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NSGA II for Configuration Optimization of Cold Chain Logistic Network with Fully Shared Facilities and Equipments

Qu-Bo Yu

School of Transportation and Logistics
Southwest Jiaotong University, Chengdu, China, 610031
New Corridor Logistics Group Co., Ltd. of Sichuan Port and Shipping Investment
Chengdu, China, 610000
55791672@qq.com

Le-Yao An*

School of Transportation and Logistics
Southwest Jiaotong University, Chengdu, China, 610031
National Engineering Laboratory of Integrated Transportation Big Data Application Technology
Southwest Jiaotong University, Chengdu, China, 610031
alyyy0626@gmail.com

Qing-Feng Yu

School of Transportation and Logistics
Southwest Jiaotong University, Chengdu, China, 610031
National Engineering Laboratory of Integrated Transportation Big Data Application Technology
Southwest Jiaotong University, Chengdu, China, 610031
yuqingfeng2021@163.com

Xiao-Wei Liu

School of Transportation and Logistics
Southwest Jiaotong University, Chengdu, China, 610031
New Corridor Logistics Group Co., Ltd. of Sichuan Port and Shipping Investment
Chengdu, China, 610000
024415578@qq.com

Fang-Zhu Pu

New Corridor Logistics Group Co., Ltd. of Sichuan Port and Shipping Investment
Chengdu, China, 610000
410607652@qq.com

Shao-Quan Ni

School of Transportation and Logistics
Southwest Jiaotong University, Chengdu, China, 610031
shaoquanni@163.com

*Corresponding author: Le-Yao An

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Abstract. *In the face of multiple issues such as unreasonable allocation of cold chain logistics resources, environmental pollution, and energy crises, better resource integration, optimization, and upgrading are needed. One of the methods to address this is fully shared facilities and equipment of cold chain logistics network. This paper proposes the construction of a cold chain logistics resource sharing platform, which includes five main entities: supply nodes, demand nodes, demand node logistics companies, 4PL and 3PLs, aiming to achieve timely response to cold chain logistics demands. A unified optimization method for facility and equipment configuration throughout the cold chain logistics process is selected. A dual-objective programming model is constructed to minimize logistics companies' operational costs and carbon emissions. The optimization is performed on various aspects such as the types and quantities of facility and equipment configurations. To solve this dual-objective programming model, the NSGA-II intelligent algorithm is employed. The results show that compared to the sharing of single types of cold chain logistics resources such as shared delivery vehicles or shared cold storage, full sharing is an effective approach to reducing logistics companies' operational costs, carbon emissions, and idle cold chain logistics resources. It optimizes the internal allocation of cold chain logistics resources within the cold chain logistics network.*

Keywords: Facility and Equipment Configuration Optimization, Cold Chain Logistics, Fully shared, NSGAII

1. Introduction.

In recent years, consumption level continues to improve, the market demand for perishable goods such as fruits and vegetables, meat and dairy products is rapidly increasing, and the scale of the cold chain logistics industry is growing rapidly [1]. Temperature control and monitoring along FSCs (cold food supply chains) are essential for maintaining food quality and safety of perishable food products [2]. Cold chain logistics industry is still in its infancy, the infrastructure equipment such as the construction of cold storage, refrigeration car configuration and other inadequate, most of the cold chain products are circulating at normal temperature, making some of which are processed at low temperature in the warehousing link, in the cold chain transportation, distribution and other links still appear broken chain phenomenon, resulting in low circulation rate of products and relatively high operating costs of logistics company [3,4,5]. Some cold chain products have strong seasonal demand or production volume [6], leading to high idle rates of facilities and equipment during the off-season. This results in a significant waste of logistics resources, indicating a poor synergy between the required facility and equipment configurations at various logistics stages and customer demands. The different links of cold chain logistics consume a lot of energy, affecting sustainable development [7]. Road transportation, in particular, is the main component of carbon emissions [8], and uninterrupted refrigeration services, while securing the economic value of cold chain products from production to consumption, consume energy leading to significant carbon emissions [9]. Therefore, when cold chain logistics facilities and equipment are configured, in addition to considering the operating costs of logistics company, it is also necessary to promote the green and low-carbon development of cold chain logistics.

Currently, most of the research on cold chain logistics resources focuses on vehicle sharing in the distribution stage [10,11] and cold storage sharing [12] in the warehousing stage. There is a lack of research on the sharing of cold chain logistics resources throughout the entire process from raw material processing to distribution. The transportation stage of the cold chain involves multiple supply and demand nodes.To fill this gap, this paper proposes an optimization method for the configuration of cold chain logistics network infrastructure and equipment in a fully shared mode. Build a cold chain logistics resource sharing platform with logistics company as the center, including supply nodes, logistics company, distributors, Third-party logistics service providers (3PLs) [13] and Fourth-Party Logistics (4PL) [14,15]. The information feedback process of this platform is as follows:

(1) The logistics company receives fixed and partially variable goods demands from distributors or wholesalers through this platform. It determines the delivery time for variable demands within a delivery cycle based on acceptable receiving time windows for fixed customer demands and the goods capacity of delivery vehicles. Additionally, the logistics company provides customer demands feedback to the 4PL, using a multi-temperature shared delivery system with cold storage by Zhan et al. [16] to arrange delivery vehicles based on the transportation volume for different temperature layers.

(2) The logistics company will provide feedback to the supply nodes and 4PL based on customer demands on the cold chain goods ordering platform, regarding the quantity of goods required for each temperature level and the storage capacity.

(3) According to the feedback from logistics companies, 4PL arrange cold chain transportation vehicles and determine the appropriate configuration of cold storage facilities for different temperature zones, as well as other processing equipment required for storage and distribution.

In general, "Configuration Optimization of Cold Chain Logistic Network with Fully Shared Facilities and Equipments" is a new type of cold chain logistics model for logistics enterprises, which eliminates the need for self-built cold storage facilities, procurement of transportation vehicles, or configuration of other distribution and processing equipment. Instead, it utilizes a cold chain goods ordering platform to acquire customer demands and deliver cold chain goods to 4PL providers. This model allows for better adaptation to the dynamic customer demands of cold chain goods, reduces the idle rate of logistics resources, and achieves effective integration of logistics resources. It aligns with the development direction of green supply chain in cold chain logistics, mitigating environmental degradation and energy consumption issues to some extent. Logistics enterprises can save costs associated with purchasing and maintenance, avoiding the problem of high initial investment costs during operations. 4PL providers can integrate advanced facility and equipment resources to achieve efficient and specialized logistics operations, thereby improving customer satisfaction.

