D_{jl}Q_{jl} + \sum_l\sum_k D_{lk}Q_{lk} + [(1-\alpha_1)\omega_{ksli} + \alpha_1\omega_{ksmi}]\sum_l\sum_k Q_{lk}D_{ks}\right] \quad [24]$$

$$C_p' = V_e\left[\sum_j\sum_l D_{jl}Q_{jl} + \sum_l\sum_k D_{lk}Q_{lk} + [(1-\alpha_1)\omega_{ksli} + \alpha_1\omega_{ksmi}]\sum_l\sum_k Q_{lk}D_{ks}\right] \quad [25]$$

For the constraints, we add one about the probability of meeting the objective function as shownin Equation [26].

$$P(Z' \le z) \ge \alpha_1 \quad [26]$$

Also, some constraints with fuzzy variables are converted into a deterministic equivalence class after defuzzification as shown below. We replace the constraint equation [10] with equations [27] and [28] and replace [12] with equations [29] and [30].

$$\sum_j\sum_l Q_{jl} \le (1-\beta_1)\sum_j X_{jri} + \beta_1\sum_j X_{jmi} \quad [27]$$

$$\sum_j\sum_l Q_{jl} \ge (1-\beta_1)\sum_j X_{jli} + \beta_1\sum_j X_{jmi} \quad [28]$$

$$\sum_k\sum_s Q_{ks} \ge [(1-\beta_2)\omega_{ksli} + \beta_2\omega_{ksmi}]\sum_l\sum_k Q_{lk} \quad [29]$$

$$\sum_k\sum_s Q_{ks} \le [(1-\beta_2)\omega_{ksri} + \beta_2\omega_{ksmi}]\sum_l\sum_k Q_{lk} \quad [30]$$

3.3. Case study

Here, we describe the process and methods of how we obtain the data, process the data, and finally validate the model.

3.3.1. Data acquirement and processing

On EV data platforms such as Dolphin Cube[1] and DaasAuto[2] we can obtain the list of the top EV enterprises. From there, we collect data including the prediction of EV ownership, the location of EV service dealerships, the distance between different potential locations and the longitude and latitude of recycling facilities. The data of EV ownership in Xi'an covers the 2019 to 2021 period. The top EV enterprises include BYD, NIO, TESLA, GEELY, GAC AION, LEADING IDEAL, SGMW and SMART. According to the list of service dealerships of EV enterprises, we acquire their location on the map (see in Appendix I). There are 88 EV service dealerships in Xi'an. According to their distribution, we divided them into four areas. Based on *the Center of Gravity Method*, we reposition them in each area, that is, concentrate all the nodes in the area on one point. Then we use geocalculation function to calculate the distance between nodes in Excel. According to the EV data collected from Dolphin Cube from 2019 to 2022, we use the *Gray Prediction Method* (He et al., 2020) to predict the EV ownership in Xi'an from 2023 to 2035.

In this research, Lingo 18.0 is used to solve the problem. As an optimization software, it's often used in linear or nonlinear model solution because of its simple model formulation of integer problems, convenient data organization, and powerful solution performance. MATLAB is used to predict EV ownership. For the map processing, ArcGIS 10.8 is used to convert the latitude and longitude coordinates into plane coordinates and generate the node location maps, while Origin 2019b is used for data analysis and visualization.

3.3.2. Model performance

If we get the optimization results, we will conduct sensitivity analysis to evaluate it.

1) Capacity Analysis

In this research, we have three capacity constraints M_l, M_k, M_s. Suppose the scale constants for them are is α. We choose their values as shown in Table 2. We can get the new battery traveling path and distribution results under different scenarios in Lingo 18.0.

2) Environment Protection and Safety Analysis

We assess the environmental cost in terms of the carbon emission cost. For safety, we consider packaging cost as a safety cost because electrolyte leakage and explosion may occur in battery, posing safety risks.

Dissecting the objective function, we denote the profit as P_n, economic cost is denoted as E_n, the environmental cost as R_n, the safety cost as S_n and the summary of all costs as C_n.

$$P_n = R + S \quad [31]$$

$$E_n = C_t + C_o + C_c + C_r \quad [32]$$

$$R_n = C_e \quad [33]$$

$$S_n = C_p \quad [34]$$

$$C_n = C_t + C_o + C_c + C_r + C_e + C_p \quad [35]$$

The original objective function can be expressed in Equation [36–37]:

$$Z_e = P_n - C_n \quad [36]$$

$$C_n = E_n + R_n + S_n \quad [37]$$

Suppose the parameter affecting the profit P_n is ρ, the parameter affecting the summary of all costs C_n is φ, the parameter affecting the economic cost E_n is δ, the parameter affecting the environmental cost R_n is λ, and the parameter affecting the safety cost S_n is μ. The sensitivity analysis formula for the original objective function isshown in Equation [38]:

$$Z_e = \rho P_n - \varphi(\delta E_n + \lambda R_n + \mu S_n) \quad [38]$$

Table 2
The scale constant of capacity for scenarios.

Scenario	1	2	3	4	5	6	7	8	9	10
α	0.8	0.9	1	2	3	4	5	6	20	100

[1] Retrieved from https://www.dolphincube.com/.
[2] Retrieved from https://www.daas-auto.com/home.

4. A case study of Xi'an city

In Xi'an, most industry is located in the south or north of the city, while most of the car sales and service dealerships are concentrated in the center. The car sales and service dealerships are the main platforms for battery recycling. Therefore, we present Fig. 2, which shows the distribution of the EV automobile sales and service dealerships.

In Fig. 2, we also have the potential distribution of centralized hubs, battery processing centers and energy storage markets. These are concentrated in a few districts, such as the Weiyang District, Lianhu District, Yanta District, Beilin and Baqiao Districts. Other areas, such as Gaoling District, have very few service dealerships. Based on their spatial distribution, we divide these districts into four areas J1, J2, J3 and J4. Note that the latitude and longitude values are provided in Appendix I and Appendix II.

To meet the actual levels of recycling demand, we build the network model relying on the car sales and service dealerships in Xi'an. We choose the top 8 EV enterprises by sales in Xi'an as an example. These car sales and service dealerships are selected and termed as the initial nodes in this study.

Another important task of battery recycling is to predict the future recycling number to determine the scale of recycling work and nodes construction. We use the *Gray Prediction Method* to predict future ownership levels based on the EV ownership data in Xi'an from 2019 to 2022 (see Fig. 3).

The quantity of decommissioned EV batteries is affected by many factors, such as economic policy, economic development level, population density, industrial distribution, and people's preference for EVs in the predicted region (Kumar et al., 2021). Based on this, our research divides the production and sales of EVs into four regions from the perspective of geographical location and selects two economic factors of population density and economic development level to predict the amount of EV decommissioned batteries that are recycled in different areas in Xi'an. The two factors reflect the overall economic situation in different consumption or recycling regions J, as shown in Fig. 4.

