Hindawi
Journal of Advanced Transportation
Volume 2022, Article ID 5458760, 12 pages
https://doi.org/10.1155/2022/5458760

Research Article

Multimodal Transport Path Selection of Cold Chain Logistics Based on Improved Particle Swarm Optimization Algorithm

Changjiang Zheng, Kai Sun, Yuhang Gu, Jinxing Shen, and Muqing Du

College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, China

Correspondence should be addressed to Jinxing Shen; shenjx03@163.com

Received 9 February 2022; Revised 14 April 2022; Accepted 26 April 2022; Published 31 May 2022

Academic Editor: Yanyong Guo

Multimodal transport is a process of effectively moving cargoes in a single container by combining land transport (road or rail) and maritime or river transport (vessel or barge) in one transport chain. However, cold chain logistics (CCL), as a special while major kind of cargo delivery, has not been incorporated with this beneficial combination. In order to realize efficient delivery of cold chain foods (CCF), in this study, the characteristics of multimodal and CCL are analyzed and integrated to select the optimal logistics path. In establishing the path-selection model, customer satisfaction is introduced, which is reflected by arrival punctuality and the quality of CCF. An improved particle swarm optimization algorithm (IPSO) is introduced to address the model and is proven to retain a fast convergence rate and achieve outstanding solving accuracy through the experimental study. Sensitivity analysis is also conducted to present the impact of railway speed and cost variation on path selection. Results show that compared with highway transport, railway transport is preferable to the medium and long distance. The influence of railway speed improvement is more striking than cost reduction in motivating decision makers to choose railway transport mode in logistics operations.

1. Introduction

Nowadays, accompanied with an improved quality of life, the demand for enjoying fresh food will increase synchronously [1]. CCL is a special supply chain system that maintains the temperature of transport links at a specific value to forestall fresh food damage, loss, and deterioration [2]. The scale of China's CCL market has increased steadily since 2014. Meanwhile, the scale of the market is projected to reach 637 billion yuan in 2022, thus developing CCL has inevitably become a new trend for economic prosperity.

For enterprises and governments, the cost is the key element restricting the development of CCL [3]. Compared with traditional logistics, all kinds of refrigeration facilities and equipment are used in CCL to ensure the quality and safety of fresh foods [4]. Thus, CCL emits more greenhouse gas, and its energy consumption is much greater than general logistic operations [5]. Highway transport provides a convenient "door-to-door" service, however, for inter-city transport, it cannot be a thoughtful and wise choice in terms of environmental protection and delivery costs in comparison with other transport modes. Relying on Chinese regulated policies and its infrastructure construction progress, the railway operating mileage reached 150,000 kilometres by the end of 2021. Also, railway transport is less vulnerable to environmental impact and is relatively safe and stable [6]. From the perspective of sustainable development, it is more environmental friendly. Although railways have a nationwide network and huge transport capacity, it has not been fully utilized. In 2019, highway transport of CLL accounted for 89.7%, followed by waterway and airway transport, representing 8.1% and 1.2% separately, after which just 1% of CCL is transported by railway, indicating the current logistic transport framework urgently needs transformation and updates [7]. By the way, waterway transport is also a common cargo long-haul delivery mode [8]. Various transport modes could be brought into full play,

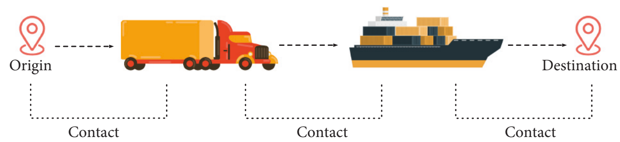

Figure 1: Sequence of multimodal transport.

and the great potential of multimodal transport is not effectively exploited [9].

Multimodal transport as an emerging mode of transport that combines different transport modes, as shown in Figure 1, has been attached much significance in China. It integrates the characteristics of multiple transport modes and has the advantage of high efficiency, low cost, and less pollution [10, 11]. The freight volume of multimodal transport in China has increased yearly, but the proportion in the total freight volume is still low, which is only 5%, indicating that advancing the development of multimodal transport is of critical significance. According to the "Notice on the Work Plan for Promoting the Development of Multimodal Transport and Optimizing the Transport Structure (2021–2025)" issued by General Office of the State Council, by 2025, the national railway and waterway freight volume will increase by about 10% and 12%, respectively, compared with 2020, and the rail-water intermodal freight volume will increase by over 15% on an annual basis. Nowadays, the increasing market demand of CCL and the long-haul delivery urges the integration of different transport modes to ensure the quality of service and cost-effectiveness. The combination of CCL and multimodal transport has opened up a new direction for cold chain transport.

Considering the perishability of CCF, the transport process requires high timeliness, but simultaneously, it is likewise necessary to pay attention to the impact on the environment and take into account economic and social benefits, which is conducive to promoting green and sustainable CCL development. Thusly, in the selection of multimodal transport mode of CCL, making a reasonable pick and combination according to the upsides and downsides of different transport modes is a necessity. And with the mounting of CCF volume and increased road congestion, existing works are concentrated on vehicle routing in certain districts and have deficiencies in inter-city long-haul for CCL problems, which are discussed in this paper as typical. This can give better play to the comparative advantages and combination efficiency of various transport modes, help to ensure product quality, reduce foods loss and costs, and even reduce the price of fresh foods, which will have a positive impact on increasing the import and export trade of fresh products and improving international competitiveness.

When it comes to model establishment, the food quality decay could be estimated in accordance with the shelf life and the conservation temperature [12]. Based on the general problem of multimodal transport path selection, the relevant model adds the effects of refrigeration, temperature and decay, and takes the minimum sum of transport, transshipment, and damage costs as the objective [13]. Carbon emission or carbon tax is also an influencing factor being considered, reflecting the impact on the environment [14]. Compared with unimodal transport, multimodal transport can distinctively reduce carbon emission with the transport time or cost decreasing reasonably [15] while the existing studies mostly focused on the highway, rarely considered the core position of the railway in CCL [16]. Railway transport, which boasts high safety, a major concern for the delivery task, should be viewed as an integral part of multimodal transport [17]. And for long-haul transport, the superiority of railway transport has become more prominent [18, 19].

