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A SCHEDULING STRATEGY OF MOBILE PARCEL LOCKERS FOR THE LAST MILE DELIVERY PROBLEM

ABSTRACT

In the form of unattended Collection-and-Delivery Points (CDP), the fixed parcel lockers can save courier miles and improve the delivery efficiency. However, due to the fixed location and combination, the fixed parcel locker cannot accommodate the change of demands effectively. In this paper, an approach to supplementing fixed lockers by mobile parcel lockers to meet the demands of the last mile delivery has been proposed. With the goal of minimizing the operating cost, the location and route optimization problems of mobile parcel lockers are integrated into a non-linear integer programming model. An embedded GA has been developed to optimally determine the locations of distribution points, the number of mobile parcel lockers needed by each distribution point and the schedules and routes of mobile parcel lockers, simultaneously. Finally, a numerical example is given to compare the optimization results of the schemes with and without the aggregation problem. The results show that the scheme with the aggregation problem can greatly save the delivery time. However, for the scheme without the aggregation problem, time windows are more continuous, so it saves the number of vehicles.

KEY WORDS

last mile delivery; mobile parcel lockers; scheduling optimization; embedded genetic algorithm; time windows;

1. INTRODUCTION

Information technology and e-commerce make the express delivery industry burst out a great vitality [1-3]. According to the Global Express Association (GEA) report in 2015, the international express delivery industry contributed 0.19 percentage points to Global GDP, considering only the members of GEA [4]. The express delivery industry is expected to grow 9% annually by 2020 [5]. However, the last mile delivery faces unprecedented challenges, consuming 28% of the total cost and being the most expensive stage in the supply chain [6, 7]. Courier service providers have shifted their focus to improve the last-mile delivery service.

Home delivery, a typical mode of last mile delivery, faces the challenges of mismatch of time windows, high error rate of delivery addresses and fragmentation [8]. To overcome the drawbacks of the home delivery mode, other delivery modes, such as Collection-and-Delivery Points (CDP), drones, autonomous vehicles, etc., have been successively proposed. As a typical form of CDP, the fixed parcel locker has been successfully implemented in Italy, the United States, Germany, Singapore, Poland, China, Japan, and other countries [9]. Fixed parcel lockers are considered as an environmentally friendly delivery mode and have been studied by some scholars [10-13]. The studies on fixed parcel lockers can be broadly divided into two directions. One is the exploratory research. Qualitative analysis or experimental simulations were performed, based on survey data or existing data, to understand the use status of parcel lockers and their impacts on the city and environment [14-17]. The other focuses on the application practices related to parcel lockers. Faugère and Montreuil [9] redesigned the parcel locker so that it can be flexibly disassembled and reorganized to adapt to changes in demands. Deutsch and Golany [8] established an integer linear mathematical model for the location of the parcel lockers. The objective function aims to maximize the total operating profit. Gatta et al. [18] proposed an environment-friendly crowdshipping, where subway passengers are crowdshippers, and fixed parcel lockers placed in the subway network are delivery addresses. This helps reduce unnecessary trips. However, in addition to information and communication technology (ICT), extra costs for land use on the sites, such as shopping centres, residential areas, etc., are required to construct a set of fixed parcel lockers. Some businesses claim that fixed parcel lockers have left them at a loss because of huge initial investments and customers unwilling to pay for their use [19]. Zenezini et al. [20] demonstrated that the popularity of fixed parcel lockers requires a long period of time.

In order to overcome the shortcomings of fixed parcel lockers, a few companies that manufacture fixed parcel lockers have developed a new type of parcel lockers with the characteristic of mobility. At present, those mobile parcel lockers, which are electrified vehicles with a number of lockers installed, are owned and operated by the manufacturing companies themselves or the companies whose constituent companies have manufactured those parcel lockers. To the best of our knowledge, two operation modes are currently employed by the mobile parcel locker providers, and depicted in *Figure 1*, even though the second one is rarely used due to its complexity. For mode A, a number of mobile parcel lockers are dispatched from a depot to a set of demanding sites and parked at these sites over a long period (e.g. a week), unless a recharging or maintenance task is required. This operation mode is relatively simple, as only the sites, where the mobile parcel lockers are parked, and the number of mobile parcel lockers need to be determined based on the delivery demands. In this paper, the term *distribution points* is used to refer to the sites to accommodate the mobile parcel lockers and assume that they are a subset of the whole demand points. In other words, a number of demand points are selected as distribution points where a number of mobile parcel lockers can be placed to cover the demands for the neighbouring demand points. Therefore, mode A requires both the locations of distribution points and the number of mobile parcel lockers for each distribution point to be determined. However, the advantage of mobile parcel lockers may not be fully taken by mode A as its adaptability to the demand variation is relatively limited. In mode B, a mobile parcel locker is allowed to move to the next distribution point when the demands at the current point have been successfully served within its service time window. More specifically, each mobile parcel locker is required to serve the serval distribution points one by one after leaving the depot and return to the depot after visiting all the distribution points assigned. This means, mode B involves route planning for each mobile parcel locker, apart from the determination of distribution points and the number of mobile parcel lockers. The work presented in this paper focuses on mode B.