The remaining sections of this paper are organized as follows. In Section II, a literature review is presented. Section III proposes specific optimization strategies and develop an optimization model. Section IV focuses on the algorithm and case study design to provide the optimized configuration results under a full sharing mode. Finally, Section V provides a summary and future work.

2. **Related Work.**

This paper discusses the optimization of the whole process of cold chain logistics in terms of facility and equipment configuration under the sharing mode based on Internet of things, which is significant for the high quality and sustainable development of cold chain logistics. The related literature mainly covers two parts: logistics resource sharing and cold chain logistics based on Internet of things.

2.1. **Logistics resource sharing.**

Recently, the sharing economy has increasingly promoted the development of the sharing model in the logistics industry, continuously integrating logistics resources and optimizing resource allocation. The sharing of logistics resources mainly includes the sharing of storage resources, transportation resources, distribution resources and so on [17]. Currently, research on the sharing of logistics resources mainly focuses on the sharing of single types of logistics resources such as delivery vehicles or warehouses.

Logistics efficiency can be improved by sharing resources between logistics companies and logistics service providers [18]. Zhang et al. [19] proposed a new collaborative vehicle routing model for shared delivery vehicles and segments. Liu et al. [20] proposed that when the transportation resources of logistics company are limited and the capacity of multiple distribution centers is uneven, factors such as multiple goods, multiple models, product mutual exclusivity and product-vehicle matching should be considered, and a nonlinear planning model was established for the vehicle routing problem of multiple centers, multiple models, and the existence of vehicle rental and sharing. Wang et al. [21] constructs a dual-objective optimization model for minimizing logistics cost and number of vehicles to discuss the number of vehicles used in global sharing and non-sharing modes, analyzes the changes of logistics cost under different modes with examples, and offers a new research approach to the logistics distribution problem in vehicle sharing mode. Fan H et al. [22] researches the logistic enterprise multi-region joint distribution problem under the vehicle and customer resource sharing mode, which effectively improves the logistic distribution efficiency. Wang et al. [23] constructs a dual-objective optimization model that minimizes the operating cost and the number of delivery vehicles, including the rental cost, energy cost, service cost and penalty cost of violating time windows of delivery vehicles, which provides a reference for the rational allocation of delivery vehicles under the sharing mode. At present, most company' cold chain storage mostly adopt the model of self-built, supplemented by rental [24], and most of the relevant researches are generalizations of the mode. Li et al. [25] proposes a strategy for sharing warehousing resources and distribution routing, comparing the maximum potential benefits for shared and non-shared warehouse resources, and analyzing the main application scenarios for shared warehousing facilities and equipment.

With the gradual introduction of low-carbon and green economy into cold chain logistics, Chen et al [26] considered the carbon emission cost and supplemented the existing model. Liu et al. [8] constructed a Joint Distribution-Green Vehicle Routing Problem (JD-GVRP) model, which combines carbon emissions and cold chain logistics company sharing distribution vehicles with cold chain logistics, significantly reduces carbon emission cost. Chen et al. [27] proposed in this paper to minimize costs incurred in the entire transportation process, solved a waitable time-varying multi-depot vehicle routing problem.

2.2. **Cold chain logistics based on Internet of things.** China's cold chain logistics resources are not well configured, and it is difficult to adapt to the dynamic changes in market demand. At present, the development of the Internet of Things is promoting the progress of the cold chain logistics industry [28], relying on the Internet to build a shared logistics platform [29] to obtain information about goods and process them, publish and match the supply and demand information of logistics resources , so as to meet the information needs of various logistics company. Zhang et al. [30] proposed that customers and logistics companies send out goods and transportation demands through transportation platform respectively, which will make real-time arrangements for the working condition of transportation vehicles based on the dynamic demand. Each logistics enterprise is also using Internet of Things (IOT) data to continuously guide the storage operation in order to improve the construction level of green logistics [14]. Kang et al. [31] proposed that the communication network infrastructure connected at IOT nodes can collect and exchange data through sensors or devices.

However, the above literature only focuses on the sharing of vehicles during the distribution process or refrigerated warehouse during the storage process, without considering various types of key facilities and equipments throughout the entire cold chain logistics process, and does not provide specific optimization methods for facility equipment configuration. It only proposes the use of the IoT to build an information sharing platform for dynamic logistics demand processing, which has certain limitations.

This paper optimizes the configuration of facilities and equipment within the scope of the cold chain logistics network under a fully shared mode. It relies on the logistics network and 4PL to achieve timely response to dynamic demand. Various types of key facilities and equipment are considered, and a unified optimization method is employed to build a dual-objective optimization model that minimizes the operating costs and carbon emissions of logistics enterprises. NSGA-II is applied for solving this model.

3. Model formulation.

3.1. Problem Description.

We consider the whole process of circulation and processing, storage, cold chain transportation, distribution and real-time monitoring of cold chain goods among supply nodes, demand nodes, and distributors, as shown in Figure 1. Table 1 lists the key facility amenities and equipment that need to be configured for each segment and the types of costs involved. In this paper, under the fully shared model, it is assumed that the key facilities and equipment provided by the 3PL in Table 1 are already equipped with logistics network devices such as OBU [32], WBAN [33,34], temperature and humidity control, detection and remote sensing [35].

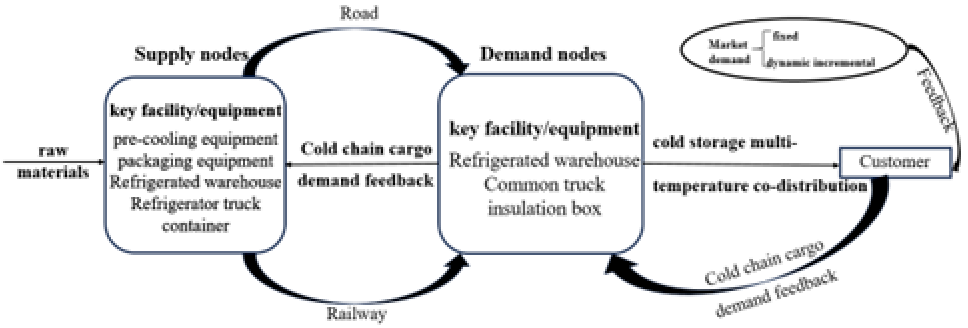


Figure 1. Cold chain logistics whole process

Table 1. Key facilities and equipment

logistics link	key facility/equipment	Cost type
Circulation processing	pre-cooling, packaging equipment	Sharing cost
Cold Chain Storage	Refrigerated warehouse, refrigerator	Sharing cost, carbon emissions
Cold Chain Transportation	Refrigerator truck, container	Sharing cost, carbon emissions
Cold Chain Distribution	Common truck, insulation box	Sharing cost, carbon emissions

The quantity and types of facility and equipment configurations are subject to changes based on market dynamics. Specifically, the cold chain distribution segment adopts cold storage multi-temperature co-distribution method [36]. The customer demand for this segment consists of both fixed demand and dynamic demand, with the dynamic demand being considered as additional demand during specific time periods. The distribution of cold chain goods is carried out based on the following principles: (1) If the distribution vehicle receives an additional dynamic demand from customers at a specific moment , while ensuring the fulfillment of the customer's fixed demand time window, the logistics company needs to complete the delivery volume of goods, which is equal to $q_{gh}^{f}+\omega_{gh}^{f}$. (2) If the time at which the additional dynamic demand is issued, denoted as T_0 , does not meet the fixed demand time window, the 4PL needs to divide the time period and send the distribution vehicle demand to the 3PLs. The required completion volumes of goods are denoted as q_{gh}^{f} and ω_{gh}^{f} respectively.

