Modeling and Optimization of Pure Electric Vehicle Path Planning-Siting Based on Enterprise Self-built Microgrid and Energy Storage System

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Abstract. In order to reduce greenhouse gas emissions from road transportation and create a low-carbon and energy-saving society, it will become a trend to use electric logistics vehicles to complete urban logistics tasks in the logistics transportation industry. Compared with traditional fuel vehicles, electric logistics vehicles have many advantages such as low pollution and low energy consumption, which are highly concerned by the government, enterprises and consumers. The model of this paper is established based on the Location-Routing Problem and the time window constraint and the electric logistics vehicle power supply problem are considered in this integer planning model. To solve the above problems, an improved WOA is proposed in this paper, which variable neighborhood search operators are added in the original WOA to avoid falling into local optimum. WOA-VNS makes the search more efficient and gets more accurate solutions in reasonable time. By comparing the initial and final solutions of the randomized case, through the algorithm, the total transportation distance is shortened by about 33.9%, the construction cost of the charging pile is reduced by 61.5% and penalty costs can be avoided. It shows the effectiveness of the model establishment and the efficiency of the solution method.

Keywords: Path Planning-Site Selection · Electric Storage System · Pure Electric-Logistics Vehicle · WOA-VSN

1 Introduction

According to a report, global greenhouse gas emissions in 2021 is about 40.8 billion tons. The transportation sector accounts for 25% of the total greenhouse gas emissions, with CO2 emissions caused by road transport accounting for more than 70% [13]. Power generation companies are encouraged to build their own energy storage or peaking capacity by the National Development and Reform Commission and the National Energy Administration [8]. Governments and companies have started to consider the use of electric logistics vehicles and the replacement of traditional fuel vehicles with renewable energy sources to complete urban logistics and distribution operations to mitigate the greenhouse effect.

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In terms of charging and switching site selection, Wang et al. (2019) [12] studied the siting problem of EV switching stations under a soft time window; Zhao (2021) [15] used the Cuckoo Search and NSGA-II algorithm for the siting of switching stations and charging stations; and Zhang (2021) [14] considered the mileage anxiety of electric logistics vehicle drivers, modeled the charging selection behavior of drivers and mileage anxiety in the road network as the site selection objective. In terms of path planning, Chen (2021) [2] studied the path planning problem of pure electric vehicles in urban logistics based on Genetic Algorithm, while Fan (2020) [4] studied the multi-energy vehicle path problem based on the improved Genetic Algorithm of Beetle Antennae Search Algorithm; Wang (2018) [11] studied the path planning problem of electric vehicles with nonlinear battery depreciation and solved by using CPLEX. Sun (2020) [10] used FLOYD algorithm to improve greedy algorithm to study the problem of electric logistics vehicle charging facility layout and the optimization of distribution path, while Liu et al. (2020) [6]. Studied a two-stage open low-carbon site-path problem based on path flexibility and solved by Dijkstra and CPLEX. Li et al. (2022) [9] established a mixed integer planning model and designed a three-stage algorithm to study common distribution site-path optimization problem. In the study of grid-connected microgrids, Lin et al., (2021) [7] studied the microgrid optimization scheduling problem based on adaptive weight improvement WOA, and Golpîra et al. (2018) [5] studied the introduction of an intelligent energy-efficient production plan in the case of grid-connected microgrids and wind power generation, and the results showed that the plan was able to produce products at least 1.95% lower cost than traditional manufacturing systems. Duarte et al. (2020) [3] studied a multi-process production scheduling based on on-site renewable energy supply with energy storage system and grid as backup, meanwhile the impact of time and level of use policy on power purchase cost of the national grid supply price was considered. Chen et al. (2017) [1] artificially reduced the impact of uncertainty within the microgrid due to electric vehicle charging, wind power and solar power generation on the CCHP-MG operational economics, a two-stage adjustable robust optimization method was proposed to achieve the minimum operating cost of CCHP-MG.