However, which demand points should be selected as the distribution points to accommodate mobile parcel lockers, how many mobile parcel lockers should be assigned, and what route should

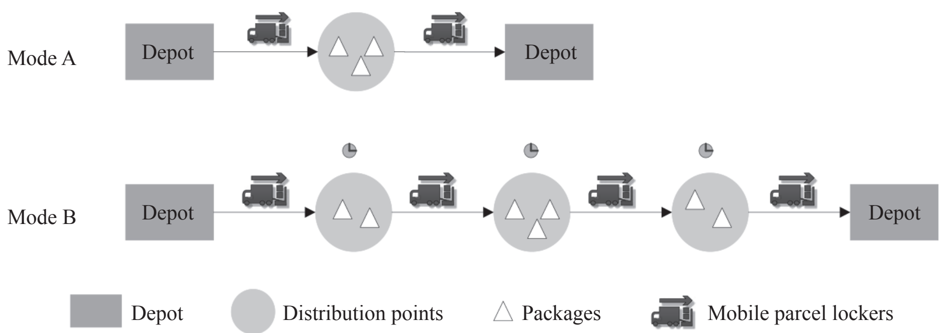

Figure 1 – Operation modes of mobile parcel lockers

each mobile parcel locker take. To solve these three questions simultaneously motivates us to formulate this as an optimization problem and name it as the operating problem in this paper. However, this optimization problem is different from the Vehicle Routing Problem (VRP) or the Vehicle Routing Problem with Time Windows (VRPTW), as it attempts to solve the locations of distribution points, the number of mobile parcel lockers (i.e. fleet size), and the route planning at the same time. That is, the number and locations of distribution points are not known in advance, while for traditional VRP / VRPTW, the number and locations of distribution points are predetermined [21]. Mobile parcel lockers are rarely studied. This paper is devoted to the research of a general method to solve the mobile parcel locker operating problem when mode B is employed. To this end, an optimization model is proposed with the aim of minimizing the operating cost, including the costs of transportation and maintenance of mobile parcel lockers, by determining the locations of distribution points, the number of mobile parcel lockers, and the route for each parcel locker simultaneously, which is the main contribution of this work. Another contribution of this work is that an embedded genetic algorithm has been developed to find the optimal solution. For the traditional home delivery mode, each demand point is regarded as a distribution point. In other words, it does not include the process of the determination of the distribution points from all demand points, which is also termed as *the aggregation problem* in this paper, to reflect the aggregation of a number of demand points into a cluster associated with a distribution point. It is interesting to see the impact on the operating plan if the mobile parcel lockers operate in a similar way as the traditional home delivery mode. For this reason, a comparative study was performed on the difference of solutions with and without the aggregation problem.

The rest of this paper is arranged as follows. The second Section describes the establishment process of the model that optimizes the operating problem of mobile parcel lockers. In the third Section, an embedded GA designed to solve the operating problem of mobile parcel lockers is introduced. A numerical example is given in the fourth Section which is followed by a concluding Section with a number of findings.

2. PROBLEM FORMULATION

The symbols employed in this paper are shown in *Table 1*.

This paper initially considers such a network G (N, A), which contains n nodes, including a depot, where a group of mobile parcel lockers can be accommodated at idle time, and (n-1) demand points, where a number of mobile parcel lockers should be docked for delivery purpose. The set of nodes is denoted as N. A is an $N \times N$ matrix, each element of which represents the shortest distance (shortest time or mileage) between two connected nodes. The research assumes: (1) Under the constraint of self-pick-up distance, a set of distribution points can be formed by merging demand points, where the distribution point is one of the demand points within its acceptable self-pick-up distance range; (2) It is allowed that multiple mobile parcel lockers visit the same distribution point to meet the demands of that distribution point; (3) With the constraint of time window for picking up goods, mobile parcel lockers should reach the distribution point within the required time range.