With the concept of green logistics development in the cold chain logistics market, this paper takes carbon emission as one of the objective functions, including carbon emission in transportation and storage process. Another objective function is the logistics enterprise operation cost, including transportation cost, fixed equipment cost, cold storage rooms sharing cost, penalty cost and damage cost. A two-objective optimization model is established for both

3.2. Model assumptions.

The construction of cold chain logistics facilities and equipment configuration optimization model will be set up by taking the following assumptions into considerations:

- Cold chain products are stored in refrigerated warehouses, without considering storage in refrigerated containers;
- When logistics company share refrigerated warehouses, they do not consider other costs such as labor and electricity consumption generated by the entry and exit of products between refrigerated warehouses, and only consider the sharing costs and carbon emissions;
- The supply relationship between the supply node and the logistics enterprise, the logistics enterprise and the customer is known;
- Each customer can only get one service from a fixed warehouse, and both the customer demand and the delivery time window are known;
- Distribution vehicles always travel at a uniform speed and do not need to return to the warehouse at the end of the final customer service;
- The cold chain transportation speed is used at a constant value for both road or rail transportation modes;
- The vehicles owned by 3PLs are guaranteed to meet the transportation needs of logistics companies.
- The new cold chain goods requirements from customers need to have the same time range for receiving as the fixed goods.

3.3. Model formulation.

3.3.1. *Symbols and parameters.* Table 2 shows the symbols and parameters used in this paper. Table 3 shows the decision variables used in this paper.

Table 2. Description of symbols

Symbols	**Description**
$m \in M$	Cold chain products supply nodes set
$n \in N$	Cold chain products demand nodes set
$g \in G$	Demand node's logistics company set
$h \in H$	Supply node's logistics company set
Q_{mn}^{f}	Demand of raw materials for each temperature layer of node n on node m

q^f_{gh}	Fixed freight of each temperature layer distributed from warehouse g to customer h
ω^f_{gh}	New freight of each temperature layer distributed from warehouse g to customer h
Q^f_{gh}	Total amount of each temperature layer distributed from warehouse g to customer h
Q^f_g	Total amount of cold chain products distributed at each temperature layer of logistics company g
δ^f_g	Proportion of fixed distribution freight to total demand for each temperature layer of warehouse g
δ^f_m	Proportion of cold chain transport volume to demand node shared storage capacity
k^f_g	Proportion of fixed distribution freight in each temperature layer of warehouse g
θ^1_m	Proportion of raw materials for the distribution processing
θ^2_m	Packaging required Proportion of raw materials to be packaged
c_o	rail transport means' price per unit
c_f	Damage cost for cold chain goods at different temperature layers.
c_a	different types of refrigerator trucks' price per unit
c_1	pre-cooling equipment's sharing cost
c_2	packaging equipment's sharing cost
c_b	Unit transportation cost of common trucks
α_1	waiting cost due to the early arrival
α_2	punishment cost due to the late arrival
c_d	different types of cold storage room's sharing cost
d^o_{mn}	Rail transport distance between nodes m and n
d^A_{mn}	Road transport distance from m to n
d_{gh}	Distance between g and h
v_o	Rail transport speed
v_a	refrigerator truck transport speed
v_b	common trucks transport speed
$t^{k^b_h}_h$	Time point when vehicle k^b_h arrives at customer h
T_0	The time when the logistics company receive the dynamic customer demand
$[T_{1h}, T_{2h}]$	Time window in which the customer expects to be served
$[T'_{1h}, T'_{2h}]$	Time window in which customer h can be served
β_o	Container full-load factor
β_a	refrigerator truck full-load factor
β^f_b	Various temperature layers insulation box full-load factor
z_g	Delivery times per day for logistics company g
G_o	Rated capacity of railroad containers
G_a	Rated capacity of refrigerator trucks
G_b	Loading capacity of common trucks
G^f_b	Rated capacity of insulation box for each temperature layer
$G^f_{k^b_h}$	Actual payload for each temperature layers of delivery vehicles.
f_{ld}	Goods flow per unit of pre-cooling equipment service
f_{bz}	Goods flow per unit of packaging equipment service
$k^b_h \in K_b$	Collection of shared delivery vehicles required by customer h

η_d	Volume utilization of cold storage room
ρ_f	Calculated density of cold chain products
$\overline{V_{zl}}$	Cooling capacity per unit of refrigeration equipment service
A_a	Fuel consumption per 100km of refrigerator trucks during transportation
A_o	Fuel consumption per unit freight turnover of railroad train
P	Real power of refrigeration equipment
P_d	The coefficient values of the carbon emissions of regional electricity
P_a	Carbon emission coefficient for Refrigerated Vehicles
P_b	Carbon emission coefficient for common trucks
P_o	Carbon emission coefficient for Rail Vehicles
φ_o	Average turnover of railroad trains in a quarter
φ_a	Average turnover of refrigerated cars in a quarter
φ_B	Average number of deliveries to customers in a cycle of logistics company
σ	Corruption rate of cold chain products
μ	Fuel consumption growth coefficient for common trucks
ρ_0	Unit fuel consumption of a common trucks with no load
t_{ld}	Daily working time of the pre-cooling equipment
t_{bz}	Daily working time of the packaging equipment

Table 3. Decision variables

Symbols	**Description**
x_{mn}^{o}	0-1 value, When rail transportation is used from node m to node n, $\mathrm{x}_{mn}^{o}=1$; otherwise, $\mathrm{x}_{mn}^{o}=0$
x_{mn}^{A}	0–1 value, When road transportation is used from node m to node n, $\mathrm{x}_{mn}^{A}=1$; otherwise, $\mathrm{x}_{mn}^{A}=0$
Q_{mn}^{o}	Demand for containers from node m to node n in a quarter
Q_{mn}^{a}	Demand for refrigerator truck from node m to node n in a quarter
Q_{m}^{1}	Demand for pre-cooling equipment in a quarter
Q_{m}^{2}	Demand for packaging equipment in a quarter
V_{m}^{f}	Nominal volume of different types of cold storage rooms in the supply node m
V_{n}^{f}	Nominal volume of different types of cold storage rooms in the demand node n
K_{h}^{b}	The number of different types of shared common trucks when cold chain goods are delivered to customer h

3.3.2. *Objective function.* The cold chain logistics facility and equipment configuration optimization model proposes in this paper includes two objective functions of logistics enterprise cost and carbon emission.