On the other hand, few established models consider the relationship between customers' expectations and punctuality, not taking food freshness as an index to measure customer satisfaction. Only when the transport process smoothly proceeds and cargoes intactly arrived will the customer satisfaction rate be improved [20]. Timeliness significantly influences customer satisfaction in logistics delivery tasks. The most common method of building a customer satisfaction rate model considering timeliness is the fuzzy set theory [21]. Considering the inflexibility of the fixed time window, which causes the problem intractable or the failure to find the optimal solution, the fuzzy soft time window is adopted [22, 23]. In CCL, food freshness will also influence customer satisfaction. Widodo et al. [24] have studied that consumers' impetus to buy a batch of perishable foods is largely affected by the quality of foods. The longer the transport time, the faster the food quality decays. When the quality decreases to a certain value, customers' desires to buy perishable foods begin to decline significantly. Bortolini et al. [25] proposed that the quality change of perishable foods has a certain linear relationship with transport time. Generally, the quality change law can be used to express the nexus of transport time and the shelf life of perishable foods. In this paper, food freshness is integrated with arrival time satisfaction to obtain the total satisfaction weight, with which the model is able to reflect various interests of different logistics participants.

The major contributions of this paper are summarized as follows:

(1) Multimodal transport is incorporated into CCL, and the characteristics of both are considered to establish the model.
(2) Customer satisfaction is integrated to reflect time penalty and food decay.
(3) The devised IPSO is utilized to solve the model and has proven to be effective.
(4) The case analysis proves the practicability and feasibility of the proposed model and the effectiveness of the adopted methods. The sensitive analysis is carried out to reflect the railway speed and cost impact on the tendency to choose railway transport mode.

The rest of the paper is organized as follows. Section 2 formulates the methodology of establishing the multimodal

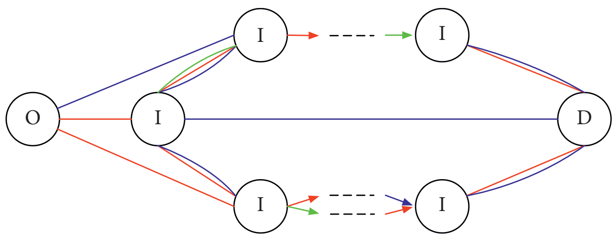

Figure 2: Multimodal transport network diagram.

transport path-selection model of CCL. Section 3 proposes the solution method to cope with the proposed model. Section 4 presents the case study to validate our proposed model and carries out a sensitivity analysis to quantitatively discuss the railway impacts on path selection. Finally, the conclusions of this paper and some future research directions are discussed in Section 5.

2. Model Building

2.1. Problem Description. In a certain multimodal transport network, the start point, the endpoint, and the freight volume are predetermined. Considering the actual situation of logistics delivery, the CCF are transported by highway, railway, or airway, respectively, from the origin to the destination. There will be more than one path to be chosen, at the same time, every path has a different transport modes combination. The diagram of the multimodal transport network is shown in Figure 2, at least one transport mode can be chosen. The decision makers need to select the transport path and mode in pursuing minimum cost and guaranteeing the satisfaction of customers.

2.2. Problem Assumptions. To facilitate the study, the assumptions are as follows:

(i) The path is acyclic, that is, the same transport node or path can be passed at most once

(ii) The transport speed and volume are constant

(iii) If the foods need to be transferred, only one transshipment can occur at the transshipment node

(iv) Different transport modes, i.e., highway, railway, and airway, can be chosen at each node

(v) The temperature during the transport process is stationary

(vi) The transport time is only regarded as the time between nodes, and the microscopic time of the inner-city transport is not considered

(vii) The carbon emission is associated with the quality of cargoes, while it is only reflected in the process of refrigeration

Table 1: Subscripts and parameters used in mathematical formulations.

Symbol	Description
K	Transport mode set
N	Network node set
M	Transshipment node set
Q	Total quantity of cargoes
c_{1ij}^{k}	Transport cost from node i to node j in mode k per unit cargo (¥/kg)
$c_{2i}^{kk'}$	Transshipment cost from mode k to mode k' in node i per unit cargo (¥/kg)
c_{31}	Refrigeration costs generated during transport per hour (¥/h)
c_{32}	Refrigeration costs generated during transshipment per hour (¥/h)
c_4	The price per unit cargo (¥/kg)
c_5	The carbon tax per unit CO_2 (¥/kgCO_2)
e_{ij}^{k}	Carbon emission from node i to node j in mode k per unit distance (kgCO_2/km)
$e_{i}^{kk'}$	Carbon emission from mode k to mode k' in node i per unit cargo (kgCO_2/kg)
e	Carbon emission of refrigeration equipment per unit cargo and hour (kgCO_2/kg·h)
d_{ij}^{k}	Transport mileage from node i to node j in mode k
v_{ij}^{k}	Transport speed from node i to node j in mode k
t_{ij}^{k}	Transport time from node i to node j in mode k
$t_{i}^{kk'}$	Transshipment time from mode k to mode k' in node i
μ	Time uncertainty coefficient
ξ	The proportion of food damage
δ	The freshness decay coefficient
x_{ij}^{k}	Binary value, if mode k is selected from node i to node j, the value is 1, 0 if is otherwise
$y_{i}^{kk'}$	Binary value, if the mode changes from k to k' in node i, the value is 1, 0 if is otherwise.

2.3. Variable Definitions. Table 1 summarizes the parameter definitions and their notation for the model.

2.4. Model Development.

(1) Transport cost (C_1). Transport cost refers to the fuel consumption during transport, which is directly proportional to the transport distance, but it varies from different transport modes. The transport cost can be expressed as follows:

$$C_1 = \sum_{i,j\in N} \sum_{k\in K} Qc_{1ij}^{k} d_{ij}^{k} x_{ij}^{k}. \tag{1}$$

(2) Transshipment cost (C_2). Transshipment cost refers to the cost of cargoes due to the switch of transport mode at the transshipment node. The transshipment cost can be expressed as follows:

$$C_2 = \sum_{i\in N} \sum_{k,k'\in K} Qc_{2i}^{kk'} y_{i}^{kk'}. \tag{2}$$

(3) Refrigeration cost (C_3). Refrigeration cost is the cost of refrigeration to maintain the temperature in the

vehicle, including those during the process of transport and transshipment. The refrigeration cost can be expressed as follows:

$$C_3 = c_{31} \sum_{i,j\in N} \sum_{k\in K} Qt_{ij}^{k} x_{ij}^{k} + c_{32} \sum_{i\in N} \sum_{k,k'\in K} Qt_i^{kk'} y_i^{kk'}. \quad (3)$$

(4) Damage cost (C_4). The quality and value of CCF gradually decrease with the actual delivery time T_t. The quality f shows the characteristics of exponential change [26, 27]. It is assumed that in the process of transport, the temperature of cargoes is invariant, so the freshness decay coefficient δ can well be considered a constant. Hence, the damage cost can be expressed as

$$\begin{aligned} C_4 &= c_4 \cdot \xi \cdot Q(1 - f), \\ f &= e^{-\delta T_t}, \\ T_t &= \mu \sum_{i,j\in N} \sum_{k,k'\in K} \left(t_{ij}^{k} x_{ij}^{k} + t_i^{kk'} y_i^{kk'} \right). \end{aligned} \quad (4)$$

(5) Carbon emission cost (C_5). In order to create environmental sustainability, the carbon tax is imposed on carbon emissions as an important means to limit carbon emissions. Carbon emission cost exists in the process of transport, transshipment, and refrigeration. It is related to the fuel consumption increased with growing distance and time. The total emission cost can be expressed as

$$C_5 = c_5 \cdot \left[\sum_{i,j\in N} \sum_{k\in K} e_{ij}^{k} d_{ij}^{k} x_{ij}^{k} + \sum_{i\in N} \sum_{k,k'\in K} Qe_i^{kk'} y_i^{kk'} + Q \cdot e \cdot T_t \right]. \quad (5)$$

(6) Customer satisfaction (λ). The cost factor reflects the benefits of operators, and the demand of customers can be expressed by customer satisfaction including time satisfaction and food freshness satisfaction. The satisfaction is within the range [0, 1].

