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Research Paper

A Location Selection Model for Pre-warehouse of Fresh E-commerce Retailer

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ABSTRACT: *From the perspectives of both enterprises and customers, a location selection model of pre-warehouse for fresh e-commerce retailer was established with the dual objectives of maximizing enterprise profit and customer satisfaction. The model comprehensively considered the unique attributes of fresh food products to construct the objective functions and constraint conditions. The NSGA-II algorithm was used to obtain the optimal solution of the model. The empirical study performed on a fresh e-commerce platform verified that the established model effectively optimized the pre-warehouse location layout for the platform.*
KEYWORDS: *Pre-warehouse Location, Objective Optimization, NSGA-II Algorithm, Fresh E-commerce*

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I. INTRODUCTION

Fresh food products are closely linked to people's daily lives. The emergence of the pre-warehouse pattern has increased the orders of fresh food product on online e-commerce platforms. The pre-warehouse pattern involves the establishing of multiple small warehouses near residential communities with concentrated customers. Then the e-commerce retailers sell and deliver fresh food products to customers from these pre-warehouses within thirty minutes or one hour. The pre-warehouse pattern not only solves the "last-three-kilometers" problem that plagues customers but also ensures the freshness and timely distribution of fresh food products. It has become one of the main operating patterns in the fresh food e-commerce industry.

The location selection of pre-warehouses is a crucial consideration once the pattern is adopted. Current researches usually treated the location selection of pre-warehouses in the fresh food industry as an objective optimization problem. Reference [1] put forward a model of "supermarket central warehouse + convenience store pre-warehouse", and established the corresponding mathematical model by taking the minimum construction cost and the highest customer satisfaction as the two constraints. Reference [2] established a pre-warehouse location model under the new retail environment with the goal of minimizing costs, considering constraints such as the number of proposed pre-warehouses, store areas, service radius and so on. Reference [3] established a mixed integer programming model with the goal of maximizing customer time satisfaction and minimizing the cost of site selection, and designed a hybrid immune simulated annealing algorithm to improve the search efficiency of the algorithm. Reference [4] established a multi-objective programming model from the perspectives of cost reduction and delivery efficiency to rationally plan the layout of pre-warehouses and demand points.

This paper studies the location selection problem of pre-warehouses from a dual-objective perspective. The first objective is to maximize enterprise profits, and the second objective is to maximize customer satisfaction. By considering the service radius of the pre-warehouse as a constraint, the paper constructs the pre-warehouse location selection model and uses a fast non-dominated sorting genetic algorithm with elitism to obtain the optimal solution. To validate the model, an empirical case study is conducted on a fresh e-commerce enterprise, achieving an optimal location selection plan for the enterprise that maximizes both its profits and customer satisfaction.

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II. PROBLEM DESCRIPTION

2.1 Problem Description

To maximize the enterprise profit and customer satisfaction, factors such as transportation conditions, market coverage, and geographical location must be taken into consideration during the location selection process. Good transportation conditions can ensure the operational efficiency of the pre-warehouse. Market coverage determines the service scope of the pre-warehouse. And geographical location affects customers' acceptance of the pre-warehouse. Here, the location selection problem of pre-warehouse is described as: a fresh e-commerce enterprise needs to establish several pre-warehouses in a certain area to respond to customers' online shopping needs. With the known size, location, and commodity demands of customers, the best location for the pre-warehouse needs to be selected and the corresponding distribution plan needs to be formulated to maximize enterprise profit while ensure the maximum customer satisfaction.

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

- The demand points will not change within a certain period of time, and each demand point will only be served by one pre-warehouse.
- The central warehouse directly delivers commodities to the pre-warehouses, rather than directly to the demand points.
- The fresh food demand within the coverage area of each pre-warehouse is fully satisfied, without considering stockouts or transfers between pre-warehouses.
- One vehicle can serve multiple demand points within its service area, but each demand point can only be served by one vehicle.