(1) **Logistics enterprise cost.**

The cost of logistics company mainly consists of five types of costs: transportation cost, fixed equipment cost, cold storage rooms sharing cost, penalty cost and damage cost.

Transportation cost.

Transportation cost mainly includes the cold chain transportation cost from the supply node to the demand node and the distribution cost from the logistics enterprise at the demand node to the customer. Among them, C_1 mainly depends on the turnover of cold chain products, while C_1' depends on the distance traveled by the distribution vehicle, and for cold chain transportation, it also needs to determine the transportation mode. The calculation formula is as follows:

$$Q_{mn}^{f} = \sum_{g \in G} \sum_{f \in F} \sum_{h \in H} \mathrm{q}_{gh}^{f} \Big/ \delta_{g}^{f} \tag{1}$$

$$C_1 = 10^{-3} \sum_{f \in F} \sum_{m \in M} \sum_{n \in N} \sum_{a \in A} \left(\varphi_a \cdot \mathrm{x}_{mn}^{A} \cdot Q_{mn}^{f} \cdot d_{mn}^{A} \cdot c_a + \varphi_o \cdot \mathrm{x}_{mn}^{o} \cdot Q_{mn}^{f} \cdot d_{mn}^{o} \cdot c_o \right) \tag{2}$$

$$C_1' = \sum_{g \in G} \sum_{h \in H} \sum_{b \in B} \varphi_B \cdot c_b \cdot k_h^b \cdot d_{gh} \tag{3}$$

Fixed equipment Sharing Costs.

The types of equipment involved in fixed equipment sharing costs are mainly packaging equipment and pre-cooling equipment required for the supply node m, it can be formulated as:

$$C_2 = 90 \times \sum_{m \in M} \left(Q_{\mathrm{m}}^{1} \cdot c_1 + Q_{\mathrm{m}}^{2} \cdot c_2 \right) \tag{4}$$

Cold storage rooms sharing cost.

Cold storage rooms sharing cost C_3 is incurred at both the supply nodes and the demand nodes.

$$C_3 = 90 \times \sum_{f \in F} c_f \cdot \left(\sum_{m \in M} V_m^f + \sum_{n \in N} V_n^f \right) \tag{5}$$

Penalty cost.

Penalty cost C_4 arises from the delivery vehicle delivering outside the expected time window and within the acceptable time window of the customer. Customers have certain requirements for the delivery time range, which generally divided into two kinds of hard time window and soft time window [37]. hard time window means the expected delivery time of customers, and soft time window means the acceptable delivery time of goods to customers. The mismatch between the arrival time of delivery vehicles and the receiving time of customers will adversely affect the quality of cold chain products and customer inventory management. Early arrival will cause idle delivery vehicles, drivers, etc., generating waiting time costs, and delayed arrival may lead to a series of problems for customers in sales and other aspects, reducing customer satisfaction and generating delayed arrival costs.

$$C_{4}^{advance} = \alpha_1 \sum_{h \in H} \sum_{K_h^b \in K_b} \sum_{k_h^b \in K_h^b} \sum_{b \in B} \varphi_B \cdot k_h^b \cdot \max \left(T_{1h} - t_{h}^{k_h^b}, 0 \right), T_{1h} > t_{h}^{k_h^b} > T_{1h}' \tag{6}$$

$$C_{4}^{delay} = \alpha_2 \sum_{h \in H} \sum_{K_h^b \in K_b} \sum_{k_h^b \in K_h^b} \sum_{b \in B} \varphi_B \cdot k_h^b \cdot \max \left(t_{h}^{k_h^b} - T_{2h}, 0 \right), T_{2h}' > t_{h}^{k_h^b} > T_{2h} \tag{7}$$

$$C_4 = C_{4}^{advance} + C_{4}^{delay} \tag{8}$$

Damage cost.

Damage cost ignores the additional goods damage caused by the goods handling process, and only considers the damage to the freshness of the products caused by the time changes in the cold chain transportation and distribution [38], respectively, expressed as and , calculated as follows:

$$C_5 = 10^{-3} \times \left(\begin{array}{l} \displaystyle\sum_{m \in M} \sum_{a \in A} \sum_{f \in F} \varphi_a \cdot c_f \cdot \mathrm{x}_{mn}^{A} \cdot Q_{mn}^{f} \left(1 - e^{-\sigma \left(\frac{d_{mn}^{a}}{v_a} \right)} \right) \\ \displaystyle + \sum_{m \in M} \sum_{f \in F} \varphi_o \cdot c_f \cdot \mathrm{x}_{mn}^{o} \cdot Q_{mn}^{f} \left(1 - e^{-\sigma \left(\frac{d_{mn}^{o}}{v_o} \right)} \right) \end{array} \right) \tag{9}$$

$$C_5' = 10^{-3} \cdot c_f \sum_{f \in F} \sum_{b \in B} \sum_{g \in G} \sum_{h \in H} \varphi_B \cdot Q_{gh}^{f} \left(1 - e^{-\sigma \left(\frac{d_{gh}}{v_b} \right)} \right) \tag{10}$$

(2) **Carbon emission.**

The carbon emission of cold chain logistics mainly includes the transport carbon emissions generated by the cold chain transportation means and the refrigeration carbon emissions generated by the refrigeration equipment in the storage link.

transport carbon emissions

The transportation carbon emissions are related to the fuel consumption of vehicle driving, involving two scenarios: cold chain transportation and cold chain distribution.