(a) Time satisfaction (λ_t). Time satisfaction is described as the relationship between actual arrival time and expected arrival time. Enterprises have upfront inventory consumption cycles, early or late receipt will increase the cost of refrigerated inventory. The relationship between time satisfaction and total transport time is shown in Figure 3. $[T^E, T^l]$ represents the days sales of inventory, i.e., keeping the inventory for normal operation in this period [28]. With the consumption of inventory, the unit inventory cost of fresh products decreases and cargoes can be delivered at the scheduled time with increased time satisfaction. $[T^e, T^l]$ represents the optimal arrival time with the maximum satisfaction. $[T^l, T^L]$ is the safety stock period of the enterprise. When the arrival time is later than T^l, the safety stock will be consumed [29]. At this time,

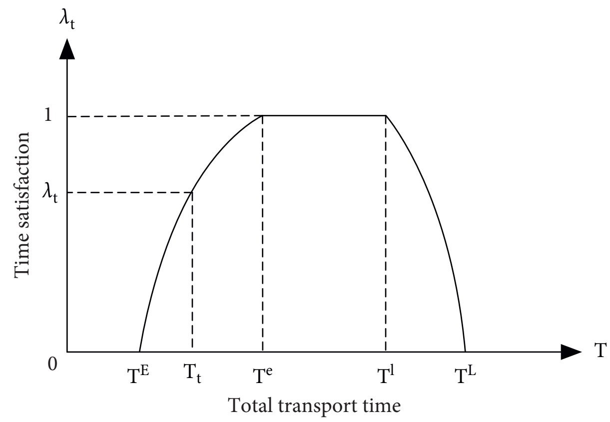

Figure 3: Time satisfaction function.

customers are more sensitive to inventory consumption and their satisfaction decreases significantly. The indication is shown in (6).

$$\lambda_t = \begin{cases} 0 & T_t \le T^E \\ \left(\dfrac{T_t - T^E}{T^e - T^E} \right)^{\phi_1} & T^E < T_t < T^e \\ 1 & T^e \le T_t \le T^l \\ \left(\dfrac{T^L - T_t}{T^L - T^l} \right)^{\phi_2} & T^l < T_t < T^L \\ 0 & T_t \ge T^L \end{cases}, \quad (6)$$

where ϕ_1 and ϕ_2 are sensitivity indexes.

(b) Food freshness satisfaction (λ_f). In the beginning, the quality reduces but there are no discernible changes, and the satisfaction is 1. Subsequently, the satisfaction descends as the falling of food freshness. While if the freshness is lower than a certain value, the food cannot be sold considering the spoilage and the satisfaction is reduced to 0. The food freshness satisfaction is expressed by piecewise function as

$$\lambda_f = \begin{cases} 1 & T_t \le \text{QRP} \\ 1 - \dfrac{T_t - \text{QRP}}{M - \text{QRP}} & \text{QRP} < T_t < M, \\ 0 & T_t \ge M \end{cases} \quad (7)$$

where QRP (quality reduction point) represents the threshold of T_t without observing quality decrease [15], and the corresponding quality is f_1. M represents the threshold of T_t corresponding to quality that can be accepted by customers, and the corresponding quality is f_2. The relationship between quality and food fresh satisfaction with time is shown in Figure 4.

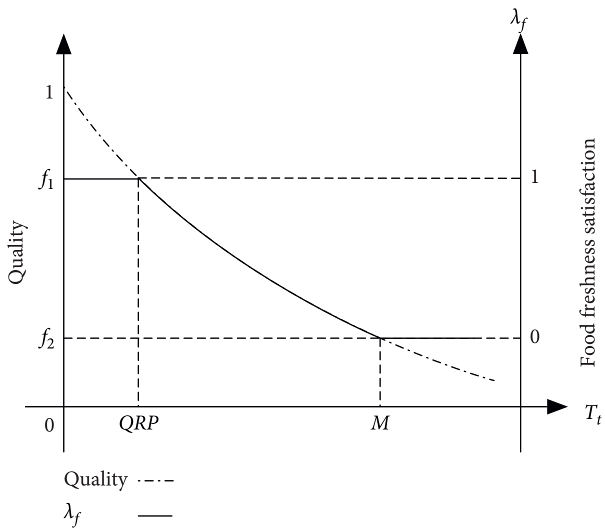

Figure 4: Quality loss and food fresh satisfaction with time.

2.5. Model Establishment. The goal of multimodal transport for CCL is to minimize the transport cost, transshipment cost, refrigeration cost, damage cost, and carbon emission cost, and maximize the total customer satisfaction simultaneously. Therefore, we integrate all these factors into one mathematical model that can be expressed as follows:

$$\begin{aligned} &\min Z = \frac{C}{\lambda}, \\ &C = C_1 + C_2 + C_3 + C_4 + C_5, \\ &\lambda = \lambda_t \cdot \lambda_f. \end{aligned} \tag{8}$$

s.t.

$$\sum_{k\in K} x_{ij}^k \leq 1, \quad \forall i, j \in N, \tag{9}$$

$$\sum_{k,k'\in K} y_i^{kk'} \leq 1, \quad \forall i \in M, \tag{10}$$

$$x_{hi}^k + x_{ij}^{k'} \geq 2y_i^{kk'}, \quad \forall h, i, j \in N, \forall k, k' \in K, \tag{11}$$

$$\sum_{i,j\in N}\sum_{k\in K} t_{ij}^k + \sum_{i\in N}\sum_{k,k'\in K} t_i^{kk'} \leq T. \tag{12}$$

Constraint (9) indicates that only one transport mode can be chosen between two adjacent nodes. Constraint (10) indicates that only one transshipment can occur at the transshipment node. Constraint (11) indicates that the transport mode during transshipment is continuous. Constraint (12) indicates that the total transport time should not exceed the set boundary.

