Cold Chain Logistics Distribution Path Planning of Fresh Products in Beijing Subcenter

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Abstract: With the gradual development of a capital city subcenter, numerous residents gradually move to the subcenter, increasing the demand for fresh food. Thus, an adequate supply of fresh food to the subcenter should be guaranteed, while reducing the logistics costs, maintaining the quality and quantity, complying with sustainable development, and cooperating with the city to complete the food basket logistics and distribution. Accordingly, we propose the optimization of logistics distribution paths for fresh products. After field research, we found that the main fresh product distribution point in the Beijing subcenter is the Baliqiao wholesale market, one of Beijing’s vegetable basket projects, and the main distribution targets are large- and medium-sized markets in the subcenter. We optimize a fresh food distribution path model using minimum total cost and carbon emissions as the objective function according to the layout of the subcenter, and the best path is determined using improved ant colony optimization. The optimization results provide a basis for fresh food distribution in the capital city subcenter. We use scientific methods to analyze the travel routes of vehicles transporting fresh products in the subcenter to obtain the best distribution path for logistics companies, aiming to reduce the waste of resources and pollution to the environment by reducing the overall distribution costs and carbon emissions. Therefore, this type of study can benefit logistics companies and the subcenter population while contributing to sustainable development.

Keywords: capital city subcenter; fresh products; path planning; improved ant colony optimization

1. Introduction

In the Opinions of the State Council of the CPC Central Committee on Creating a Better Development Environment to Support the Reform and Development of Private Enterprises, the Party Central Committee states the necessity to promote the upgrading of the quality and growth of all types of companies, including private ones, to increase the concentration of fresh agricultural product distribution, promote cost reduction, consumption reduction, and efficiency, and play a greater role in helping farmers to increase their profits, aiming to achieve rural revitalization and protect and improve people’s livelihoods. In addition, the State Council Opinions on Supporting the High-Quality Development of Beijing’s Sub-City Centers states the necessity to promote the green development of the capital subcenters, deepen reform and opening up, and improve the quality of harmonious and adequate living. Furthermore, in the 14th Five-Year Plan, it is estimated that by 2035, the subcenters of the capital Beijing will gain at least 400,000 to 500,000 inhabitants coming from the central city. Therefore, fresh food logistics and distribution in the Beijing subcenter should be developed to improve efficiency and ensure quality. With the continuous development of the subcenter and the improvement in people’s quality of life, the demand of subcenter residents for fresh and safe food is also increasing, highlighting the importance of path planning for fresh food logistics and distribution throughout the subcenter. The development of the logistics industry is the premise, and
sustainability is essential. In fact, without the development of the logistics industry, sustainability is unfeasible, and without sustainability, the logistics industry stagnates. Overall, logistics development is the basis for the sustainable economic development of a country or region. Hence, it is important to optimize the distribution of fresh food in the Beijing subcenter.

We consider the capital city subcenter as the research object and optimize the fresh food cold chain logistics distribution path using ant colony optimization. As the subcenter continues to develop, the demand for fresh and safe food increases because it is a self-evident necessity of the population [1]. Nevertheless, guaranteeing the delivery of fresh products and reducing the costs of delivery have become great challenges. Researchers worldwide have performed relatively comprehensive research on vehicle path planning, using various algorithms to solve various models. However, scarce research is available on path planning for distributing fresh products in urban subcenters. We adopt the relatively mature ant colony optimization, a probabilistic algorithm for path planning, to solve a distribution model for fresh products in the capital city subcenter [2].

The Beijing subcenter is densely populated and has a high and continuous demand for fresh food. Its distribution area includes most of Tongzhou New City. This area is complex, and the distribution routes are diverse. By relying only on logistics delivery drivers to plan their own routes, high delivery costs and local congestion can occur. In addition, the long delivery time of fresh products is likely to cause product spoilage and waste. Hence, we use scientific methods to analyze the fresh food vehicle routes in the subcenter, to determine the best route for fresh food logistics companies in the capital and reduce the overall fresh food cold chain logistics distribution costs [3–5].

Path planning is difficult to solve by using an accurate algorithm. Instead, heuristic algorithms can be used to achieve satisfactory results [6,7]. For instance, ant colony optimization has good robustness and parallelism, being widely used for solving path planning problems. We consider the Beijing subcenter and improve ant colony optimization for application to a fresh food cold chain logistics distribution path model to obtain the best distribution routes for fresh food. While reducing the distribution cost, our method can also reduce the waste of resources, benefit logistics companies and the population in the subcenter, and contribute to sustainable development [8,9].

The structure of this paper is as follows: Section 2 introduces the two related research areas, namely fresh product logistics and distribution and logistics distribution path planning. Section 3 gives the model establishment. Section 4 introduces the algorithm and the flow chart of the algorithm, and gives the results and discussion. Conclusions are given in Section 5.

2. Literature Review

This study involves two related research areas, (1) fresh product logistics and distribution and (2) logistics distribution path planning, which are analyzed in this section.

2.1. Fresh Product Logistics and Distribution

Fresh product logistics and distribution is an important area that has been widely studied. Research on fresh product logistics outside China was performed earlier than domestic research and has gradually perfected the theoretical background. As the starting research point of domestic and foreign scholars is different, the research focus is also different.

Ju-Chia et al. [10] argued that fresh products should be efficiently used throughout the distribution process, with transportation and packaging equipment, strict requirements for temperature measurement, real-time monitoring throughout the processes, and anomaly alarms to prevent accidents. Morganti et al. [11] presented a framework for last-mile food distribution with analysis of fresh food and urban export food distribution. Bortolini et al. [12] considered that the food quality depends on the delivery time; by fo-
cusing on the market demand and farmers’ production capacity, they constructed a multiobjective distribution optimization model comprising distribution costs, carbon footprint, and delivery time to optimize a fresh food distribution network. Pan et al. [13] improved the success rate of delivery services by using customer information to predict the absence of clientele by mining electricity consumption data to estimate customers’ unavailability at the point of fresh food delivery. Malihe et al. [14] designed a multiobjective mathematical model comprising distribution costs, carbon emissions, service time, and customer satisfaction.

With the rapidly growing demand for fresh products, diverse fresh products are available, and domestic research on their logistics distribution has increased. Zhao et al. [15] constructed a path optimization model for the distribution of fresh products by electric vehicles under time-varying traffic conditions, with the minimum total economic cost as the objective function. Focusing on the uncertainty of return volume, Wang et al. [16] designed a model of a fresh product multiobjective distribution network under uncertainty to minimize the distribution costs and carbon emissions while maximizing social benefits. Feng et al. [17] analyzed the sources of cargo loss and carbon emissions and constructed a single-objective fresh product distribution path optimization model with the minimum sum of costs. This model aimed to minimize the sum of costs. Dantzig et al. [18] constructed a two-level capacity-limited model considering customer classification, and designed a two-stage heuristic algorithm for solving the model based on customer prioritization involving core and non-core customers and minimizing the total distribution costs.

2.2. Logistics Distribution Path Planning

Foreign research on cold chain logistics distribution path planning started earlier than that in China, with the path optimization problem being proposed by Dantzig and Ramser in 1959 to obtain the minimum path for a fleet of gasoline trucks. Since then, this problem has become a key research direction in combinatorial optimization, computer applications, logistics, and other disciplines.

