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Research Paper

An Optimization Model for Parcel Lockers Layout

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ABSTRACT: *From the perspectives of both enterprises and customers, a layout optimization model for parcel lockers was established and an improved genetic algorithm for constraint optimization was used to obtain the optimal layout strategy of parcel lockers. Some numerical experiments were performed on a medium-scale residential community in a logistics park. The experimental results revealed that the established model is suitable for the actual situation of parcel lockers layout and the solution algorithm showed good convergence.*
KEYWORDS: *Parcel Lockers Layout, Objective Optimization, CFLP Model, Genetic Algorithm*

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I. INTRODUCTION

With the rapid development of social economy and the improvement of people's living quality, the fresh logistics has become increasingly prominent. However, due to the high preservation requirements of fresh products and the complex transportation environment, the reliability and efficiency of fresh logistics are faced with great challenges. In order to solve the last-mile delivery problem of fresh logistics, the introduction of parcel lockers has become a solution that has attracted much attention and is worth exploring.

At present, the researches about parcel lockers mainly focus on the location optimization and routing planning. Reference [1] proposed a bilevel programming model to optimize the location of community smart parcel lockers with the upper-level model maximizing the profit of a third-party smart parcel locker supplier and the lower-level model maximizing user satisfaction. Reference [2] proposed a novel solution to the automated parcel lockers location problem by combining mixed-integer linear programming and greedy heuristics algorithms. Reference [3] formulated the location-routing problem which determines the optimal stopover location for mobile parcel lockers throughout the day and plans corresponding delivery routes and a hybrid Q-learning-network based method was developed to resolve the computational complexity of the resulting large problem instances while escaping local optima. Reference [4] proposed a tailored tabu search algorithm by taking into account the recourse cost to optimally determine the a priori routes for a set of mobile parcel lockers.

Different from the above researches, this paper places emphasis on the layout of parcel lockers. By considering the costs of parcel lockers suppliers and the improvement of customer satisfaction, the paper models the layout problem of parcel lockers as a capacitated facility location problem and uses the improved genetic algorithm for constraint optimization to solve it. Some numerical experiments on a medium-scale residential community in a logistics park are performed and the effective solution of parcel lockers layout for the community is offered to explore the practical application of the proposed model.

II. PROBLEM DESCRIPTION

2.1 Problem Description

In the context of intense market competition, business cost and customer satisfaction are the two important concerns. The control and reduction of cost is very important for the long-term sustainable development of an enterprise. At the same time, customer satisfaction is one of the important indicators to measure the quality of an enterprise’s products or services. Focusing on the two objectives of enterprise cost and customer satisfaction, this paper studies how to change the layout and coverage area of parcel lockers with constrained conditions to meet the customer demand with the cost as low as possible.

To simplify the problem, the following premises and assumptions are made:

- Each customer can only go to one parcel locker to pick up goods.
- The temperature in the process from the regional distribution center to parcel lockers and in the parcel lockers remains unchanged. The freshness of products will refer to Arrhenius equation [5]. The loss of freshness is only related to the time in the distribution process, which is transformed into a linear relationship between distance and vehicle speed in this paper. The freshness loss per unit mileage is 1. Regardless of special conditions such as congestion, vehicle speed and customer pick-up speed remain constant.
- The freshness of products is 1 when starting from the regional distribution center, without consider- ing the product loss caused by the links before that.
- The number of regional distribution centers, the number of alternative points of parcel lockers, the number of parcel lockers, the location of demand points and the number of demand points are all known.
- The refrigeration function of parcel lockers is relatively complete, and after the fresh products arrive at parcel lockers, customers can pick up the goods quickly. Therefore, there is no decline in the freshness of products in parcel lockers.

2.2 Symbol Definition

The symbols are defined as follows:

$K = \{k|k = 1,2,3...m\}$: Denotes the collection of distribution centers;

$I = \{i|i = 1,2,3...n\}$: Denotes an alternative collection of parcel lockers;

$J = \{j|j = 1,2,3...o\}$: Denotes a collection of customers;

x_{ki}: Denotes the quantity of fresh products shipped to parcel lockers *i* from distribution center *k*;

x_{ij}: Denotes the quantity of fresh products picked up by customer *j* from parcel lockers *i*;

d_{ki}: Denotes the distance between distribution center *k* and the parcel lockers *i*;

d_{ij}: Denotes the distance between parcel lockers *i* and customer *j*;

d_{opt}: Denotes the optimal pick-up distance expected by customers;

d_{max}: Denotes the farthest pick-up distance accepted by customers;

v_c: Denotes the average delivery speed of delivery vehicles;

v_p: Denotes the average pick-up speed of customers;

c_{ki}: Denotes the unit freight of vehicles from the distribution center *k* to parcel lockers *i*;

c_i: Denotes the unit operating cost of parcel lockers *i*;

c_g; Denotes the unit construction cost of parcel lockers;