2.2 Symbol Definition

The symbols are defined as follows:

O : Supply Center

I : Pre-warehouse Set

J : Demand Point Set

q_{oi} : Annual transport volume from central warehouse *o* to pre-warehouse *i* (t)

q_{ij} : Annual transport volume from pre-warehouse *i* to demand point *j* (t)

d_{oi} : Distance from the central warehouse *o* to pre-warehouse *i* (km)

d_{ij} : Distance from pre-warehouse *i* to demand point *j* (km)

f_1 : Unit freight cost from central warehouse to pre-warehouse (Yuan/km・kg)

f_2 : Unit freight cost from pre-warehouse to demand point (Yuan/km・kg)

B : Annual depreciation cost of equipment in pre-warehouse (Yuan/year)

D_1 : Basic salary of indoor sorting person in pre-warehouse (Yuan /year・person)

D_2 : Basic salary of deliveryman in pre-warehouse (Yuan /year・person)

D_3 : Salary of manager in pre-warehouse (Yuan /year)

m_i : Number of indoor sorting person in pre-warehouse

n_i : Number of deliveryman in pre-warehouse

A_i : Annual lease cost of pre-warehouse (Yuan /year)

β : Other operating costs in pre-warehouse (excluding lease cost) (Yuan /year)

R : Annual total revenue of the fresh e-commerce enterprise (Yuan)

μ : Freshness decay rate of fresh product

l : Minimum freshness satisfaction

λ : Time satisfaction weight

$F(t_{ij})$: Delivery efficiency satisfaction function

$G(t_{ij})$: Product freshness satisfaction function

x_i : Whether to choose *i* as a pre-warehouse

y_{ij} : Whether demand point *j* is supplied by pre-warehouse *i*, with 1 indicating *yes* and 0 indicating *no*.

III. OBJECTIVE FUNCTION

3.1 Total Profit

- Annual Sales Revenue

The annual sales revenue refers to the total sales income of all fresh products sold by the fresh e-commerce retailer to all demand points within one year. Here it is denoted as *R*.

- Transportation Cost

The transportation cost is an important component of the entire logistics system, mainly involving the transportation from the central warehouses to the pre-warehouses and the final delivery from the pre-warehouses to the demand points. Since different transportation tools are used for these two tasks, there are also differences in their unit transportation rates.

The transportation from the urban sorting center to the pre-warehouses typically employs box-type cold chain trucks, and their unit freight rate is relatively high, denoted as f_1. The final delivery from the pre-warehouses to the demand points generally utilizes electric vehicles, and their unit freight rate is relatively low, denoted as f_2. Then the transportation cost can be calculated as:

$$c_1 = \sum_{i \in I} f_1 q_{oi} d_{oi} x_i + \sum_{i \in I} \sum_{j \in J} f_2 q_{ij} d_{ij} y_{ij} \qquad (1)$$

- Labor Cost

The labor cost is an important cost for fresh e-commerce retailers, representing the total annual salary paid to staff working in pre-warehouses. Labor cost is related to the calculation method of salaries for different staff and the corresponding number of personnel. Generally, three types of personnel are equipped in pre-warehouses: management, sorting, and delivery. Different personnel have different job responsibilities and salaries. Each pre-warehouse is equipped with two management personnel, and the number of sorting and delivery personnel is set as m_i and n_i , respectively.

$$c_2 = \sum_{i \in I} (D_1 m_i + D_2 n_i + D_3) x_i \qquad (2)$$

- Depreciation Cost

The depreciation cost refers to the cost of wear and tear on the hardware facilities (such as cold storage equipment, shelves, office equipment, etc.) and software facilities (such as management systems) purchased for the pre-warehouse. The cost is evenly distributed over each year based on normal wear and tear, and is set as a fixed value of *B*.

$$c_3 = \sum_{i \in I} B x_i \qquad (3)$$

- Operating Cost

The annual operating cost covers the rental expenses of the pre-warehouse, the cost of packaging material consumption, and utility expenses such as water and electricity. Among them, rental expenses are closely related to the geographical location of the pre-warehouse, while packaging materials and utility expenses are directly proportional to the volume of goods handled within the warehouse. Therefore, they are classified as other operational expenses.

$$c_4 = \sum_{i \in I} (A_i + \beta q_{oi}) \qquad (4)$$

3.2 Customer Satisfaction

- Delivery Time Satisfaction

The delivery time satisfaction refers to the level of customers' satisfaction with the time efficiency of delivery services. In the context of location selection, there are five commonly used forms to represent time satisfaction: linear, convex-concave, cosine distribution, descending exponential Sigmoid, and descending half-Gumbel distribution [5]. Among these, the linear time satisfaction function stands out due to its simplicity, ease of comprehension, and intuitive nature. Its trend is straightforward, making it capable of clearly expressing how satisfaction evolves over time. It offers certain advantages, particularly in scenarios that require straightforward, visually appealing, and easily optimizable decisions by adopting the linear time satisfaction function in location selection. Therefore, the linear time satisfaction function is employed here. Additionally, it is assumed that customers have a psychological threshold for the shortest acceptable delivery time (denoted as *L*) and the longest tolerable delivery time (denoted as *U*). Then, the function for delivery time satisfaction can be represented as:

$$F(t_{ij}) = \begin{cases} 1 & t_{ij} \le L_j \\ \dfrac{U_j - t_{ij}}{U_j - L_j} & L_j < t_{ij} \le U_j \\ 0 & t_{ij} > U_j \end{cases} \tag{5}$$