We omit the repair, replacement and recycling of batteries after the EV purchase and vehicle disposal, therefore we assume that the sales of EVs and the number of batteries are the same. Therefore, when combined with the above Fig. 3 prediction of EV ownership in Xi'an, it is expected that the number of EVBs on the market will reach 31.0159 million by 2035. Without the domestic recycling system of EVBs that has not yet been established, the domestic recycling rate of decommissioned batteries is between 10% and 15% (Liu et al., 2020). It is estimated that the recycling volume of batteries will reach about 3.877 million by 2035. Based on Fig. 4, considering the population density and GDP, we average the two factors and obtain their percentage. From which, the amount of decommissioned batteries for EVs in Xi'an can be obtained, and shown in Table 3.

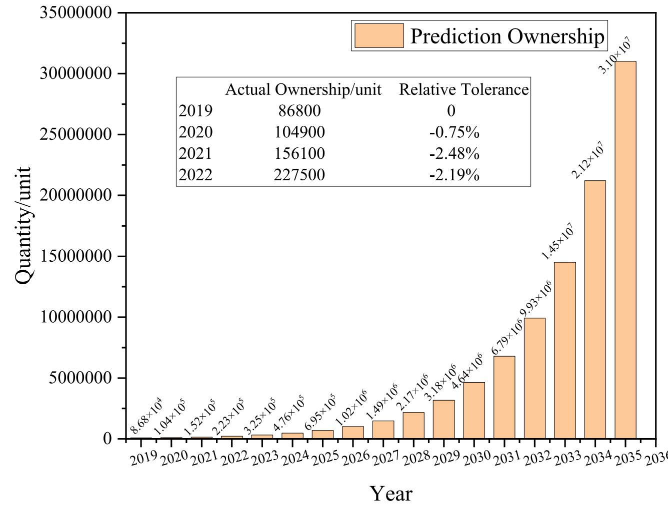

Fig. 3. Prediction results of EV ownership in Xi'an.

After the EVs are sold, their batteries are managed by consumers. Due to consumers' willingness, the number of decommissioned batteries is uncertain. We reflect those using fuzzy functions. The triangular fuzzy number indicates the recycling amount of EV decommissioned batteries and fuzzy membership is mapped within 10% of the fuzzy center numbers, as shown in Table 4.

Due to the large number of car sales service dealerships, we attempt to reduce the dimension of the network by *the Center of Gravity Method* according to region division. We group the car sales service dealerships as four regional centers according to the recycling areas, J1 to J4, and we assign one centralized hub in each area.

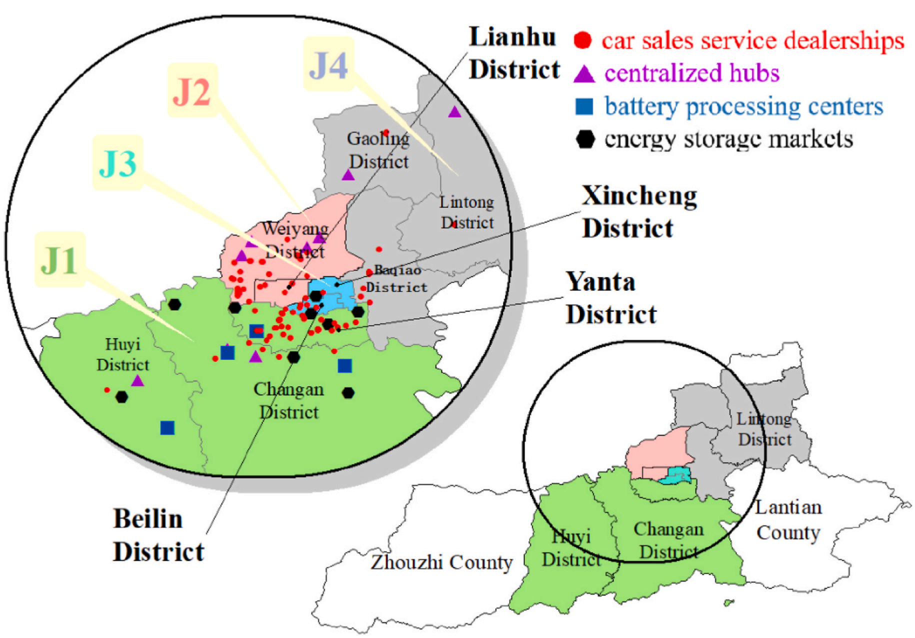

Fig. 2. Distribution of EV decommissioned battery recycling area and potential facility locationsin Xi'an.

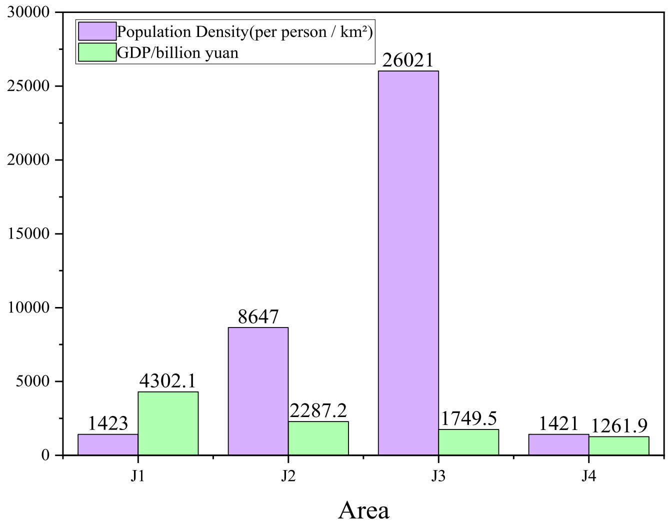

Fig. 4. The overall economic situation of different recycling areas in Xi'an.

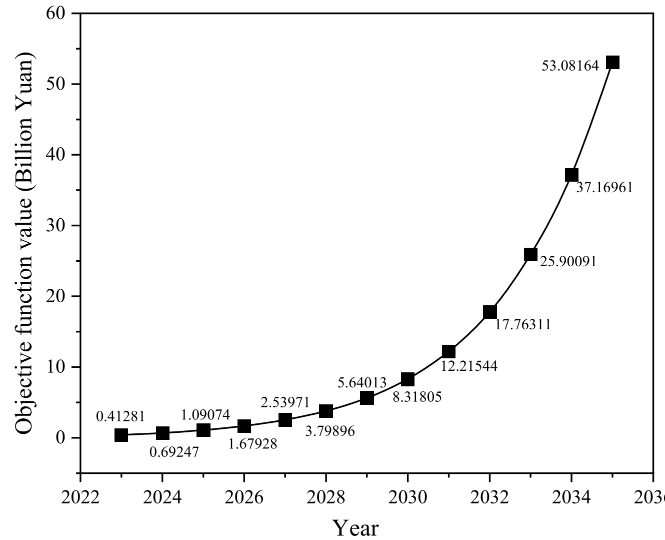

Fig. 5. The objective function values from 2023 to 2035.

