

Power Battery Recycling Path Planning Considering Risk and Priority Scheduling

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Abstract

As power batteries from new energy vehicles reach retirement, the need for efficient and safe recycling is becoming urgent. Existing studies often focus on cost and transport efficiency, while risks such as leakage and explosion, and inefficiencies from small-scale, fragmented collections, are overlooked. This study proposes a priority-based scheduling strategy that classifies recycling tasks into emergency and normal levels based on inventory thresholds and storage duration. A mixed-integer programming model is developed, integrating constraints like minimum load limits and urban traffic peaks. The model is validated in five simulated scenarios. Results show a 100% task completion rate and vehicle load factors ranging from 92.4% to 97.9%. In emergency-heavy cases, the priority mechanism improves efficiency significantly. These findings highlight the model's role in enhancing reliability and mitigating risk, offering useful insights for optimizing battery recycling and guiding hazardous waste transport policy.

Keywords

Power Vehicle; Reverse Logistics; Route Optimisation; Priority.

1. Introduction

With the rapid development of China's new energy vehicle industry, the problem of power battery decommissioning on a large scale has gradually emerged. According to the data of China Automotive Technology Research Centre, combined with the end-of-life, life cycle and other indicators, it is expected that by 2030 the annual decommissioning of used batteries will reach 70,800 tonnes. It can be seen that the number of decommissioned power batteries for new energy vehicles in China will increase in the future, and the demand for power battery recycling and disposal will become more and more urgent. At the same time, China's government has been accelerating power battery recycling-related policies in recent years. Among them, the "new energy vehicle used power battery comprehensive utilization industry norms ^[1]" further refine the management requirements of the gradient use and recycling, strengthen the comprehensive utilization of safety and environmental protection responsibility. 2025 February, the National Regular Session of the State Council to consider and pass the sound new energy vehicle power battery recycling system action plan. The meeting pointed out that at present, China's new energy vehicle power battery has entered a large-scale decommissioning stage, and it is particularly important to comprehensively improve the level of power battery recycling capacity. It is necessary to strengthen the whole chain management, build a standardised, safe and efficient recycling system, use digital technology to strengthen the monitoring of the whole life cycle flow of power batteries and realise the traceability of the whole process of production, sales, dismantling and use. In this context, the construction of an efficient power battery recycling system has become a key path to achieving the "double carbon" goal and resource recycling. However, there are some deficiencies in power battery recycling in China.

Improper disposal of these batteries may lead to heavy metal pollution, electrolyte leakage and other environmental risks. At the same time, strategic metals such as lithium (Li), cobalt (Co) and nickel (Ni) in decommissioned batteries have a very high regeneration value. Therefore, how to optimise the logistics network of reverse power battery recycling has become a hot topic of current research.

Several scholars have studied the logistics network for power battery recycling by combining different factors respectively, such as a multi-participant collaborative reverse logistics network (RLN) for the recycling and remanufacturing of electric vehicle batteries, which deals with the uncertainties in the quantity and quality of recycling by introducing a fuzzy optimisation model and optimises the decision-making of the facility siting, the number of facilities, and the direction of flow in the network^[2]. A mixed-integer linear programming (MILP) model can also be constructed by combining the collection, testing, reconditioning, remanufacturing, and recycling of batteries to minimise the cost of the waste battery recycling network^[3]. There are also scholars who have studied the power battery recycling network from the perspective of other disciplines, constituting the idea of building a power battery recycling network from a unique perspective. Taking a German OEM as an example, the development of the recycling network from a single facility to multiple nodes and tiers from 2030 to 2044 was simulated, and it was eventually found that with the gradual expansion of the network and the upgrading of the facility capacity, the average recycling and treatment cost per battery was significantly reduced^[4]. In a systematic review of the current state of research on the supply chain of lithium-ion batteries from production to recycling, it was found that a holistic life-cycle perspective that integrates the design, manufacturing, use, and recycling of batteries can improve the economics and sustainability of the supply chain^[5]. In the complex decision-making problem of 3PRL supplier selection for electric vehicle power battery recycling, a linguistic Pythagorean hesitant fuzzy MULTIMOORA decision-making method can be used to achieve scientific evaluation and reliable ranking of candidate suppliers, which can provide a credible decision-making basis for the government and enterprises in battery recycling cooperation^[6]. From the perspectives of recyclers and consumers, promoting formal recycling through a subsidy mechanism can promote the efficient operation of the battery recycling system^[7].

Many other scholars have taken smart technologies such as the Internet and big data or related factors into account in the power battery recycling network to provide more ideas for the optimisation of the power battery recycling network. The introduction of big data technology can integrate battery recycling information, optimise transport routes and improve transport efficiency^[8]. The "Internet+" based used battery recycling system for electric bicycles can combine offline recycling, online platform trading and traceability management, solving the problems of low efficiency, weak supervision and low participation of traditional recycling systems^[9]. In the power battery network optimisation problem considering uncertainties such as carbon price fluctuations, market demand stochasticity and supply chain structure selection, it is found that self-operated recycling is suitable in scenarios with high carbon price fluctuations or low recycling rates, whereas hybrid recycling is appropriate in scenarios where total recycling rates are required or carbon prices are stable, since outsourcing can reduce the cost^[10]. A bi-objective optimisation model was constructed by incorporating the type of facility technology as a key factor in the design decision of a recycling network for used batteries, and a recycling network design that is both economical and environmentally friendly was proposed^[11]. When the battery transport and logistics (BTL) model combines distributed energy storage (DES) and railway transport system, it is found that the model can improve the capacity of renewable energy consumption and reduce the transport cost after solving it by using the branch delimitation method and genetic algorithm. ^[11]. A mixed integer nonlinear programming (MINLP) model is proposed for the electric vehicle battery recycling system with cross-network co-operation, comparing three modes of no co-operation, partial co-operation and full co-operation, and deeply analysing the costs and benefits under different co-operation levels, which reveals the advantages of cross-network co-operation in terms of cost reduction and efficiency enhancement^[12]. Considering the phenomenon of recycling batteries with different qualities and uses in the battery recycling process, a multilevel reverse logistics network (RLN) was designed and

predicted using triple exponential smoothing with a GM (1,1) model to enhance the recycling efficiency and reduce carbon emissions^[13].

Many other scholars have investigated the impact and effect on logistics and path optimisation by setting the priority of different factors, for example, a Robust Labeling Algorithm (RLA) has been designed to optimise the distribution scheme in consideration of uncertain priority allocation and the need for multi-trip distribution, and combined with a path generation strategy to ensure the robustness of the solution^[14]. In Internet of Things (IoT) logistics scenarios, considering the phenomenon of uneven resource allocation, the priority of tasks can be calculated based on the Analytical Hierarchy Process (AHP), and tasks with higher priority will be assigned to fog nodes or the cloud for processing according to the conditions, which further optimises the process of task offloading and scheduling in logistics^[15]. Considering scenarios with different levels of risk, a combined decision support system based on the Interval Roughness Improved Order Priority Approach (I-OPA) and Comprehensive Compromise Solution Approach (CoCoSo) is proposed for Public Postal Operators (PPOs) to help decision makers to make more rational choices under uncertainty conditions^[16]. Shared autonomous vehicle (SAV) scheduling and path planning methods can also be investigated by combining convoy travelling and intersection priority control mechanisms, which can provide dedicated lanes for SAVs on convoy-travelling road sections, reduce intersection delays, and improve the overall efficiency of urban traffic by setting up priority strategies^[17].