The requests of one demand point are jointly satisfied by multiple courier service providers. In order to make full use of the capacity of mobile parcel lockers, they can be used by multiple courier service providers. Therefore, the operating problem of mobile parcel lockers is assumed as follows in this paper. The empty mobile parcel locker with a tour plan assigned departs from the depot and is loaded by couriers from logistic companies at the distribution point when it reaches a distribution point. After completing the delivery task at the current distribution point, it goes to the next distribution point. Such process continues until all delivery tasks for a set of distribution points are completed and then the mobile parcel locker returns to the depot. *Figure 2* is the sketch map of the operating problem of mobile parcel lockers involving one depot, two mobile parcel lockers and three express delivery companies. Under the constraint of the self-pick-up distance σ, the demand points 4, 5, 6, 7 are merged into the distribution point 4, and the demand points 10, 11 are merged into the distribution point 10. It is assumed that a mobile parcel locker can hold up to four packages, then distribution point 4, which has 8 packages to delivery (see *Figure 2*) requires two mobile parcel lockers in response to all requests. The mobile

Table 1 – Symbols

Indices	
n	Number of nodes
N	Set of nodes
A	An $N \times N$ matrix composed of the shortest distances between each pair of nodes
{1}	Depot
m	Number of mobile parcel lockers
M	Set of mobile parcel lockers
Parameters	
α	Cost per hour
β	Maintenance cost of each mobile parcel locker
t_{ij}	Travel time of (i, j) arc
D_i	Demand at the i-th demand point
B_i	Number of fixed parcel lockers at the i-th demand point
Q_{si}	Capacity of each fixed parcel locker at the i-th demand point
l_{ij}	Distance between the i-th demand point and the j-th demand point
L	Acceptable upper limit of the self-pick-up distance
Q_m	Capacity of each mobile parcel locker
u_i	Real number, i=2, 3…,n
T	Daily working hours of the mobile parcel locker
a_i	The earliest time for mobile parcel lockers to reach the i-th distribution point
b_i	The latest time for mobile parcel lockers to reach the i-th distribution point
a_{ip}	The lower limit of the time window of the i-th demand point covered by the p-th distribution point
b_{ip}	The upper limit of the time window of the i-th demand point covered by the p-th distribution point
W	A very large positive number
θ	Daily average purchase cost
Decision variables	
x_{ij}	Binary variable. If the (i, j) arc is used, then x_{ij}=1, otherwise, x_{ij}=0
P_k	Binary variable. If the k-th mobile parcel locker is used, P_k=1, otherwise, P_k=0
y_{ij}	Binary variable. If the i-th demand point is covered by the j-th demand point, then y_{ij}=1, otherwise, y_{ij}=0
S_i	Service time of mobile parcel locker at the i-th distribution point
g_{ik}	The moment when the k-th mobile parcel locker arrives at the i-th distribution point
U_i	Number of mobile parcel lockers required at the i-th distribution point

parcel locker returns to the depot after completing the delivery tasks and cannot violate the time window constraint at each node.

It is assumed that the number of mobile parcel lockers is sufficient and all the delivery tasks are completed by fixed parcel lockers and mobile parcel lockers.

An optimization model is established with the goal of minimizing the operating cost of mobile lockers, including transportation cost and maintenance cost, as shown in *Formula 1*.

$$\min Z_1 = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{m} \alpha t_{ij} x_{ij} P_k + \sum_{k=1}^{m} \beta P_k \tag{1}$$

where x_{ij} and P_k are decision variables.

$$x_{ij} = \begin{cases} 1, & (i,j)\text{arc is traversed} \\ 0, & \text{otherwise} \end{cases} \quad ,\forall (i,j) \in A \tag{2}$$

$$P_k = \begin{cases} 1, & \text{the } k\text{th mobile parcel locker is used} \\ 0, & \text{otherwise} \end{cases} \quad ,\forall k \in M \tag{3}$$

Firstly, the demand points where the fixed parcel lockers cannot accommodate all the demands should be identified as the targets for the mobile parcel lockers and this can be mathematically expressed as:

$$D_i > B_i Q_{si}, \quad \forall i \in N/\{1\} \tag{4}$$

When a mobile parcel locker is docked at a distribution point, the customers of the distribution point and the customers of the demand points covered by this distribution point can pick up or send out parcels from or to the mobile parcel locker. It is further assumed that each demand point can only be covered by one distribution point, and the distance between the distribution point and the demand points covered by it should not exceed the generally accepted maximum distance of self-pick-up. This implies that the following constraints should be held.

$$\sum_{j=2}^{n} y_{ij} = 1, \quad \forall i \in N/\{1\} \tag{5}$$

$$y_{ij} l_{ij} \le L, \quad \forall i,j \in N/\{1\} \tag{6}$$

Multiple mobile parcel lockers can jointly serve a distribution point to ensure that all the demand within the radiation range of the distribution point is met. The radiation range is defined as the acceptable upper limit L of the self-pick-up distance that generally refers to the maximum walking distance. The number of mobile parcel lockers required by each distribution point should not exceed the total number of mobile parcel lockers.