Among them, the carbon emissions of cold chain transportation are calculated as follows:the distance-based method is used to calculate the carbon emissions of road transportation due to the relatively high loading rate of refrigerated cars; the calculation of railroad transportation is based on the turnover of cold chain products.

$$C_6 = \sum_{m \in M} \sum_{n \in N} \left[10^{-2} \cdot \sum_{a \in A} \varphi_a \cdot \mathrm{x}_{mn}^{A} \cdot Q_{mn}^{a} \cdot d_{mn}^{A} \cdot A_a \cdot P_a + 10^{-3} \cdot \varphi_o \cdot \sum_{f \in F} \mathrm{x}_{mn}^{o} \cdot Q_{mn}^{f} \cdot d_{mn}^{o} \cdot A_o \cdot P_o \right] \tag{11}$$

Different from cold chain transportation, cold chain distribution link customer demand is smaller, the load factor of ordinary trucks is lower, When the vehicle travels at a certain speed, the fuel consumption is influenced by the vehicle load. According to [8], fuel consumption per unit mileage can be expressed as follows:

$$\rho_{k_h^b} = \rho_0 + \mu \cdot \sum_{f \in F} G_{k_h^b}^{f} \tag{12}$$

$$C_6' = \sum_{b \in B} \sum_{g \in G} \sum_{h \in H} \sum_{k_h^b \in K_h^b} \varphi_B \cdot k_h^b \left(\rho_0 + \mu \cdot \sum_{f \in F} G_{k_h^b}^{f} \right) d_{gh} P_b \tag{13}$$

Storage Carbon Emissions

Carbon emissions in the storage link are mainly generated by refrigeration equipment, and the daily electricity consumption is determined based on the set temperature value and volume of each type of cold storage rooms, and the calculation method of "ICE-E" [39] is used.

$$C_7 = 2160 \times \sum_{m \in M} \sum_{n \in N} \sum_{f \in F} P \cdot P_d \cdot (V_m^f + V_n^f) \tag{14}$$

3.3.3. *Modelling.* Thus, the mathematical model is expressed as follows:

$$minC_{qy} = C_1 + C_1' + C_2 + C_3 + C_4 + C_5 + C_5' \tag{15}$$

$$minC_{sh} = C_6 + C_6' + C_7 \tag{16}$$

Constraints:

$$Q_{mn}^{o} \geq \sum_{f \in F} \left(Q_m^f / G_o \cdot \beta_o \right) \tag{17}$$

$$Q_{mn}^{a} \geq \sum_{f \in F} \left(Q_m^f \big/ G_a \cdot \beta_a \right) \tag{18}$$

$$Q_m^1 \geq \sum_{f \in F} \theta_m^1 \cdot Q_m^f \big/ \overline{f_{ld}} \cdot t_{ld} \tag{19}$$

$$Q_m^2 \geq \sum_{f \in F} \theta_m^2 \cdot Q_m^f \big/ \overline{f_{bz}} \cdot t_{bz} \tag{20}$$

$$\sum_{f \in F} V_m^f \geq \sum_{f \in F} \frac{Q_m^f}{\eta_d \cdot \rho_f \cdot \delta_m^f} \tag{21}$$

$$\sum_{f \in F} V_n^f \geq \sum_{f \in F} \sum_{g \in G} \sum_{h \in H} \frac{Q_{gh}^f}{\eta_d \cdot \rho_f \cdot \delta_g^f} \tag{22}$$

$$K_h^b \geq \left\lceil \max \left\{ \sum_{f=1} \mathrm{Q}_{gh}^f \Big/ G_b^f \cdot \beta_b^f, \sum_{f=2} \mathrm{Q}_{gh}^f \Big/ G_b^f \cdot \beta_b^f, \sum_{f=3} \mathrm{Q}_{gh}^f \Big/ G_b^f \cdot \beta_b^f \right\} \right\rceil \tag{23}$$

Formula (17) and (18) specify the minimum shared quantity limits for refrigerated vehicles or containers required for different transportation modes in the cold chain transport phase. Formula (19) and (20) specify the minimum shared quantity of refrigeration and packaging processing equipment required. Formula (21) and (22) respectively establish the minimum shared nominal volume of refrigerated storage rooms with different temperature zones required at supply nodes and demand nodes. Formula (23) stipulates the minimum shared quantity of delivery vehicles required for each customer at demand nodes on a daily basis.

4. **Algorithm and experiments.**

4.1. **Algorithm design.**

The cold chain logistics facility equipment configuration optimization problem studied in this paper-objective optimization problem, which does not yield a unique optimal solution but a set of optimal solutions, commonly known as the Pareto-optimal set [40]. Based on NSGA, Deb proposed NSGA II [41], which features a fast non-dominated sorting process, Pareto-archived evolution strategy, parameterless approach, and simple yet effective constraint handling methods,and better convergence ability [42,43,44], aiming to find a more diverse set of solutions and converge closer to the true Pareto-optimal set. Therefore, this paper employs the NSGA II algorithm for solving the problem, and the specific steps are as follows:

4.1.1. *Encoding.* In this study, a binary encoding method is used to encode the chromosomes. Each encoding position corresponds to the value of a decision variable, as shown in Figure 2. The length of the chromosome is A+2M+N×F+M×F+H×B+5.

Figure 2. Encoding

4.1.2. *Parameter setting.* The parameter settings mainly include the population size NIND = 30, maximum number of iterations MAXGEN is set to 1500, elite iteration count, selection probability, crossover probability, and mutation probability.

4.1.3. *Generating the initial population.* Generate and decode the chromosome matrix for the initial population. Set the evolution generation $Gen = 1$, and calculate the objective function values for the individuals in the initial population. Determine if the first generation of sub-population has been generated. If it has been generated, set the evolution generation $Gen = 2$. Otherwise, perform fast non-dominated sorting, selection, crossover, and mutation on the initial population to generate the first generation of sub-population and set the evolution generation $Gen = 2$.

4.1.4. *Generating the new parent population.* Merge the parent and offspring populations to form a new population. Determine if a new parent population has been generated. If not, calculate the objective function of the individuals in the new population and perform operations such as fast non-dominated sorting, crowding distance calculation, and elite strategy to generate the new parent population. Otherwise, repeat this step.

4.1.5. *Generating offspring.* Perform selection, crossover, and mutation operations on the generated parent population to generate the offspring population.

4.1.6. *Checking evolution generation.* Check if Gen is equal to the maximum evolution generation. If not, set $Gen = Gen + 1$ and return to step 3. Otherwise, the algorithm terminates.

4.1.7. *Pseudocode.* Provide pseudocode for the fast non-dominated sorting process of NSGA II, as shown in Table 4.