From a comprehensive viewpoint, most existing research on power battery recycling in China centers on optimizing network-level cost and facility efficiency. However, few studies explore operational-level issues, such as emergency dispatching, load balancing, or time-sensitive risks in the actual recycling process. Given the nature of power battery recycling-characterized by small and fragmented batches-vehicles often suffer from low load factors, leading to frequent empty trips and inefficient operations. More critically, retired power batteries pose considerable safety risks if not handled in time. Electrolyte leakage, heavy metal pollution, and even explosion hazards may arise from prolonged storage. To address these, the Chinese national standard GB/T 38698.2-2023 strictly limits the storage time: 30 days for Class A batteries and 15 days for Class B batteries with minor risk. These regulatory constraints highlight the urgency of designing a recycling system that not only considers efficiency but also incorporates safety and compliance factors.

Despite these real-world requirements, most existing models do not explicitly consider such safety constraints, nor do they propose practical mechanisms for priority-based dispatching. Rarely are real-time vehicle scheduling, task urgency, and regulatory policies integrated into a unified optimisation framework. These gaps significantly reduce the applicability of prior work in actual urban recycling operations.

In response, this study develops a priority-based path planning model that explicitly incorporates risk constraints, vehicle loading requirements, and regulatory time limits to enhance the realism, safety, and operational efficiency of power battery recycling.

Specifically, the contributions of this study are as follows:

- (1) A scheduling framework is developed by incorporating safety constraints arising from battery storage risks and policy-based limitations related to urban commuting patterns.
- (2) A dual-priority scheduling mechanism is proposed, combining urgency and inventory-related risk to improve both safety and vehicle load efficiency.
- (3) A mixed-integer programming model is formulated using battery storage duration and inventory thresholds as dynamic dispatch triggers, incorporating minimum load constraints and time window restrictions.
- (4) Five realistic scenarios are designed to simulate, compare, and validate the model's robustness and applicability under different operational conditions.

2. Model Construction

2.1 Problem Description and Model Assumptions

2.1.1. Problem Description

In the dynamic scheduling scenario of the urban power battery recycling system, there are many recycling points and a recycling centre where power batteries can be centrally recycled in each region, and each recycling point has corresponding staff and intelligent devices to monitor the inventory status and storage cycle of power batteries. When the storage volume of power batteries at a recycling point reaches 80% of its maximum inventory, an ordinary recycling request will be sent to the recycling centre; if the storage volume exceeds 95% of the maximum inventory or the number of days of storage of a single batch of batteries exceeds 45 days, an emergency recycling requests will be sent to the recycling centre, which needs to be recycled immediately. The recycling centre implements different scheduling strategies according to the type of request issued by the recycling point: for normal recycling requests, the recycling centre will consolidate the same type of requests in the region and start the vehicles for reasonable transportation only when the total load is close to 70% of the maximum carrying capacity of the vehicles; for emergency recycling requests, regardless of the current scale of the task, it is necessary to immediately deploy special vehicles to perform point-to-point recycling, and all transportation All transport periods are strictly avoided during morning and evening traffic peaks.

Route planning takes minimising the total distance travelled as the core objective, and at the same time integrates the constraints of load balancing, transport time and route continuity, and realises multi-factor collaborative decision-making through mathematical optimisation models. Through dynamic sensing, demand grading and optimal allocation of resources, the system effectively coordinates the normal operation efficiency and emergency response capability and provides reliable technical support for the construction of urban power battery green cycle system.

2.1.2. Basic Assumptions

- (1) The geographic location, maximum inventory, number of batteries, number of vehicles and maximum load of the recycling centre and each recycling point are known.
- (2) There are multiple power battery recycling points, and all vehicles start from the recycling centre and return to the recycling centre after completing the task.
- (3) The recycling centre uses a uniform vehicle, i.e., the vehicles have the same rated load, and the power batteries recovered from the recycling service outlets cannot exceed their rated load.
- (4) The range of the vehicle meets the longest driving demand in a single day, there is no energy loss in loading and unloading operations, the whole journey is even and the road section is flat.
- (5) The situation of refuelling or charging in the middle of the recycling process is not considered, i.e. refuelling or charging can only be done when returning to the recycling centre after completing the task.
- (6) One vehicle can serve multiple recycling points, but one and only one vehicle can serve a recycling point.
- (7) Normal recycling requests are allowed to be dispatched across days, and emergency recycling requests need to be completed on the same day.
- (8) Dynamic disturbances such as traffic congestion and weather are not considered, and problems such as battery breakage and deformation are not considered.

2.2 Model Parameters and Decision Variables

2.2.1. Set

Set	
N	The set of all recycling points ($n=0,1,\dots, N $), where the recycling point 0 indicates the recycling centre, and 1~ n indicates each recycling point.
V	The set of vehicles ($m=1,2,\dots, V $), where m is the total number of vehicles.
T	The set of periods ($t=1,2,\dots, T $) for $t=24$ hours.
P	Contains the set of peak hour markers from 7-9 am and 5-7 pm ($P \subseteq T$).

2.2.2. Parameters

Parameter	
bit	Inventory rate of recycling point i at time t , between 0 ~ 1.
s	Vehicle travelling speed of 40 km/h.
d_{ij}	Distance from recycling point i to recycling point j . q_i
q_i	The current total weight of the battery at the recycling point i . q_i
Q_v	The maximum load of vehicle v is 6 tonnes.
Q_i	The maximum storage capacity of recycling point i is 3 tonnes.
τ	The service time of the vehicle at the recycling point is 0.5 hours.
uit	The state of recycling point i at time t (0 means no request is sent, 1 means request is sent and the battery storage capacity is greater than or equal to 80% and less than 95%, 2 means request is sent and the battery storage capacity reaches 95%, 3 means the battery storage time is more than 15 days).
fit	The number of days the battery has been stored at recycling point i . When $t = 0$, it is the next day, i.e., $f+1$.

2.2.3. Decision Variables

Decision variables	
x_{ijv}	$x_{ijv}= 1$ if vehicle v travels from recycling point i to recycling point j , and 0 otherwise.
y_{iv}	$y_{iv}= 1$ if vehicle v visits recycling point i , and 0 otherwise.
z_v	$z_v= 1$ if vehicle v is scheduled to be used, 0 otherwise.
δ_v	Denotes the departure time of each vehicle.