Table 3
The amount of decommissioned batteries recycled in 2035.

Recycling Area	Percentage	Battery Recycling Volume
J_1	0.243	942,111
J_2	0.234	907,218
J_3	0.438	1,698,126
J_4	0.085	329,545
Total	1	3,877,000

Table 4
The fuzzy numbers indicate the amount of decommissioned batteries in different recycling areas in Xi'an.

Recycling Area	$(X_{jli}, X_{jmi}, X_{jri})$
J_1	(847,900, 942,111, 1,036,322)
J_2	(816,496, 907,218, 997,940)
J_3	(1,528,313, 1,698,126, 1,867,939)
J_4	(296,591, 329,545, 362,500)

In addition, the costs and profits of recycling network are shown in Table 5.

4.1. Results

The following describes the results of the recycling network optimization with fuzzy programming derived from Section 3 for the Xi'an City of China. The objective function values of network are shown in Fig. 5. The objective function value in the y-axis represents the best profit of the RL network for decommissioned batteries.

Table 5
Costs and profits of recycling network.

Variable	Value
T_e(yuan)	18
U_e(yuan)	3.6
P_e (yuan)	3000
R_e (yuan)	30,000
V_e (yuan)	50
S(yuan)	800
CO_l (yuan)	10
CO_k(yuan)	50
F_l (yuan)	800,000
F_k(yuan)	20,000,000
M_l (unit)	500,000
M_k (unit)	1,080,000
M_s (unit)	260,000

We can see with the quantity of the batteries is growing, as are the profit levels. By 2035, total profits exceed 53 billion yuan. As the trend shows, at present, the increase in profits experiences over in the short term will not be high. However, if the industrial construction and layout of battery recycling can be completed, huge profit levels may be obtainable. The recycling of decommissioned batteries could, therefore become an important driver of GDP growth in Xi'an.

As collected, we have nine potential centralized hubs, four potential battery processing centers and ten energy storage markets. Here, we give the battery traveling distribution optimization results from 2023 to 2035 (see in Fig. 6).

There are only L6, K3 and S4 used from 2023 to 2027. That is when the number of batteries is small, and as such it is more profitable to choose one recycling facility for each stage. From 2028 to 2030, L7, L8, K4 and S4 are chosen. In later years, there are more facilities put into service. The results show us, from now to 2030, the construction of the recycling network should be precise and done at a small-scale with few facilities built. In small-scale network construction, since the distance between facilities and capacity constraints are key factors affecting the choice of battery path, we should pay attention to the location and scale of the facilities in construction, so as to avoid wasting resources. It should be noted that despite the increase in the scale of recycling, there are still some potential locations that we do not choose, such as L3. This result tells us that not all potential locations are suitable for building a recycling facility, although they have some recycling capabilities.

4.2. Sensitivity analysis

In this section, we present a sensitivity analysis from two perspective: 1) we change the facility's capacity limit to test for battery flow and facility utilization; 2) we test the cost and profit parameters and analyze if the third-party recycling enterprises are able to obtain a certain level of profit or control the loss within a certain range under the premise of ensuring environmental benefit and safety.

4.2.1. Capacity Analysis

In Section 4.1, we provide the optimal traveling path and quantity distribution in different years. The result shows although the quantity of batteries is large, there are also some locations we that have not been chosen. This is due to two reasons: (1) capacity constraints; and (2) distance. If one facility is closer to another but its capacity is small, batteries are more likely to choose one that is further away when the