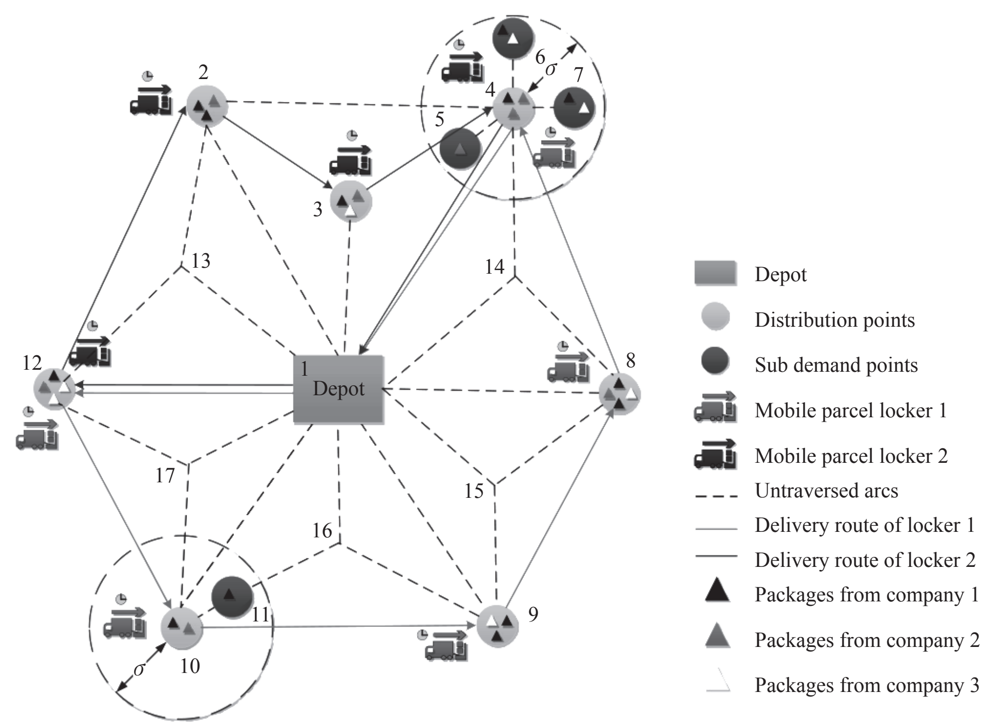

Figure 2 – Sketch map of the operating problem for mobile parcel lockers

$$\sum_{i=2}^{n} y_{ij} D_i \le \sum_{k=1}^{m}\sum_{i=1}^{n} x_{ij} P_k Q_m + \sum_{i=2}^{n} y_{ij} B_i Q_{si}, \quad \forall j \in N/\{1\} \tag{7}$$

$$\sum_{k=1}^{m}\sum_{i=1}^{n} x_{ij} P_k \le m, \quad \forall j \in N/\{1\} \tag{8}$$

The time windows of the demand points covered by a distribution point should have a common time period. As shown in *Formula 9*, for the distribution point p, the maximum value of the lower limits of the time windows of the demand points covered by it should not exceed the minimum value of the upper limits of the time windows.

$$\max_p \{a_{ip}\} < \min_p \{b_{ip}\}, \quad \forall i,p \in N/\{1\} \tag{9}$$

For each node, the number of vehicles leaving it should be equal to the number of vehicles arriving at it. Moreover, the same distribution point cannot be repeatedly visited by the same mobile parcel locker in a delivery route.

$$\sum_{k=1}^{m}\sum_{i=1}^{n} x_{ij} P_k = \sum_{k=1}^{m}\sum_{q=1}^{n} x_{jq} P_k, \quad \forall j \in N \tag{10}$$

$$\sum_{i=1}^{n} x_{ij} P_k = \sum_{q=1}^{n} x_{jq} P_k \le 1, \quad \forall j \in N/\{1\}, \forall k \in M \tag{11}$$

The delivery route of the mobile parcel locker should be a closed loop with the depot as the starting and the ending point.

$$u_i - u_j + n x_{ij} P_k \le n - 1, \quad 1 < i \ne j \le n, \forall k \in M \tag{12}$$

The delivery time of the mobile parcel locker is the sum of travel time and service time, and should not exceed its maximum daily working time.

$$\sum_{i=1}^{n}\sum_{j=1}^{n} (t_{ij} + S_i) x_{ij} P_k \le T, \quad \forall k \in M \tag{13}$$