3. Improved Particle Swarm Optimization Algorithm

Particle swarm optimization (PSO) is an evolutionary algorithm attributed to Kennedy and Eberhart [30]. The basic PSO is feasible to realize and fast to converge; however, there remain some problems such as premature convergence and sticking to local optimum. In order to improve the robustness of the algorithm, relative methods are proposed to improve the algorithm.

3.1. Standard PSO. In standard PSO, suppose that in the D-dimension of the search space, a swarm of N particles is represented as potential solutions, and each swarm i is associated with two vectors, i.e., the position vector $x_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$ and the velocity vector $v_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$. For the $k+1^{th}$ iteration, the position and velocity of particle i on dimension d are updated as follows:

$$v_{id}^{k+1} = \omega v_{id}^k + c_1 r_1 \left(p_{id} - x_{id}^k\right) + c_2 r_2 \left(p_{gd} - x_{id}^k\right), \tag{13}$$

$$x_{id}^{k+1} = x_{id}^k + v_{id}^k, \tag{14}$$

where (13) is the updated formula of particle velocity, (14) is the position formula of particle position, ω is the inertia weight, c_1 and c_2 are learning rates representing the cognitive ability of particles, r_1 and r_2 are two random numbers within [0, 1] to regulate learning between particles, p_i is the historical best position found so far for i^{th} particle, and p_g is the global best position found currently.

3.2. Adaptive Dynamic Inertia Weight. The inertia weight plays a role in balancing the global and local search ability of particles. While the fixed inertia weight is not conducive to the equilibrium between early and late stage of optimization, this paper adjusts the value of inertia weight according to the change in cost and satisfaction. Considering the cost and satisfaction simultaneously, the ratio of the distance of individual particles from the optimal value to the average distance of all particles from the optimal value is adjusted adaptively and dynamically, which further improves the search performance of the algorithm. The inertia weight of nonlinear adaptive dynamic adjustment is expressed as

$$\begin{aligned} &\omega = \omega_{\min} + \gamma\left(\omega_{\max} - \omega_{\min}\right), \\ &\gamma = \frac{\left(C_i - C_{\min}\right)/\left(C_{avg} - C_{\min}\right) + \left(\lambda_{\max} - \lambda_i\right)/\left(\lambda_{\max} - \lambda_{avg}\right)}{2}, \end{aligned} \tag{15}$$

where the minimal and maximal weights $\omega_{\min}$ and $\omega_{\max}$ are usually set to 0.4 and 0.9 [31, 32], γ is the nonlinear dynamic adjustment coefficient, C_i and λ_i are the total cost and the total customer satisfaction separately, $C_{\min}$ and C_{avg} are the minimal and average total cost, and $\lambda_{\max}$ and λ_{avg} are the maximal and average total customer satisfaction.

3.3. Cauchy Mutation. As the swarm leader, the elite particles guide other particles in the swarm. Once the elite particles fall into the local optimum, the whole swarm can easily fall into the local optimum. The disturbance can help elite particles jump out of the previous optimal region to the

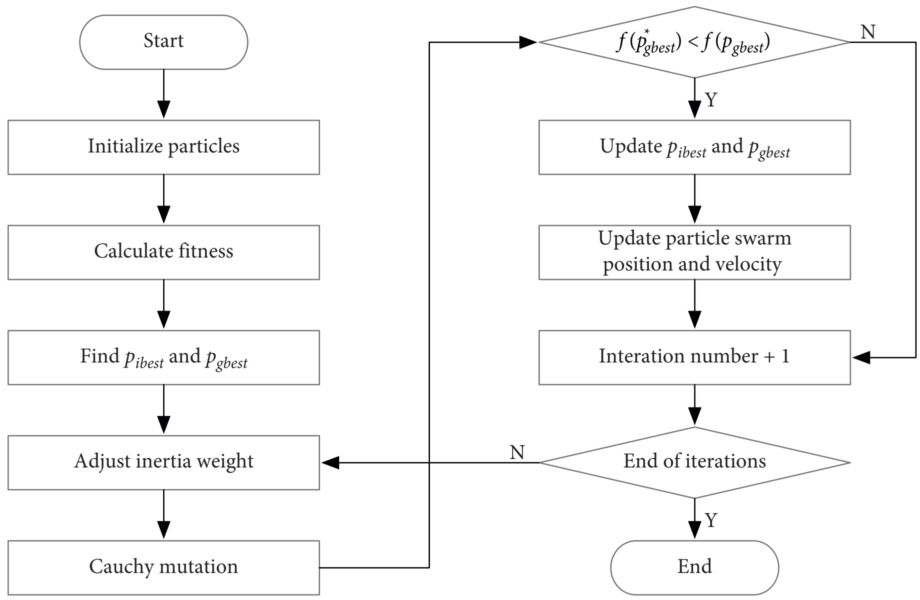

Figure 5: Flowchart of IPSO.

new region, forming a second convergence. Compare the fitness value $f(p^*_{\text{gbest}})$ with $f(p_{\text{gbest}})$. If $f(p^*_{\text{gbest}}) < f(p_{\text{gbest}})$, then $p_{\text{gbest}} = p^*_{\text{gbest}}$, otherwise round it off. To this end, Cauchy distribution is applied to swarm optimal particles for learning. The elite particle disturbance using the Cauchy distribution is

$$p^*_{\text{gbest}} = p_{\text{gbest}} + \eta \text{Cauchy}(\theta, \alpha), \quad (16)$$

where η is a random number within [0, 1], $Cauchy(\theta, \alpha)$ is the standard Cauchy distribution, when $\theta = 0$, $\alpha = 1$, the probability density function can be defined as

$$\varphi(x) = \frac{1}{\pi} \arctan(x) + \frac{1}{2}. \quad (17)$$

As a proportional parameter of Cauchy distribution, α determines the disturbance amplitude, which decreases linearly with the iterative process.

$$\alpha^{k+1} = \alpha^k - \frac{1}{t_{\max}}, \quad (18)$$

where $t_{\max}$ is the maximum number of iterations. When the initial value is large, the particle swarm will obtain enough disturbance, and with the deepening of evolution, the mutation will gradually decrease, so that the particle swarm can better converge to the global optimum.

Compared to the general PSO, adaptive dynamic inertia weight can improve the search ability and convergence rate simultaneously. Also, with the mutation of elite particles, the coincidence falling into the local optimum will decline, thus ensuring the solving performance. The IPSO flowchart is shown in Figure 5.

4. Case Study

4.1. Case Description. In order to realize the efficient, economic, and green transport of CCF, 10 major hub cities in China are assumed as nodes and labelled, starting from Guiyang in the southwest of China, and ending in Shenyang in the northeast, as shown in Table 2. Due to the lack of inland waterways, this paper substitutes waterway with airway as one of the transport modes. The distribution of transport nodes and arcs in the network is shown in Figure 6. The transport distance between node pairs is shown in Table 3. Among them, the highway distance is obtained by

Table 2: The node number of cities.