3. Model Construction

3.1 Objective Function

$$\min Z = \sum_{v \in V} \sum_{i \in N} \sum_{j \in N} d_{ij} x_{ijv} \quad (1)$$

3.2 Constraints

$$\sum_{v \in V} y_{iv} \leq 1, \forall i \in N \setminus \{0\} \quad (2)$$

$$\sum_{j \in N} x_{0jv} = z_v, \forall v \in V \quad (3)$$

$$\sum_{i \in N} x_{i0v} = z_v, \forall v \in V \quad (4)$$

$$\sum_{i \in N} x_{ijv} = \sum_{k \in N} x_{jkv}, \forall j \in N, v \in V \quad (5)$$

$$u_{iv} - u_{jv} + (n+1)x_{ijv} \leq n, \forall i, j \in N \setminus \{0\}, i \neq j, v \in V \quad (6)$$

$$2 \leq u_{iv} \leq n+1, \forall i, j \in N \setminus \{0\}, v \in V \quad (7)$$

$$\sum_{i \in N \setminus \{0\}} q_i y_{iv} \leq Q_v z_v, \forall v \in V \quad (8)$$

$$\delta_v \notin P, \forall v \in V \quad (9)$$

$$t_{jv} \geq t_{iv} + \frac{d_{ij}}{s} + \tau - M(1 - x_{ijv}), \forall i, j \in N, v \in V \quad (M \text{ is a big enough constant.}) \quad (10)$$

$$\sum_{v \in V} w_{iv} \geq 1, \text{ if } u_{it} \geq 2, \forall i \in N \setminus \{0\}, t \in T \quad (11)$$

$$\sum_{v \in V} y_{iv} = 1, \forall i \in \{k \in N \setminus \{0\} \mid u_{kt} \geq 2\} \quad (12)$$

$$x_{ijv} \in \{0, 1\} \quad (13)$$

$$y_{ijv} \in \{0, 1\} \quad (14)$$

$$z_v \in \{0, 1\} \quad (15)$$

$$\delta_v \in T \quad (16)$$

The objective function (1) is to minimise the total distance travelled by all trips; Eq. (2) ensures that each recycling point can only be visited once by a vehicle; Eq. (3) and Eq. (4) ensure that vehicles depart from the recycling centre and return to the recycling centre; Eq. (5) ensures that the flow rate is balanced in front of and behind the recycling point; Eq. (6) and Eq. (7) are designed to prevent the phenomenon of sub-circuits in the paths; Eq. (8) is the vehicle loading constraint; Eq. (9) ensures that the departure time is issued in the middle of off-peak hours; Eq. (10) defines the arrival time t_{iv} to ensure the transport continuity; Eq. (11) indicates that at least one vehicle is scheduled to retrieve if

there is a retrieval point i satisfying $uit \geq 2$ in a special case; Eq. (12) guarantees that the emergency recycling request will be handled for sure; Eqs. (13) ~ (16) are the domains of definitions of the relevant variables.

4. Model Solving

Mixed Integer Programming (MIP) is a mathematical optimisation technique for solving linear programming problems with integer and continuous variables, which can deal with both integer and continuous variables at the same time, and guarantee the global optimality of the solution through branch-and-bound and cut-plane methods, which can be implemented by solvers such as Gurobi and CPLEX. It can be implemented by solvers such as Gurobi and CPLEX, which can improve the efficiency of solving large-scale problems.

Thus, the MIP algorithm can be used to solve the battery recycling problem. The idea is to transform the actual battery recycling scheduling problem into a mathematical planning model by defining the decision variables, objective function and constraints, and then use a special solver to find a solution that satisfies all the constraints and optimises the objective function. In this study, x_{ijv} , y_{iv} and z_v are all 0-1 integer variables and δ_{vis} also an integer variable, and the objective function and constraints are linear functions, which makes it suitable for solving using the MIP algorithm. In this study, we use Gurobi 12.0.1 and its built-in branch-and-bound and cut-plane methods to find the combination of values of the decision variables that satisfy all the constraints minimise the objective function, and ultimately output the vehicle scheduling plan and its corresponding performance metrics.

5. Case Analysis

5.1 Example Description

Table 1. Location of each recycling point and the amount of batteries recycled

Node	Longitude	Latitude	Battery Recovery Volume	Node	Longitude	Latitude	Battery Recycling Volume
1	116.48296	39.97323	2.1	16	116.26934	39.99447	1.1
2	116.35150	39.86618	1.8	17	116.63085	40.11311	1.2
3	116.24469	39.80501	1.1	18	116.18718	40.03599	1.1
4	116.17075	40.09557	2.7	19	116.33507	39.76312	2.5
5	116.53226	40.08792	1.3	20	116.44188	40.04785	1.7
6	116.24469	40.11086	2.1	21	116.12145	39.91735	2.4
7	116.65550	39.95794	2.4	22	116.50761	39.74532	2.4
8	116.40080	40.16438	1.9	23	116.19540	39.73346	2.1
9	116.27756	40.00381	1.3	24	116.53226	39.98853	1.0
10	116.31864	39.78207	2.3	25	116.67193	39.79871	2.0
11	116.12145	39.71325	2.7	26	116.21183	40.08345	1.9
12	116.57334	40.14145	1.3	27	116.66372	39.98260	2.1
13	116.62264	39.72090	1.1	28	116.51583	39.88769	1.8
14	116.58977	39.98852	2.7	29	116.63907	39.75125	2.2
15	116.46653	39.82030	3.0	30	116.42545	40.10124	2.2

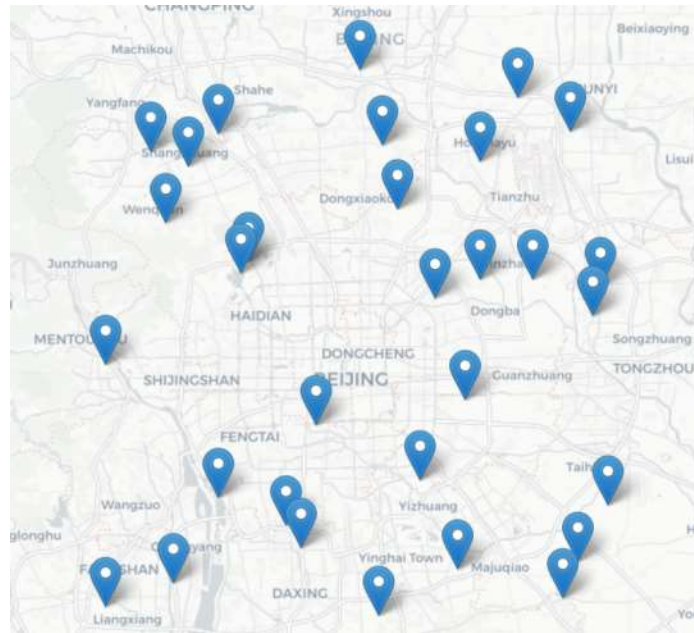


Fig.1 Geographical distribution of each recycling point

The example of this paper is to select the reverse logistics network data of two head new energy vehicle enterprises A and B in Beijing, whose data sources include the Power Battery Recycling Industry Report (2023 Edition), relevant references and some data obtained from on-site interviews. The geographic locations of each recycling point and recycling centre are shown in Fig.1, and the location of one recycling centre is known to have a longitude of 116.42114 and a latitude of 39.70571, while the latitude and longitude locations of the remaining 30 recycling points and the number of batteries recycled are shown in Table 1.

5.2 Arithmetic Example Solving

According to the calculation results of the Gurobi solver, the recycling points that send out emergency recycling requests include 6 recycling points such as 5, 10, 15, 20, 25, 30, etc., and the ones that send out normal recycling requests include 4, 11, 14, 19, etc. The final optimal solution of the solver is shown in Table 2, the recycling centre needs to send out 4 vehicles, such as 1, 5, 6, 10, etc., to complete all the emergency recycling requests and normal recycling requests, and the total distance travelled by the 4 vehicles is 401.5 kilometres, and their loading capacity is 6, 5.7, 6 and 5.4 tonnes, which is more than 90% of the loading capacity and meets the constraints in the model.