The distribution point has an earliest pickup time a_i and the latest arrival time b_i. A mobile parcel locker should not reach a distribution point earlier than a_i or later than b_i.

$$a_i \le g_{ik} \le b_i, \quad \forall i \in N, \ k \in M \tag{14}$$

It is assumed that there is no extra time consumption other than travel time and service time. If the mobile parcel locker traverses the arc $(i,j) \in A$, then $g_{jk} = g_{ik} + S_i + t_{ij}$ [22].

$$g_{ik} + S_i + t_{ij} \ge g_{jk} - W(1 - x_{ij} P_k) \tag{15a}$$

$$g_{ik} + S_i + t_{ij} \le g_{jk} + W(1 - x_{ij} P_k), \quad \forall (i,j) \in A, \ k \in M \tag{15b}$$

For a depot that has been equipped with non or inadequate mobile parcel lockers, *Formula 1* can be expressed as *Formula 16* to determine how many mobile parcel lockers should be allocated to the depot.

$$\min Z_2 = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{m} \alpha t_{ij} x_{ij} P_k + \sum_{k=1}^{m} \beta P_k + \sum_{k=1}^{m} \theta P_k \tag{16}$$

Let $m = \sum_{k=1}^{m} \sum_{i=1}^{n} \sum_{j=2}^{n} x_{ij} P_k$, that is, even if each mobile parcel locker can only serve one distribution point in a day, the task can be also completed with the demand being set as 85% quantile of the annual demand. Then $\sum_{k=1}^{m} P_k$ is the number of mobile parcel lockers which should be theoretically allocated to a depot.

3. THE EMBEDDED GA

To solve the optimization problem formulated as above, we have developed an embedded GA that has two layers. The interaction between the two layers is realized with the outer layer to offer a set of feasible distribution points which is fed into the inner layer where the optimal distribution route is generated.

3.1 Outer-layer GA

Population initialization. A chromosome in the outer layer is coded into $V = (v_{ij})_{((n-1)\cdot(n-1))}$ matrix by adopting the binary coding scheme, and n-1 represents the number of demand points. If a demand point is selected as the distribution point, the corresponding gene locus is 1, otherwise 0. The population size is set as 100, and the initial population is generated randomly. *Figure 3* shows that demand points 4, 6, 8, 10, 12, and 14 are selected as distribution points, covering demand points {2, 3, 4}; {5, 6, 7}; {8}; {9, 10}; {11, 12, 13}; and {14}, respectively. It should be noted that {1} represents the depot.

Evaluation. The objective of the outer-layer GA is to select feasible distribution points by examining the *Constraints 5-9*. If a chromosome represents a feasible solution, it will be selected and fed into the inner-layer GA and the cost of the best chromosome will be assigned to it after the inner-GA evolves. Otherwise, a significant large value will be assigned to the infeasible chromosome in order to eliminate the possibility that it can be selected for the further process by the inner-GA.

Selection. Stochastic tournament is applied. Each time a pair of individuals is selected by the roulette wheel firstly, and then they compete for survival, and the feasible solution is selected, repeatedly so, until the selection is complete.

Genetic operator. The classic crossover (i.e. one-point crossover) and mutation operations are performed to generate offspring based on the individuals selected.

	2	3	4	5	6	7	8	9	10	11	12	13	14
2	0	0	1	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	0	0
4	0	0	1	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0
6	0	0	0	0	1	0	0	0	0	0	0	0	0
7	0	0	0	0	1	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	0	0	0
10	0	0	0	0	0	0	0	0	1	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0
12	0	0	0	0	0	0	0	0	0	0	1	0	0
13	0	0	0	0	0	0	0	0	0	0	1	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 3 – A chromosome in the outer layer

3.2 Inner-layer GA

If {4,6,8,10,12,14} is a feasible distribution point scheme generated by the outer-layer GA, the number of mobile parcel lockers required by each distribution point can be derived directly and are 2, 3, 2, 2, 2, 1 for this case. Then, the best routes of mobile parcel lockers can be calculated by the inner-layer GA, as follows.

Population initialization. The chromosomes of the inner-layer GA are suitable to be represented as sequences of positive integers to show the order in which the distribution points are visited. Similarly, an initial population including 100 individuals is randomly generated. *Figure 4* shows an example of a chromosome in the inner layer, which represents the route plans for a fleet consisting of 4 mobile parcel lockers.

The mobile parcel locker departs from the depot and returns to the depot after visiting all distribution points assigned to it. For example, the route for the first one is 1-6-8-4-1.