Table 4. Pseudocode of Fast Non-dominated Sorting

steps	**Fast Non-dominated Sorting**
Input	*Pop_unity: population P* *Rank = (rank_1, rank_2...)*
Output	Individual hierarchy ranking

Step 1

```
for ($p \in P$ ) do
    S_p = empty set; n_p = 0 (Record the set of solutions dominated by $p$ as $S$;
record the number of solutions dominating $p$ as $n$.)
end for
```

Step 2

```
for ($p \in P$ ) do
    if cv[p] = 0 and cv[q] = 0 (cv represents the constraint conditions (17)-(25)
        if p dominates q
            Then, S_p = S_p U q
        elif q dominate p
            Then, n_p= n_p+ 1
    elif cv[p] > 0 and cv[q] = 0
        Then, S_p = S_p U q
    elif cv[p] = 0 and cv[q] > 0
        if q not in S_p
    Then, n_p= n_p+ 1
    end if
end for
```

Step 3

```
p = 1
When Rank_p != empty set
    H = empty set
    For each p belonging to Rank_p
        For each q belonging to S_q
        n_q = n_q - 1
        If n_q = 0
            Then q_rank = p + 1, H = H U q
    p = p + 1
    F_p = H
```

4.2. **Case study.** This study selected three types of perishable goods: fruits and vegetables, dairy products, and seafood, representing ambient products *(f=1)*, refrigerated products *(f=2)*, and frozen products *(f=3)*, respectively. It is assumed that the six-digit distributors at the demand nodes initiate fixed and variable temperature layer goods requirements to the cold chain logistics company, while also providing feedback to a specific goods supply node logistics enterprise. The daily fixed demand information of distributors, including different temperature layer goods for different seasons, desired service time windows, and acceptable service time windows, are shown in Tables 5. The dynamic daily additional goods demand of distributors during different seasons is shown in Table 6. In the peak and off-peak seasons, the logistics enterprise's demand information for goods at different temperature layers is shown in Table 7. When goods flow between different entities, the operating parameters of loading tools correspond to different transportation modes, as shown in Table 8. The location information between the logistics enterprise and corresponding distributors is shown in Table 9. The main parameter settings are presented in Table 10.

Table 5. Cold chain logistics off-peak and peak season distributor fixed demand

Entities			Peak season	Off-peak season	$[T_1, T_2]$	$[T'_{1h}, T'_{2h}]$
g	*h*	*f*	$q^f_{1h}(kg)$			
1	1	1	9648	3216	[9:00, 10:00]	[8:30,10:30]
		2	8004	2668		
		3	25728	8576		
1	2	1	4200	1400	[9:00, 10:00]	[8:30,10:30]
		2	2100	700		
		3	11400	3800		
1	3	1	5700	1900	[9:00, 10:00]	[8:30,10:30]
		2	2880	960		
		3	15360	5120		
2	4	1	8835	2945	[12:00,13:00]	[11:30,13:30]
		2	4875	1625		
		3	26340	8780		
2	5	1	9360	3120	[12:00,13:00]	[11:30,13:30]
		2	5445	1815		
		3	23940	7980		
2	6	1	10470	3490	[12:00,13:00]	[11:30,13:30]
		2	5220	1740		
		3	28050	9350		

Table 6. Cold chain logistics off-peak and peak season distributor dynamically demand

h	f	Peak season	Off-peak season	T_0
		ω^f_{1h}(kg)		
1	1	235	705	9:00
	2			
	3			
2	1			9:00
	2	275	825	
	3			
3	1			9:00
	2			
	3	795	2385	
4	1			11:00
	2	825	2475	
	3			
5	1	250	750	11:00
	2			
	3			
6	1			11:00
	2	180	540	
	3			

Table 7. Demand and warehousing situation at the supply node

Period	**temperature layer**	**Supply quantity at node m(kg)**	**Storage capacity at node m (kg)**
peak season	1	97300	121625
	2	59608	74510
	3	789678	987098
off-peak season	1	35020	43775
	2	26696	33370
	3	275946	344932

Table 8. Operational Parameters of loading tools for different transportation modes

Tools	*Rated load capacity*	*full-load factor*	*Transportation cost*	*Speed*	*fuel consumption*
container	20t	95%	0.0553RMB/(t·km)	55 km/h	0.05L/(t*km)
Refrigerator truck	34t 17t	95%	1RMB/(t·km)	80 km/h	20L/(100km) 18L/(100km)
common truck	18t 10t	/	25RMB/km	30 km/h	/

Table 9. Location information of demand nodes (unit: km)

depot	*Coordinate*
g=1	(1.4, 2.0)
g=2	(21.3, 24.5)
h=1	(11.6, 16.1)
h=2	(12.6, 11.8)
h=3	(14.1, 14.4)
h=4	(37.2, 35.8)
h=5	(49.8, 55.0)
H=6	(41.2, 48.4)

Note: Customers 1, 2, and 3 are serviced by logistics company g=1, while customers 4, 5, and 6 are serviced by logistics company g=2.

Table 10. Location information of demand nodes

Symbols		*Unit*	*Value*		*Symbols*		*Unit*	*Value*
d^a_{mn}		Km	271		$\overline{V_{zl}}$		Kw/h	182
d^o_{mn}		Km	285		$\overline{f_{ld}}$		Kg/t	500
θ^1_m		None	100%		$\overline{f_{bz}}$		Kg/t	500
G^f_b	*b=1*	Kg	*f=1*	4140	P		kw	60
			f=2	2700	σ		None	0.002
			f=3	11160	$t^{k_b}_l$		min	15
	b=2		*f=1*	2300	ρ_0		L/100km	16.5
			f=2	1500	μ		L/(t·100km)	11
			f=3	5580	P_d		tCO2/(kw·h)	0.853
C_f	*f=1*	RMB/t	2500		ρ_0		L/(100km)	16.5
					ρ_f	*f=1*	Kg/m3	350
	f=2		4500			*f=2*		1000
						f=3		400
	f=3		8000		β^f_b		None	0.8
c_d	*d=1*	Rmb/(m^2·mth)	38.2		z_g		times	1.2
	d=2		97.9		θ^2_m		None	80%
	d=3		93.36					

4.3. **Optimized results.** Based on the IoT-based sharing mode, the unified optimization results for facility and equipment configuration throughout the cold chain logistics process are shown in Figure 3 for the off-peak season and Figure 4 for the peak season. From these figures, representative points A, B, C, D, and E are selected to provide specific facility and equipment configuration optimization solutions.