Table 2. Calculation example solution results

Vehicle number	Route	Number of recycling points passed	Total distance travelled (km)	Load (tonnes)
Vehicle 1	0→10→25→20→0	3	114.5	6.0
Vehicle 5	0→15→14→0	2	69.4	5.7
Vehicle 6	0→19→30→5→0	3	100.9	6.0
Vehicle 10	0→11→4→0	2	116.7	5.4

The visualised path planning diagram for this algorithm is shown in Fig.2. It can be seen that in the power battery recycling path planning problem considering the time window constraints of the commuting peak and the priority response situation, the vehicle scheduling can satisfy all the demands and ensure the utilisation rate of the vehicle load and the safety of the people's life in the city.

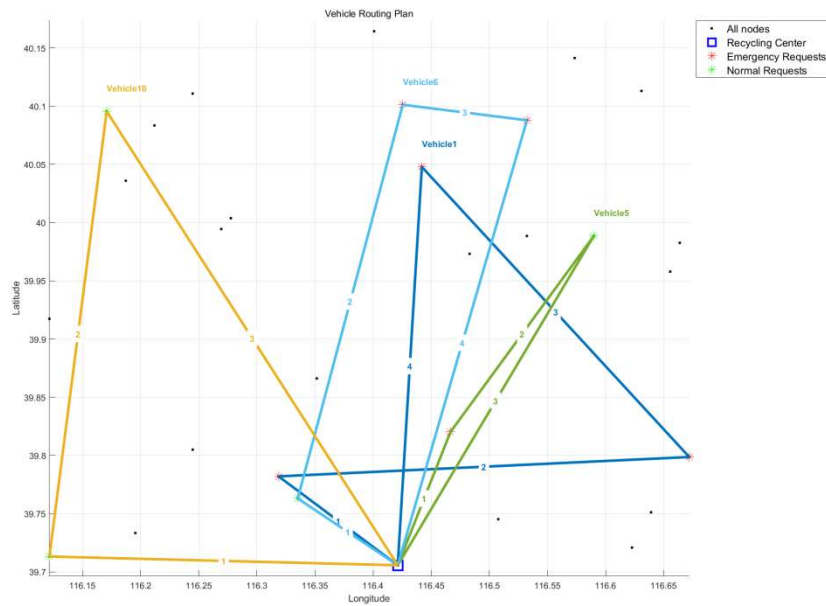


Fig.2 Vehicle path planning diagram

5.3 Result Analysis

With the increasing improvement of the power battery recycling system, the demand for adapting to different scenarios of different intensities is also getting stronger and stronger, so in order to analyse the performance of the logistics network of this study in different scenarios in a more in-depth way, this study divides the different scenarios according to the intensity of the recycling request and sets up five different scenarios of normal recycling request and emergency recycling requests for further study. The five scenarios are divided according to the density of the vehicle travelling routes from low to high, as follows:

- (1) Low-density type: 5 emergency recycling requests and 5 normal recycling requests.
- (2) Medium-density type: 10 emergency recycling requests and 10 normal recycling requests.
- (3) Ordinary dominant type: 5 emergency recycling requests, 20 normal recycling requests.
- (4) Balanced type: 15 emergency recycling requests, and 15 normal recycling requests.
- (5) Emergency leading type: 20 emergency recycling requests, 5 normal recycling requests.

Since the number of tasks is randomly assigned, this study conducted 30 solvers for each of these five scenarios and statistically analyzed the results of these solvers as follows.

5.3.1. Low-density Type Result Analysis

Table 3. Low-density type scenario solution results

Vehicle number	Route	Number of recycling points passed through	Total distance travelled (km)	Loading capacity (tonnes)
Vehicle 1	0→23→9→5→12→0	4	131.1	6.0
Vehicle 2	0→28→21→0	2	90.4	4.2
Vehicle 7	0→13→14→16→3→0	4	114.4	6.0

The low-density type imitates the solution situation of vehicle scheduling and path planning when the number of tasks is small and the number of the two tasks is comparable, and one of the optimal solutions is selected here for analysis. It consists of 5 emergency recycling requests such as 5, 9, 14, 16 and 21, and 5 normal recycling requests such as 3, 12, 13, 23 and 28. From Table 3 and Fig.3, it can be seen that by arranging three vehicles to carry out the recycling tasks, all the emergency

recycling tasks and ordinary tasks can be completed, with a total route of 335.84 km, an average single-point service distance of 33.58 km, and an average load factor of about 90.0%.

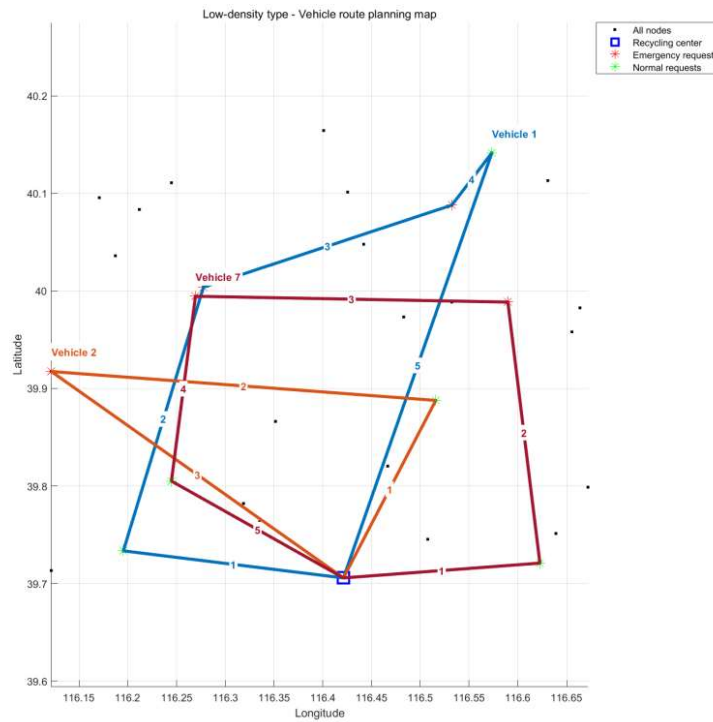


Fig.3 Low-density type scenario solving results

5.3.2. Analysis of Medium-density Type Results

The medium-density type mimics the solution scenario of vehicle scheduling and path planning when the number of tasks is relatively medium and the number of two tasks is comparable, and one of the optimal solutions is selected here for analysis. It consists of 10 emergency recycling requests such as 2, 4, 9, 12, 16, 17, 22, 24, 25, 28, etc., and 10 normal recycling requests such as 6, 7, 8, 11, 14, 15, 18, 20, 21, 30, etc. From Table 4 and Fig.4, it can be seen that arranging 7 vehicles to carry out the recycling tasks can complete all the emergency recycling tasks and ordinary tasks, with a total route of 797.56 km, an average single-point service distance of 39.88 km, and an average load factor of about 92.4%.