In recent years, practical complexities and variable influencing factors have been considered for path planning in logistics distribution. Kuo et al. [19] fully considered the path problem of garbage collection vehicles with fuzzy demand and demonstrated the advantages of their proposed genetic algorithm—ant colony optimization—over other methods on eight datasets under vehicle capacity constraints. Hosseinanabadi et al. [20] combined the open vehicle routing problem and gravitational emulation local search to reduce the transportation costs of all the vehicles in a fleet considering that the vehicles do not return to the warehouse after completing distribution. Poonthalir [21] investigated the impact of transportation costs caused by the time spent by vehicles at facilities such as gas stations and toll booths, and solved the corresponding vehicle queuing model using a chemical reaction algorithm. Heler [22] proposed a genetic algorithm for splitting delivery vehicle compartments to avoid mixing different products in a vehicle and validated the solution on a large dataset. Sadykov [23] proposed an efficient bidirectional label correction algorithm to solve a heterogeneous fleet path problem with capacity and time constraints. Goel et al. [24] used the multimodal property of the firefly algorithm to improve the local optimal and stagnant search of an optimization group, thereby improving the search capability of ant colony optimization. Gunawan et al. [25] studied the combination of the vehicle routing problem and cross-docking, and proposed a two-stage algorithm based on column generation, with the first stage using the domain search algorithm to obtain a set of candidate paths, and the second stage dividing this set to satisfy different constraints and finally determine the optimal solution.

Although research on cold chain logistics distribution path planning in China started relatively late, it has achieved fruitful results. Starting from the mid to late 1990s, continuous research accumulation, development, and gradual improvement have been achieved. In 2020, Zhao et al. [26] deeply analyzed the basic theory of optimal vehicle
scheduling and optimization algorithms for solving different types of problems and designed a basic vehicle scheduling system. Zhu et al. [27] focused on the impact of real-time traffic changes for vehicle path optimization that combines an initialized path with traffic route dynamics, thus obtaining satisfactory path optimization solutions for an unstable traffic network. By proposing a distribution method based on weight correction, Hu et al. [28] used an improved genetic algorithm to solve the path distribution problem of multiple warehouses and multiple distribution locations for single-vehicle carriers, suitably addressing the problem of one overloaded vehicle and other vehicles being empty in actual transportation. Wang et al. [29] established a multiobjective e-commerce logistics path optimization model based on the intelligent water drop algorithm, which combines fuzzy time and time penalty functions and takes customer satisfaction as the optimization objective; they verified that the algorithm can provide a correct global solution. Zhang et al. [30] proposed an adaptive genetic gray wolf algorithm with improved update and a genetic strategy for the vehicle routing problem with capacity constraints; they confirmed improvements in global convergence and solution accuracy. Zou [31] proposed a clustering algorithm based on e-commerce logistics distribution path optimization to divide administrative areas for delivery and weighted objective functions such as cargo weight and the time efficiency index; the corresponding distribution path was planned according to the actual demand of a delivery order. Yang [32] extended path models based on the traveling salesman problem and vehicle routing were established by Hu et al., who considered multiple unmanned aerial vehicles and fleets delivering and picking up goods together; the established models reduced costs compared with single-fleet delivery.

Existing studies on the path planning of fresh product distribution show that heuristic algorithms are generally adopted for path optimization, and theoretical model design and algorithm optimization are emphasized. However, few studies have considered specific regional cases to model and optimize. By analyzing existing path optimization algorithms and the characteristics of fresh product logistics and distribution for path planning, we improve ant colony optimization with a positive feedback mechanism such that the path search converges continuously while avoiding local optima and likely reaching the global optimal solution. In addition, ant colony optimization can be further improved according to real-world problems, being suitable for obtaining distribution routes in the Beijing subcenter. The improved ant colony optimization can reach the global optimal solution.

3. Distribution Path Optimization Model

3.1. State of Development of Beijing Subcenter

The planned scope of the Beijing subcenter is the original site of Tongzhou New Town, located in Tongzhou, in the eastern part of Beijing, China, with a total area of approximately 155 km². The aim is to drive the coordinated development of the Beijing–Tianjin–Hebei region, relieve the functions of the capital, improve the spatial layout of Beijing, reduce the increasingly severe urban disease rates, and explore new spaces for urban development. In 2012, the Beijing Municipal Committee proposed to focus on Tongzhou and build an urban subcenter with very complete functions. The main food basket of the capital city’s subcenter is the Beijing Baoqiao Agricultural Products Center Wholesale Market, located in Baoqiao, Beijing. This is the source of most fresh products for the subcenter and an important part of Beijing’s vegetable basket program, which aims to ensure the supply of fresh products for the population in the eastern part of Beijing.

For the Beijing subcenter, logistics and vehicle management strictly follow the local rules and regulations, and Beijing’s policy support for fresh food logistics is also implemented in the subcenter. The subcenter enjoys certain preferences and convenience in
terms of highway tolls and accessibility. Especially during the coronavirus disease pandemic, it has adopted a policy of no quarantine and no closure for people with normal temperature and good health.

The prohibition strategy of the Beijing and Tongzhou District is roughly the same regarding the delivery times for any distribution location. Specifically, Beijing’s policy does not allow large trucks to drive outside the allowed timeframe; otherwise, they are stopped by the traffic police. In addition, the policy has strong requirements, and delivery activities rarely exceed the timeframe. Moreover, fewer vehicles drive at night [33–36], the roads are unobstructed, distribution locations are close, and the 7 h delivery timeframe is enough to distribute all goods. Therefore, the timeframe is neglected in algorithms of logistics distribution path planning because once a truck enters overtime, distribution cannot be completed and the overtime penalty is meaningless. Similarly, we apply ant colony optimization without considering the timeframe for path planning.

There is only one main fresh food distribution center for the Beijing subcenter, and this center is considered in the model. As a single type of vehicle is usually bought in a batch for logistics distribution, we adopt a multiple-vehicle distribution structure with a single vehicle type in the model. We also set the maximum load for the delivery vehicles, the farthest vehicle driving distance, specific distribution locations in the subcenter, and the fresh food demand per distribution location.

The model objective is to minimize the transportation distance while maximizing the delivery of goods, thus reducing costs and maximizing the revenue of the distribution center and locations [37].

3.2. Assumptions for Distribution Path Optimization Model

To facilitate the abstraction of the real problem as a mathematical model for calculations and quantification, the following assumptions are made for model construction before performing path optimization [38-40]:

1. The geographic locations of the distribution center and locations for delivery in the subcenter are determined. There is no refusal to deliver, no delivery personnel are unable to complete the delivery or deliver the goods during delivery, and every delivery is completed.

2. One type of distribution vehicle is considered with the same basic configuration, maximum load capacity, and maximum operating distance. In addition, no differences regarding service time and minor faults are considered. The demand for goods at each distribution location is below the maximum load capacity of the vehicle.

3. Items from different distribution locations can be mixed and transported without affecting the movement of vehicles or the loading and handling of goods.

4. All types of items at each distribution location can be mixed and transported simultaneously, and the required transport and storage conditions can be ensured by any vehicle.

5. Regardless of driving and road conditions, all the transport vehicles travel at the same speed.

6. All the roads are clear, without uncertain conditions, such as blockages and road closures, and the wait time for traffic lights is expressed as a distance, which is the same per kilometer of travel.

7. The distribution center has enough goods for delivery, without shortage. In addition, a logistics distribution vehicle can travel to different distribution locations to deliver the remaining goods after completing a delivery in one place and then return. However, each distribution location can only have one delivery vehicle, thus preventing multiple vehicles from carrying goods for the same delivery.
8. A proportion of goods may be damaged during transportation, and the damage is related to the time for distribution. Thus, damage to goods only occurs during transportation. As conditions such as road status and speed are assumed constant during transportation, the distance is directly proportional to the damage rate of goods.