Number	Name of node city
1	Guiyang
2	Chongqing
3	Changsha
4	Xi'an
5	Wuhan
6	Zhengzhou
7	Taiyuan
8	Jinan
9	Shijiazhuang
10	Shenyang

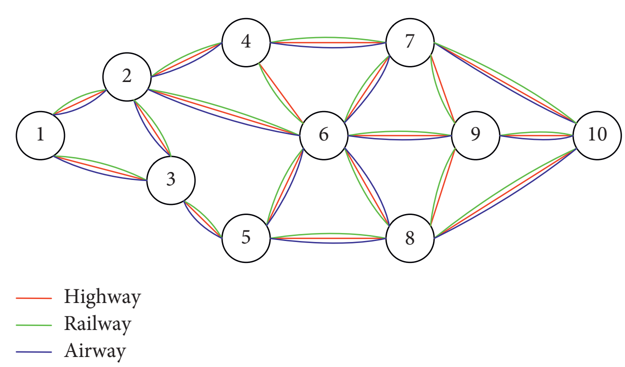

Figure 6: Schematic diagram of multimodal network.

Table 3: Transport distance between node pairs.

Adjacent node	Distance (km)		
	Highway	Railway	Airway
(1, 2)	375	347	343
(1, 3)	775	706	667
(2, 3)	892	1040	644
(2, 4)	694	960	580
(2, 6)	1153	1390	895
(3, 5)	333	362	288
(4, 6)	483	505	—
(4, 7)	602	579	514
(5, 6)	513	536	480
(5, 8)	846	1182	729
(6, 7)	432	646	346
(6, 8)	446	401	359
(6, 9)	418	412	421
(7, 9)	223	232	—
(7, 10)	1160	1195	1032
(8, 9)	313	593	—
(8, 10)	976	991	803
(9, 10)	962	963	876

Table 4: Transport mode parameters.

Transport mode	Transport cost (¥/t·km)	Average speed (km/h)	Carbon emissions ($kgCO_2$/t·km)
Highway	0.35	80	0.0212
Railway	0.165	60	0.0043
Airway	0.6	600	0.1922

referring to the national highway odometer, the railway distance is obtained from the Railway Customer Service Centre of China, and the air transport distance is obtained by referring to the flight mileage of China Southern. The unit transport cost, average speed, and carbon emission of each transport mode are shown in Table 4. The unit transshipment cost, time, and carbon emission between different modes of transport are shown in Table 5. The values of other parameters in the case are shown in Table 6. The algorithm parameters for the proposed IPSO are as follows: the number of particles N is 40, dimension D is 30, $c_1 = c_2 = 1.193$, the initial value of disturbance amplitude α is 1, and the number of iterations is 200. The software for the case is MATLAB 2016a equipped on Intel Core i5-11320h CPU (2.7 GHz).

4.2. Result Analysis. The optimal path of multimodal transport in CCL is from Guiyang ⟶ Chongqing ⟶ Xi'an ⟶ Taiyuan ⟶ Shijiazhuang ⟶Shenyang, the section from Guiyang to Taiyuan is highway transport, and the other sections are railway transport. The total cost is ¥ 41,009.33, and the total satisfaction is 0.810. The multimodal transport path of CCL conforms to the actual transport situation and is basically consistent with China's geographical transport environment, which shows that the model is feasible for solving practical multimodal transport problems. Compared with unimodal transport by highway, which is shown in Figure 7, the transport cost of multimodal transport fell by over 8%, and the number for total cost fell by 2%, which shows the cost advantage of railways in multimodal transport. The carbon emission cost accounts for about 10% of the total cost, which is closely related to refrigeration. Meanwhile, the two transport modes, i.e., unimodal and multimodal transport, satisfy the maximum time satisfaction respectively, but in terms of food freshness, limited to the railway speed, the railway takes longer than the highway in the same path, and the food freshness satisfaction decreases along with the increase of refrigeration cost and carbon emission cost. This shows that the short-haul transport cannot considerably reflect the environmental advantage of railways in CCL. Also, the result manifests the cost advantage of railway transport in multimodal transport concerning with long-haul transport, further suggests that improving the share of railway in long-haul transport is crucial. For airway transport, which is not manifested in the current result, cargoes could be transported by airway with high timeliness but higher cost than other modes, while it is appropriate to arrive at the specified time and it may be a sensible scheme to transport by airway in certain paths.

In the multimodal transport of CCL, transport cost accounts for more than the counterpart of damage and refrigeration cost. Reducing transport cost is an effective method to promote the transport transformation from highways to railways. Compared with highways, railways have advantages in cargo transport over medium and long distance. The 14th Five-Year Plan specifically states to accelerate the "highway to railway" transport over medium-and-long distance, adjust the transport structure, reduce transport costs, and promote the overall green and low-carbon transformation of transport. Improving transport efficiency and reducing transport cost of the railway are usual ways to increase the volume of railway freight. To explore the effects of different railway speeds and costs on the results of multimodal transport path optimization, sensitivity analysis is conducted in the following sections.

4.3. Sensitivity Analysis. Based on the above case of multimodal transport of CCL, this paper studies the impacts of railway transport speed and cost on the path selection, cost, and satisfaction of CCL through sensitivity analysis.

4.3.1. Sensitivity Analysis of Railway Transport Speed. The change in railway transport speed directly affects the competitiveness of highways and railways. Improving railway transport speed can ensure the efficiency of CCL and attract operators to choose environmentally railway transport. Therefore, railway transport speed varies from the lower to the upper bound (40~80 km/h) in steps of 10 km/h, whilst other parameters remain the same. The optimal path at each railway speed is obtained as shown in Table 7. Meanwhile, the indicators of cost and satisfaction are obtained, as shown in Figure 8.

According to the results of optimal path selection, with the increase in speed, the transport path has changed, and the proportion of railways in multimodal transport mileage has gradually increased, except for the scenario of speed

Table 5: Transshipment parameters.

Transshipment	Highway			Railway			Airway		
	Cost (¥/TEU)	Time (h/t)	Carbon emission ($kgCO_2$/t)	Cost (¥/TEU)	Time (h/t)	Carbon emission ($kgCO_2$/t)	Cost (¥/TEU)	Time (h/t)	Carbon emission ($kgCO_2$/t)
Highway	—	—	—	150	0.267	1.56	200	0.2	3.12
Railway	150	0.267	1.56	—	—	—	300	0.35	6
Airway	200	0.2	3.12	300	0.35	6	—	—	—

Table 6: Other parameters.