In this paper, an electric logistics vehicle charging station siting and path planning model are constructed with a soft time window with energy storage system and grid as energy backup under the supply of renewable energy from enterprise microgrid, with the objective of cost minimization, and solved by the WOA-DNS algorithm.

2 Model Establishment

2.1 Problem Description

A distribution center has K electric logistics vehicles of the same model, the maximum capacity of the vehicle battery is Q, the maximum load capacity is W, a total of demand points is N, the demand of points i is w_i, the required arrival time is $[E_i, L_\mathrm{i}]$. If the vehicle arrives at the point later than L_i, need to pay a penalty fee. Each vehicle departs from the distribution center with a full charge and eventually returns to the distribution center. Due to the limitation of battery capacity, the vehicles may need to be charged at the self-built charging station halfway. Encouraged by the national policy, the company chooses to build its own renewable energy power station and energy storage power station, as well as peak power purchase. It is required to develop a reasonable distribution route and choose a reasonable location of charging stations as well as the amount of purchased power, so that the distribution cost can be minimized while meeting the demand.

2.2 Description of Symbols

T : Collection of time, indexed by t, $t \in \{1, 2, ..., 24\}$.

L : Collection of electricity consumption ladder, indexed by l.

R : Collection of renewable energy, indexed by r.

V : Collection of demand points in a circuit, $V = \{1, 2, ..., N\}$.

K : Collection of electric logistics vehicle numbers.

V_0 : equal to $V + \{0\}$, Where 0 is the distribution center.

V_{N+1} : equal to V + { N + 1} , Where $N + 1$ is the distribution center.

$V_{0,N+1}$: equal to V + { 0} + { N + 1} .

d_{ij} : Distance from point *it* o point *j,* Unit: *m*

ts_i : Service hours of the vehicle at the point i, Unit: *h*

v : Vehicle travel speed, Unit: *km/h.*

$c_{1/2}$: Vehicle electricity cost per unit mile / fixed cost of travel.

c_3 : Construction cost of charging piles.

Q : Battery capacity of electric logistics vehicles, Unit: *kWh*.

$[E_i, L_i]$: The time window of the point i.

λ : Cost per unit time penalty for late arrival of vehicles.

W : Vehicle load capacity, Unit: t

α : Number of vehicles mobilized.

a/b : Charging/power consumption rate of electric logistics vehicles, Unit: kWh/h.

$t_{ik}^{A/L}$: Actual time of vehicle k arrival/departure i.

$q_{ik}^{A/L}$: Remaining charge at the point i of arrival/departure of the vehicle k from the demand point, Unit: *kWh*.

E_{max} : ESS Maximum storage space.

E_0, E_t : Initial storage volume of ESS, storage volume at time period.

$\eta^{+/-}$: charge/discharge efficiency of ESS.

$r^{+/-}$: charge/discharge volume of ESS.

$S_{r,t}$: The amount of renewable energy r available during the time period t

$S'_{l,t}$: The amount of energy available at the time t of the grid phase l.

$c_{r,t}$: Unit price of renewable energy r in time t.

$c'_{l,t}$: The unit price of energy in the time t period of the grid phase l.

D_t : The power required by the charging station during the period t.

$e_{r,t}$: The consumption of renewable energy r during the period t.

$e'_{l,t}$: The consumption of grid energy in the phase l during the period t.

e'_t : The amount of renewable energy and grid energy consumed during the time period that is not used for ESS.

X_{ijk} : Decision variable, with a value of 1 if the vehicle k travels from i to j.

Y_i : Decision variable, value of 1 if charging station is established at the point i.