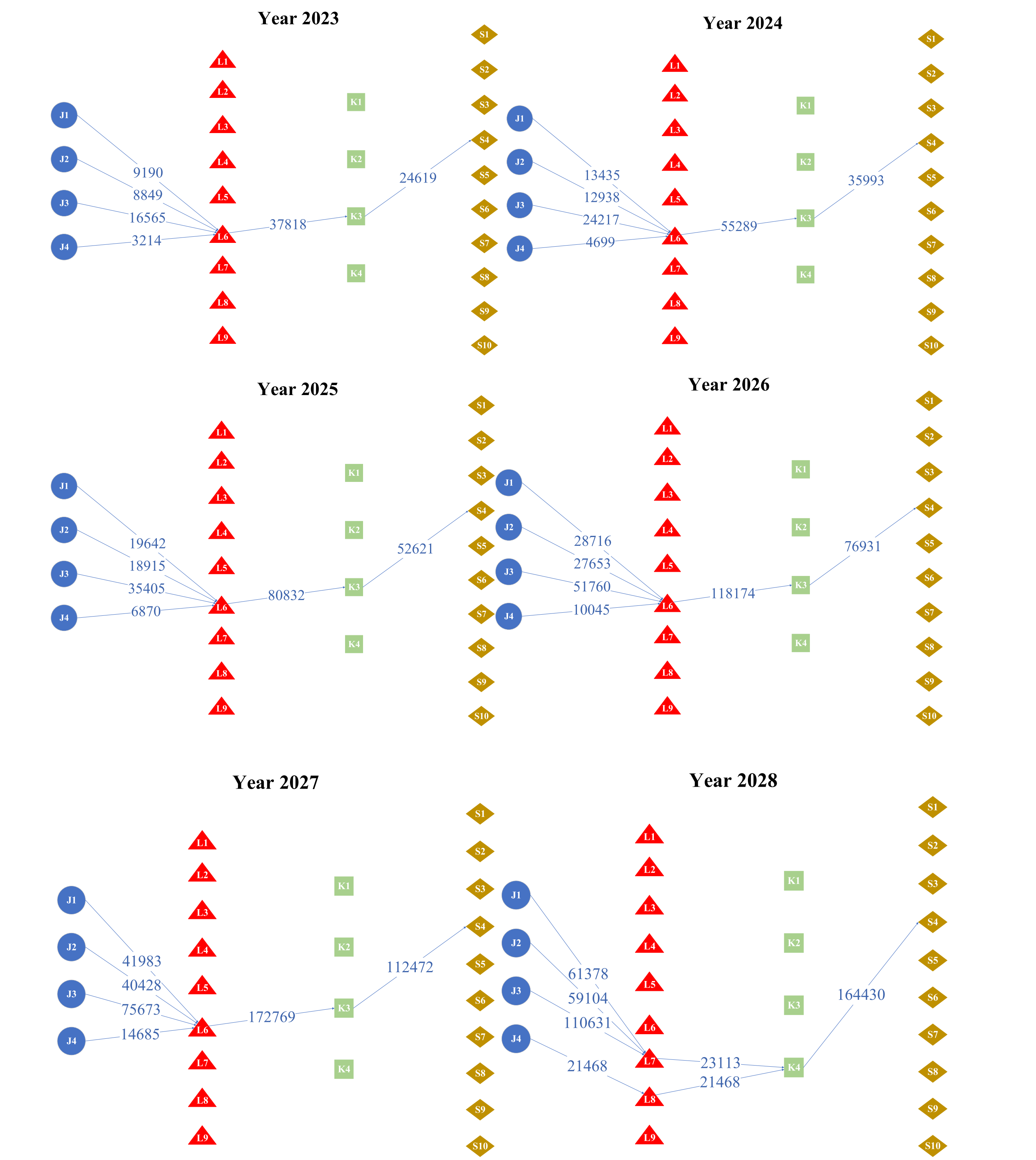

Fig. 6. The optimal results of battery traveling path and distribution from 2023 to 2035.

facility with a smaller capacity is already fully occupied. In this study, the distance between different facilities is known and we premise the maximum capacity in calculation. However, during the actual construction, the maximum capacity of each facility is not promising to contain infinite decommissioned batteries, as it will be influenced by the size of that location, its geographical location (whether it is close to a river or residential area, etc.), and local environmental policies (noise restrictions, etc.). Therefore, we test the capacity constraints here.

Based on Section 3.3.2, taking decommissioned battery recycling in 2035 as an example, we change the maximum capacity of each facility. The results are shown in Fig. 7. In scenario 1, the capacity of each facility is too small to satisfy the recycling needs. As such, these results are not presented. As defined in Table 2, here we select Scenario 2 ($\alpha = 0.9$), Scenario 6 ($\alpha = 4$), Scenario 8 ($\alpha = 6$) and Scenario 10 ($\alpha = 100$) to show the results of site selection under different capacity constraints.

When the scale constant is less than 1, we aimed to investigate

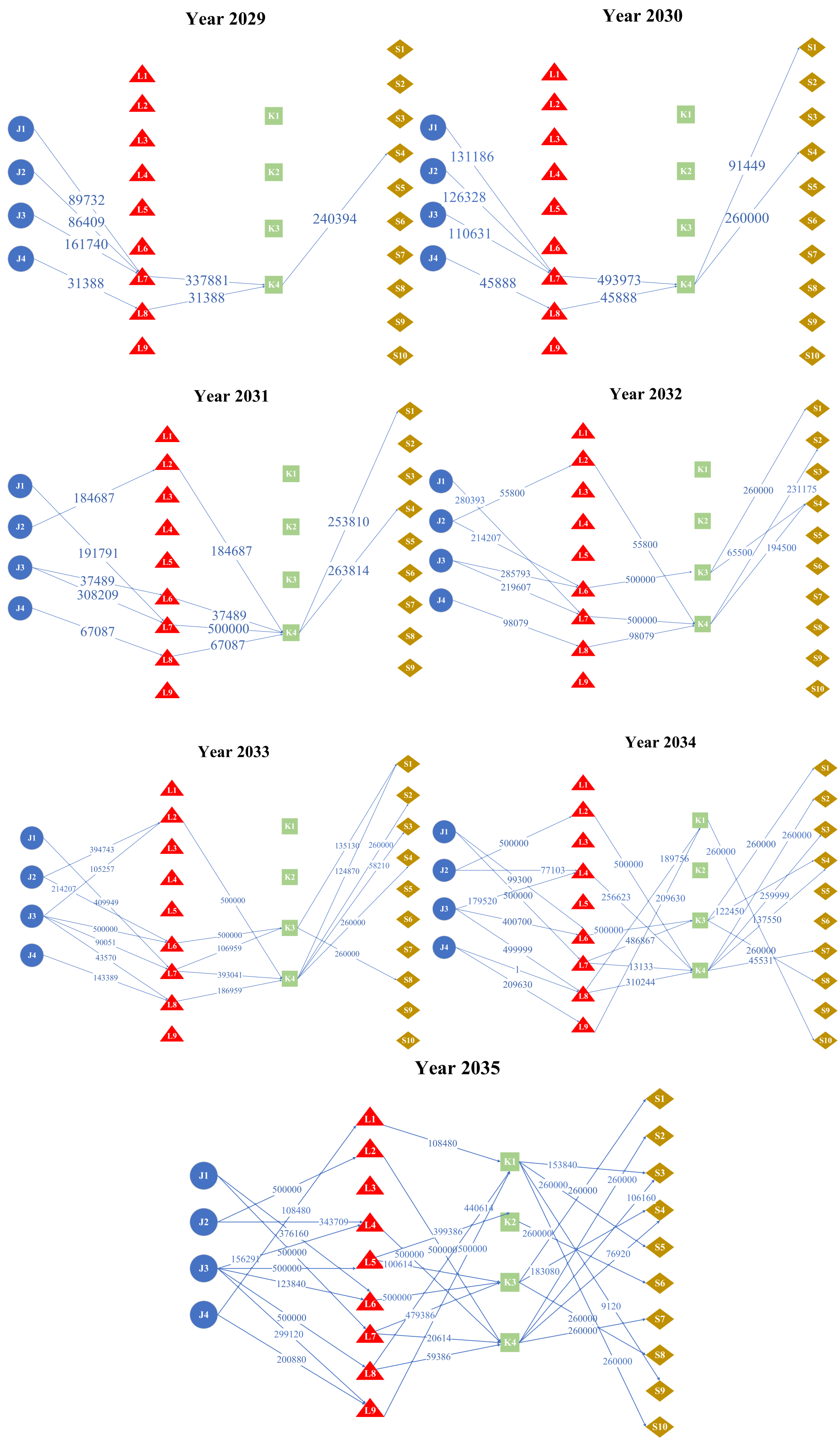

Fig. 6. (*continued*).