θ: Denotes the sensitivity coefficient of fresh products;

M_k: Denotes the maximum processing capacity of distribution center *k*;

N_i: Denotes the maximum processing capacity of parcel lockers *i*;

D_j: Denotes the demand of demand point *j*;

μ: Denotes the unit loss cost of fresh products;

β: Denotes the average unit price of fresh products;

$F(d_{ij})$: The expression of the distance penalty cost function;

f_d: Denotes the unit cost of distance penalty function;

Z_i: Denotes whether parcel lockers are set up at location *i*;

y_{ij}: Denotes whether parcel lockers *i* serves customer *j*;

Cij.per: Denotes the pick-up cost;

P_0: Denotes the minimum on-time probability accepted by customers.

III. MODEL CONSTRUCTION

3.1 CFLP

Capacitated Facility Location Problem （CFLP）is a location selection method proposed by Yoichi Antimachi of Japan for limited capacity and limited scale of logistics distribution center. CFLP location selection model is not universal. It has the following three characteristics for application: First, the number of distribution centers is definite; Second, the distribution capacity of distribution centers is limited; Third, the transportation distance from each distribution center to customers and customers' demand are definite. It can exert advantages, reduce redundant steps and make the calculation simple and clear to using CFLP model to solve the problems satisfying the above three characteristics.

In view of this, this paper apply the CFLP model to the layout optimization of parcel lockers to seek the relative optimal solution of serving customers, by considering the factors such as processing capacity, location, economic benefits of the distribution process and so on.

3.2 Cost Function

The enterprise cost includes the construction cost and operating cost of parcel lockers as well as transportation cost of fresh products. The cost is stated as C_1:

$$C_1 = c_g I + \sum_i \sum_j c_i x_{ij} y_{ij} + \sum_k \sum_i c_{ki} x_{ki} d_{ki} \quad (1)$$

3.3 Customer Satisfaction Function

The factors affecting customer satisfaction include the freshness of products, the costs brought by customers in the process of picking up goods from parcel lockers, and the timeliness of delivery expected by customers.

In order to facilitate calculation, this paper converts various customer satisfaction factors into the relevant cost factors consistent with enterprise costs, including distance penalty cost, freshness penalty cost and pick-up cost. Let the customer satisfaction function be C_2, then:

$$C_2 = \sum_i \sum_j f_d F(d_{ij}) + \sum_k \sum_i \sum_j \beta\mu \left[1 - (1-\theta)^{\frac{d_{ki}}{v_c}+\frac{d_{ij}}{v_p}}\right] x_{ij}(d_{ki} + d_{ij}) y_{ij} + \sum_i \sum_j c_{ij,per}\, x_{ij} y_{ij} d_{ij} \quad (2)$$

In Equation (2), the distance penalty cost means parcel lockers should be as close as possible to customers. The penalty costs $F(d_{ij})$ is expressed as:

When $d_{ij} \le d_{opt}, F(d_{ij}) = 0$ (3)

When $d_{opt} < d_{ij} \le d_{\max}$, $F(d_{ij}) = 1 - \frac{dij_{max}}{dopt_{max}}$ (4)

When $d_{ij} > d_{max}, F(d_{ij}) = 1$ (5)

The product freshness is mainly related to the temperature and time. Here the varying relationships between substance and temperature as well as between substance and time are modified according to the Arrhenius equation $\varphi t = (1-\theta)t$.

3.4 Objective Function Combination

The cost function and customer satisfaction function are combined to form a new objective function which minimizes cost:

$$MinU = C_g I + \sum_i \sum_j C_i x_{ij} y_{ij} + \sum_k \sum_i c_{ki} x_{ki} d_{ki} + \sum_i \sum_j f_d F(d_{ij}) + \sum_k \sum_i \sum_j \beta\mu[1 - (1-\theta)^{\frac{d_{ki}}{v_c}+\frac{d_{ij}}{v_p}}] x_{ij}(d_{ki} + d_{ij}) y_{ij} + \sum_i \sum_j c_{iij,per} x_{ij} y_{ij} d_{ij} \quad (6)$$

Constraints:

$\sum_k x_{ki} \le n_i k$ (7)

$$\sum_j x_{ij} \leq n_i j \quad (8)$$
$$\sum_i x_{ij} = D_j \quad (9)$$
$$\sum_k x_{ki} = \sum_j x_{ij} k \quad (10)$$
$$0 \leq \sum_k x_{ki} \leq MZ_I \quad (11)$$
$$0 \leq \sum_j x_{ij} \leq MZ_i \quad (12)$$
$$\sum_i y_{ij} = 1 \quad (13)$$
$$z_i = \begin{matrix} 0, No \\ 1, Yes \end{matrix} \quad (14)$$
$$y_{ij} = \begin{matrix} 0, No \\ 1, Yes \end{matrix} \quad (15)$$

Equation (7) indicates that the amount of goods transported from the distribution center k to the parcel lockers i does not exceed the processing capacity of distribution center k. Equation (8) indicates that the amount taken from parcel lockers i does not exceed its processing capacity. Equation (9) indicates that the quantity of goods taken by customer j from parcel lockers i is equal to the customer's demand. Equation (10) indicates that the quantity shipped to parcel lockers i is equal to the quantity taken by all customers from parcel lockers i. Equation (11) indicates that if and only if the parcel lockers is established at site i, distribution center k will distribute goods to parcel lockers i. Equation (12) indicates that customer j will pick up goods from parcel lockers i if and only if parcel lockers is set up at site i. Equation (13) indicates that for any customer j, there is a parcel lockers i to serve it. Equation (14) means z_i is equal to 0 if the enterprise doesn't set up parcel lockers at site i, otherwise 1. Equation (15) means y_{ij} is equal to 0 if the parcel lockers i doesn't serve demand point j, otherwise 1.

Through a customer survey, we found that a large number of customers often order products near off-duty time or on the way home, and hope can take the goods in time. Therefore, we takes into account another constrained condition to characterize customer satisfaction, that is the time probability that the distribution center k delivers products to parcel lockers i should meet the customers' pick-up demand. Under the case where the delivery speed follows the normal distribution, the probability is formulated as:

$$P_{ki} = p\left(t_{ki} \leq t_{ij}\right) = p\left(\frac{d_{ki}}{v_c} \leq t_{ij}\right) = p\left(v_c \geq \frac{d_{ki}}{t_{ij}}\right) = 1 - Fv_c\left(\frac{d_{ki}}{t_{ij}}\right) \quad (16)$$

In Equation (16), t_{ki} refers to the travel time from the distribution center k to the parcel lockers i and t_{ij} refers to the delivery time requested by customer j.

Based on Equation (16), the customer satisfaction can be expressed as

$$p_n = \frac{\sum_k \sum_i x_{ij} p_{ki}}{\sum_i x_{ij}} = \frac{\sum_k \sum_i x_{ij}\left[1 - Fv_c\left(\frac{d_{ki}}{t_{ij}}\right)\right]}{\sum_k d_{ki}} \quad (17)$$

Then, the following constrained condition will be added:

$$P_n \geq P_0 \quad (18)$$

IV. NUMERICAL EXPERIMENTS

4.1 Experiment Case

The numerical experiments are carried out on the Community A in the Majuqiao Logistics Park located in the southeast of Beijing city in China. The logistics park is well equipped with advanced storage facilities, transportation facilities and logistics management systems, which can provide efficient logistics services and warehousing solutions to meet the needs of enterprises. At the same time, the park is large in scale, with a great number of warehouses and logistics enterprises, providing diversified logistics services including warehousing, distribution, transportation, etc. to meet the needs of different industries.

Currently, Community A has twelve residential buildings. Each residential building is looked as a demand point. The distance between each demand point and the distribution center is measured through Baidu Map and shown in Figure 1.