- Product Freshness Satisfaction

Simultaneously, given the perishable nature of fresh produce, customers pay close attention to its freshness. The paper adopts the monotonically decreasing function described in reference [5] to represent how product freshness changes over time.

$$\varphi_{(t_{ij})} = e^{-\mu t_{ij}} \tag{6}$$

Customers will have a psychological upper limit for the freshest acceptable condition, denoted as *G*, and a lower limit for the least acceptable freshness level, denoted as *K*. The freshness satisfaction function for customers can be represented as:

$$G(t_{ij}) = \begin{cases} 1 & G_j \le \varphi_{(t_{ij})} \\ (1-l)\dfrac{G_j - \varphi_{(t_{ij})}}{G_j - K_j} & K_j \le \varphi_{(t_{ij})} \le G_j \\ 0 & \varphi_{(t_{ij})} < K_j \end{cases} \tag{7}$$

IV. PRE-WAREHOUSE LOCATION SELECTION MODEL

4.1 Model Construction

- Objective Function

$$\max T_1 = R - (c_1 + c_2 + c_3 + c_4) \tag{8}$$

$$\max T_2 = \sum_{i \in I} \sum_{j \in J} [\lambda F(t_{ij}) + (1-\lambda) G(t_{ij})] y_{ij} \tag{9}$$

- Constraints

$$\sum_{i \in I} q_{oi} x_i = \sum_{i \in I} \sum_{j \in J} q_{ij} y_{ij} \tag{10}$$

$$\sum_{i \in I} y_{ij} = 1 \tag{11}$$

$$y_{ij} d_{ij} \le L_i \tag{12}$$

$$x_i = \begin{cases} 1 & \text{if } i \text{ selected as pre-warehouse} \\ 0 & \text{if } i \text{ not selected as pre-warehouse} \end{cases} \tag{13}$$

$$y_{ij} = \begin{cases} 1 & \text{if pre-warehouse } i \text{ serves demand point } j \\ 0 & \text{if pre-warehouse } i \text{ doesn't serve demand point } j \end{cases} \tag{14}$$

For the above equations, Equation (8) represents the maximization of total profits; Equation (9) represents the maximization of customer satisfaction; Equation (10) represents the balance constraint of logistics from the central warehouse o to the pre-warehouse i and the pre-warehouse to the demand point; Equation (11) indicates that a demand point can only be served by one pre-warehouse; Equation (12) represents the service radius of the pre-warehouse; Equation (13) indicates whether the alternative location i is selected as a pre-warehouse; Equation (14) indicates whether the pre-warehouse *i* serves the demand point *j*.

4.2 Solving Algorithm

Non-dominated Sorting Genetic Algorithm II (NSGA-II) is one of the classic algorithms for multi-objective optimization, renowned for its fast running speed and excellent convergence of solution sets. Therefore, NSGA-II is employed to solve the dual-objective location problem of the pre-warehouse here.

- Coding method

As the algorithm does not directly deal with decision variables, it is necessary to encode the chromosomes specifically for the practical problem. Common coding methods include binary coding, real number (floating-point) coding, permutation coding, etc. This paper adopts the real number coding method.

- Population initialization

During the population initialization phase, the population size needs to be set and initial solutions generated. The size of the population has an impact on the performance of the solution, computational complexity and speed.

- Non-dominated sorting and calculation of crowding distance

The initial population is subject to non-dominated sorting and calculation of crowding distance to stratify the population and determine the relationship of crowding degree among individuals of the same level. This step aids in selecting the optimal individuals during the selection phase.

- Genetic operations

Selection: Individuals are selected through the tournament selection method. In the tournament method, a certain number of individuals are randomly selected from the population with replacement, and the best individual among them is chosen to be included in the offspring. We randomly select half the population size of individuals each time, select the individual with the lowest Pareto rank from these chosen individuals, and then select the individual with the largest crowding distance from that level as the optimal individual to be included in the offspring. This process is repeated until the offspring population size reaches the initialized population size.

Crossover: Crossover is a key method for generating new individuals and distinguishes genetic algorithms from other algorithms. Among evolutionary algorithms, common crossover operators include simulated binary crossover (SBX) and differential evolution (DE). We select DE operator to randomly choose several positions of two individuals for crossover operation. The crossover probability is typically high, ranging from 0.8 to 0.95.