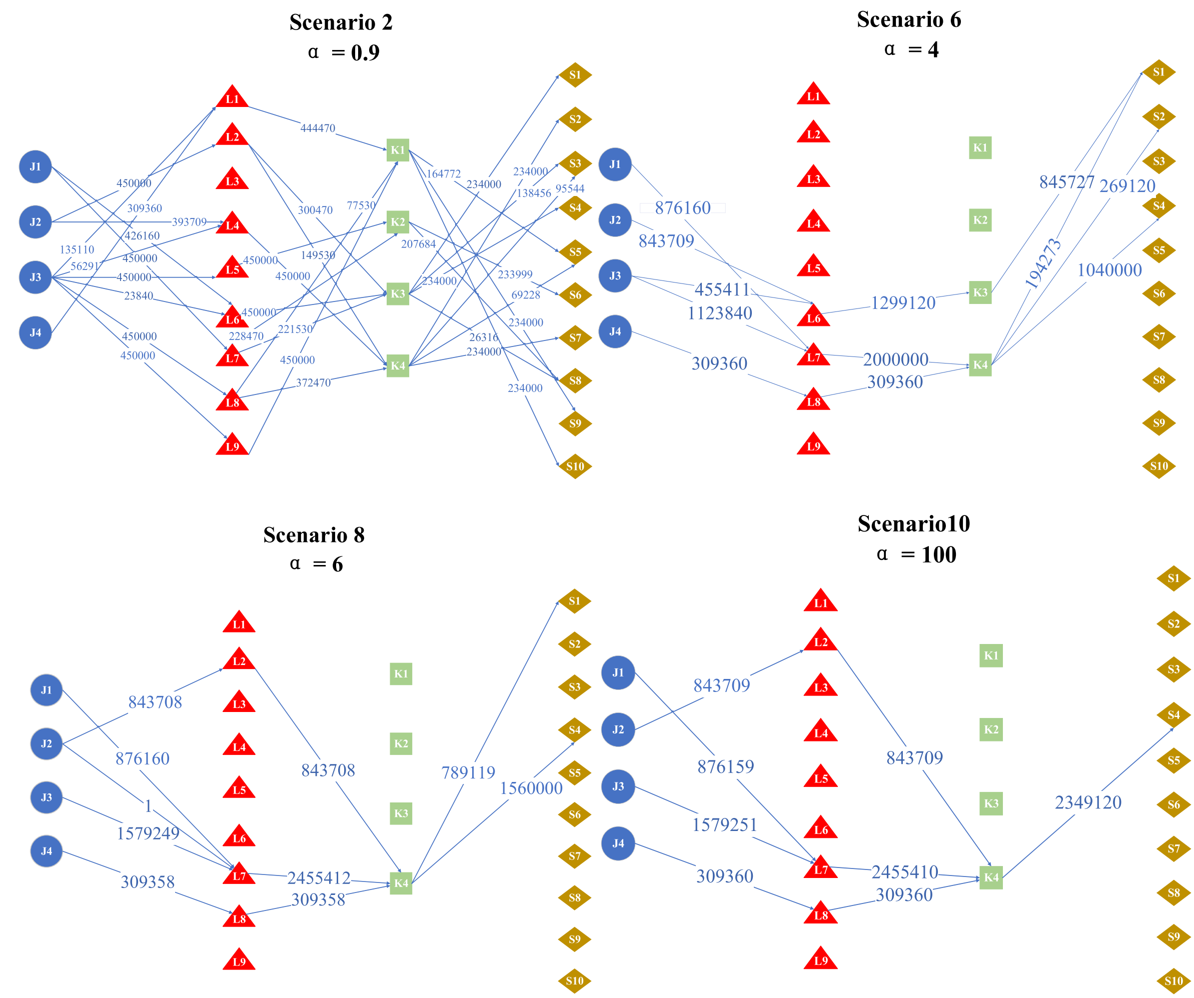

Fig. 7. The optimal results of site selection under capacity scenarios.

changes when the maximum capacity of each facility is reduced. However, in Scenario 1 ($\alpha = 0.8$), because of the smaller capacity constraints, facilities cannot accommodate too many batteries, from which no feasible solutions are available. In Scenario 2 ($\alpha = 0.9$), we can see that almost all the facilities were chosen, except L3. When the scale constant increases from 1 to 6, we need to look for the emergence of potential trends and find facilities that can always be chosen. From our analysis, our results show us that the number of facilities that can be chosen continually falls. To determine the most used facilities, we conduct a series of estimations using 20 and 100 as the respective scale constants. From this, we find that only L2, L7, L8, K4, and S4 remain. Among these facilities, K4 is managed by third-party enterprises. Therefore, if the third-party enterprises plan to construct a battery processing center (K), it will be better to construct in the location of K4 and K3. The scale should be determined by the recycling quantity and local situations. In fact, L2, L7 and L8 are relatively closer to J1~J4. Similarly, K4 is closer to L and S4 is closer to K. The decommissioned batteries always choose the closer facilities.

Based on the above results of four scale constant of scenarios, we have selected the best locations for L, K and S in Scenario 8 ($\alpha = 6$) and Scenario 10 ($\alpha = 100$); refer to Fig. 8 with L2, L7, L8, K4, and S4. We define the utilization rate of a facility as the quantity of batteries received by facilities closer to the maximum capacity constraints. We analyze the selected facilities further in terms of their utilization rates in different scenarios.

Obviously, when the maximum capacity we promise is smaller, the utilization rate is higher. Compared with L2 and L8, the utilization rate

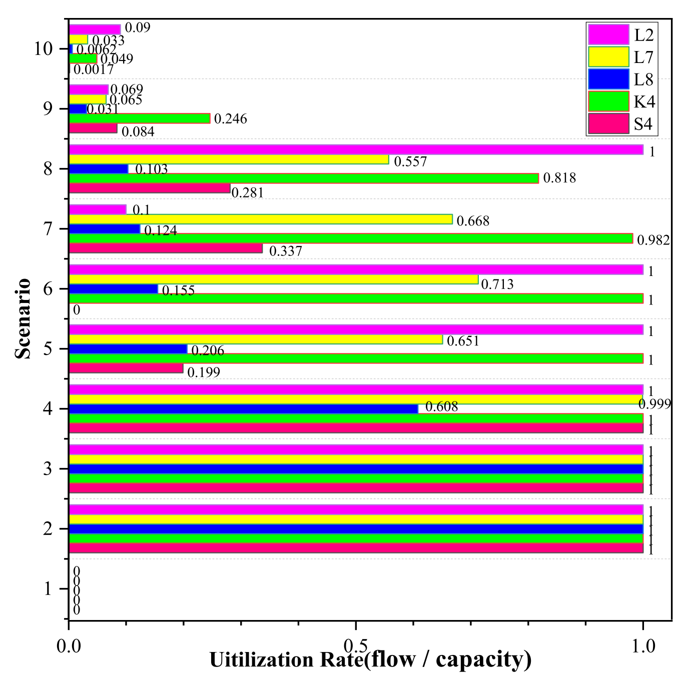

Fig. 8. The utilization rate of L2, L7, L8, K4, S4 in different scenarios.

of L7 is higher. This may be because L7 is closer to J1∼J4. In our model, we promised there are very high-capacity centralized hubs, battery processing centers and energy storage markets in Scenario 9 and 10, however that was not possible. The low utilization rate also reflects that, during this stage, when the recycling quantity of decommissioned batteries has not reached a very large scale, the development of very large factories is not suitable. Even if we can reach a large scale in the future, the reality will not allow us to do so because the level of resources available are limited. Therefore, the splitting of facilities represents a major trend in the future network development of Xi'an. For example, the battery processing center established in this study has many functions and may be split into multiple different functional facilities in the future to promote battery shunting.