Evaluation. *Formula 1* is chosen as the cost function in the inner-layer GA to minimize the operating cost, which is the general goal of the embedded GA.

Selection. A roulette wheel is constructed to select a set of chromosomes to produce the offspring.

P_1					P_2						P_3					P_4			
1	6	8	4	1	1	14	6	10	12	1	1	8	4	10	1	1	6	12	1

Figure 4 – A chromosome in the inner layer

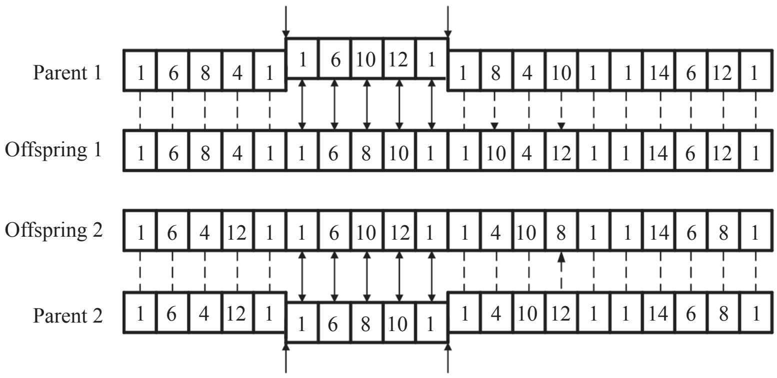

Figure 5 – Crossover in the inner layer

Crossover. The partially-mapped crossover operator [23] is adopted. For a distribution point with huge demand, multiple mobile parcel lockers are required to jointly perform the delivery task. This implies that a distribution point may appear in the route of multiple mobile parcel lockers. To ensure that the demands of distribution points can still be met after the crossover, only after the number of distribution points that appears in the chromosome is sufficient, the partially-mapped crossover operator can be executed. An example is given in *Figure 5*. Firstly, the two parents exchange the portions between the cut points. Then, the remaining parts of offspring 1 and offspring 2 are sequentially filled with the elements of parent 1 and parent 2. In addition, a distribution point can only be replaced by a mapping point until it has appeared sufficient times. For example, elements 8 and 10 in parent 1 have been replaced with 10 and 12 in offspring 1, respectively. Element 12 in parent 2 should be replaced with 10 first, but this violates Constraint 11, so it is necessary to use the mapping again to replace element 10 with 8.

Mutation. To increase the probability of feasible solutions and the diversity of the population, this paper proposes a heuristic swap mutation, as shown in *Figure 6*. First, identify the positions from left to right that appear non-first. Then select two unfixed positions at random from the parent. Finally, produce the offspring by swapping the selected positions.

Figure 7 presents the pseudocode of the algorithm.

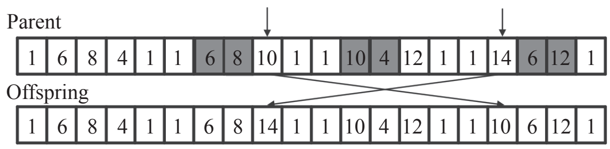

Figure 6 – A heuristic swap mutation in the inner layer

```
ALGORITHM
    BEGIN
        t=0;
        Initialize the outer-layer population P_1(t);
        Calculate the fitness value for P_1(t);
        While (the convergence or stopping condition is violated) do
            begin
            t=t+1;
            Select P_1(t) from P_1(t-1) into the inner-layer GA.
                t' = 0;
                Initialize the inner-layer population P_2(t');
                Calculate the fitness value for P_2(t');
                While (the convergence or stopping condition is
                 violated) do
                    begin
outer-layer         t' = t' + 1;
        inner-layer Select P_2(t') from P_2(t' - 1);
                    Generating a new P_2(t') by performing
                    genetic operator on P_2(t');
                    Calculate the fitness value of P_2(t');
                    end
                end
            Generating a new P_1(t) by performing genetic operator on P_1(t);
            Calculate the fitness value of P_1(t);
            Calculate the fitness value of P_2(t');
            end
        end
    END
```