9. The distribution vehicle returns to the distribution center after completing the assigned delivery.

By combination with the specific distribution practice, this study conducts an in-depth study on the temperature, cargo damage, and other costs generated in the process of cold chain logistics distribution, sets the goal as minimizing the overall distribution cost and carbon emissions, and establishes the optimal path model of cold chain logistics distribution. Under the precondition of reducing the whole logistics distribution expenditure, the distribution needs of customers can be met and the circulation loss can be reduced.

3.3. Distribution Path Optimization Modeling

3.3.1. Symbol Description

The known parameters of the subcenter fresh distribution path optimization model of the capital city studied in this paper are as follows:

- \( k = \{1, 2, ..., m\} \): Number of refrigerated trucks owned by the distribution center;
- \( \bar{v} \): Average speed of a refrigerator vehicle, unit \( km/h \);
- \( P_1 \): Cost per unit fresh product, unit \( yuans/kg \);
- \( P_2 \): Unit gas pollutant emission cost, unit \( yuans/kg \);
- \( P_3 \): Unit fixed-use cost of refrigerated vehicle, unit \( yuans/vehicle \);
- \( P_4 \): Unit fuel consumption cost, unit \( yuans/kg \);
- \( P_5 \): Unit cooling cost during transportation, unit \( yuans/h \);
- \( P_6 \): Unit cooling cost during unloading, unit \( yuans/h \);
- \( \theta_1 \): Represents the corruption rate in the process of transporting fresh products;
- \( \theta_2 \): Represents the corruption rate in the handling process of fresh products;
- \( d_{ij} \): Represents the distance between delivery locations \( i \) and \( j \), unit \( km \);
- \( Q \): Maximum load of refrigerated truck, unit \( kg \);
- \( q_i \): Represents the demand amount of the distribution point \( i \), unit \( kg \);
- \( Q_i \): Represents the remaining cargo weight of the refrigerated truck when it leaves the distribution location \( i \), unit \( kg \);

\[
x_i^k = \begin{cases} 1, & \text{The vehicle } k \text{ serves delivery point } i \\ 0, & \text{Otherwise} \end{cases}
\]

\[
x_{ij}^k = \begin{cases} 1, & \text{The vehicle } k \text{ travels from delivery point } i \text{ to } j \\ 0, & \text{Otherwise} \end{cases}
\]

3.3.2. Determine the Objective Function

(1) Fixed cost

Fixed cost refers to the cost incurred when a vehicle provides delivery services to customers, which is only related to the number of vehicles used, including the labor costs of drivers, vehicle wear and tear costs, and use costs, etc. The expression of fixed cost is as follows:

\[
W_1 = k \times P_3
\]  

(2) Fuel consumption cost

Refrigerated trucks consume a large amount of fuel during driving. According to the research of relevant scholars, the fuel cost is not only related to the driving distance, but also closely related to the cargo volume. According to the relevant literature, in this paper, the fuel consumption of 100 km when the load weight is \( Q_i \) is defined as \( \rho(Q_i) \), in which
the fuel consumption is \( \rho^* \) when the load is full and \( \rho_0 \) when the load is empty. According to the relevant academic literature on fuel formula research [41],

\[
\rho(Q_i) = \rho_0 + \frac{\rho_0 - \rho}{q} Q_i
\]

(2)

Then, fuel consumption can be expressed as:

\[
F_g = d_{ij} \times \rho(Q_i) \times f \times 10^{-5}
\]

(3)

Therefore, the transportation fuel cost of a refrigerated truck can be expressed as follows:

\[
W_2 = \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ijl}^k [P_a (d_{ij} \times \rho(Q_i) \times f \times 10^{-5})]
\]

(4)

Here, \( \rho(Q_i) \) represents the fuel consumption of 100 km for the load weight \( Q_i \), unit \( L/100 \text{ km} \); \( F_g \) indicates fuel consumption, unit \( kg \); \( f \) is a constant, 840 \( kg/m^3 \).

(3) Cost of goods damage

In the process of cold chain transportation, due to the perishability of fresh products, it will raise the damage rate of fresh products and form a damage cost. The cost of goods damage in the process of transporting fresh products consists of two parts. The first part is the decay and loss caused by the change of goods over time in the process of transporting vehicles. The second part is the opening and closing of the door in the loading and unloading process, which will accelerate the loss caused by the air flow inside and outside the car. These two losses together constitute the loss of the fresh distribution process. Considering the influence of factors such as the temperature interaction between the compartment and the outside world, loading and unloading, and opening and closing doors during transportation, this paper introduces the variable function of refrigerated goods quality [42]:

\[
Q(t) = Q_0 \times e^{-\theta t}
\]

(5)

where \( Q_0 \) represents the initial quality of fresh goods, \( Q(t) \) represents the quality of goods at \( t \), and \( \theta \) represents the corruption rate. Therefore, the above formula can be used to represent the damage degree of goods in the transportation process and the loading and unloading process, respectively. In the transportation process, the loss of goods demand at each distribution place will increase with the increase in transportation time, so the loss of goods in the transportation process can be expressed as \( Q_i (1 - e^{-\theta \lambda (t_k^i - t_k)} \); in the loading and unloading process after arrival at the distribution location, since the goods at the distribution location have already been delivered, the damage to goods affected by the opening and closing process is only the quantity of goods after leaving the distribution location. Therefore, it can be expressed as \( Q_i (1 - e^{-\theta \lambda t_k^i}) \).

According to the quantity of goods damage in the two processes, the calculation formula of the goods damage cost can be obtained as follows:

\[
W_3 = P_t \sum_{k=1}^{m} \sum_{l=0}^{n} \left[ x_{ijl}^k Q_i (1 - e^{-\theta \lambda (t_k^i - t_k)} \right]
\]

(6)

The loading and unloading time of the goods is proportional to the weight of the goods, as follows:

\[
\hat{t}_i^k = \frac{Q_i}{\lambda}
\]

(7)

where, \( \lambda \) is the loading and unloading efficiency, which is a fixed value.

(4) Refrigeration cost

In the process of cold chain transportation, a large amount of energy will be consumed to generate cool air to maintain the low-temperature environment of fresh products, so refrigeration costs will be incurred. The refrigeration cost is generally divided into
the refrigeration cost in the transportation process and the refrigeration cost in the unloading process to maintain the low-temperature environment of the vehicle. Therefore, the refrigeration cost can be expressed as:

\[ W_s = P_s \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ij}^k \rho(Q_i) x_{ij}^k \]  
\[ + P_s \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{i=0}^{n} x_{ij}^k t_{ij}^k \]  
\[ (8) \]

In particular, since the refrigerated vehicle is regarded as running at a constant speed in the transportation process, the traveling time at distribution location \( i \) to \( j \) can be expressed as:

\[ t_{ij}^k = \frac{d_{ij}}{v} \]  
\[ (9) \]

(5) Carbon emission cost

Refrigerated trucks will cause a large amount of carbon emissions in the running process, which will cause harm to the environment, and then produce carbon emission costs. Considering the carbon emission costs and carbon emissions in the transportation process, carbon emissions can be effectively reduced, so as to realize the green development of cold chain logistics. According to relevant literature research, the relationship between automobile carbon emissions and fuel consumption is linear [43], and the formula is as follows:

\[ T = F_g \times e \]  
\[ (10) \]

where:
\( T \): carbon emissions;
\( F_g \): fuel consumption, \( kg \);
\( e \): fuel emission factor.