Table 4. Medium-density type scenario solution results

Vehicle number	Route	Number of recycling points passed through	Total distance travelled (km)	Load (tonnes)
Vehicle 1	0→28→8→0	2	105.1	3.7
Vehicle 2	0→11→7→0	2	113.2	5.1
Vehicle 4	0→15→20→9→0	3	88.9	6.0
Vehicle 6	0→22→21→17→0	3	144.0	6.0
Vehicle 7	0→16→4→30→0	3	114.3	6.0
Vehicle 9	0→2→24→6→18→0	4	118.8	6.0
Vehicle 10	0→25→14→12→0	3	113.3	6.0

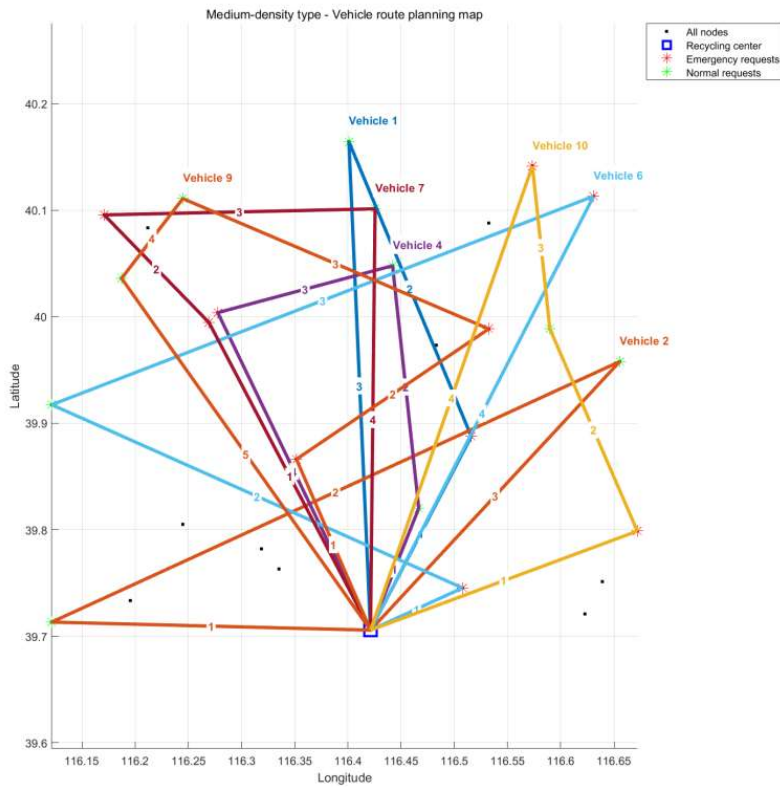


Fig.4 Vehicle path planning for medium-density type scenario

5.3.3. Analysis of the Results of the Ordinary Dominant Type

The ordinary dominant type is to mimic the solution situation of vehicle scheduling and path planning when the task volume is very large and the normal recycling requests are significantly more than the emergency recycling requests, and one of the optimal solutions is selected here for analysis. It consists of 5 emergency recycling requests such as 5, 7, 13, 25, 26, and 20 normal recycling requests such as 1, 2, 3, 4, 6, 8, 9, 12, 14, 16, 17, 18, 19, 20, 22, 23, 24, 27, 28, 30, and so on. From Table 5 and Fig.5, it can be seen that arranging 8 vehicles to come for the recycling tasks can complete all the emergency recycling tasks and ordinary tasks, with a total driving route of 902.26 km, an average single-point service distance of 36.09 km, and an average load factor of about 93.5%.

Table 5. General dominant scenario solution results

Vehicle number	Route	Number of recycling points passed through	Total distance travelled (km)	Loading capacity (tonnes)
Vehicle 1	0→3→26→5→0	3	120.6	4.3
Vehicle 3	0→6→4→17→0	3	141.9	6.0
Vehicle 4	0→13→25→28→16→0	4	102.3	6.0
Vehicle 5	0→2→1→27→0	3	87.7	6.0
Vehicle 6	0→23→20→30→0	3	110.4	6.0
Vehicle 8	0→14→8→0	2	110.9	4.6
Vehicle 9	0→24→7→12→9→0	4	130.3	6.0
Vehicle 10	0→22→19→18→0	3	98.2	6.0

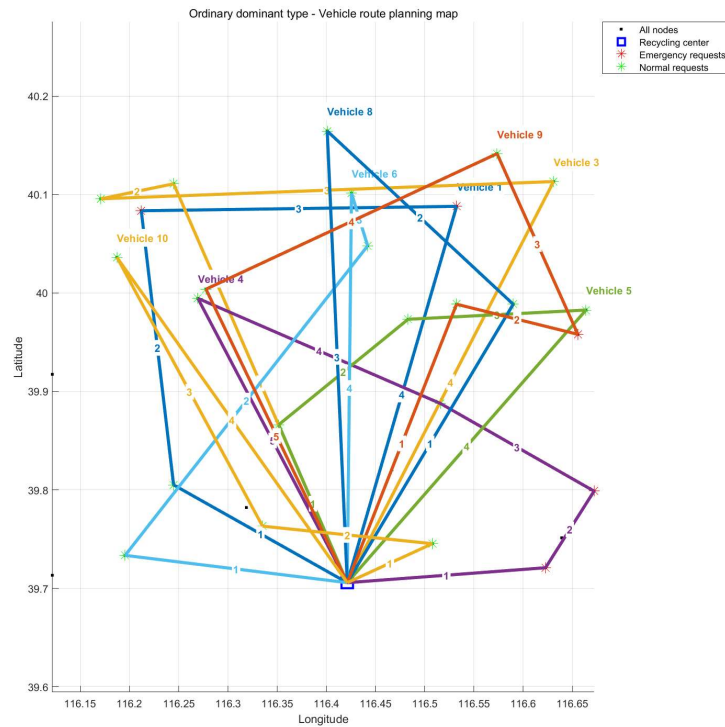


Fig.5 Vehicle path planning diagram for normal dominant type scenario

5.3.4. Analysis of Balanced Type Results

The balanced type mimics the solution scenario of vehicle scheduling and path planning when the number of tasks is very large and the number of two tasks is equal, and one of the optimal solutions is selected here for analysis. It consists of 15 emergency recycling requests such as 3, 6, 10, 11, 13, 14, 16, 19, 21, 22, 23, 24, 27, 28, 29, and 15 normal recycling requests such as 1, 2, 4, 5, 7, 8, 9, 12, 15, 17, 18, 20, 25, 26, 30, and so on. From Table 6 and Fig.6, it can be seen that arranging 10 vehicles to carry out the recycling tasks can complete all the emergency recycling tasks and ordinary tasks, with a total driving route of 1089.5 km, an average single-point service distance of 36.32 km, and an average load factor of about 95.8%.

Table 6. Balanced Scenario Solving Results

Vehicle number	Route	Number of recycling points passed through	Total distance (km)	Loading capacity (tonnes)
Vehicle 1	0→22→20→8→0	3	107.2	6.0
Vehicle 2	0→19→29→12→0	3	129.7	6.0
Vehicle 3	0→25→14→9→0	3	108.0	6.0
Vehicle 4	0→2→1→6→0	3	108.1	6.0
Vehicle 5	0→7→17→5→16→0	4	120.0	6.0
Vehicle 6	0→3→21→0	2	69.8	3.5
Vehicle 7	0→13→30→4→0	3	132.8	6.0
Vehicle 8	0→23→28→27→0	3	105.4	6.0
Vehicle 9	0→15→18→26→0	3	98.4	6.0
Vehicle 10	0→10→11→24→0	3	110.1	6.0