Parameters	Value
Q	1 TEU (20t)
c_{31}	8 (¥/h)
c_{32}	12 (¥/h)
c_4	10 (¥/kg)
c_5	0.5 (¥/$kgCO_2$)
e	10 ($kgCO_2$/kg·h)
ξ	0.3
δ	0.003
μ	1
ϕ_1	0.5
ϕ_2	0.8
T^e	42 (h)
T^l	48 (h)
T^E	36 (h)
T^L	52 (h)
T	60 (h)
f_1	0.95
f_2	0.6

from 40 km/h, which contains airway transport, to 50 km/h. The airway transport significantly increases the cost, correspondingly cargoes will arrive earlier.

In the later stage of speed incrementation, railway transport undertakes the main transport tasks from the scenario of the speed of 60 km/h to 80 km/h. The rapid cost decline caused by the path optimization has converted to a subtle decline in the transport time caused by the increase in railway speed. In the process of speed incrementation from 60 km/h to 70 km/h, the mode of transport has changed from road-rail combined transport to whole-journey railway transport, and the total transport cost has dropped significantly. Meanwhile, food freshness satisfaction gradually improves, which is also shown in the decline in damage and refrigeration cost. When the speed reaches 80 km/h, the speed advantage will lead to the prearrival of food and lead to a decrease in time satisfaction, but with the cost advantage of railways, the optimal path is still whole-journey railway transport.

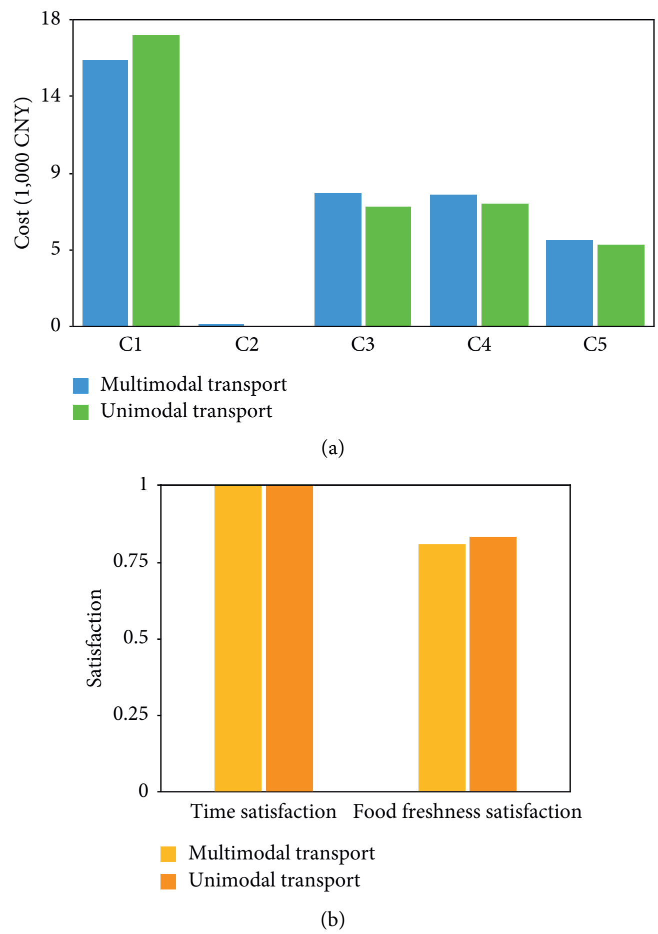

Figure 7: Comparison chart between multimodal transport and unimodal transport. (a) Cost. (b) Satisfaction.

4.3.2. Sensitivity Analysis of Railway Transport Cost. Changes in railway transport cost will affect the transport cost of CCL. Appropriately reducing railway transport cost can urge CCF to be transported by railway. Therefore, on the premise of keeping other conditions unchanged, take the variation rate of railway transport cost as a step of 10% and change within the range of −20%~20%. The optimal path at each railway transport cost is obtained as shown in Table 8. Meanwhile, the indicators of cost and satisfaction are obtained as shown in Figure 9.

According to the results of optimal path selection, the proportion of railway mileage increases with the reduction of railway transport cost. The optimal path with transport cost reduced by 10% and 20% is identical, and the proportion of railway has reached 71.40%, respectively. But with the continuous rise, the proportion of railway transport mileage begins to decline. The rise in railway transport cost will lead to an increase in the transport cost and total cost, then operators will switch to faster highway transport to ensure the freshness of CCF, which is reflected

Table 7: Changes in the optimal path with railway transport speed.

Speed (km/h)	Optimal path	Proportion of railway mileage (%)
40	1 →(Highway) 2 →(Highway) 6 →(Railway) 8 →(Airway) 10	14.68
50	1 →(Railway) 2 →(Highway) 4 →(Highway) 7 →(Highway) 10	12.38
60	1 →(Highway) 3 →(Highway) 4 →(Highway) 7 →(Railway) 9 →(Railway) 10	41.70
70	1 →(Railway) 3 →(Railway) 5 →(Railway) 6 →(Railway) 9 →(Railway) 10	100.00
80	1 →(Railway) 3 →(Railway) 5 →(Railway) 8 →(Railway) 10	100.00

→: Highway, →: Railway, →: Airway.

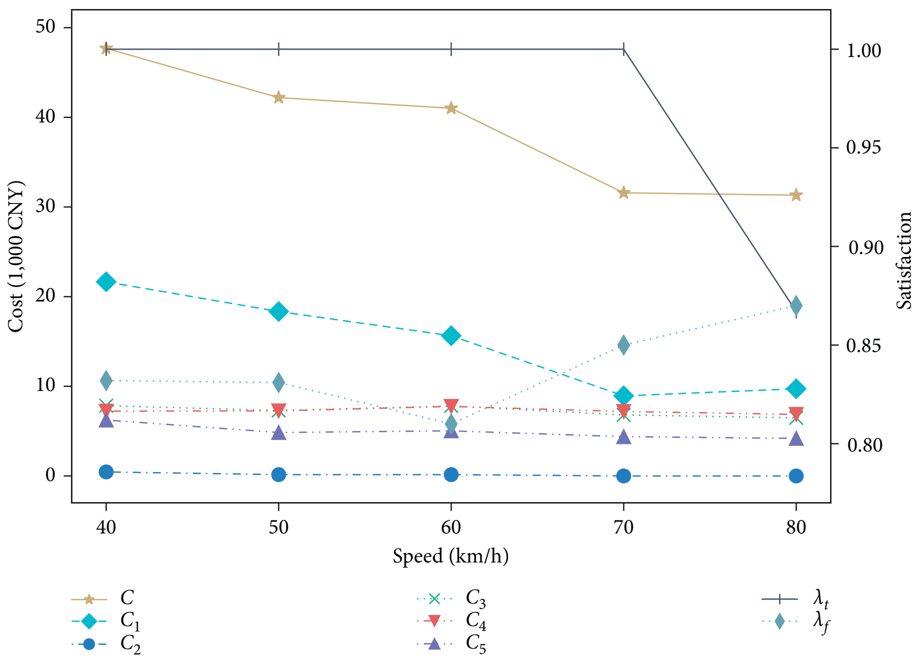

Figure 8: Cost and satisfaction of optimal paths with different railway transport speeds.