Therefore, the carbon emissions of the whole distribution and transportation process are expressed as:

\[ T = \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ij}^k \rho(Q_i) x_{ij}^k \times f \times e \times 10^{-5} \]  
\[ (11) \]

Therefore, the carbon emission cost can be expressed as:

\[ W_5 = P_s \times \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} (d_{ij} x_{ij}^k) \sum_{l=0}^{n} x_{ij}^k \rho(Q_i) x_{ij}^k \times f \times e \times 10^{-5} \]  
\[ (12) \]

Based on the above analysis, we can obtain the first objective function of the five costs for optimization: fixed cost, fuel cost, damage cost, cooling costs, and the cost of carbon emissions. The second objective function is to minimize carbon emissions, and the multi-objective approach considers carbon emissions in the cold chain logistics path optimization model with the objective function:

\[ MinW = k \times P_s + \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ij}^k [P_s(d_{ij} x_{ij}^k \rho(Q_i) x_{ij}^k \times f \times 10^{-5})] \]
\[ + \sum_{k=1}^{m} \sum_{l=0}^{n} W_3 + P_s \sum_{k=1}^{m} \sum_{l=0}^{n} [x_{ij}^k \rho(Q_i) x_{ij}^k \times f \times e \times 10^{-5}] \]
\[ + \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ij}^k t_{ij}^k + P_s \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ij}^k t_{ij}^k \]
\[ + P_5 \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ij}^k (d_{ij} x_{ij}^k \rho(Q_i) x_{ij}^k \times f \times e \times 10^{-5}) \]
\[ + P_2 \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ij}^k (d_{ij} x_{ij}^k \rho(Q_i) x_{ij}^k \times f \times e \times 10^{-5}) \]
\[ (13) \]

\[ MinT = \sum_{k=1}^{m} \sum_{l=0}^{n} \sum_{j=0}^{n} x_{ij}^k (d_{ij} x_{ij}^k \rho(Q_i) x_{ij}^k \times f \times e \times 10^{-5}) \]  
\[ (14) \]
3.3.3. Define the Constraints
After the objective function is determined, its constraints need to be determined according to the analysis of the real situation. The constraints are as follows:

1. Transport vehicles uniformly start from the processing and distribution center and return to the processing and distribution center after serving all the designated distribution locations.
2. Each distribution location shall have only one refrigerated truck for distribution and the required distribution quantity of the store shall be met.
3. The sum of demand at each distribution location on each path should not exceed the maximum carrying weight of the refrigerated trucks, and the total number of distribution paths should not exceed the number of vehicles.
4. The refrigerated vehicle runs on the path at a constant speed, and the driving distance of each refrigerated vehicle cannot exceed the prescribed maximum driving distance.

3.3.4. Construct the Path Optimization Model
According to the capital city’s fresh cold chain logistics distribution situation and the requirement of fixed costs, fuel consumption in the process of considering transportation costs, damage costs, cooling costs, and carbon emissions, and according to the total distance, speed, and other constraints, we seek to minimize the costs and minimize carbon emissions in the cold chain logistics path optimization model.

According to the above analysis of the objective function and the establishment of constraints, the path optimization model of fresh product distribution in the subcenter of the capital city is constructed as follows:

\[
\text{MinW} = k \times P_3 + \sum_{k=1}^{m} \sum_{i=0}^{n} x_{ij}^{k} \left[ p_4 (d_{ij} \times \rho (Q_i) \times f \times 10^{-5}) \right] + \\
\sum_{k=1}^{m} \sum_{i=1}^{n} W_3 + P_1 \sum_{k=1}^{m} \sum_{i=0}^{n} \left[ x_{ij}^{k} q_i \left( 1 - e^{-\theta_1 (t_{ij} - \theta_0)} \right) \right] + x_{ij}^{k} Q_i \left( 1 - e^{-\theta_2 t_{ij}^{k}} \right) + \\
P_5 \sum_{k=1}^{m} \sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} t_{ij}^{k} + P_6 \sum_{k=1}^{m} \sum_{i=1}^{n} x_{ij}^{k} Q_i + \\
P_2 \sum_{k=1}^{m} \sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} \left( d_{ij} \times \rho (Q_i) \times f \times 10^{-5} \right) 
\]

\[
\text{MinT} = \sum_{k=1}^{m} \sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} \left( d_{ij} \times \rho (Q_i) \times f \times 10^{-5} \right) 
\]

\[
\sum_{i=1}^{n} x_{i}^{k} \leq 1, i = 0, k = 1, 2, ..., m 
\]

\[
\sum_{k=1}^{m} x_{ij}^{k} \leq m, i = 0 \quad (18)
\]

\[
\sum_{k=1}^{m} x_{i}^{k} = \left\{ \begin{array}{ll} 1, i = 0, 1, 2, ..., n & \\
0, m, i = 0 & (19) \end{array} \right.
\]

\[
\sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} \leq L, k = 1, 2, ..., m 
\]

\[
\sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} d_{ij} \leq L, k = 1, 2, ..., m 
\]

\[
t_{ij}^{k} = \sum_{i=0}^{n} \sum_{j=0}^{n} x_{ij}^{k} \left( t_{ij}^{k} + t_{i}^{k} + t_{j}^{k} \right), j = 1, 2, ..., n 
\]

\[
\left( t_{ij}^{k} \right) = \rho_0 + \frac{\rho_1 - \rho_0}{q} Q_i 
\]

Equation (15) represents the minimum total distribution cost, which consists of five parts: the fixed cost, fuel consumption cost, cargo damage cost, refrigeration cost, and gas emission cost of the cold chain transportation truck;

Equation (16) shows the lowest carbon emission;

Equation (17) indicates that each refrigerated truck starts from the distribution center and finally returns to the distribution center;

Equation (18) indicates that the total weight of the goods transported by the refrigerated truck on each path cannot exceed the maximum carrying weight of the refrigerated truck;
Equation (19) indicates that the number of vehicles in the distribution center meets the number of vehicles used for distribution;

Equation (20) indicates that there are a total of \( m \) vehicles in the distribution center, and each distribution location has and can only be served by one refrigerated vehicle;

Equation (21) indicates that the maximum driving distance of each refrigerated vehicle does not exceed \( L \);

Equation (22) represents the continuity of the transportation process and the transfer from distribution location \( i \) to \( j \);

Equation (23) represents the 100 km fuel consumption of a refrigerated truck when the load weight is \( Q \).

4. Algorithm Design and Result Analysis

Considering the state of development of the Beijing subcenter, model assumptions, relevant data, and constructed path optimization model, we applied a novel improved ant colony optimization to obtain the best distribution routes. The information about distribution locations, centers, and vehicles in the subcenter was collected, and the optimization algorithm was improved by tailoring it to the specific case and improving its efficiency. Then, the functional model was solved, and the code was implemented in the MathWorks MATLAB software to obtain the optimal routes.

4.1. Ant Colony Optimization

4.1.1. Overview

Ant colony optimization is a metaheuristic algorithm inspired by the pheromone laying and tracking behavior of various ant species. Ant colonies can find the shortest path to a food source in different environments, and the algorithm inspired by this behavior provides a stochastic solution by adjusting pheromone information based on the search experience of the colony and possible heuristic information to build candidate solutions for the problem of interest. The implementation of the ant colony optimization algorithm can be summarized as follows:

1. In the absence of pheromones, ants choose the direction to move in according to their own habits. When a pheromone is detected, the ants move according to the probability of pheromone concentration.
2. Ants leave behind pheromone traces associated with their home/food when searching for food/their home. As the distance travelled increases, less pheromones are deposited.
3. The pheromones evaporate over time.

4.1.2. Algorithm Formulation

To obtain a solution, each ant in the colony is assumed to leave pheromones on the branches through which it travels along path \((i, j)\). To force the ants to follow a valid route, the ants are not allowed to travel through areas previously visited until the peregrination is complete (this can be controlled by a taboo table). Thus, the two core steps of ant colony optimization are path construction and pheromone update.