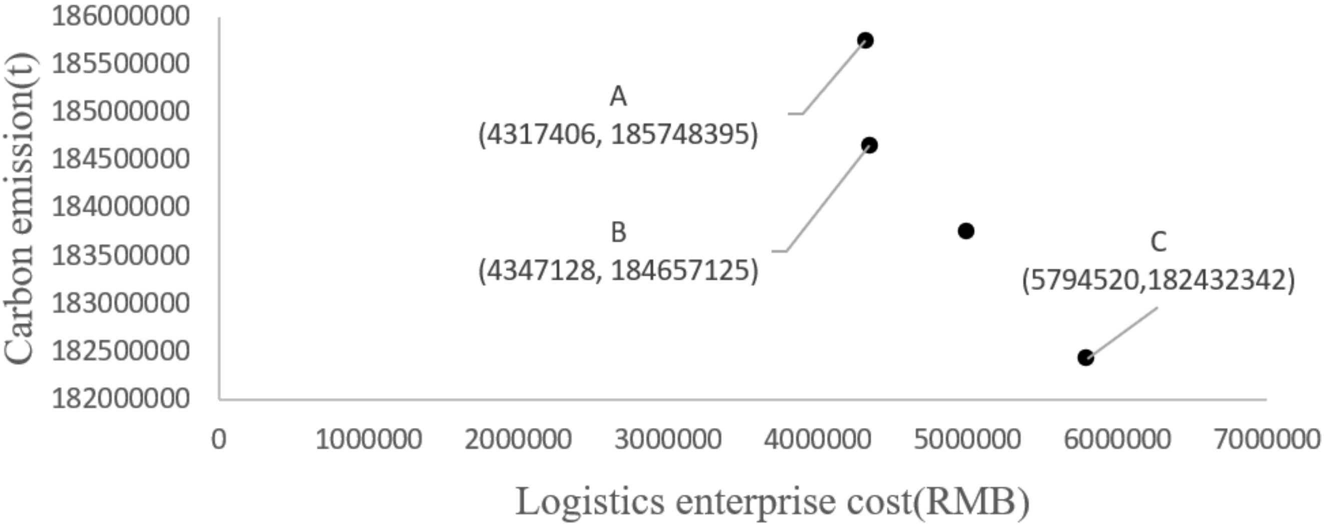


Figure 3. Optimization results in off-peak season

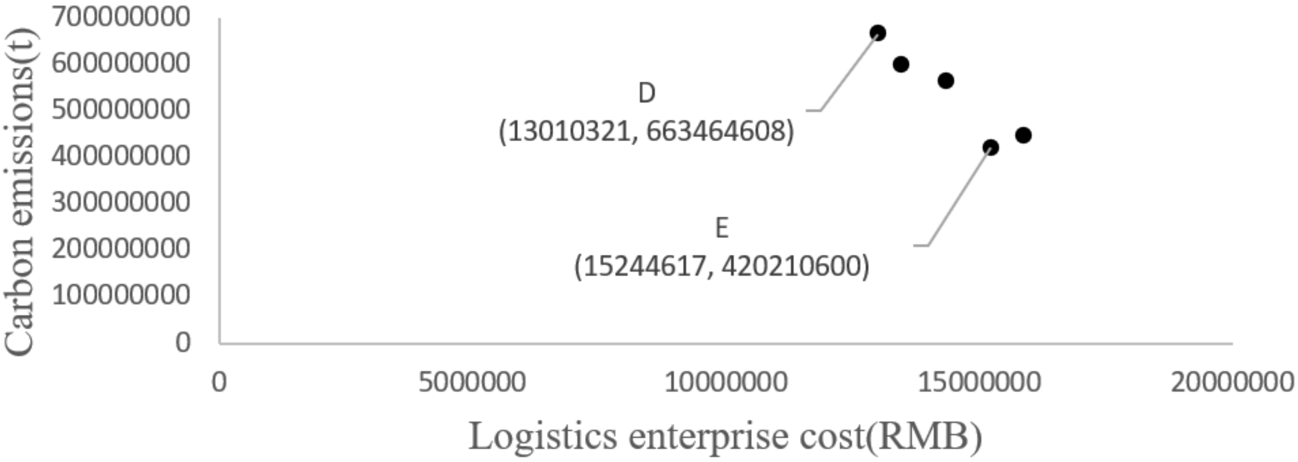
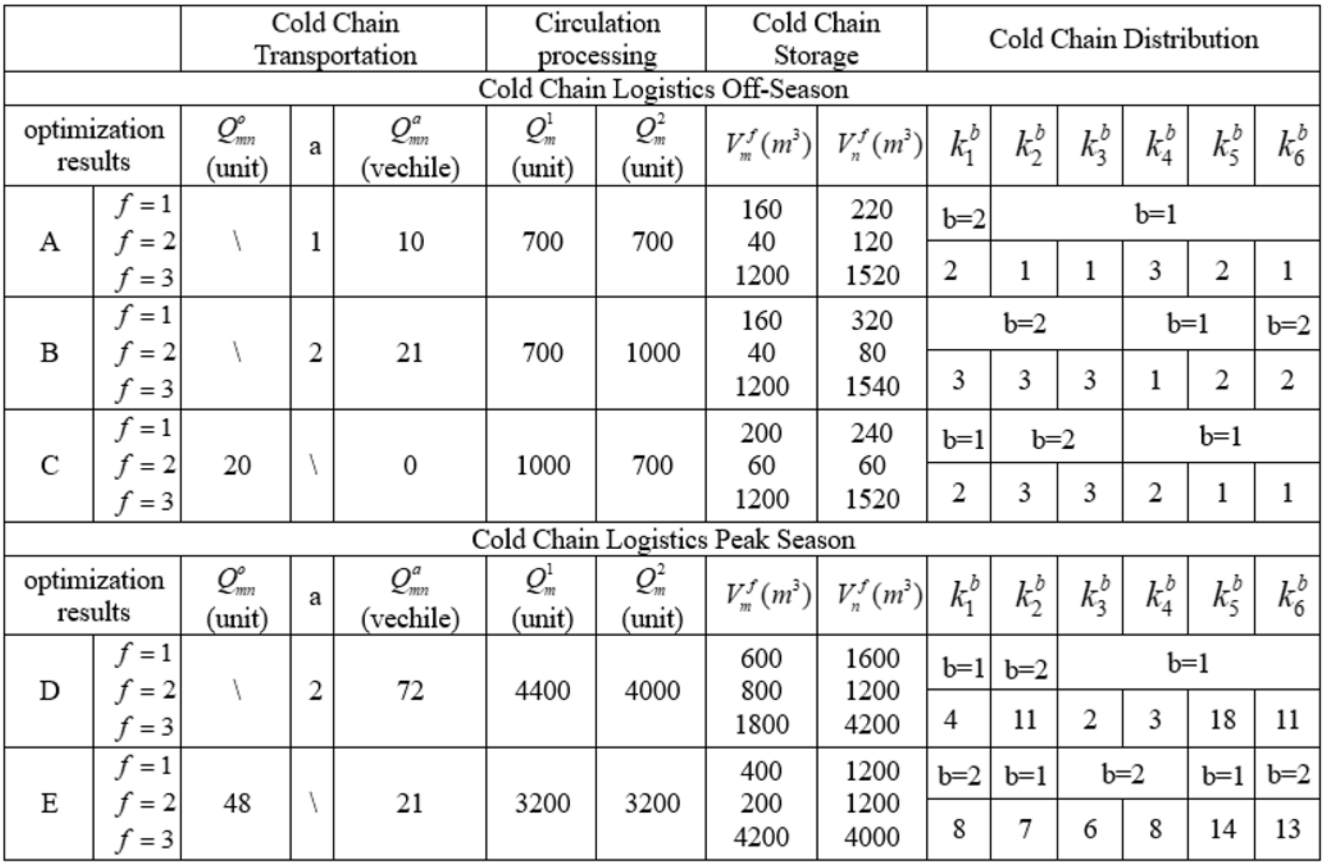