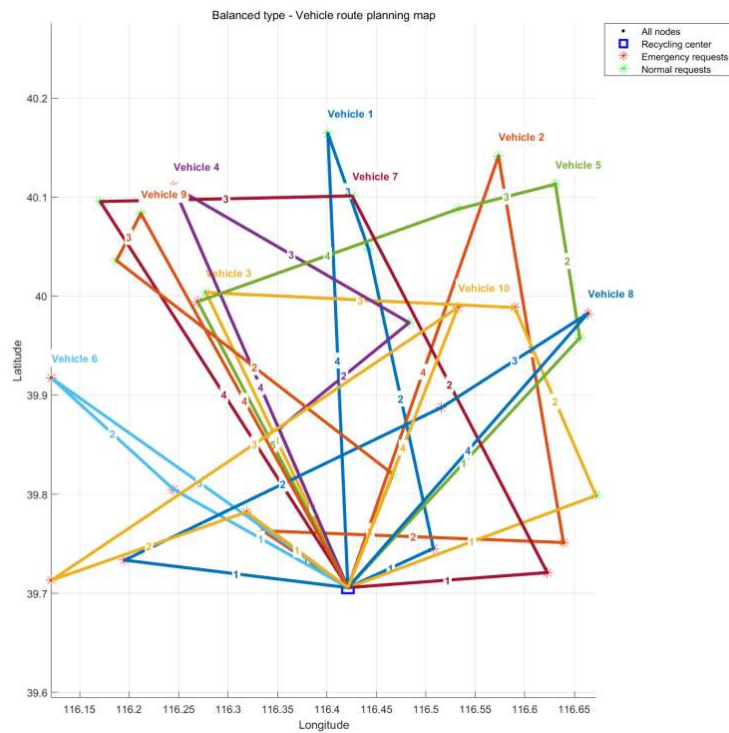


Fig.6 Vehicle path planning in balanced scenario

5.3.5. Emergency-dominated Result Analysis

The emergency dominated type is to mimic the solution situation of vehicle scheduling and path planning when the task volume is extremely large and the emergency recycling requests are significantly more than the normal recycling requests, and one of the optimal solutions is selected here for analysis. It consists of 20 emergency recycling requests such as 2, 3, 4, 5, 8, 9, 12, 14, 15, 17, 18, 20, 21, 22, 23, 24, 25, 26, 28, 30, etc., and 5 normal recycling requests such as 6, 10, 16, 19 and 27. From Table 7 and Fig.7, it can be seen that arranging 8 vehicles to carry out the recycling tasks can complete all the emergency recycling tasks and ordinary tasks, with a total driving route of 872.97 km, an average single-point service distance of 34.92 km, and an average load factor of about 97.9%.

Table 7. Emergency Dominant Scenario Solution Results

Vehicle number	Route	Number of recycling points passed through	Total distance travelled (km)	Loading capacity (tonnes)
Vehicle 1	0→23→26→25→0	3	132.7	6.0
Vehicle 2	0→22→5→30→0	3	99.9	5.9
Vehicle 3	0→19→2→20→0	3	81.0	6.0
Vehicle 5	0→28→27→6→0	3	124.1	6.0
Vehicle 6	0→3→9→18→12→17→0	5	138.9	6.0
Vehicle 8	0→21→4→0	2	103.4	5.1
Vehicle 9	0→15→16→8→0	3	112.0	6.0
Vehicle 10	0→10→24→14→0	3	81.0	6.0

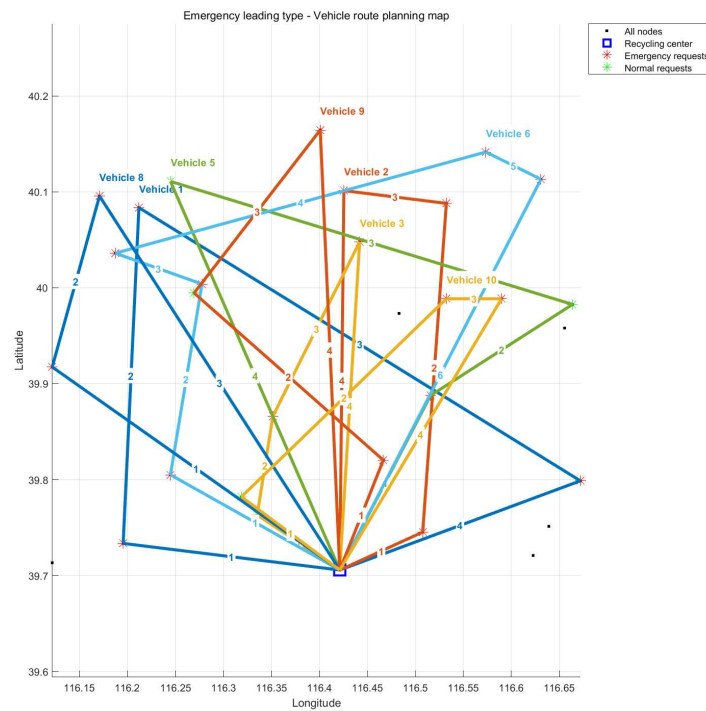


Fig.7 Vehicle path planning for emergency dominated scenario

5.3.6. Comprehensive Comparative Analysis

In order to further verify the effectiveness of the models and methods, this study conducted 30 groups of repetitive experiments for these 5 scenarios, and counted the optimal solutions for each group of experiments, including the total distance travelled, the number of vehicles and the model robustness and other indicators. According to Table 8, these five models can satisfy the emergency and normal recycling requests in all scenarios, in which the balanced type has the most total distance travelled while using the least number of vehicles; the medium-density balanced type uses the most number of vehicles and the low-density type has the least total distance travelled.

Table 8. Comparison of solutions for five scenarios

Scenario	Total Distance Travelled (kilometres)	95% CI	Number of Vehicles	95%CI	Emergency Completion Rate (%)	Normal Completion Rate (%)
Low-den	388.9212	17.5992	8.6000	0.1356	100	100
Med-den	731.5285	12.6417	10.0000	0.1092	100	100
Ord	912.0847	20.3408	8.4667	0.1816	100	100
Bal	1091.0000	16.5661	3.8333	0.0000	100	100
Emer	937.3426	18.1635	6.9000	0.1783	100	100

The comparison of the metrics of these five scenarios is shown in Fig.8. Firstly, about the number of their request point distribution, in the figure it can be seen that the number of request points in the balanced type is the highest with 30 and the number of emergency recycling requests and normal recycling requests is the same, and the number of request points in the low-density type is the lowest and the number of the two types of recycling requests is also the same. Then according to the average single point service distance, 40km is the longest in the medium-density type scenario and the low-density type is the shortest. Then in the number of vehicles and total distance it can be seen that the

balanced type uses the highest number of vehicles and the longest distance, while the low-density type uses the lowest number of vehicles and the shortest total distance travelled. Based on the vehicle load factor, all the load factors can exceed 90%, with the emergency dominated scenario having the highest average load factor per vehicle. According to the two indicators representing the solution effect, the request completion rate and the solution time, the request completion rate is 100%, which indicates that the solution result can satisfy all the recycling requests, and at the same time, among these five scenarios, the solution time of the emergency leading type is the longest, and the solution time of the low-density type is the shortest. These can show that the solution results of this study are reasonable and credible.