1. Path construction:

\[
P^k_{ij}(t) = \begin{cases} 
\frac{[\tau_{ij}(t)]^\alpha [\eta_{ij}(t)]^\beta}{\sum_{j' \in I_k(i)} [\tau_{ij'}(t)]^\alpha [\eta_{ij'}(t)]^\beta}, & j \in I_k(i) \\
0, & \text{others}
\end{cases}
\]

where \( P^k_{ij}(t) \) is the probability that \( k \) ants in the \( t \)-th generation choose to move from location \( i \) to \( j \), \( \alpha \) is the pheromone importance, \( \beta \) is the relative importance of heuristic factor \( \eta_{ij} \), and \( I_k(i) \) represents the available locations for selection by ant \( k \) (each location can be visited only once). In this study, we set \( \eta_{ij} = \frac{1}{d_{ij}} \).
(2) Pheromone update:

\[
\tau_{ij}(t + n_1) = (1 - \rho)\tau_{ij}(t) + \Delta \tau_{ij}(t + n_1)
\]

(25)

where \(\tau_{ij}(t)\) denotes the pheromone left along the path from location \(i\) to \(j\) by the ant in the \(t\)-th generation. The amount of information along path \((i, j)\) at generation \(t + n_1\) can be adjusted according to Equation (25), where:

\[
\Delta \tau_{ij} = \sum_{i=1}^{n_2} \Delta \tau_{ij}^k
\]

(26)

which denotes the pheromones left by \(n_2\) ants along path \((i, j)\) and

\[
\Delta \tau_{ij}^k = \frac{Q}{L_k}
\]

(27)

which denotes the pheromones left by ant \(k\) along path \((i, j)\). In the equations above, \(Q\) is the total number of pheromones possessed by an ant over its lifetime, \(L_k\) is the circumference length of ant \(k\), \(n\) is the number of ants, and \(\rho\) is the rate of pheromone evaporation.

4.2. Improved Ant Colony Optimization

4.2.1. Improvements to Ant Colony Optimization

Conventional ant colony optimization in path planning for fresh product logistics and distribution has two main disadvantages. (1) A local optimal solution may be obtained. In other words, during optimization, the algorithm lacks a global search capability, and the solutions found by individual ants may be similar. Consequently, the algorithm stagnates and converges before finding the global optimum. (2) The search time may be excessively long, and the search may jump between local optima and the global optimum. To avoid these disadvantages, we designed an improved ant colony optimization for path planning to support fresh product logistics and distribution in a subcenter. The following improvements were devised:

(1) Ants have different rules for state transition;
(2) Different pheromone update rules are defined;
(3) A constraint is added to the ant path considering the model of this study, such that the path constraint not only reflects state transition but also existing knowledge when the ant selects the next node to visit.

This improved ant colony optimization is based on a theoretical study and the incorporation of practical conditions to improve the solution. The corresponding state transition and pheromone update rules are described below.

(1) Improved state transition rules for ant colony optimization. In the original ant colony optimization, ants move according to the probabilistic transition rule in Equation (24), which can easily lead to long search times owing to the lack of learning from previous search results. To improve the search performance, we explore new paths and establish equilibrium using existing knowledge through a novel path selection mechanism.

When \(q \leq q_o\),

\[
P_{ij}^l(t) = \begin{cases} 
\arg \max \left\{ [\tau_{ij}(t)]^a [\tau_{ij}(t)]^p + \frac{1}{[\tau_{ik} - \tau_{ij}] + [\tau_{ik} - L_k]} \right\}, j \in J_k(i) \\
0, \text{ others}
\end{cases}
\]

(28)

When \(q > q_o\),

\[
P_{ij}^k(t) = \frac{[\tau_{ij}(t)]^a [\tau_{ij}(t)]^p}{\sum_{j \in J_k(i)} [\tau_{ij}(t)]^a [\tau_{ij}(t)]^p} + \frac{1}{\sum_{j \in J_k(i)} [\tau_{ik} - \tau_{ij}] + [\tau_{ik} - L_k]}, j \in J_k(i)
\]

(29)

0, others
where \( q \) is a random number in \([0, 1]\) and \( q_0 \) is a pseudo-random factor. When \( q \leq q_0 \), the probability search is carried out. Using the ant state transition rule of improved ant colony optimization, ant \( k \) considers the amount of pheromone along each path for selecting the next node, \( j \), to visit, and a random factor combined with a random proportion is used to balance existing knowledge with the exploration of new paths. When ant \( k \) selects its next location, existing knowledge is first considered to determine the probability of moving from location \( i \) to \( j \). Individual ants tend to use existing knowledge for selecting the next location, ensuring that all the possibilities that satisfy the model requirements are traversed and likely reaching a realistic global optimum.

(2) Pheromone update rules. In the original ant colony optimization, the pheromone update mechanism is relatively simple. For the next move, the shortest path information obtained in the previous loop is mostly neglected, undermining the algorithm’s performance. We introduce the following improvements into the pheromone update rule:

\[
\nabla T^k_{ij} = \begin{cases} 
    \frac{q}{L_k}, & \text{if } (i, j) \in T \\
    0, & \text{else}
\end{cases}
\]

(30)

where \( Q \) is the amount of pheromones generated by an ant after completing the current round of visits, \( L_k \) is the length of the currently available optimal path, and \( T \) is the combination of nodes at each distribution location along the current optimal path.

In a search cycle, the pheromones along each stored path are adjusted locally according to Equation (25) to prevent all ants from entering the same path prematurely and falling into a local optimum. When the ant completes \( n \) search cycles, the pheromones along the current optimal path are adjusted globally according to Equation (30).

4.2.2. Solving Procedure

(1) Parameter initialization is applied to define and assign the distance matrix, demand matrix, and other model parameters. In this study, we set the number of ants to 80 and constructed pheromone matrix \( T \) and path record \( Table \).

(2) When the number of iterations is below the maximum, i.e., \( iter < iter_{\text{max}} \), ant colony optimization proceeds as follows.

(3) First, construct the paths of all ants. Each ant starts from the distribution center, and for each ant, \( r \) is randomly assigned a value in \([0, 1]\). If \( r < 0.5 \), the path transition probability is calculated for each remaining distribution location that has not been visited, and the next location, \( j \), to be visited is selected based on the maximum path transition probability. If \( r > 0.5 \), the path transition probability is recorded, and the node is selected according to the roulette-wheel method for the next location, \( j \), to be visited. The selected node is placed in the \( Table \), which contains the recorded paths.

(4) After moving to the first visited distribution location, the next possible location to be visited is selected based on the relevant constraints among the available unvisited locations. The next location that can be visited must satisfy the following conditions: (i) the node has not been searched, and (ii) the total distance currently travelled is less than the maximum distance that can be travelled by a vehicle. If a location satisfies the above conditions, according to the transition rule in step 3, the next distribution location to be visited is determined from the available locations, and the location is added to the \( Table \). If no location satisfies the conditions, ant \( k \) must return to the distribution center and visit a new location starting from there.

(5) If ant \( k \) has searched all the locations, go to step 6. Otherwise, return to step 3.

(6) The next ant starts visiting the locations according to steps 3–5. After constructing the paths of all ants when the search finishes, closed routes starting and ending at the distribution center are obtained, thus filling the \( Table \).
The total distance travelled by each ant along its path is calculated, and the optimal path is selected according to the shortest distance. This optimal path is stored, and the corresponding optimal value is obtained.