4.2.2. Environment Protection and Safety Analysis

The issues of environmental protection and safety are important factors of consideration. The carbon emissions generated from many aspects of the recycling network, are harmful to the environment. As dangerous goods, batteries also have many safety hazards in their transportation and handling. Therefore, we conduct a sensitivity analysis here.

Based on the methodology in Section 3.3.2, we define the scale constant of environmental and safety costs from 0.5 to 5 (see in Fig. 9).

In Fig. 9, we show that with the increase of environmental factor λ, the optimal value of the objective function declines, indicating that third-party recycling enterprises must invest more in personnel, equipment and funds to ensure that the carbon emissions in the battery recycling process are kept to a minimum, which is not always conducive to driving profit. Due to the continuous development of the battery recycling industry, the construction of the decommissioned battery recycling network is becoming more mature, the selection of recycling paths is becoming more reasonable, while the recycling technology is becoming more sophisticated. Given such developments, the impact of the environmental cost will continue to grow smaller.

The small impact of the safety cost parameter μ is due to the assumption in this study that there is no electrolyte leakage, vehicle damage or casualties while battery shipping or processing. In fact, in the actual recycling process, this potential risk always exists. Once the problem occurs, the impact will suddenly increase, so even if the impact of safety cost is small, enterprises should pay attention to the safety of decommissioned battery recycling to prevent accidents. In Fig. 9, we show that the profit parameter ρ plays a positive correlation role and the cost parameter φ plays a negative correlation role. Parameter ρ has a greater impact on the network, indicating that the income exceeds the expenditure from third-party enterprises.

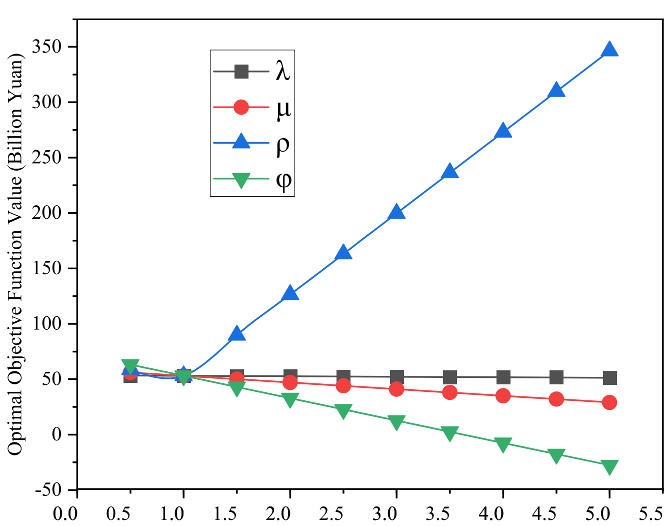

Fig. 9. Effect of parameter changes on the optimal function value.

5. Discussion and implications

This study solves the problem of optimizing the recycling network of decommissioned batteries in the Xi'an City of China with fuzzy programming to consider the uncertainties in recycling batteries. We mainly consider that the recycling entities are third-party recycling enterprises, and there are also some government participation (the government should give subsidies for decommissioned batteries). Our work is calculating the costs and profits of third-party recycling enterprises to provide network design references for all responsible entities (including EV manufacturers, battery manufacturers, third-party recycling enterprises or governments). Costs and profits are the main concerns of third-party recycling enterprises, however sensitivity analysis is essential to be used to evaluate the environmental and security factors in recycling process, so recycling entities should pay attention to environmental and safety factors.

5.1. Planning implications

1) We use actual data from the city of Xi'an, China, to apply a network optimization model that seeks to establish a recycling network that is based on a third-party outsourcing mode. We find that with the increasing quantity of decommissioned batteries, third-party enterprises can become more profitable.
2) From the optimal traveling path and distribution of decommissioned batteries, we can see that more potential locations are selected when the battery quantity is large. Therefore, in small-scale recycling, we need to construct fewer facilities. One facility should have multiple functions, like the battery processing center constructed in this study. To face the larger scale of recycling needed in the future, we can split the multi-functional facilities into many facilities with different functions. The battery recycling process can in turn become more precise and promote the recycling technology development.
3) In our sensitivity analysis, we analyze the impact of maximum capacity constraints and evaluate the site selection results from its utilization rate. We show that batteries are more likely to choose a site that is closer to them. We also compare costs and profits and search for the effect of carbon emission cost and packaging cost. According to our sensitivity analysis, we emphasize that third-party enterprises should balance profitability and environmental protection.

5.2. Managerial implications

Our study also provides several meaningful practical applications. Under the requirements and calls for a "dual carbon" policy that China strives to peak carbon emissions before 2030 and achieve carbon neutrality before 2060, the Chinese EV industry has developed rapidly. The first batch of EVBs is due to be decommissioned in the near future. Therefore, accelerating the construction of an effective battery recycling system is the primary problem that many regions urgently need to solve.

Although facing the tide of decommissioning batteries, many cities or regions in China still lack targeted construction plans. Firstly, there are many regions with unqualified battery recycling enterprises in the decommissioned battery recycling market, resulting in a low battery recycling rate. Therefore, to promote systematic recycling, governments should focus on the individualized differences between regions, while also looking to accelerate the formulation of policies according to factors such as existing resources, economic development level, industrial development dynamics and battery recycling scale in the region.

Secondly, governments should accelerate the improvement of the construction of enterprise recycling qualification assessment systems, include more third-party enterprises with recycling capabilities in the whitelist and regulate market chaos. First, the EV manufacturers in

China must accelerate the construction of a battery traceability system. It can cooperate with departments to establish an effective battery supervision system. On the other hand, it can promote the development of decommissioned battery reverse logistics and ensure high recycling rates are achieved.

Finally, EV manufacturers should choose an appropriate recycling approach. How to better integrate the construction of the decommissioned battery recycling network with local policies and the development of enterprises is an important issue that automobile manufacturers should consider. For consumers, their willingness to buy EVs will be affected by external factors. If the government can enact more policies to strengthen the recycling and management of decommissioned batteries, businesses can continuously improve their own technical capabilities and in doing so provide a strong guarantee that government policies will be implemented, and that a highly effective EV battery recycling system will be built. Consumers' willingness to buy EVs will also gradually increase, forming a virtuous circle of sustainable development.