Figure 4. Optimization results in peak season



		Cold Chain Transportation			Circulation processing		Cold Chain Storage		Cold Chain Distribution					
Cold Chain Logistics Off-Season														
optimization results		Q_{mn}^{o} (unit)	a	Q_{mn}^{a} (vechile)	Q_{m}^{1} (unit)	Q_{m}^{2} (unit)	$V_{m}^{f}(m^3)$	$V_{n}^{f}(m^3)$	k_1^b	k_2^b	k_3^b	k_4^b	k_5^b	k_6^b
A	$f=1$ $f=2$ $f=3$	\	1	10	700	700	160 40 1200	220 120 1520	b=2	b=1				
									2	1	1	3	2	1
B	$f=1$ $f=2$ $f=3$	\	2	21	700	1000	160 40 1200	320 80 1540	b=2			b=1		b=2
									3	3	3	1	2	2
C	$f=1$ $f=2$ $f=3$	20	\	0	1000	700	200 60 1200	240 60 1520	b=1	b=2		b=1		
									2	3	3	2	1	1
Cold Chain Logistics Peak Season														
optimization results		Q_{mn}^{o} (unit)	a	Q_{mn}^{a} (vechile)	Q_{m}^{1} (unit)	Q_{m}^{2} (unit)	$V_{m}^{f}(m^3)$	$V_{n}^{f}(m^3)$	k_1^b	k_2^b	k_3^b	k_4^b	k_5^b	k_6^b
D	$f=1$ $f=2$ $f=3$	\	2	72	4400	4000	600 800 1800	1600 1200 4200	b=1	b=2	b=1			
									4	11	2	3	18	11
E	$f=1$ $f=2$ $f=3$	48	\	21	3200	3200	400 200 4200	1200 1200 4000	b=2	b=1	b=2		b=1	b=2
									8	7	6	8	14	13

Figure 5. Configuration results of facilities and equipment for cold chain logistics

4.4. **Analysis.** To demonstrate the superiority of the fully shared facility and equipment mode, Table 12 provides a comparative analysis of the cold chain logistics resource allocation quantity or scale, transportation cost generated by shared or self-purchased vehicles, and storage cost generated by shared or self-built cold storage facilities between the fully shared model and the single cold chain logistics resource sharing model during peak and off-peak seasons. The self-built cold storage considers construction costs, electricity expenses, equipment investment, depreciation fees, labor costs, and other expenses, while the self-purchased vehicles consider procurement, labor, depreciation, and other costs.

Table 11. Comparative Analysis

(a) Off-peak season

Mode	*vehicles configured (veh)*	*Cold storage capacity (m3)*	*vehicles cost (RMB)*	*Storage cost (RMB)*	*Total Cost (RMB)*	*cost savings (%)*
Fully shared	*b=1* 3 *b=2* 9	*f=1* 480 *f=2* 120 *f=3* 2740	30657	114829	145486	86.55
Common truck	*b=1* 3 *b=2* 9	*f=1* 480 *f=2* 120 *f=3* 2740	30657	451085	481742	55.50
Refrigerated warehouse	*b=1* 3 *b=2* 11	*f=1* 480 *f=2* 120 *f=3* 2740	630500	114829	745329	31.09
Non-sharing	*b=1* 3 *b=2* 11	*f=1* 480 *f=2* 120 *f=3* 2740	630500	451085	1081585	\

(b) Peak season

Mode	*vehicles configured (veh)*	*Cold storage capacity (m3)*	*vehicles cost (RMB)*	*Storage cost (RMB)*	*Total Cost (RMB)*	*cost savings (%)*
Fully shared	*b=1* 3 *b=2* 9	*f=1* 2200 *f=2* 2000 *f=3* 6000	39852	350676	390528	87.80
Common truck	*b=1* 3 *b=2* 9	*f=1* 2200 *f=2* 2000 *f=3* 6000	39852	989381	1029233	67.85
Refrigerated warehouse	*b=1* 3 *b=2* 11	*f=1* 2200 *f=2* 2000 *f=3* 6000	2211500	350676	2562176	19.95
Non-sharing	*b=1* 3 *b=2* 11	*f=1* 2200 *f=2* 2000 *f=3* 6000	2211500	989381	3200881	\

As can be seen from the above results, the configuration of a cold chain logistics network considering the fully shared facility and equipment model is superior to a single facility and equipment configuration sharing mode. This not only reduces the number of logistics resources required within the cold chain logistics network but also lowers the operational costs for logistics companies.

5. **Conclusion and future work.** The unreasonable configuration of cold chain logistics facilities and equipment, high energy consumption, and high costs have made resource allocation a pressing issue. This study proposes the "Configuration Optimization of Cold Chain Logistic Network with Fully Shared Facilities and Equipment" to achieve better resource allocation optimization. Firstly, the premise of full sharing is introduced, which involves establishing a cold chain logistics resource sharing platform, leveraging 4PL supply chain management, and specialized facilities and equipment configuration by 3PLs. Secondly, a dual-objective optimization model is built based on a unified optimization method to minimize logistics company operating costs and carbon emissions. The NSGA II intelligent algorithm is applied for solution generation. Finally, a comparative analysis is conducted under multiple scenarios, considering indicators such as the number of vehicles, cold storage construction volume, transportation costs, warehousing costs, vehicle acquisition costs, cold storage construction costs, and idle rates, to demonstrate the superiority of this model.

This study provides some reference for the optimization of cold chain logistics facility and equipment configuration, promoting the development of cold chain logistics towards low cost, low carbon emissions, and high efficiency. It also enables logistics companies to effectively reduce upfront investment risks.

However, there are still some unreliable factors in the actual sharing of logistics resources. By establishing a cold chain logistics sharing platform, dynamic communication or feedback of demand information can be achieved among the parties involved. Logistics companies and 3PL will also sign agreements to ensure the timely delivery of shared vehicles, enhance customer satisfaction, and ensure the long-term development of logistics companies and 3PLs alike.

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