The optimal path is used to update pheromone matrix $\tau_u$ and obtain the corresponding optimal path and solution.

The number of iterations is increased by one. Steps 1–7 are repeated, and the optimal solution of the current iteration is compared with that of the previous iteration. The solution with the shortest paths is stored along with the corresponding optimal path. This optimal solution is used to update pheromone matrix $\tau_u$, and the corresponding optimal path and solution are obtained.

Repeat step 9 until reaching the maximum number of iterations, $\text{iter}_\text{max}$. Then, the algorithm terminates by providing the optimal solution and paths across iterations. We draw the optimal paths and determine the optimal solution for distribution. The flowchart of the improved ant colony optimization is shown in Figure 1.

**Figure 1.** Flowchart of improved ant colony optimization proposed in this study.
4.3. Main Fresh Food Distribution Center and Distribution Locations in Beijing Subcenter

4.3.1. Selection of Distribution Centers and Locations and Geographic Area

In the Beijing subcenter, the fresh food required by large and small stores and supermarkets mainly comes from the Beijing Baliqiao wholesale market, which supplies the subcenter and the entire Tongzhou District.

A steady stream of large and small vehicles travels daily between the Baliqiao wholesale market and neighborhood streets in the subcenter. Many convenience stores and food stalls do not have a large daily demand for fresh food, but their owners need to go to the Baliqiao wholesale market every day to ensure fresh and safe food owing to limitations in storage capacity and methods. These owners generally use their vehicles for carrying products. As the daily demand is small, neither logistics companies nor the Baliqiao market distribute fresh food to small businesses. In addition, the small demand and profit impede small businesses in paying for the services of logistics companies, as no scale effect can be achieved by such businesses. The vehicles owned by small businesses are intended to supply one vegetable stall or convenience store, and unique transportation routes are selected. Every convenience store is generally competitive, without needing to collaborate with other stores to buy goods or carry out path planning. In fact, existing mapping software tools such as Baidu Maps and Gaode Maps are sufficient for path planning in small businesses.

Large supermarkets in the subcenter have partnerships with the wholesale markets owing to the large daily demand for fresh products, large range of services provided, and wide subcenter coverage, giving these companies importance in distribution [44]. Many supermarkets belong to one of the numerous chains available in Beijing, and problems including fresh food distribution are solved by the parent company, which leads to the cooperation with wholesale markets. These supermarkets and medium-sized markets are directly supplied by a wholesale market. As there is a one-to-many relation between the wholesale markets and large/medium companies, distribution path planning becomes relevant. Therefore, we consider supermarkets as the main distribution locations for path planning. Information on the Baliqiao wholesale market and the distribution locations considered in this study is listed in Table 1.

**Table 1.** Information on distribution center and locations considered in this study.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Beijing Baliqiao Agricultural Products Center Wholesale Market</td>
<td>No. A27, Tonghui North Road, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>2</td>
<td>Yonghui Supermarket</td>
<td>B1F, Wanda Plaza, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>3</td>
<td>Carrefour (Beijing Tongzhou Store)</td>
<td>2F, Sunshine New Life Plaza, No. 48 JiuKeShu West Road, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>4</td>
<td>Woomei Supermarket (Ximen Store)</td>
<td>No. 256 Xinhua Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>5</td>
<td>Grocery Store</td>
<td>No. 103, Tong Chao Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>6</td>
<td>Beijing Hualian</td>
<td>B1, Building 14, Tianshi Mingyuan, Yangzhuang Beili, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>7</td>
<td>China Resources Vanguard (Vanguardlife)</td>
<td>The ground floor of Building No. 18, Barker Residence, Yile North Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>8</td>
<td>Material Mart (Tongzhou Longhu Store)</td>
<td>No. 25, Hanbidian Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>9</td>
<td>Jingkelong (Beiguan Store)</td>
<td>Houyao Shang Village, Yongshun Town, Tongzhou District, Beijing</td>
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<td>Location</td>
<td>Address</td>
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<td>10</td>
<td>Yonghui Supermarket (Hanbi Store)</td>
<td>Halfbidian Commercial Street, Yiluzhong Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>11</td>
<td>Jingkelong (Yudaihe Store)</td>
<td>No. 350, Yudaihe East Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>12</td>
<td>Woomei Supermarket (Li-yuan Store)</td>
<td>B1F, Guiyou Building, No. 1 Yunjing East Road, Liyuan Town, Tongzhou District, Beijing</td>
</tr>
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<td>13</td>
<td>Jingkelong (Jukeshu Store)</td>
<td>No. 29, JiKeShu East Road, TongZhou District, Beijing</td>
</tr>
<tr>
<td>14</td>
<td>Jingkelong (Dongguan Store)</td>
<td>No. 32 Xinhua East Street, Tongzhou District, Beijing (near Dongguan Bridge)</td>
</tr>
<tr>
<td>15</td>
<td>Material Mart (Luyuan Store)</td>
<td>No. 59, Luyuan South Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>16</td>
<td>Material Mart (Tuqiao)</td>
<td>Near the entrance of Tuqiao Station of the Batong Line, Liyuan Town, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>17</td>
<td>Material Mart (Tongzhou Sanmaifang Store)</td>
<td>1F, Jiafolin Building, No. 186 Liyuan North Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>18</td>
<td>Yue Man Street Life Supermarket</td>
<td>119-116, North Gate of Yueshanshui District, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>19</td>
<td>Miojin Supermarket (Huaye Oriental Rose Store)</td>
<td>B1F, Building 33, Linheli Road, Tongzhou District, Beijing</td>
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<tr>
<td>20</td>
<td>Supermarket Fat (Tongrui Jiayuan Store)</td>
<td>B1F, Building 20, Tongrui Jiayuan, Luyuan East Road, Yongshun Town, Tongzhou District, Beijing</td>
</tr>
<tr>
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<td>Material Mart (Yuqiao Middle Road Store)</td>
<td>2/F, No. 6 Yuqiao Middle Road, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>22</td>
<td>Lotus (Tongzhou Store)</td>
<td>No. 132, Yunhe West Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>23</td>
<td>Jingkelong Supermarket (Longwangzhuang Store)</td>
<td>Longwangzhuang Village, Yongshun Town, Tongzhou District, Beijing (near Jinshitan Dalian Seafood Farmers’ Cuisine)</td>
</tr>
<tr>
<td>24</td>
<td>BHG Life Supermarket (Tongzhou Wuyi Hualian Center, No. A3, Tonghu Street, Tongzhou District, Beijing Store)</td>
<td>B1, BHG Mall Beijing Hualian Wuyi Shopping</td>
</tr>
<tr>
<td>25</td>
<td>Jingkelong (Qiaozhuang Store)</td>
<td>Building 34, Yunqiao Home, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>26</td>
<td>Zhengda Youxiang (Li-yuan Store)</td>
<td>The ground floor of No. 10 building, Yuanjing East Road, Liyuan Town, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>27</td>
<td>Yonghui Supermarket (Taihu Taihe Store)</td>
<td>1F, G/F, Taihe No. 1 Courtyard, South 3rd Street, Zhanqian Street, Tongzhou District, Beijing</td>
</tr>
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<td>28</td>
<td>Material Mart (California Town Store)</td>
<td>No. 153, Qunfang Zhong San Street, Tongzhou District, Beijing</td>
</tr>
<tr>
<td>29</td>
<td>Material Mart (Longqing Yuan Store)</td>
<td>B-4-01, Building 38, No. 2, Longqing Garden, Tongzhou District, Beijing</td>
</tr>
</tbody>
</table>

4.3.2. Distance Analysis of Distribution Locations

We found many solutions similar to ant colony optimization that use the straight-line distance between distribution locations as a measure. When the distance between distribution locations is considered, the straight-line distance and coordinates can be used to
calculate the corresponding distances. The analysis of these methods and their results can be summarized as follows [45]:

1. These methods facilitate large-scale path planning, save costs, and a correlation exists between the straight-line and actual distances, thus providing a valid reference.