5.3. Policy implications

Xi'an as a Chinese EV industry base has its own set of unique characteristics. For example, the domestic electric vehicle brand BYD set up its production base in Xi'an and the EV ownership in Xi'an is currently at the forefront of work being done across the country. Therefore, by using Xi'an as an example, this study proposes to optimize the layout of the recycling industry according to local conditions, which can provide an important reference point for governments that are seeking to improve laws and regulations and formulate a standardized system for the battery recycling industry.

However, at present, the construction of the Xi'an decommissioned battery recycling system is still at an early stage of development, with BYD still relying on itself to recycle EV batteries. At the same time, the number of firms with battery recycling qualifications in the Shaanxi Province is still small, while the number of businesses engaged in battery recycling is large. As the level of decommissioned battery recycling continues to grow, Xi'an needs to consider whether to develop more qualified third-party enterprises in the future or choose to further expand the scale of the recycling network. In order to do so, it can rely on the industrial base to promote the formation of industrial alliances of EV manufacturers and include the positive logistics process of EVs from the initial production stage, through to sales, and into the construction of recycling networks, the likes of which needs further consideration.

In addition, in order to improve the recycling business system and accelerate the improvement of power battery recycling efforts, the Chinese government may introduce the "Management Measures for the Recycling and Utilization of New Energy Vehicle Power Batteries" in the near future. This study can provide reference for policy formulation. The recycling of decommissioned EV batteries is unique because of its safety risks, potential environmental pollution, significant revenues, and costs. Therefore, while encouraging recycling, China has also formulated some laws and regulations, which strictly scrutinize the qualifications of recycling businesses, which has standardized the recycling process. Although the battery recycling industry has great developmental potential, as a third-party recycling business, we cannot ignore the safety and environmental concerns in pursuing unlimited profits. Decision makers and business managers should rely on standardized operations and scientific management to obtain appropriate levels of profitability and actively undertake the right kind of social responsibilities and community engagement.

5.4. Future work

This study has some limitations, which provide an opportunity for better understanding the future configuration of EV recycling networks. First, in terms of network construction, this study only proposes to build a third-party outsourcing modefor several EV manufacturers in Xi'an. The current distribution of recycling outlets in Xi'an is relatively dense, the data is clear, and the network construction is easier to form scale effects. Future studies should take into account the individual differences in different regions, as there may be a small number of automobile enterprises or a fragmented distribution of recycling outlets.

Second, in terms of network design, this study only considers the issue of battery recycling after dismantling EVs, while not considering who runs the recycling market and how it will cooperate with third-party enterprises to recycle the rest of a car's frame. In addition, in terms of the modeling process, this study only considers the uncertainty of the quantity and quality of the recycling that is being conducted, while the uncertainty of the recycling time can also be considered in the future. Furthermore, this study only considers network design from the perspective of cooperation between third-party recycling enterprises and automobile enterprises, while future research could involve entrusting battery recycling to more than one third-party enterprise, so there may be competition and cooperation across the marketplace at the same time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

A-1. The Location of Car Sales Service Dealerships

Table 1
The Location of Car Sales Service Dealerships

Number	Automobile Sales Service Dealership	Longitude	Latitude
1	NIO Authorized Service Center (Yanta)	108.9635	34.2032
2	NIO Space (Xi'an Xiying TIME)	108.9703	34.222
3	NIO Space (Xi'an Vientiane Tiandi)	108.9529	34.1999
4	NIO (Kate Mall)	108.9366	34.229

(continued on next page)

Table 1 (*continued*)