2.3 Modeling

Firstly, the model of Location-Routing Problem is established as follows, which is constrained by load capacity and soft time window.

$$\begin{aligned} \mathrm{minC} = {} & \mathrm{c}_1 \sum_{\mathrm{i}\in \mathrm{V}_{0,\mathrm{i}} \neq \mathrm{j}} \sum_{\mathrm{j}\in \mathrm{V}_{\mathrm{N}+1}} \sum_{\mathrm{k}\in\mathrm{K}} \mathrm{d}_{\mathrm{ij}}\mathrm{X}_{\mathrm{ijk}} + \\ & \lambda \sum_{i\in V_0} \sum_{k\in K} X_{ijk} \max\left(t_{ijk}^{A} - L_i, 0\right) + \\ & c_3 \sum_{i\in V_0} Y_i + c_2 \cdot \alpha + \\ & \sum_{t\in\tau}\left(\sum_{r\in R}\left(c_{r,t} \cdot e_{r,t}\right) + \sum_{l\in L}\left(c_{l,t}^{'} \cdot e_{l,t}^{'}\right)\right), \end{aligned} \tag{1}$$

s.t

$$\sum_{k\in K} X_{ijk} = 1, \forall i \in V, \forall j \in V_{N+1}, i \neq j, \tag{2}$$

$$\mathrm{f}(x) = \omega \cdot \phi(x) + b \tag{3}$$

$$\min_{\omega,b,\xi} \frac{1}{2}\|\omega\|^2 + c\frac{1}{2}\sum_{i=1}^{k}\xi_i^2 \tag{4}$$

$$\begin{aligned} & t_{ik}^{L} = max\left(t_{ik}^{A}, E_i\right) + ts_i + Y_i \frac{Q-q_i^L}{a}, \\ & \forall i \in V_0, \forall k \in K, \end{aligned} \tag{5}$$

$$\begin{aligned} & t_{jk}^{A} = \sum_{i\in V_0} X_{ijk}\left(t_{ik}^{L} + \frac{d_{ij}}{v}\right) \\ & \forall j \in V_{N+1}, \forall k \in K, i \neq j \end{aligned}, \tag{6}$$

$$0 \leq \sum_{j\in V} \sum_{i\in V_0} w_j X_{ijk} \leq W, \forall k \in K, \tag{7}$$

$$q_{0k}^{L} = Q, k \in K, \tag{8}$$

$$q_{ik}^{L} = \begin{cases} Q, & \sum_{j\in F} q_{ik}^{L} - b\frac{d_{ij}}{v} < 0 \\ q_{ik}^{A}, & \sum_{j\in F} q_{ik}^{L} - b\frac{d_{ij}}{v} \geq 0 \end{cases} \tag{9}$$

$$0 \leqslant E_t \leqslant E_{max}, \forall t \in T \tag{10}$$

$$E_t = E_{t-1} + \eta^{+} \cdot r_t^{+} - r_t^{-}/\eta^{-}, \forall t \in T \tag{11}$$

$$e_t^{\prime} + r_t^{+} = \sum_{r\in R} e_{r,t} + \sum_{l\in L} e_{l,t}^{\prime}, \forall t \in T \tag{12}$$

$$\sum_{l \in L} e'_{l,t} \leqslant \sum_{l \in L} S'_{l,t}, \forall t \in \tau \tag{13}$$

$$0 \leqslant e_{r,t} \leqslant S_{r,t}, \forall r \in R, t \in T \tag{14}$$

$$0 \leqslant e'_{l,t} \leqslant S'_{l,t}, \forall l \in L, t \in T \tag{15}$$

$$Y_i = \begin{cases} 1, \sum\limits_{j \in F} q_{ik}^L - b\frac{d_{ij}}{v} < 0 \\ 0, \sum\limits_{j \in F} q_{ik}^L - b\frac{d_{ij}}{v} \leqslant 0 \end{cases} \tag{16}$$