2. Many actual routes are difficult to determine, and considering straight lines avoids the time-consuming determination of actual distances between distribution locations.

3. A route involves various elements, and the application of path planning should have data support and guidance, but this is not as simple and convenient as considering the straight-line distance.

Despite being convenient, the feasibility and accuracy of path planning decline, likely causing route deviations when considering straight-line distances. In practice, the use of coarse approximations is erroneous and can lead to incorrect results. In this study, we decided that the path distance obtained after combining various route analyses, traffic light waiting, route closure, and other factors of specific city roads can represent the distance between the distribution locations obtained with the help of the path planning function in Gaode Maps. Hence, we expect more accurate results and realistic path planning for practical deployment.

As multiple recommended routes may be generated when using the path planning function of Gaode Maps, only one should be set as the reference route. We consider the following selection criteria for a route:

1. The recommended route with the shortest path is preferred.

2. The route with fewer traffic lights is preferred if the candidate route lengths are similar.

3. For a moderate difference in route length and a large divergence in the number of traffic lights, the route with fewer traffic lights is preferred. The distances between the distribution center and locations identified in Table 1 are listed in Tables 2 and 3. The numbers 1 to 29 in Tables 2 and 3 correspond to the numbers of the names of each distribution place in Table 1, respectively.

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| 18    | 5  | 4.6| 6.9| 5.1| 8.4| 6.4| 7.4| 8.8| 2.7| 8.4| 6.1| 8.5| 6.6| 4.9| 3.8|
| 19    | 7.8| 6.1| 3.3| 6.3| 6.1| 5.6| 5.2| 5.1| 7  | 4.8| 4  | 3.2| 2.8| 4.1| 8.1|
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| 22 | 6.4 | 5 | 3.8 | 5.2 | 5.6 | 5.1 | 4.3 | 5.7 | 5.5 | 5.3 | 2.8 | 3.8 | 3 | 2.7 | 6.7 |
| 23 | 5.7 | 7 | 7.6 | 5.8 | 9.3 | 9.4 | 8.1 | 9.5 | 3.5 | 9.1 | 4.7 | 7.8 | 7.3 | 3.3 | 0.8 |
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| 25 | 6.5 | 4.8 | 4.1 | 4.9 | 5.9 | 5.4 | 4.6 | 6 | 5.2 | 5.7 | 2.4 | 4.2 | 2.8 | 2.3 | 6 |
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| 27 | 14.7 | 13.3 | 11.2 | 14 | 11.7 | 12.5 | 10.7 | 8.7 | 14.7 | 10.6 | 13.5 | 12.2 | 11.6 | 14.7 | 27.4 |
| 28 | 8.1 | 6.5 | 3.6 | 6.6 | 6.5 | 6 | 4.9 | 4.7 | 7.4 | 5 | 4.7 | 3.5 | 3.2 | 5.5 | 9.5 |
| 29 | 11.3 | 10.1 | 9.2 | 9.8 | 12.2 | 10.3 | 9.7 | 11.1 | 11.9 | 10.7 | 7.7 | 9.2 | 8 | 7.5 | 10.3 |
Table 3. Distances between pairs of distribution centers and locations identified in Table 1 (continued).

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4.3.3. Distribution Vehicles

As we did not have specific information available about the distribution vehicles at the time of the study and there are many types of distribution vehicles in Beijing, we used a projection approach. According to relevant data, a fresh food wholesale market delivers 1080 tons of fresh food per day in 100 distribution vehicles. Thus, we projected that the wholesale market distribution vehicles are generally 10-ton load vehicles. Then, by analyzing the local vehicle market according to the available characteristics, we selected the most popular cold chain distribution vehicle to gather the information listed in Table 4.

Table 4. Distribution vehicle information.

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<td>25 L</td>
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<tr>
<td>Type of machinery</td>
<td>Insulated car</td>
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<tr>
<td>Chassis model</td>
<td>DFH1180E7</td>
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<tr>
<td>Power rating</td>
<td>180 kW</td>
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</table>
Rated load capacity | 9990 kg
--- | ---
Tire specification | 10
Number of tires | 6
Emission standards | National 6
Drive method | Rear drive
Fuel type | Diesel
Model | DFH5180XLCEX7
Overall mass | 7880 kg
Wheelbase | 5000 mm
Number of axes | 2
Total mass | 18,000 kg
Maximum speed | 105 km/h
Item number | 13,647,299,677

4.3.4. Demand at Distribution Locations

As every supermarket belongs to a different company and demand data are not disclosed or up-to-date, the exact demand of the supermarkets cannot be determined. Thus, we estimated the demand as follows. We surveyed various supermarkets in Beijing in 2021. The 5-day average fresh food supply of 592 stores belonging to eight supermarket chains (e.g., Material Mart and Jingkelong) was 1179.4 tons. Most distribution locations in urban subcenters contained large supermarkets, and the distribution demand was assumed to be similar to the estimate. We estimated the average daily fresh food demand for a single store to be 1.992 tons. For the medium-sized supermarkets in the distribution locations, which were not included in the survey in Beijing, we estimated a volume of approximately half of that of large supermarkets, and their coverage was also smaller than that of large supermarkets. Thus, we estimated their demand to be approximately half of that of large supermarkets. The estimated demand of each distribution location is listed in Table 5.

**Table 5. Estimated demand at distribution locations.**

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<tr>
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<td>Carrefour (Beijing Tongzhou Store)</td>
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<tr>
<td>4</td>
<td>Woomei Supermarket (Ximen Store)</td>
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<td>Grocery Store</td>
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<td>Beijing Hualian</td>
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<td>7</td>
<td>China Resources Vanguard (Vanguardlife)</td>
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<td>Material Mart (Tongzhou Longhu Store)</td>
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<td>Jingkelong (Beiguan Store)</td>
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4.4. Results and Analysis

(1) Results with load tolerance

Considering daily fluctuations in the amount of goods to be delivered, accrual to 5% of the maximum load of the vehicle as a tolerance margin, the maximum weight of the vehicle was 9.49 tons. The optimized routes considering tolerance are listed in Table 6.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Distribution Route</th>
<th>Full Load Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Supermarket Fat (Tongrui Jiayuan Store)</td>
<td>1.992</td>
</tr>
<tr>
<td>21</td>
<td>Material Mart (Yuqiao Middle Road Store)</td>
<td>1.992</td>
</tr>
<tr>
<td>22</td>
<td>Lotus (Tongzhou Store)</td>
<td>0.996</td>
</tr>
<tr>
<td>23</td>
<td>Jingkelong Supermarket (Longwangzhuang Store)</td>
<td>1.992</td>
</tr>
<tr>
<td>24</td>
<td>BHG Life Supermarket (Tongzhou Wuyi Hualian Store)</td>
<td>0.996</td>
</tr>
<tr>
<td>25</td>
<td>Jingkelong (Qiaozhuang Store)</td>
<td>1.992</td>
</tr>
<tr>
<td>26</td>
<td>Zhengda Youxiang (Liyuan Store)</td>
<td>0.996</td>
</tr>
<tr>
<td>27</td>
<td>Yonghui Supermarket (Taihu Taihe Store)</td>
<td>1.992</td>
</tr>
<tr>
<td>28</td>
<td>Material Mart (California Town Store)</td>
<td>0.996</td>
</tr>
<tr>
<td>29</td>
<td>Material Mart (Longqing Yuan Store)</td>
<td>1.992</td>
</tr>
</tbody>
</table>

The routes are specified as follows:

Vehicle 1: Beijing Baliqiao Agricultural Products Center Wholesale Market–Zhengda Youxiang (Liyuan Store)–Material Mart (California Town Store)–Material Mart (Tuqiao Store)–Miojin Supermarket (Huaye Oriental Rose Store)–Material Mart (Longqing Yuan Store)–Beijing Baliqiao Agricultural Products Center Wholesale Market.