Figure 7– Pseudocode of the embedded GA

4. NUMERICAL EXAMPLE AND DISCUSSION

A simple distribution network with 32 nodes (see *Table 3* for information related to each node), is used to evaluate the optimization approach proposed in this paper to solve the operating problem of mobile parcel lockers. The depot is equipped with 4 mobile parcel lockers, and the working time is from 08:00 to 20:00. The basic monthly salary of a courier is ¥3,000. Each mobile parcel locker delivers about 120 packages every day. The commission for delivering a package is ¥1.2. It can be calculated that the labour cost is ¥20/hour/vehicle. According to the operation information (as shown in *Table 2*) of the mobile parcel locker provided by an operating company during a survey, some conclusions can be drawn. The battery capacity of the mobile parcel locker can meet the daily energy consumption demand including the energy consumption during driving and parking, so it is reasonable not to consider the charging problem of the mobile locker during transportation. The charge for commercial electricity is ¥0.85/kWh, and the driving cost can be calculated as ¥0.71/hour/vehicle. The monthly communication cost of each mobile parcel locker is ¥120, that is, ¥4/day/vehicle. The battery pack containing two batteries should be replaced every two years, that is, the maintenance cost of batteries is ¥2.5 /day/vehicle. Other expenses, including handling package rejection and return, are about ¥300 a month, or ¥10/day/vehicle. Therefore, the unit time cost α is ¥20.71/hour/vehicle, and the daily maintenance cost β is ¥16.5/day/vehicle.

There are 31 demand points with specific pickup time requirements within the depot's service scope. Since the daily working time of the courier is 12 hours, the time window is represented by sub-intervals of [0.720 minutes] to simplify the calculation. *Table 3* shows the basic information of nodes in the distribution network.

Table 2 – The operation data of the mobile parcel locker

Items	Numerical values
Power consumption during driving	800W
Power consumption during parking	45W
Battery capacity	10kWh
Charge for commercial electricity	¥0.85/kWh
Communication cost	¥120/month/vehicle
Price of battery	¥900
Other costs	¥300/month/vehicle

Source: An operating company

Table 3 – Node information

Node number	1	2	3	4	5	6	7	8	9	10	11
X coordinates [m]	693	62	160	622	1,200	24	74	248	194	947	815
Y coordinates [m]	709	846	767	840	879	646	649	669	545	681	564
D	0	20	30	15	1	2	10	30	50	70	28
a	0	120	150	60	320	160	90	160	150	20	80
b	720	320	360	120	550	320	380	310	300	180	200
Node number	12	13	14	15	16	17	18	19	20	21	22
X coordinates [m]	417	28	518	1,300	818	1200	30	1,200	13,20	1,100	335
Y coordinates [m]	461	471	450	484	392	387	364	387	316	294	256
D	40	16	15	15	10	20	2	35	48	20	35
a	80	120	330	230	80	60	180	240	260	180	210
b	420	240	540	600	140	570	300	480	450	420	480
Node number	23	24	25	26	27	28	29	30	31	32	
X coordinates [m]	204	566	563	725	1,100	27	196	310	427	1,300	
Y coordinates [m]	230	222	70	179	170	101	16	25	57	38	
D	36	10	16	45	30	2	20	15	10	100	
a	150	270	150	350	390	180	300	330	180	200	
b	240	510	480	630	600	410	480	480	660	690	

Table 4 – Distribution point information

Distribution point number	5	8	11	13	20	25	27
Sub-demand points	5	2 3 6 7 8 9 12	4 10 11 16	13 18 23 28	15 17 19 20 21 32	14 22 24 25 26 29 30 31	27
D	1	182	123	56	238	166	30
U	1	3	2	1	4	3	1
a	320	160	80	180	260	350	390
b	550	300	120	240	420	660	600

There are 31 demand points merged into seven distribution points in the outer-layer GA, which are shown in black in *Figure 8*. The information of distribution points is shown in *Table 4*.

After the inner-layer GA, the routing strategies and costs of mobile parcel lockers are calculated. The operating problem of mobile parcel lockers described in this paper involves the aggregation problem, which also reflects the characteristic of aggregating delivery addresses for them. Using the embedded GA, the locations of distribution points and the number and route plans of the mobile lockers are simultaneously obtained. For the traditional home delivery, all demand points are regarded as distribution points. If the same operating scheme is applied to the mobile parcel lockers, the solution can be obtained without considering the aggregation problem. By comparing the results of the two schemes, the impact of the aggregation on the solution can be examined. The results with and without the aggregation problem are shown in *Table 5*.