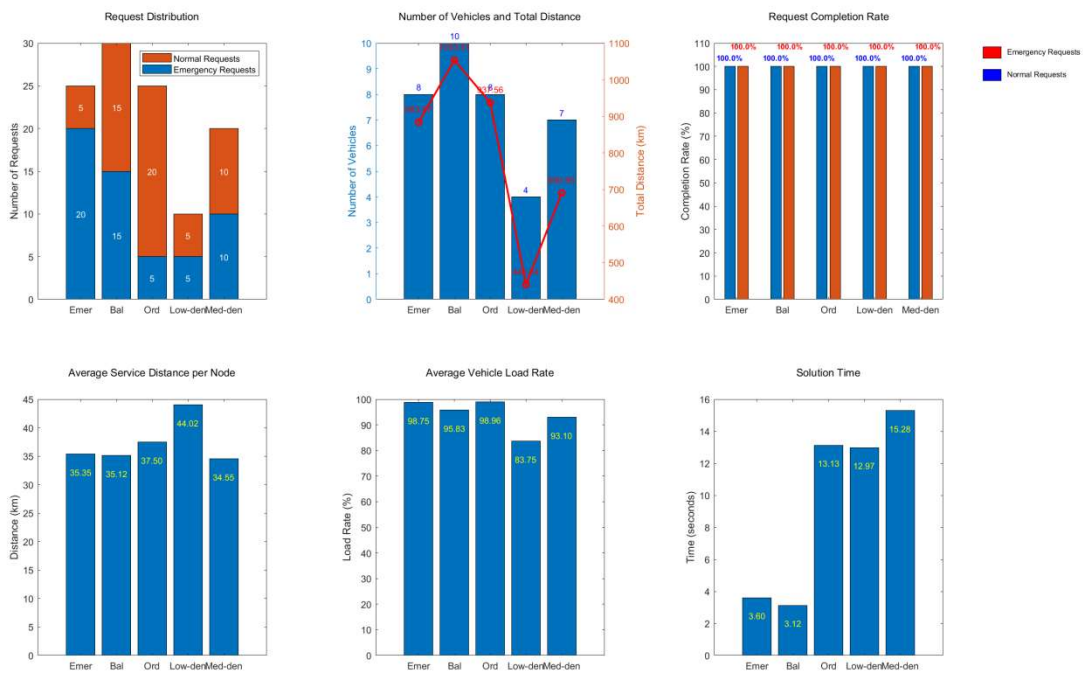


Fig.8 Comparison of various indexes of the solving process and results for the five scenarios

First of all, the total distance travelled by vehicles in these five scenarios, as shown in Fig.9, the shortest distance travelled by the low-density type is at 371.3 km, the longest distance travelled is at 406.5 km, and the average distance is at 388.9 km; the shortest distance travelled by the medium-density type is at 718.9 km, the longest distance travelled is at 744.2 km, and the average distance is at 731.5 km; and the shortest distance travelled by the normal-dominant type is at 891.7 km, and the average distance is at 891.7 km. Distance travelled was 891.7 km, the longest distance travelled was 932.4 km, and the average distance was 912.1 km; the shortest distance travelled was 1074.4 km, the longest distance travelled was 1107.5 km, and the average distance travelled was 1091.0 km for the balanced type; and the shortest distance travelled was 919.2 km, the longest distance travelled was 955.5 km, and the average distance travelled was 937.3 km for the emergency-led type. The average distance travelled was 937.3 km. Overall, the shortest total distance travelled is for the low-density type, while the longest is for the balanced type. According to the coefficients of variation in Fig.10, the coefficient of variation for the low-density type is 0.125, which is the most unstable scenario with the largest fluctuation in distance; the coefficient of variation for the medium-density type is 0.05, which is relatively stable; the coefficient of variation for the general-dominant type is 0.06, which is moderately stable and slightly higher than the 0.055 for the emergency-dominant type, and the two are very close to each other; and the coefficient of variation for the balanced type is 0.045, which is the most stable. 0.045, which is the most stable scenario with the least distance fluctuation.

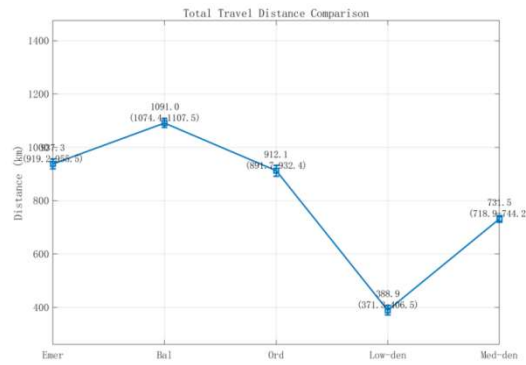


Fig.9 Comparison of total distance travelled for five scenarios

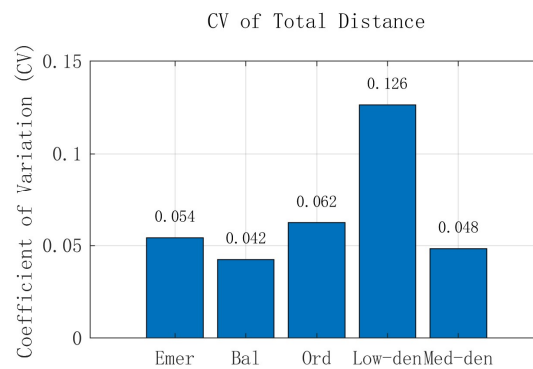


Fig.10 Coefficient of variation of total distance for five scenarios

Next, the number of vehicles used in these five scenarios is analysed, as can be seen in Fig.11, the low-density scenario uses a minimum of three vehicles, a maximum of four vehicles, and an average of about four vehicles; the medium-density scenario uses a minimum of six vehicles, a maximum of seven vehicles, and an average of about seven vehicles; the normal-dominant scenario uses a minimum of eight vehicles, a maximum of nine vehicles, and an average of about 8 vehicles; the Balanced used the highest and most consistent number of vehicles, all 10 vehicles; the Emergency Dominant scenario used a minimum of 8 vehicles, a maximum of 9 vehicles, and on average about 9 vehicles. Combined with the coefficients of variation in Fig.12, the balanced type used the highest number of vehicles, the low-density type used the lowest number of vehicles, and in the high-density scenario, the normal dominant type used the lowest number of vehicles, 8.