Equation (1) indicates the cost of vehicle electricity, fixed cost, penalty cost, charging post establishment cost and energy consumption cost; Eq. (2) indicates that each demand point is served by only one vehicle; Eq. (3) indicates that each vehicle starts from the distribution center and eventually returns to the distribution center; Eq. (4) indicates flow conservation, the number of vehicles entering the demand point is always equal to the number of vehicles leaving the point; Eq. (5) and (6) respectively indicate the arrival and departure times of the demand point; Eq. (7) indicates that the sum of the demands of each vehicle visiting the demand point cannot exceed the maximum load capacity of the vehicle; Eq. (8) indicates that the vehicle leaves the distribution center with a full charge; Eq. (9) indicates the power state of the vehicle leaving the demand point; Eq. (10) indicates that the energy stored in the ESS cannot exceed the maximum limit; Eq. (11) indicates the source of the energy stored in the ESS; Eq. (12) indicates the energy consumed during the time period. Equation (13) (14) (15) indicates that the amount of energy consumed does not exceed the amount of energy available; and Eq. (16) indicates the decision variable Y_i that determines whether to establish a charging post at the point i.

3 Algorithm Improvement

WOA is a meta-heuristic optimization algorithm that simulates the hunting behavior of humpback whales. In the WOA, the position of each humpback whale represents a feasible solution, and the global optimum is sought by simulating three behaviors of the whale: encircling prey, bubble net hunting and searching for prey, seeking global optimality. In order to improve the solution efficiency, the variable neighborhood search method is added to improve the efficiency of the original whale swarm algorithm to jump out of the local optimum. The Variable Neighborhood Search is used to improve the efficiency and accuracy of the computation by using different neighborhood search operators.

3.1 WOA-VNS

3.1.1 Behavior of Prey Encirclement

WOA assumes that the current candidate position is the target prey or close to the optimal target, and the other candidate positions try to move to the optimal position and update their positions, and the mathematical expression is as follows:

$$\vec{D} = \left| \vec{C} \cdot \overrightarrow{X^*}(t) - \vec{X}(t) \right| \tag{17}$$

$$\vec{X}(t+1) = \overrightarrow{X^*}(t) - \vec{A} \cdot \vec{D} \tag{18}$$

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \tag{19}$$

$$C = 2\vec{r}_2 \tag{20}$$

$$a = 2 - \frac{2t}{T_{max}} \tag{21}$$

Where t denotes the current number of iterations, T_{max} denotes the maximum number of iterations, X^* is the current best solution, and r_1. is a random number between 0 and 1.

3.1.2 Behavior of Hunting

The humpback whale has two hunting behaviors, contraction envelope mechanism and spiral update position, and the specific mathematical expression is as follows: where p is a random number between 0 and 1.

$$\vec{X}(t+1) = \begin{cases} \overrightarrow{X^*}(t) - \vec{A} \cdot \vec{D}, & \text{if } p < 0.5 \\ \overrightarrow{D'} \cdot e^{bl} \cdot cos(2\pi l) + \overrightarrow{X^*}(t), & \text{if } p \leqslant 0.5 \end{cases} \tag{22}$$

3.1.3 Behavior of Prey Search

The prey search behavior is based on $\vec{A}$, the position of the search band in the exploration phase is updated according to the randomly selected search agent, when $\left|\vec{A}\right| > 1$ the WOA algorithm is allowed to perform a global search, the expression is as follows:

$$\left|\vec{D} = \right|\vec{C} \cdot \overrightarrow{X_{\text{rand}}} - \vec{X}| \tag{23}$$

$$\vec{X}(t+1) = \overrightarrow{X_{\text{rand}}} - \vec{A} \cdot \vec{D} \tag{24}$$

Although WOA can jump out the local solution to a certain extent, but the efficiency of searching the optimal solution is low, so WOA-VNS algorithm is proposed, which means that variable neighborhood search operators are added in this paper to improve the convergence efficiency.

3.1.4 Variable Neighborhood Search Operators

Hybrid variable neighborhood search operators 2-Opt, Insert and Swap are added in the WOA, that can improve the efficiency and quality of search. The specific process is shown in Fig. 1.