Table 8: Changes in the optimal path with railway transport cost.

Change rate of cost (%)	Optimal path	Proportion of railway mileage (%)
−20	1 →(Railway) 3 →(Railway) 5 →(Railway) 6 →(Railway) 8 →(Airway) 10	71.40
−10	1 →(Railway) 3 →(Railway) 5 →(Railway) 6 →(Railway) 8 →(Airway) 10	71.40
0	1 →(Highway) 3 →(Highway) 4 →(Highway) 7 →(Railway) 9 →(Railway) 10	41.70
+10	1 →(Highway) 3 →(Highway) 4 →(Highway) 7 →(Highway) 9 →(Railway) 10	33.71
+20	1 →(Railway) 3 →(Highway) 5 →(Highway) 8 →(Highway) 10	21.78

→: Highway, →: Railway, →: Airway.

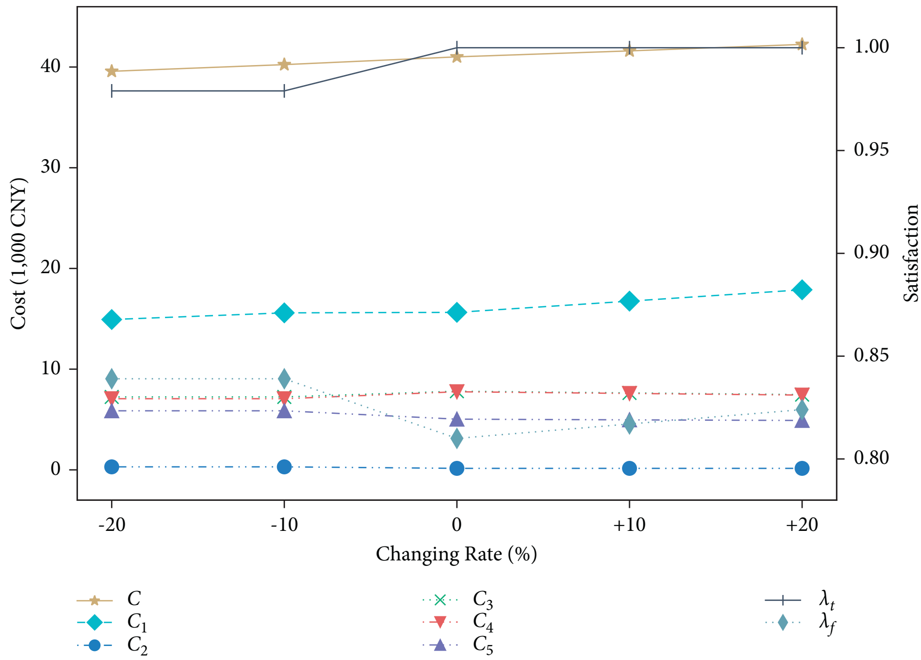

FIGURE 9: Cost and satisfaction of optimal paths with different railway transport cost.

in food freshness satisfaction and the proportion of highway mileage.

On the other hand, although the total transport cost increases with the increase of railway transport cost, the carbon emission cost decreases because the reduction of transport time reduces the carbon emission generated by refrigeration simultaneously. Since in the multimodal transport of CCL, the carbon emission and the food freshness are related to transport time. The improvement of railway transport speed contributes to lower transport time and is more conducive to the adjustment of transport structure than that of the reduction of transport cost. In the meantime, significantly reducing transport cost will not distinctively change the transport structure to a certain extent.

5. Conclusion

This paper integrates multimodal transport with CCL to investigate the path-selection problem. Given the perishability of CCF, damage cost, and food freshness satisfaction are introduced, then the path-selection model is established considering influencing factors of multimodal transport. The IPSO is proposed based on its outstanding solution performance. Next, the case of a multimodal network of major hub cities was adopted to apply our established model, which solved the proposed path-selection problem. The results were discussed and analyzed, and suggestions for a path-selection scheme were given for reference. At last, sensitivity analysis of railway transport speed and cost proves that the increases in speed can reduce transport cost, improve customer satisfaction, and adjust transport structure more effectively than the reduction of cost, which offers further insight into CCL development. In general, this paper provides theoretical support for the research of macro-CCL and testified that railway plays an important role in reducing cost, increasing efficiency, maintaining low carbon, and protecting the environment in CCL. These could provide a reasonable reference for the implementation of decision-making measures.

There are several promising future research directions stemming from this study. The same batch of cargoes can be separated during the transport to satisfy the demand of different regions, which is worth studying in the path-selection problem given a specific scenario. Besides, considering the long-haul multimodal transport, the surrounding temperature will change with the change of location, which will also affect the refrigeration equipment. The influence of heat transfer and leakage of refrigeration equipment on energy consumption is also a significant direction for exploring. Also, the exact transport time could be referred from related enterprises to make our database more reliable and persuasive. Such extensions will make our study more scientific and functional and be addressed in our future works.

Data Availability

The file of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The work described in this paper was sponsored by Jiangsu Transportation Science and Technology Project (2021G09).

References

[1] S. Zhang, N. Chen, X. Song, and J. Yang, "Optimizing decision-making of regional cold chain logistics system in view of low-carbon economy," *Transportation Research Part A: Policy and Practice*, vol. 130, pp. 844–857, 2019.

[2] Y. Yu and T. Xiao, "Analysis of cold-chain service outsourcing modes in a fresh agri-product supply chain," *Transportation Research Part E: Logistics and Transportation Review*, vol. 148, Article ID 102264, 2021.

[3] S. Liu and C. Zhang, "Optimization of urban cold chain transport routes under time-varying network conditions," *Journal of Advanced Transportation*, vol. 2021, Article ID 8817991, 16 pages, 2021.

[4] M. Babagolzadeh, A. Shrestha, B. Abbasi, Y. Zhang, A. Woodhead, and A. Zhang, "Sustainable cold supply chain management under demand uncertainty and carbon tax regulation," *Transportation Research Part D: Transport and Environment*, vol. 80, Article ID 102245, 2020.

[5] X. Zhang, J. S. L. Lam, and Ç. Iris, "Cold chain shipping mode choice with environmental and financial perspectives," *Transportation Research Part D: Transport and Environment*, vol. 87, Article ID 102537, 2020.