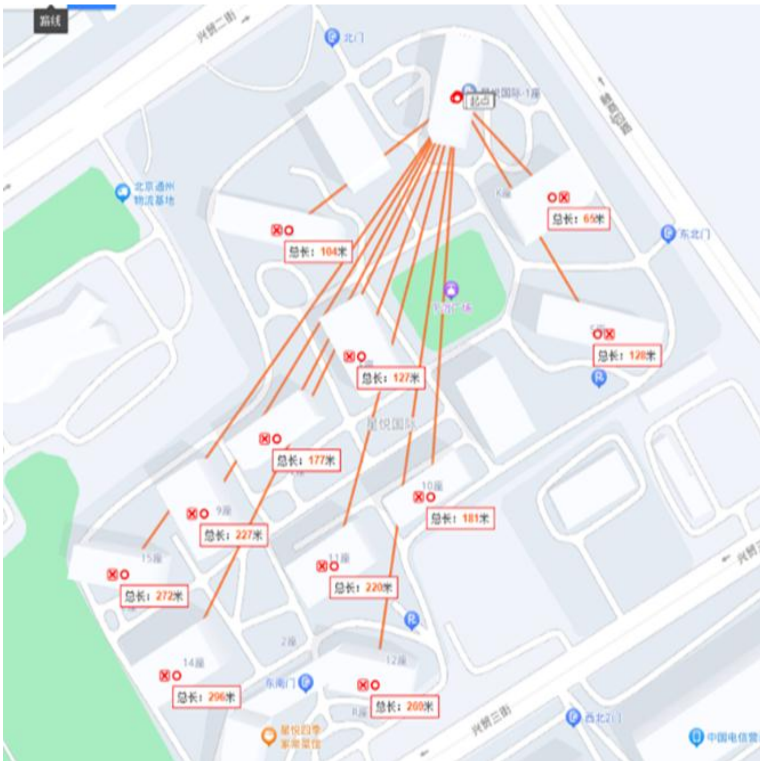

Figure 1: Distance between demand points and distribution center

According to the actual investigation, the relevant parameters are set as shown in Table 1.

Table 1: Parameter settings

Parameter	Value	Parameter	Value
d_{opt}	50 meter	M_k	500 unit
d_{max}	250 meter	N_i	100 unit
V_c	5 meter per second	f_d	100 Yuan per meter
V_p	1.3 meter per second	β	100 Yuan per unit
P_0	80%	Θ	0.008
C_{ki}	5 Yuan per unit	μ	0.5 Yuan per unit
Cij.per	0.01 Yuan per unit per meter		

4.2 Experiment Analysis

The model solving algorithm adopts an improved genetic algorithm for constraint optimization. The algorithm uses the PMX single point crossover and targeted mutation ideas to improve the convergence speed of the algorithm and avoid getting stuck in local optimal solutions [6]. Python programming software VScode was used for experiment analysis. By changing the variable values of the parcel lockers number, population size and iteration times, four different experiments were conducted to obtain the optimal layout strategy and optimal fitness respectively. The experimental results are shown in Table 2.

Table 2: Experimental results

Experiment	I	II	III	IV
Number of parcel lockers	2	3	3	4
Population size	100	500	500	500
Iterations	50	50	100	100
Optimal fitness	7732	5144	2578	15465

According to the experimental results, the optimal fitness in experiment I is 7732. When two set of parcel lockers are established, the fitness is mainly affected by the customer satisfaction function. The fitness increases rapidly with the increase of the unit penalty cost. It can be seen that two set of parcel lockers cannot well meet the needs of twelve demand points in Community A. So the number of parcel lockers is increased to conduct experiment II. In experiment II, the optimal fitness is 5144. But in fact the fitness is not optimal after the maximum iterations are reached. Then the maximum number of iterations was increased to 100 to conduct experiment III. In experiment III, the optimal fitness is 2578, which is better than the previous two experimental results and the output results are stable. In order to make the experimental results more comprehensive and accurate, experiment IV was conducted by increasing the number of parcel lockers to 4. The optimal fitness in experiment IV was 15465, far exceeding 2578 in experiment III. According to the sensitivity analysis, after the number of parcel lockers reached 3, enterprise costs such as construction cost and maintenance cost increased sharply with the increase of parcel lockers number. Therefore, three set of parcel lockers are the optimal quantity.

Table 3: Layout strategy of parcel lockers

Parcel lockers location	Demand points covered
Building 3	Building 3,7,9,11,12
Building 5	Building 1,5,6
Building 10	Building 2,4,8,10

To sum up, the optimal layout strategy of parcel lockers in community A is to establish parcel lockers at alternative demand points No.3, No.5 and No.10. The parcel lockers at No.3 are responsible for the demand points3, 7, 9, 11 and 12. The parcel lockers at No. 5 cover the demand points 1, 5 and 6. The parcel lockers at No. 10 are responsible for the demand points 2, 4, 8 and10. The minimum cost of the optimal layout of parcel lockers is 2578 Yuan.

V. CONCLUSION

Based on the characteristics of fresh products and parcel lockers, this paper improved the traditional CFLP model from the following two sides. One side is the freshness penalty cost was added to the CFLP model to characterize the feature of fresh products easy to rot. The other side is to consider the benefits both related to enterprises and customers with minimizing enterprise costs on the premise of customer satisfaction.

According to the numerical experimental results, the improved CFLP model is suitable for the actual situation of layout optimization of parcel lockers and the genetic algorithm for constraint optimization has good convergence. However, some assumptions were made to simplify the model and there are still some complex cases that have not been considered. So the further improvement of the model will be the focus of future research.

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