Number	Automobile Sales Service Dealership	Longitude	Latitude
5	NIO Space (Xi'an Jindi Plaza)	108.988,159	34.203,976
6	NIO Center (Xi'an High-tech CUHK)	108.898,324	34.222,818
7	NIO Center (Xi'an Creative Valley)	109.012949	34.2125
8	NIO Space (Xi'an Yitian Holiday World)	108.973,151	34.269,276
9	NIO Center (Xi'an Weiyang)	108.944,944	34.337,652
10	NIO (Xi'an Jingkai)	108.930,283	34.330,605
11	NIO Space (Xi'an Chang'an Vanke Plaza)	108.897,342	34.158,487
12	Tesla (Zhongda International Store)	108.897,751	34.222,055
13	Tesla (Qujiang Yintai City Hall A)	108.963,625	34.206,908
14	Tesla Experience Center (Xi'an Jinye)	108.859,021	34.203,391
15	Tesla High-tech Wanda Experience Store	108.89176	34.208,302
16	Tesla Qujiang Creative Valley Experience Center	109.013136	34.211,684
17	Tesla Experience Center (Xi'an Xidi Port Experience Store)	108.945,175	34.337,959
18	TESLA (Mingguang Road Tesla Center)	108.929,084	34.332,926
19	TESLA (South 2nd Ring Road)	108.908,551	34.24045
20	Wuling New Energy (Shihua Avenue)	108.867,607	34.322,022
21	Wuling New Energy (Silk Road Blue Ocean)	108.829,209	34.26771
22	Wuling New Energy Maintenance Service Station	108.829,229	34.304,737
23	Wuling New Energy Xi'an Experience Center	108.855,792	34.237,958
24	Wuling New Energy Xi'an Experience Center LING HOUSE (Belfry)	108.942,403	34.258,991
25	Wuling New Energy Xi'an Direct Store Lingshop (Qujiang Longhu)	108.992,298	34.215,831
26	Wuling New Energy (Xi'an Kaishi Hengtong Service Shop)	108.824,965	34.272,574
27	Shanxi Yuantong Wuling Service Shop (West Checheng)	108.818,016	34.292,783
28	BYD Auto Dynasty Network (Xi'an Jingtai Service Shop)	109.05436	34.25243
29	BYD Auto Dynasty Network (Xi'an Xingdi Service Shop)	109.052894	34.300,973
30	BYD Auto Dynasty Network (Yadi Road Xinjing Tengfei Service Shop)	108.845,581	34.181,708
31	BYD Auto Dynasty Network (Shanxi Longcheng Tianxiang Service Shop)	108.819,357	34.320,529
32	BYD Auto Dynasty Network (Zaoyuan Xinjing Tengfei Service Shop)	108.864,185	34.279,876
33	BYD Auto Dynasty Network (Xi'an High-tech Service Shop)	108.89199	34.207,618
34	BYD Auto Dynasty Network (Xi'an Aotong Service Shop)	108.845,781	34.253,524
35	BYD Auto Dynasty Network (Shanxi Longcheng Yuxiang Service Shop)	108.907,726	34.26994
36	BYD Auto Dynasty Network (Xinghong Yuedi Hanhuacheng Service Shop)	108.998,608	34.208,559
37	BYD Auto Dynasty Network (Xindi Haorui Golden Eagle International Service Shop)	108.901,301	34.233,359
38	BYD Lintong Jingcheng Authorized Repair Shop	109.200,008	34.386,395
39	BYD Auto (Qianyuan Xinjing Gaoling Direct Store)	109.083154	34.546,466
40	BYD Auto Xi'an Shengshiluqi (Qujiang)	108.965,481	34.205,641
41	BYD (Xi'an Zhengyao Huitong Huyi Store)	108.599,484	34.100,954
42	BYD Auto Shaanxi Yihua New Energy Experience Hall	108.864,545	34.204,228
43	BYD Auto Ocean Network (Xi'an Yishen Service Shop)	108.815,968	34.293,694
44	BYD New Energy Silk Road Blue Ocean After-sales Service Station	108.835,791	34.274,765
45	Ideal Car Xi'an Xiangda Tianjie Retail Center	109.037815	34.262,199
46	Ideal Car (CityOn Shopping Center)	108.94611	34.337,765
47	Ideal Car (Changan Sunshine World Showroom)	108.868,628	34.170,886
48	Ideal Car (Qujiang Jindi Plaza)	108.988,443	34.203,314
49	Ideal Car (High-tech Wanda Retail Center)	108.89059	34.20855
50	Ideal Car (Xi'an Xixian MixC Retail Center)	108.830,632	34.290,217
51	Ideal Car (Century Jinhua Science and Technology Road)	108.903,312	34.232,243
52	Ideal Car (High-tech Zhongda International Retail Showroom)	108.897,174	34.221,169
53	Ideal Car Xi'an Economic Development Retail Center	108.93025	34.331,452
54	Ideal Car (Old City Root G Park Showroom)	108.920,399	34.2847
55	Ideal Car (Vientiane Tiandi)	108.952,614	34.199,556
56	Ideal CarXi'an Aerospace Service Center	108.992,621	34.16742
57	GAC Aion Xi'an Huazhong Experience Center	108.825,993	34.276,818
58	GAC Aion Xi'an Taihua Experience Center	108.933,235	34.33045
59	GAC Aion Xi'an West Ring Experience Center	108.847,511	34.324,196
60	GAC Aian Xi'an Chanba Experience Center	109.052646	34.304,711
61	GAC Aion (Xi'an Chanba Ecological Zone Capitaland Plaza Exhibition Center Store)	109.0429	34.27676
62	GAC Aion (Landao Plaza)	108.901,441	34.210,987
63	GAC Aion (Taibai Impression City)	108.921,153	34.235,186
64	GAC Aion (Lifeng City)	108.904,034	34.197,035
65	GAC Aion (Wanda Plaza Lijiacun)	108.961,046	34.243,638
66	GAC Aion (Shenglong Plaza)	108.944,985	34.29833
67	GAC AION (Wanda Plaza Xi'an High-tech Store)	108.891,751	34.207,998
68	GAC Aion Shengan Plaza Experience Center	108.932,922	34.242,863
69	GAC Aion Xiaozhai Yintai Exhibition Center	108.940,248	34.223,227
70	AION (Wangfujing Department Store South Gate)	108.945,718	34.247,763
71	Geely (Xi'an Bohao)	108.876,082	34.185,717
72	Geely (Xi'an Guoli Chanba)	109.052836	34.304,324
73	Geely (Xi'an Chenyu Service Shop)	109.053866	34.302,885
74	Geely (Shaanxi Xinghai Flagship Service Shop)	108.917,016	34.190,145
75	Xi'an Defeng Xingyue Geely Service Shop	108.911,352	34.360,825
76	Geely (Xi'an Times Star)	109.029685	34.218,455
77	Geely Shaanxi Yilin Service Shop	108.934,393	34.326,244
78	Geely (P Xi'an Wanshun)	108.825,899	34.263,219
79	Geely (Gaoling Franchise Store)	109.081092	34.544,021
80	Geely New Energy (Xiliu)	108.787,606	34.155,519

(*continued on next page*)

Table 1 (*continued*)

Number	Automobile Sales Service Dealership	Longitude	Latitude
81	Geely Remote New Energy Vehicle Avanti Exhibition and Sales Center	108.868,345	34.321,849
82	Geely New Energy Geometry Automobile (Xi'an Dongwei)	109.053594	34.302,708
83	Shaanxi Shengkaiyuan Geely Long-Range New Energy Commercial Vehicle Franchise Store	108.826,327	34.267,789
84	Geely Auto Xi'an Jurenji Car Service Station (North Seoul Road)	108.872,338	34.281,736
85	Smart (Xi'an Liucunbao Full Function Exhibition Hall)	108.849,024	34.323,796
86	Smart (Xi'an Qujiang Yintai)	108.964,541	34.206,496
87	Smart (Xi'an Nanmen Wangfujing)	108.946,046	34.247,929
88	Smart (Xi'an High-tech Yitian Holiday)	108.881,815	34.194,261

A-2. The Location of Centralized Hubs and Energy Storage Markets

Table 2
The Location of Potential Centralized Hubs

Number	Potential Centralized Hubs	Longitude	Latitude
1	Xi'an Jingfa New Energy Co., Ltd	109.016352	34.472,915
2	Xi'an Qinzhitong Technology Co., Ltd	108.83304	34.33337
3	Xi'an Huitong New Energy Technology Co., Ltd	109.200,772	34.582,448
4	Xi'an Ruiao New Energy Technology Co., Ltd	108.849,906	34.358,123
5	Xi'an Sunshine Green Park New Energy Technology Co., Ltd	108.65295	34.118,337
6	Shanxi Huaqin New Energy Technology Co., Ltd	108.808,469	34.171,463
7	Shanxi Meidekang New Energy Technology Co., Ltd	108.856,633	34.159,998
8	Xi'an Shunzhuo New Energy Technology Co., Ltd	108.945,834	34.348,171
9	Shanxi Shenke New Energy Technology Co., Ltd	108.967,553	34.365,566

Table 3
The Location of Potential Energy Storage Markets

Number	Potential Energy Storage Markets	Longitude	Latitude
1	State Grid (Xi'an Power Supply Bureau Chang'an Branch)	108.922,153	34.156,384
2	State Grid (Wenyi South Road Power Supply Business Hall)	108.953,473	34.231,448
3	State Grid (The Great Wild Goose Pagoda Center Power Supply Office Business Hall)	108.982,775	34.213,538
4	State Grid (Yuhuazhai Business Hall)	108.820,812	34.242,548
5	State Grid (Waiting for Driving Slope Business Hall)	109.033725	34.234,762
6	State Grid (Ganting Power Supply Station)	108.625,361	34.088274
7	State Grid (Yongxing Center Power Supply Station)	108.960,866	34.261,916
8	State Grid (Gaoqiao Power Supply Office Business Hall)	108.716,685	34.24731
9	State Grid (Taoxibao Village)	109.016994	34.095444

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