Mutation: The mutation operator plays a crucial role in genetic algorithms, maintaining the diversity of the population. Single-point mutation, as a basic method, randomly selects a gene position for mutation and replaces the original value with a random number within the value range of that gene position. The mutation probability is typically low, ranging from 0.005 to 0.1.

By completing the above three operations, a subpopulation of size N is generated.

- Generation of new parent population

After generating the offspring population, the parent population and the offspring population are merged to form a new population with size 2N. Then, the mixed population is resorted based on non-domination, and crowding distance is recalculated. Using the elite selection strategy, the best N individuals are selected from the mixed population to form a new parent population.

- Termination condition judgment

The termination conditions of the algorithm are typically reaching the set number of iterations or the fitness of the best individual in the population or the fitness of the entire population no longer changing. When these conditions are met, the algorithm will stop iterating.

V. MODEL APPLICATION

5.1 Empirical Case

The fresh e-commerce platform D has established eight pre-warehouses in Chang Ping District, Beijing. Since the Chang Ping District People's Government of Beijing issued the policy on accelerating the development of high-tech enterprises, a large number of internet companies have settled in Chang Ping District, leading to a significant increase in its population trend, which is expected to continue for the next two years. Simultaneously, this growth in population has also led to an increase in demand for fresh products. Based on this growing demand, it is crucial to re-plan the layout of pre-warehouses to improve service efficiency and customer satisfaction.

The urban population of Chang Ping District has maintained a growth trend in the past decade. Based on the Census data, the population of Chang Ping District in 2023 is approximately 1.8601 million. According to the market survey data, the average monthly demand per person for fresh food products is approximately 2.5kg. Given the population of 1.8601 million, the demand for the fresh e-commerce platform D in 2023 is estimated to be 55803 tons.

5.2 Location Selection for Pre-warehouses

A) Selection of demand points

In this study, the point of interest (POI) data of residential communities in Chang Ping District was obtained through the API development tools of Amap.com. Since a suitable location for a pre-warehouse can be easily found near each residential community, the POI coordinates of 31 communities can be used as the overall demand point set. The approximate distribution of demand points in Chang Ping District is shown in Figure 1.

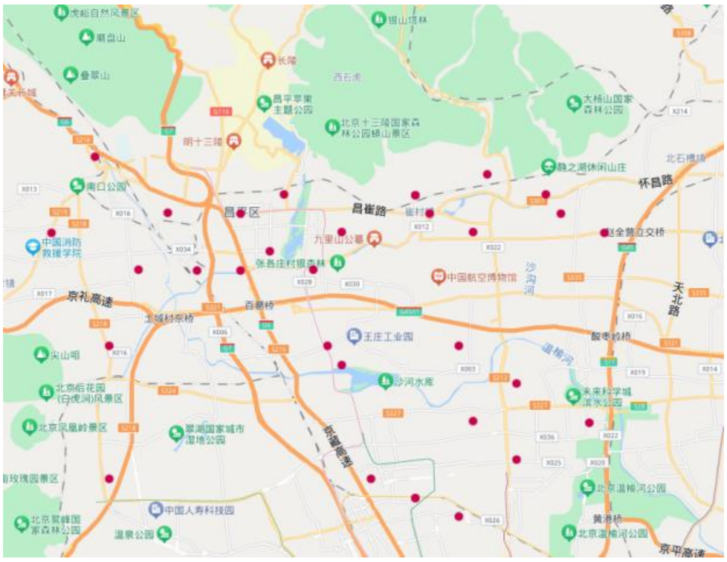

Figure 1: Distribution of demand points

B) Determination of pre-warehouse locations

For ease of analysis, k-means clustering was performed on the demand points. When K=12, the silhouette coefficient was the highest, indicating the best clustering effect within this range. Therefore, the pre-warehouses were ultimately clustered into 12 groups, and the clustering effect is shown in Figure 2.