[6] H. Zhang, Y. Li, Q. Zhang, and D. Chen, "Route selection of multimodal transport based on China railway transportation," *Journal of Advanced Transportation*, vol. 2021, Article ID 9984659, 12 pages, 2021.

[7] C. Zheng, Y. Gu, J. Shen, M. Du, G. Ma, and K. Sun, "Comprehensive evaluation of urban integrated transportation network with multivariate statistical analysis: a case study of haimen," *IEEE Access*, vol. 9, no. 9, pp. 165034–165048, 2021.

[8] S. Wang, X. Qu, T. Wang, and W. Yi, "Optimal container routing in liner shipping networks considering repacking 20 ft containers into 40 ft containers," *Journal of Advanced Transportation*, vol. 2017, Article ID 8608032, 10 pages, 2017.

[9] B. Han, M. Wan, and Y. Zhou, "Evaluation of multimodal transport in China based on hesitation fuzzy multiattribute decision-making," *Mathematical Problems in Engineering*, vol. 2020, Article ID 1823068, 8 pages, 2020.

[10] M. Chen, Y. Liu, Y. Song, Q. Sun, and C. Cong, "Multimodal transport network optimization considering safety stock under real-time information," *Discrete Dynamics in Nature and Society*, vol. 2019, Article ID 5480135, 12 pages, 2019.

[11] C. Zheng, Y. Gu, J. Shen, and M. Du, "Urban logistics delivery route planning based on a single metro line," *IEEE Access*, vol. 9, no. 9, pp. 50819–50830, 2021.

[12] A. Gallo, R. Accorsi, G. Baruffaldi, and R. Manzini, "Designing sustainable cold chains for long-range food distribution: energy-effective corridors on the Silk Road Belt," *Sustainability*, vol. 9, no. 11, p. 2044, 2017.

[13] M. A. Dulebenets, E. E. Ozguven, M. Ren, and M. B. Ulak, "Intermodal freight network design for transport of perishable products," *Open Journal of Optimization*, vol. 5, no. 4, pp. 120–139, 2016.

[14] J. Bauer, T. Bektaş, and T. G. Crainic, "Minimizing greenhouse gas emissions in intermodal freight transport: an application to rail service design," *Journal of the Operational Research Society*, vol. 61, no. 3, pp. 530–542, 2010.

[15] M. Bortolini, M. Faccio, E. Ferrari, M. Gamberi, and F. Pilati, "Fresh food sustainable distribution: cost, delivery time and carbon footprint three-objective optimization," *Journal of Food Engineering*, vol. 174, no. APR, pp. 56–67, 2016.

[16] Y. Wang, J. Zhang, X. Guan, M. Xu, Z. Wang, and H. Wang, "Collaborative multiple centers fresh logistics distribution network optimization with resource sharing and temperature control constraints," *Expert Systems with Applications*, vol. 165, Article ID 113838, 2021.

[17] P. Leleń and M. Wasiak, "The model of selecting multimodal technologies for the transport of perishable products," *Archives of Transport*, vol. 50, no. 2, pp. 7–33, 2019.

[18] M. Olkhova, Y. Davidich, D. Roslavtsev, and N. Davidich, "The efficiency of transportating perishable goods by road and rail," *Transport Problems*, vol. 12, no. 4, pp. 37–50, 2017.

[19] F. Vanek and Y. Sun, "Transportation versus perishability in life cycle energy consumption: a case study of the temperature-controlled food product supply chain," *Transportation Research Part D: Transport and Environment*, vol. 13, no. 6, pp. 383–391, 2008.

[20] W. Xu and M. Rong, "Research on optimization of expressway logistics path based on the advantages of multimodal transport in the environment of internet of things," *Wireless Personal Communications*, vol. 2021, pp. 1–17, 2021.

[21] L. F. López-Castro and J. R. Montoya-Torres, "Vehicle routing with fuzzy time windows using a genetic algorithm," in *Proceedings of the 2011 IEEE Workshop On Computational Intelligence In Production And Logistics Systems (CIPLS)*, vol. 2011, pp. 1–8, Paris, France, October 2011.

[22] S. Fazayeli, A. Eydi, and I. N. Kamalabadi, "Location-routing problem in multimodal transportation network with time windows and fuzzy demands: presenting a two-part genetic algorithm," *Computers & Industrial Engineering*, vol. 119, pp. 233–246, 2018.

[23] Y. Sun and X. Li, "Fuzzy programming approaches for modeling a customer-centred freight routing problem in the road-rail intermodal hub-and-spoke network with fuzzy soft time windows and multiple sources of time uncertainty," *Mathematics*, vol. 7, no. 8, p. 739, 2019.

[24] K. H. Widodo, H. Nagasawa, K. Morizawa, and M. Ota, "A periodical flowering-harvesting model for delivering agricultural fresh products," *European Journal of Operational Research*, vol. 170, no. 1, pp. 24–43, 2006.

[25] M. Bortolini, M. Faccio, M. Gamberi, and F. Pilati, "Multi-objective design of multi-modal fresh food distribution networks," *International Journal of Logistics Systems and Management*, vol. 24, no. 2, pp. 155–177, 2016.

[26] K. Vankerschaver, F. Willocx, C. Smout, M. Hendrickx, and P. Tobback, "Mathematical modeling of temperature and gas composition effects on visual quality changes of cut endive," *Journal of Food Science*, vol. 61, no. 3, pp. 613–620, 1996.

[27] Q. Ma, W. Wang, Y. Peng, and X. Song, "An optimization approach to the intermodal transportation network in fruit cold chain, considering cost, quality degradation and carbon dioxide footprint," *Polish Maritime Research*, vol. 25, no. 1, pp. 61–69, 2018.

[28] Z. Gołaś, "The effect of inventory management on profitability: evidence from the Polish food industry: case

study," *Agricultural Economics*, vol. 5, no. 66, pp. 234–242, 2020.

[29] S. C. Graves and S. P. Willems, "Supply chain design: safety stock placement and supply chain configuration," *Supply Chain Management: Design, Coordination and Operation*, vol. 11, pp. 95–132, 2003.

[30] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proceedings of the ICNN'95-international conference on neural networks*, vol. 4, pp. 1942–1948, Perth, WA, Australia, November 1995.

[31] Y. Shi and R. C. Eberhart, "Empirical study of particle swarm optimization," in *Proceedings of the 1999 congress on evolutionary computation-CEC99 (Cat. No. 99TH8406)*, vol. 3, pp. 1945–1950, Washington, DC, USA, July 1999.

[32] Y. Shi and R. C. Eberhart, "A modified particle swarm optimizer," in *Proceedings of the 1998 IEEE international conference on evolutionary computation proceedings, IEEE world congress on computational intelligence (Cat. No. 98TH8360)*, pp. 69–73, Anchorage, AK, USA, May 1998.