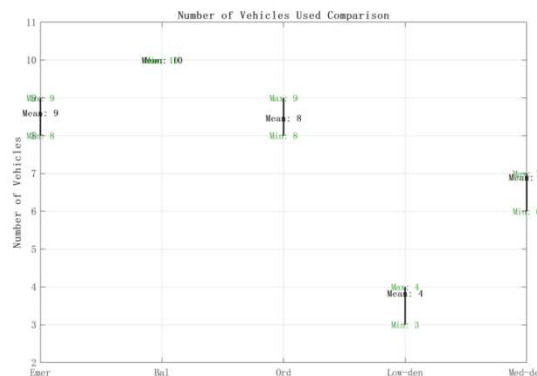


Fig.11 Comparison of the number of vehicles used in the five scenarios

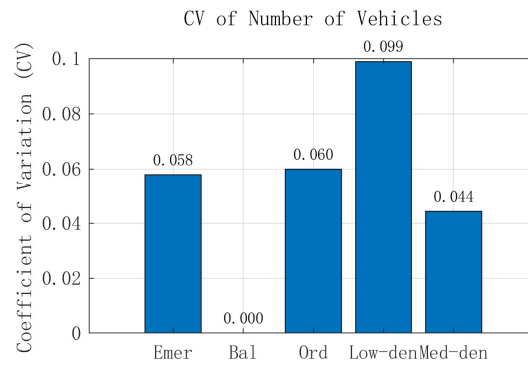


Fig.12 Coefficient of variation of the number of vehicles for the five scenarios

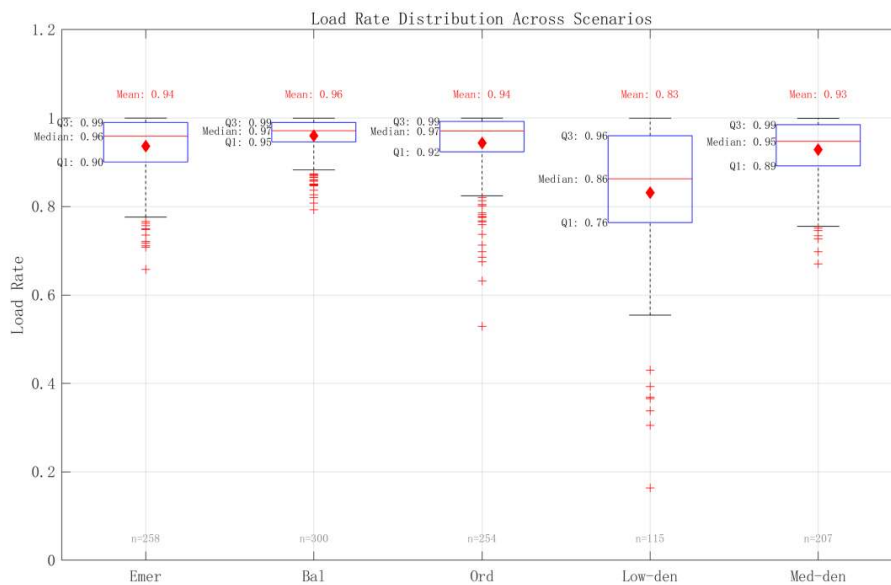


Fig.13 Load factor distribution for five scenarios

Next, the vehicle loads were analysed for the different scenarios. The mean value of the low-density type is 0.83, the median is 0.86, Q1=0.76, Q3=0.96, and IQR=0.20, so the vehicle loading rate in this scenario is the lowest and the most fluctuating, and a certain proportion of experiments show that the vehicle loading rate is between 0.76 and 0.96, which indicates that the vehicle idling situation is relatively serious, and there is a clear phenomenon of waste of resources; the mean value of the medium-density type is 0.93, median is 0.95, Q1=0.89, Q3=0.99, IQR=0.1, indicating that the stability of this scenario is insufficient, and there is a need to improve the scheduling elasticity; the mean value of the normal dominant type is 0.94, median is 0.97, Q1=0.92, Q3=0.99, IQR=0.07, but it can be seen in Fig.13 that there exists a certain proportion of experiments where the load factor is less than 0.92, which may drag down the normal operating efficiency close to full load, and the overall scheduling strategy is relatively stable, so we should pay attention to the phenomenon of uneven order distribution or path planning redundancy; the balanced type has a mean of 0.96, a median of 0.97, Q1=0.95, Q3=0.99, and IQR=0.04, which, since its mean and median are very close to each other, indicates that this scenario is the five scenarios The stability of the scenario is the strongest, and most of the experimental data are concentrated in the near-full loaded state from 0.95 to 0.99, which indicates a high and predictable vehicle utilisation; the emergency-dominated scenario is 0.94, the median is 0.96, Q1=0.90, Q3=0.99, IQR=0.09, and the graphs show that there is a phenomenon of low loads in some of the experiments, with a more significant fluctuation in the loading rate, which may be the result of no load limit triggered by the Emergency recycling request,

which means that the model sacrifices the vehicle utilisation efficiency to meet the time-sensitive requirements in this scenario.

The comprehensive robustness score table for each scenario is shown in Table 9, the lower the robustness score, the stronger the resistance of the scheduling strategy for that scenario to external perturbations (e.g., fluctuations in recycling volume, changes in paths). The table shows that the robustness score of 0.011 for the balanced type is the lowest among these scenarios, indicating that the balanced type is the most stable of the current five scenarios; the low-density scenario has the highest robustness score, reflecting the fact that the sparse amount of recycling creates system instability.

Table 9. Combined robustness scores for the five scenarios

Scenario	Robustness Score
Low-den	0.056
Med-den	0.031
Ord	0.031
Bal	0.011
Emer	0.028

The one-way ANOVA in Table 10 shows that different scenarios have a significant effect on the total distance and the number of vehicles, and the η^2 values also show that these scenario types explain more than 96% of the variance in the total distance and the number of vehicles. Taken together, the idea of dividing into different scenarios for the study is necessary, and future attempts can be made to develop scheduling models for scenario adaptation.

Table 10. ANOVA and η^2 for total distance and number of vehicles

	One-way analysis of variance (ANOVA)	Effect size analysis (η^2)
Total distance	F(4,145)=932.93, p=0.0000 ***	$\eta^2=0.963$
Number of vehicles	F(4,145)=1120.20, p=0.0000 ***	$\eta^2=0.969$

Note: * denotes $p < 0.1$, ** denotes $p < 0.05$, *** denotes $p < 0.01$, and absence of * indicates no statistically significant difference.

6. Conclusion

In this study, a mixed integer planning model integrating priority response mechanism and path optimisation is constructed for the risk control and dynamic scheduling needs in the power battery recycling logistics network, which is solved by using the Gurobi solver, and the applicability of the model in the complex recycling situation is verified by multi-scenario simulation. The final results show that under the constraint of imposing a 70% minimum load factor trigger condition, the vehicle load factor in the model ranges from 92.4% to 97.9%, which significantly improves the transport efficiency compared to the 82.5% load factor calculated in the China Freight Transportation System Assessment Project Report. This result indicates that the priority response mechanism effectively mitigates the problem of wasted transport capacity caused by the multi-batch and small-volume recycling characteristics of power batteries. Meanwhile, this study also achieves 100% task completion rate in multiple scenarios while satisfying these constraints, which shows the effectiveness of this model in optimising vehicle scheduling and improving path planning efficiency.

Based on these results, this study suggests that enterprises should flexibly configure their fleet according to the density of regional recycling volume in their daily operation management. For example, in areas with high recycling demand density, more vehicles with high loads can be arranged, and in areas with unstable recycling demand, a mix of vehicles with high and low loads can be arranged; at the same time, the enterprise and the government need to incorporate storage cycle thresholds (e.g., more than 15 days) into the daily regulation of outlets, in order to reduce the risk of battery leakage and explosions generated by storing batteries for a long period, so as to reduce the hazards to the social life and the environment; moreover, the enterprise can make use of existing Moreover, enterprises can build a real-time battery inventory monitoring platform with the help of existing mature technologies (e.g., IoT, big data, etc.) to predict the demand for power battery recycling and dynamically optimise the grading threshold.

The limitation of this study is that it does not take into account the dynamic interfering factors such as weather changes, traffic congestion, and the state of health (SOH) of batteries. The follow-up work will focus on the following directions: (1) fusing real-time traffic and weather data to establish a dynamic path planning model that considers the coexistence of temperature and risk; (2) exploring the changing rules of power battery recycling under dynamic changes of different scenarios and the corresponding response strategies.

CRedit Authorship Contribution Statement

Chuan Wen Tong: Conceptualization, Investigation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. Shan Xiong: Conceptualization, Methodology, Writing – review & editing.

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.

Nomenclature

Emer	Emergency leading type
Bal	Balanced type
Ord	Ordinary dominant type
Low-den	Low-density type
Med-den	Medium-density type

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