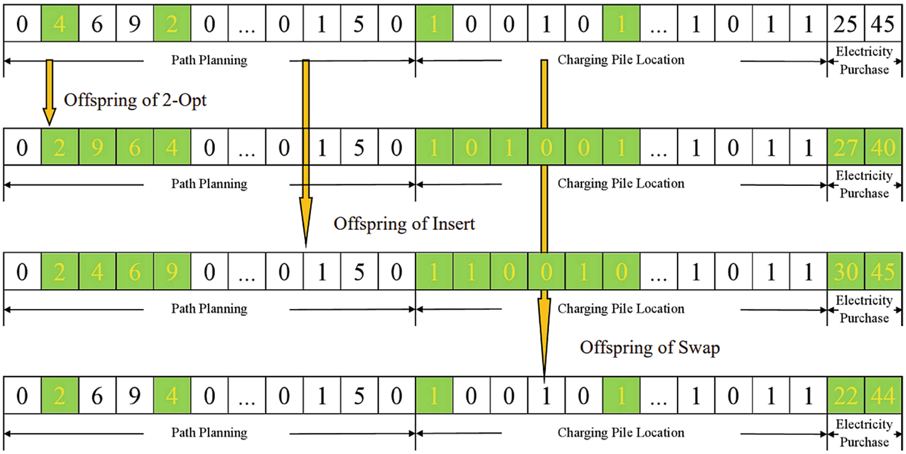

Fig. 1. Offspring of 2-Opt, Insert and Swap

3.2 Flowchart

The specific flow of WOA-DNS algorithm is shown in Fig. 2.

Parental fragment encoding:

3.3 Coding

3.3.1 Path Planning

By assigning n demand points to k vehicles, 0 denoting distribution centers,i denoting demand points, the path can be expressed as 0-i -0, with a total of n path; If the length of path 0-i -0 exceeds the maximum range of the electric vehicle logistics vehicle then charging is required at that point of demand option; The existing paths are merged to meet the maximum loading capacity. The first fragment is shown in Fig. 1.

3.3.2 Siting of Charging Piles

Using 0-1code, 0 means no charging post is built at the location, 1 means charging post is built at the location. For example, (0, 0, 0, 1, 1, 0, 1), which means the fourth, fifth and seventh demand points are selected to build charging posts out of seven candidate points.

3.3.3 Energy Supply Planning

For example, (60, 35), it means that the self-generated renewable energy is not enough to meet the total electricity demand in the period of the operation, and the grid electricity needs to be purchased at 60 kwh in period I, and 35 kwh in the period II.

4 Experimental Case

In this case, we consider the randomly generated positions in the interval of [0, 141.4214], center 0 and 30 demand points, and use Euclidean coordinates to represent the positions of each point, and generate the average demand in the interval of