Vehicle 4: Beijing Baliqiao Agricultural Products Center Wholesale Market–Material Mart (Yuqiao Middle Road Store)–Jingkelong (Qiaozhuang Store)–Lotus (Tongzhou Store)–Material Mart (Tongzhou Sanmaifang Store)–Jingkelong (Yudaihe Store)–Beijing Baliqiao Agricultural Products Center Wholesale Market.

Vehicle 5: Beijing Baliqiao Agricultural Products Center Wholesale Market–Carrefour (Beijing Tongzhou Store)–Woomei Supermarket (Liyuan Store)–Jingkelong (Jiukeshu Store)–Yue Man Street Life Supermarket–Jingkelong (Beiguan Store)–Beijing Baliqiao Agricultural Products Center Wholesale Market.

The relative coordinates of the transportation routes are shown in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Relative coordinates of transportation routes obtained considering load tolerance.

The shortest route was 121.6 km, and the number of iterations for optimization was 500. In the first 100 iterations, the total distance of the paths decreased quickly, from 143 to 124 km. Then, the distance gradually decreased until 300 iterations. Eventually, the distance converged to 121.6 km. The evolution of the improved ant colony optimization is shown in Figure 3. In the figure, we use “Iterations” and “Shortest path length” as the x- and y-axis labels.

![Figure 3](image3.png)

**Figure 3.** Optimization considering load tolerance.

(2) Results without tolerance

When the maximum vehicle load was considered for transportation, the optimization results without tolerance were as listed in Table 7.
Table 7. Routes obtained from optimization without tolerance.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Distribution Route</th>
<th>Full Load Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1–5–10–8–27–7–1</td>
<td>99.70%</td>
</tr>
<tr>
<td>2</td>
<td>1–2–11–14–22–25–1</td>
<td>89.70%</td>
</tr>
<tr>
<td>3</td>
<td>1–3–12–26–19–16–28–1</td>
<td>99.70%</td>
</tr>
<tr>
<td>4</td>
<td>1–29–24–23–20–15–18–1</td>
<td>99.70%</td>
</tr>
<tr>
<td>5</td>
<td>1–9–21–17–13–6–1</td>
<td>99.70%</td>
</tr>
<tr>
<td>6</td>
<td>1–4–1</td>
<td>19.90%</td>
</tr>
</tbody>
</table>

The routes are specified as follows:

Vehicle 1: Beijing Baliqiao Agricultural Products Center Wholesale Market—Grocery Store—Yonghui Supermarket (Hanbi Store)—Material Mart (Tongzhou Longhu Store)—Yonghui Supermarket (Taihu Taihe Store)—China Resources Vanguard (Vanguardlife)—Beijing Baliqiao Agricultural Products Center Wholesale Market.


Vehicle 3: Beijing Baliqiao Agricultural Products Center Wholesale Market—Carrefour (Beijing Tongzhou Store)—Woomei Supermarket (Liyuan Store)—Zhengda Youxiang (Liyuan Store)—Miojin Supermarket (Huaye Oriental Rose Store)—Material Mart (Tuqiao)—Material Mart (California Town Store)—Beijing Baliqiao Agricultural Products Center Wholesale Market.

Vehicle 4: Beijing Baliqiao Agricultural Products Center Wholesale Market—Carrefour (Beijing Tongzhou Store)—BHG Life Supermarket (Tongzhou Wuyi Hualian Store)—Jingkelong Supermarket (Longwangzhuang Store)—Supermarket Fat (Tongrui Jiayuan Store)—Material Mart (Luyuan Store)—Yue Man Street Life Supermarket—Beijing Baliqiao Agricultural Products Center Wholesale Market.

Vehicle 5: Beijing Baliqiao Agricultural Products Center Wholesale Market—Jingkelong (Beiguan Store)—Material Mart (Yuqiao Middle Road Store)—Material Mart (Tongzhou Sanmaifang Store)—Jingkelong (Jukeshu Store)—Beijing Hualian—Beijing Baliqiao Agricultural Products Center Wholesale Market.


The relative coordinates of the transportation routes obtained from optimization without tolerance are shown in Figure 4.
Figure 4. Relative coordinates of transportation routes obtained without load tolerance.

The optimal path length is 114.2 km, being 7.4 km shorter than the length considering tolerance. Over 500 iterations, the total path length decreased quickly in the first 100 iterations, from approximately 139 to 118 km, and then it gradually decreased, eventually improving to 114.2 km. The evolution of the improved ant colony optimization without considering tolerance is shown in Figure 5. In the figure, we use “Iterations” and “Shortest path length” as the x- and y-axis labels.

Figure 5. Optimization without load tolerance.

(3) Analysis of results

Considering a diesel fuel price of 8.2 RMB/L and vehicle consumption of 25 L/100 km, 114.2 km of fuel consumption obtained from optimization without tolerance requires 28.55 L, representing a fuel cost of 234.11 RMB. The fuel consumption of 121.6 km for optimization with tolerance is 30.4 L, representing a fuel cost of 249.28 RMB. Hence, the daily cost difference between the two optimization solutions is 15.17 RMB.
In path optimization, a large difference can occur owing to the tolerance level, which should be considered [46]. An option is adopting a stable distribution method such that each delivery has sufficient available load. Alternatively, higher efficiency can be pursued while allowing temporary changes in the distribution strategy when unexpected situations occur. These aspects require further investigation to allow flexibility according to the scenario.

5. Conclusions
The Beijing subcenter has developed rapidly in recent years, partly owing to supporting policies, and the required infrastructure should be constructed. Fresh product distribution is essential to ensure the availability of the food basket in the subcenter. We investigated the optimization of fresh food distribution in the subcenter by collecting, collating, and analyzing information about the main distribution centers and locations in the subcenter. Then, we introduced a subcenter distribution path optimization model and applied improved ant colony optimization implemented in MATLAB to obtain the best distribution routes. The solutions can reduce the costs of fresh product distribution, waste of resources, and the impact on the environment, thereby benefiting logistics companies and the population of the capital city while contributing to sustainable development.

Although the proposed path optimization model provides adequate results, further analysis and theoretical research are required. We identified the following limitations, excluded aspects, and directions for future work and improvement:

1. We neglected road conditions during actual transportation, leading to errors in the estimated distribution time. In addition, different fresh products may require a combination of different models of refrigerated vehicles for distribution. Thus, future work can consider complex road conditions and multiple optimization models.

2. The demand of distribution locations in a model should be accurate. As real demand data of the distribution locations were unavailable, we estimated them based on the average of the total demand. However, the demand likely varies across regions, and the average may be erroneous. Thus, future work can explore methods for accurately estimating the demand of specific locations.

3. We considered a single distribution center, but some locations have multiple concurrent suppliers. Future work can consider optimization for multiple distribution centers.

4. We did not consider location prioritization, which may be required in some cases with varying constraints. Prioritization can be included in future work.

5. We disregarded simultaneous delivery and pickup. In addition, when a location needs to return goods, the vehicle load changes. Moreover, one vehicle can supply various locations along its route. These aspects can also be considered in future work.

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