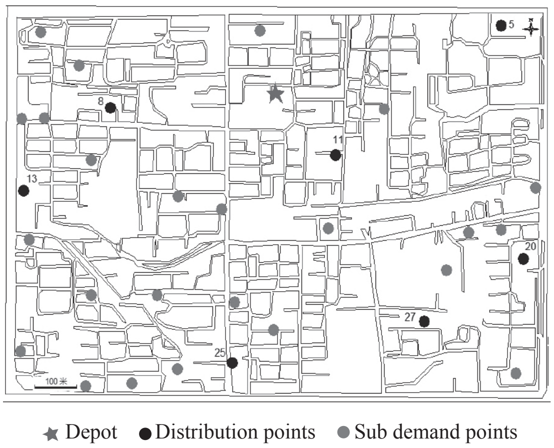

Figure 8 – Final distribution network

By comparing the results of the two schemes in *Table 5*, it is found that the difference in total costs with and without the aggregation problem is not significant. However, without considering the aggregation problem, the average delivery time of mobile parcel lockers increased by 43.56%. It is not difficult to realize that it is because visiting all the demand

Table 5 – The results were obtained from the schemes with and without the aggregation problem

Scheme with the aggregation problem			
Mobile parcel locker number	Routing strategies	Cost (¥)	Delivery time [min]
P_1	1-11-13-20-25-27-1	57.14	380.07
P_2	1-11-8-20-5-1	46.81	270.49
P_3	1-8-20-25-1	44.78	257.44
P_4	1-8-20-25-1	44.78	257.44
Total cost (¥)	193.51		
Average delivery time [min]	291.36		
Scheme without the aggregation problem			
Mobile parcel locker number	Routing strategies	Cost (¥)	Delivery time [min]
P_1	1-4-8-7-13-6-3-2-9-14-12-24-26-31-27-32-1	66.06	570.18
P_2	1-10-11-17-21-15-19-20-32-5-1	49.03	373.24
P_3	1-16-10-25-23-18-28-29-39-22-1	55.64	311.4
Total cost (¥)	170.73		
Average delivery time [min]	418.27		

points increases the travel time and service time. In addition, because the mobile parcel locker supports unattended distribution, this paper does not consider the labour cost during its service period. If all the demand points are visited in turn, the service time of the mobile parcel locker at each demand point will be shorter, implying that it will need to go to the next demand point soon after reaching one demand point and therefore it is difficult to realize unattended distribution, which greatly increases the labour cost. However, when the aggregation problem is not considered, the distribution task is relatively intensive, and fewer mobile parcel lockers can be used to complete the distribution task. This provides the logistics service providers with options to choose suitable schemes in different scenarios. For example, during the shopping festival, the two strategies can be combined to prevent "warehouse explosion", so as to quickly respond to customer requests with the least amount of mobile parcel lockers.

5. CONCLUSION

In recent years, the emergence of fixed parcel lockers around the world has made great contributions to improve the last mile delivery problem, but they have some limitations, such as fixed location and high construction costs. To make up for the weaknesses of fixed parcel lockers, express delivery service providers have developed mobile parcel lockers. Both fixed and mobile parcel lockers are CDP, which can save distribution mileage and alleviate traffic congestion, and are effective to promote sustainable logistics.

This paper assumes that all the distribution tasks are accomplished by mobile and fixed parcel lockers. The location and route optimization problems of mobile parcel lockers are integrated into a mathematical model, and an embedded GA is designed to solve the problem. In the numerical example, route strategies including aggregation problem are compared with those without the aggregation problem. The results show that the former saves delivery time and labour costs, while the latter reduces the number of mobile parcel lockers. In daily distribution, it is a wise choice to take into account both location and route optimizations. In the case of sudden increase in demand such as shopping festivals, in order to prevent "warehouse explosion", the two schemes can be combined to achieve rapid response to customer requests with the least amount of mobile parcel lockers.

In this paper, it is assumed that all customer requests are known before delivery. But many requests arrive dynamically over time in the actual delivery. With the unattended advantage of mobile parcel lockers, one driver can drive multiple mobile lockers. Therefore, the dynamic operating problem of mobile parcel lockers will be the future work of this paper. In addition, the operating optimization method of mobile parcel lockers is applicable to the delivery problem of autonomous vehicles.

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移动快递柜最后一英里配送问题的调度策略

摘要

固定快递柜以无人看管的集邮点（*CDP*）的形式，可以节省快递员的配送里程并提高配送效率。然而，由于固定的位置及组成，固定快递柜并不能有效地适应需求的变化。本文提出了一种通过移动快递柜来补充固定柜以满足最后一英里配送需求的方法。以最小化运营成本为目标，将移动快递柜的位置和路线优化问题集成到一个非线性整数规划模型中。提出了一种嵌入式遗传算法，其可以同时确定最佳的配送点的位置、每个配送点所需的移动快递柜的数量以及每辆移动柜的路线。最后，通过数值算例比较了有无集聚问题的方案的优化结果。结果表明，考虑集聚问题的方案可以大大节省配送时间。然而，对于不考虑集聚问题的方案来说，时间窗口更加连续，因此节省了移动柜的数量。

关键词

最后一英里配送问题；移动快递柜；
调度优化；嵌入式遗传算法；时间窗

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