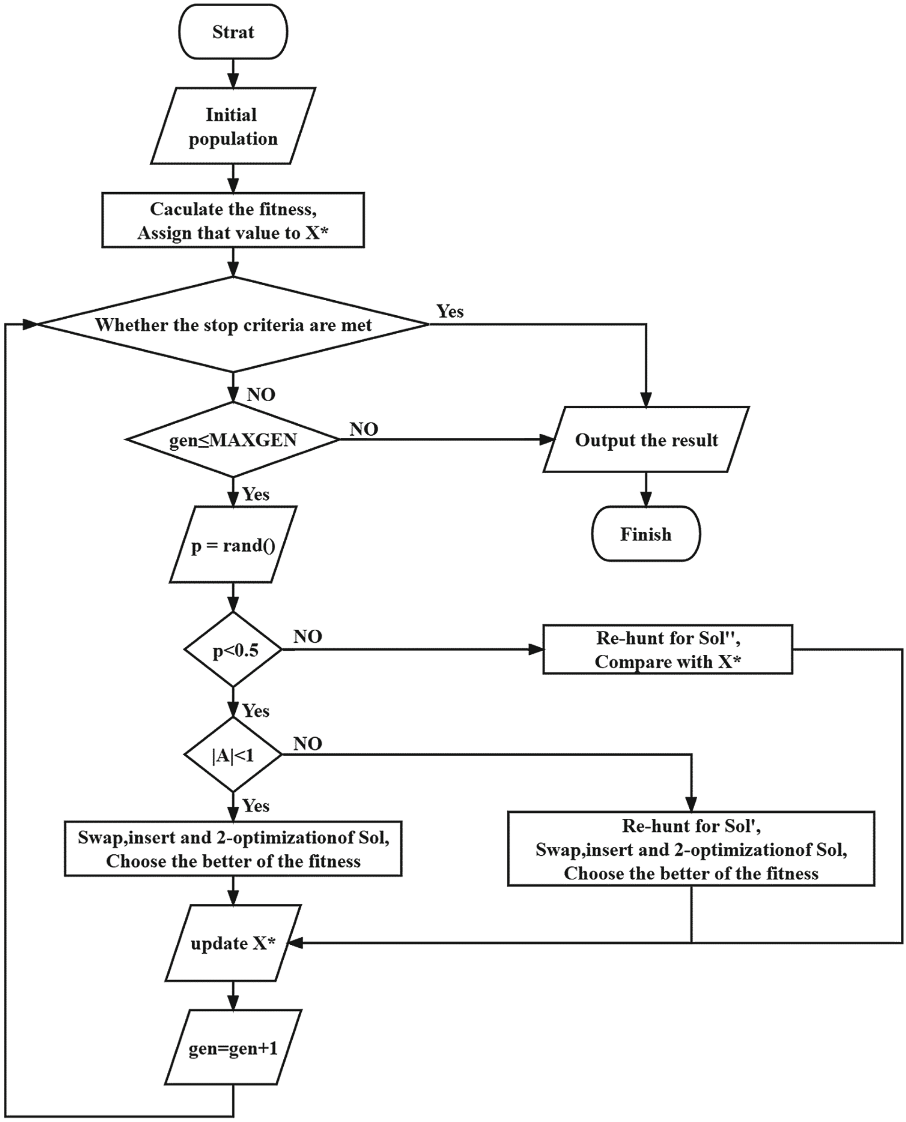

Fig. 2. The flowchart of WOA-VNS

[0, 2.5] and the upper and lower bounds of the time window in the interval [8, 20], the specific data are shown in Table 1.

Suppose the distribution center works from 8:00 to 20:00 and rotates in two shifts. The electric logistics vehicle model is the same, of which the maximum mileage is 200 km, the maximum load capacity is 2.5 t, the overload penalty cost is RMB 800 $/car$, the average speed is 80 km/h, the unit penalty cost of the vehicle being late is RMB 30/h , the fixed travel cost of the vehicle is RMB 1700 $/car$, the power consumption speed

Table 1. The data of example

Point of Demand	Horizontal Coordinate/*km*	Vertical Coordinate/*km*	Average Demand/*t*	Lower Boundary/*h*	Upper Boundary/h
0	58.8208	77.3784	0	8	8
1	42.1116	36.477	0.9109	8.9404	14.1459
2	99.2299	104.746	1.5886	8.5284	17.2505
3	141.1148	72.7559	0.7123	12.8989	13.1798
4	88.7534	140.5237	1.9894	10.0624	12.9594
5	44.1515	140.6058	1.5668	9.204	18.295
6	152.765	110.0158	0.9019	8.8198	10.1042
7	124.2088	46.6226	0.5584	10.4254	13.6656
8	141.3164	58.7741	1.2296	8.5539	14.0048
9	71.1482	141.4013	0.7559	9.3127	18.6174
10	13.5848	57.7144	1.7715	10.4601	16.1092
11	140.9055	62.2247	0.9374	8.4623	17.9719
12	141.4211	141.4212	1.4198	11.9165	14.87
13	135.8378	141.4200	1.6738	9.8242	15.343
14	141.3999	127.6458	0.0745	8.3931	17.6488
15	43.3041	16.754	0.8	11.0284	17.8884
16	51.1608	14.4166	0.6664	12.9359	17.3134
17	127.4579	103.2874	1.1694	16.7844	17.733
18	26.3531	85.245	1.0944	17.6163	19.3135
19	62.1813	54.3655	1.1558	19.4437	19.6765
20	131.6153	126.7232	0.6313	13.6283	16.1757
21	12.0887	56.8394	1.1273	16.9527	19.6982
22	136.6868	55.9441	1.4317	11.0258	20
23	71.1933	93.26	0.8534	14.668	19.5767
24	117.8128	27.5583	1.6356	13.2453	19.3898
25	125.1065	89.5367	1.7377	13.3157	15.4072
26	36.6961	64.154	0.3223	17.7175	19.4638
27	30.6942	13.4216	1.3377	13.9672	17.6619
28	139.4991	50.3862	0.7893	11.9729	18.1075
29	67.0028	70.8556	1.5047	14.9205	19.0498
30	35.4701	38.1054	1.0619	10.0914	19.098