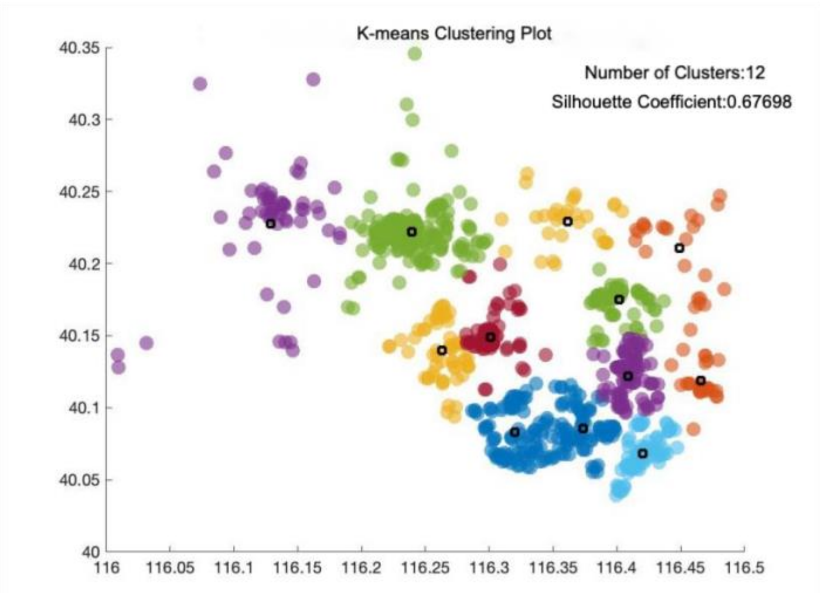

Figure 2: Clustering results for pre-warehouse locations

5.3 Solution to Pre-warehouse Location Selection Model

The NSGA-II algorithm was programmed using MATLAB R2020a software to solve the dual-objective location selection problem for fresh food pre-warehouses. Through multiple comparisons with different parameter settings, the iteration parameters ultimately were set as followings: the population size was set to 200, the maximum number of iterations was set to 300, the crossover probability was set to 0.9 and the mutation probability was set to 0.1. The algorithm was run to obtain the final Pareto Front as shown in Figure 3.

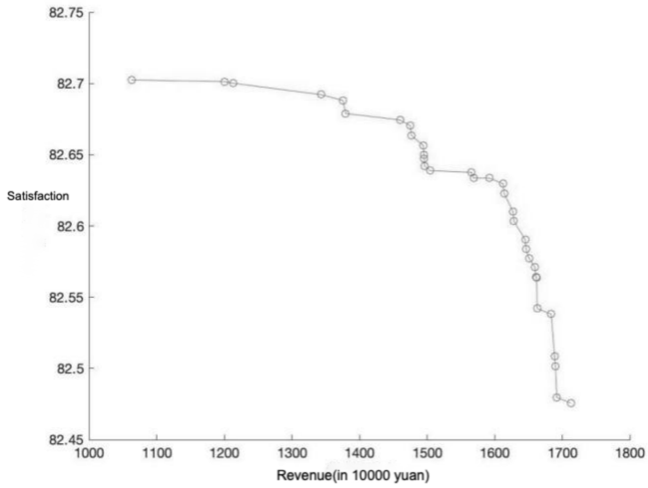

Figure 3: Pareto Front for the dual-objective pre-warehouse location selection

In Figure 3, the horizontal axis represents the first objective of maximizing enterprise profits, while the vertical axis represents the second objective of maximizing customer satisfaction. A total of 12 Pareto optimal solutions were obtained and these points are discretely distributed around an approximate curve. By comparing the 12 solutions, it was found that Solution 6 achieved a relatively balanced result between enterprise profits and customer satisfaction. The optimal pre-warehouse layout of Solution 6 is shown in Table 1.

Table 1: The optimal pre-warehouse solution

Pre-warehouse	Demand points covered	Pre-warehouse	Demand points covered
1	8,9,10,18,19	7	No demand points at present, Reserved for future
2	16	8	7,17,20,27,30,31
3	11,12,13,23,24	9	6
4	1,2,3	10	No demand points at present, Reserved for future
5	25,26,28,29	11	4,5
6	14,15,21,22	12	No demand points at present, Reserved for future

Compared to the eight pre-warehouses currently set up in Chang Ping District, the new pre-warehouse solution presented in Table 1 is more optimal. The objective function value of enterprise profits has increased by 14.80%, and the customer satisfaction has increased by 1.33%. As for the pre-warehouse 7, 10 and 12 in Table 1, they are free currently due to the limited distribution of demand points around them. But in the future, as the resident size increases and demand rises, they will be responsible for delivering certain demand points.

VI. CONCLUSION

The location decision of pre-warehouse is crucial for fresh e-commerce retailers. Taking the perspectives both from the enterprise side and the customer side, this paper established a bi-objective optimization model for the location selection of pre-warehouse. The NSGA-II algorithm is designed to solve the model. The empirical study performed on the fresh e-commerce platform D verified that the developed model and the solving algorithm are effective. The enterprise profit and the customer satisfaction were improved to varying degrees.

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