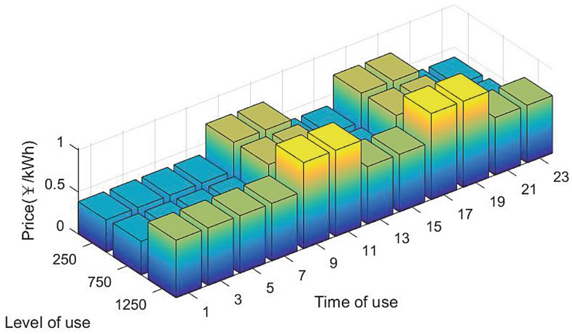

Fig. 3. Time-and-Level-Of -use

Table 2. Initial route planning results

Initial route planning	
0 → 12 → 1 → 14 → 0	0 → 20 → 27 → 26 → 0
0 → 6 → 5 → 0	0 → 28 → 18 → 0
0 → 13 → 7 → 0	0 → 22 → 30 → 0
0 → 11 → 0	0 → 24 → 23 → 0
0 → 8 → 9 → 0	0 → 17 → 21 → 0
0 → 4 → 0	0 → 25 → 16 → 0
0 → 3 → 10 → 0	0 → 15 → 29 → 0
0 → 2 → 0	0 → 19 → 0

of the logistics vehicle is 0.12 kwh/km, the maximum capacity of the electric vehicle is 24 kwh, a charging pile establishment cost is RMB 14300, and the charging rate is 28 kWh/h. The maximum energy storage capacity of the energy storage system is 240 kWh. Renewable energy generation is priced at RMB 0.05/kWh per unit and at a rate of 40 kWh/h. The electricity price of the State Grid power purchase adopts the time period and the consumption ladder pricing, as shown in Fig. 2.

The demand points are assigned to two shifts of electric logistics vehicles according to their time windows, initial results is shown in Table 2 and the WOA-VNS algorithm is solved by Matlab and obtain the following results (see Table 3) (Fig. 3):

Initial results:

The location of the charging pile:

0,1,3,7,9,12,14,16,20,21,27,28,30.

Punish cost:

RMB 53.321.

The location of the charging pile:

0, 8, 12, 14, 21.

Punish cost:

0.

Table 3. Route planning results

Route planning	
0 → 10 → 0	0 → 20 → 22 → 0
0 → 2 → 0	0 → 27 → 21 → 0
0 → 8 → 0	0 → 16 → 18 → 0
0 → 12 → 9 → 0	0 → 25 → 0
0 → 13 → 0	0 → 15 → 23 → 0
0 → 4 → 0	0 → 19 → 0
0 → 3 → 14 → 5 → 0	0 → 29 → 0
0 → 6 → 7 → 1 → 0	0 → 17 → 30 → 0
0 → 11 → 0	0 → 28 → 24 → 0
	0 → 26 → 0

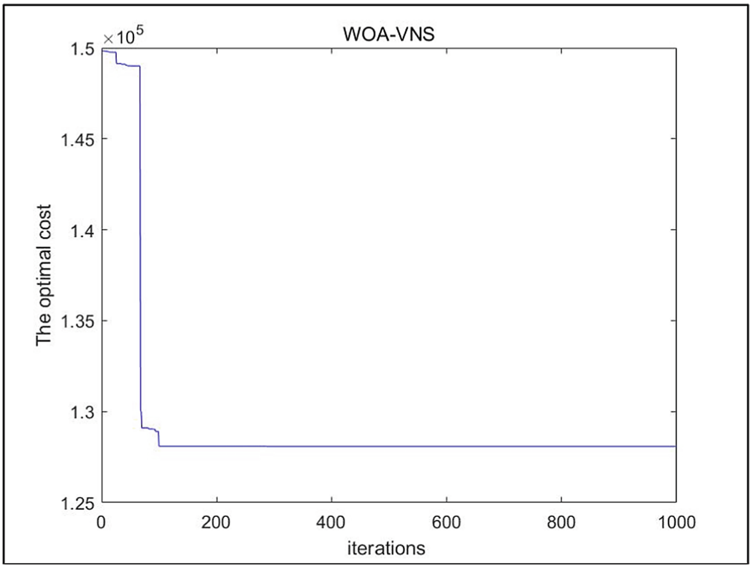

Fig. 4. The optimal cost iteration results of AM

The amount of electricity purchase before the first power purchase peak: 66 kWh.

The amount of electricity purchase before the second power purchase peak: 0 kWh.

From Fig. 4 and Fig. 5, it can be seen that total cost is about RMB 200,500. The two calculations reach convergence respectively at the 103th and 35th iterations and more details are in Fig. 4 and Fig. 5. Compared with the initial feasible solution, the total transportation distance is shortened by about 33.9%, the construction cost of the charging pile is reduced by 61.5%, penalty costs can be avoided.

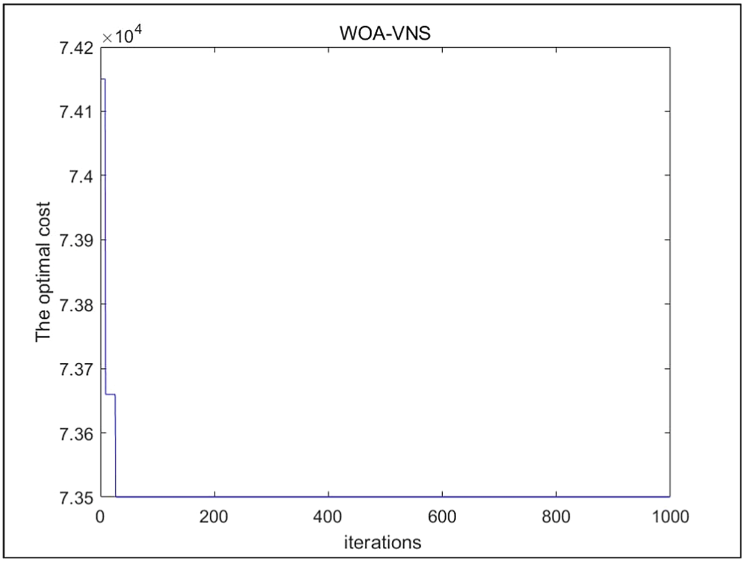

Fig. 5. The optimal cost iteration results of PM

5 Conclusion

With the encouragement and support of national policies, more enterprises with large electricity consumption will build their own renewable energy generation and storage plants in the future, and more electric vehicles will be chosen by logistics companies to complete urban distribution tasks. In this paper, under the above background, considering factors such as power grid power purchase and self-built renewable energy generation and demand point time window, an integer model of enterprise path planning- site selection and power purchase decision-making is constructed. And a WOA-VNS algorithm is proposed, and three kinds of variable neighborhood operators are used to improve the search efficiency. In order to verify the validity of the model and the efficiency of the algorithm, the above example is constructed. Comparing the initial feasible solution with the optimal solution, the total transportation distance is shortened by about 33.9%, the construction cost of the charging pile is reduced by 61.5%, penalty costs can be avoided.

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