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Research on origin-based cold storage location and routing optimization of fresh agricultural products based on hybrid whale algorithm

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With the focus on the insufficient origin-based cold storage in China, this study investigates the location and routing problem (LRP) of origin-based cold storage for fresh agricultural products. This study considers the loss of fresh agricultural products in different environments during transportation and presents a cold storage LRP model. To address this issue, a hybrid whale algorithm with heuristic rules is designed, and the effectiveness of the algorithm is verified by standard instances. Finally, taking Chenggu County as a practical case, the influence of cold storage capacity and farmers' demand for refrigeration are analysed. Experimental results show that the proposed algorithm has a good effect in solving medium-scale LRP. As the storage capacity increases, the total cost of the system can be increased by 0.086%. As farmers' demand for refrigeration increases, the total cost of the system can be increased by 34.034%. Farmers' demand has a greater impact on the system's total costs than the cold storage capacity. When optimizing the cold storage layout, changes in fresh agricultural product output in the next few years can be roughly predicted, and the most economical optimization scheme can be obtained.

Keywords LRP, Hybrid whale algorithm, Origin-based cold storage, Fresh agricultural products

With the upgrading of urban and rural residents' consumption, people's demand for fresh agricultural products is increasing. People's requirements for the freshness and timeliness are also increasing. Cold chain logistics is the key to improve the quality of fresh agricultural products and effectively losses. Cold chain logistics in urban areas of China have significantly advanced technology and services. However, there are still many problems in the cold chain of fresh agricultural products in rural areas, restricting the upward movement of fresh agricultural products. The origin-based cold storage is the core node of the origin-based cold chain. However, the number of origin-based cold storage facilities in China is insufficient, and the problem of resource imbalance is prominent. Owing to the lack of a cold chain of origin, the cold chain disconnection is easy to occur in each link of fresh agricultural products "the first kilometer". Large changes in temperature lead to an increased decay risk in the storage and transportation of fresh agricultural products, which easily leads secondary accidents. According to statistics, the loss rate of fruits, vegetables, and potatoes in China is as high as 15–25%, with an annual loss of nearly 200 million tons[1]. At the same time, fresh agricultural products are listed in the mature peak season, which is restricted by the cold storage capacity of fresh agricultural products. The problems of "difficult sale" and seasonal fluctuation of prices are prominent, and the situation of increasing farmers' production without increasing their income occurs from time to time. Therefore, the construction of origin-based cold storage has important practical significance.

The construction of origin-based cold storage is a strategic issue. Once completed, it cannot be changed in a short period of time. Unreasonable cold storage locations not only reduce turnover rates, but also increase the operating costs of origin-based cold storage. Second, unreasonable transportation routes for refrigerated trucks will increase the transportation cost and increase the loss of agricultural products[2]. In previous studies, the location allocation problem[3] (LAP) and the vehicle routing problem[4] (VRP) were commonly discussed separately.

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Herein, the location and routing collaborative optimization of the cold storage is based on the characteristics of perishable and high demand timeliness of fresh agricultural products, combined with two NP-hard problems. Through the location and routing coordination optimization of cold storage, the cold chain of origin layout is improved, the cold chain transportation efficiency is improved, and the loss rate of fresh agricultural products is reduced. It is of great significance to promote farmers' income and increase the added value of fresh agricultural products.

Many scholars have conducted in-depth research on location and routing problem (LRP). Niu et al.[5] studied the optimization of the location of waste treatment centers and the garbage collection path, and established a three-objective optimization model to achieve a balance between total cost, carbon emissions, and residents' satisfaction. At present, the research object of this problem has been extended to many aspects, but few studies have focused on "the first kilometer" origin-based cold storage. In addition, most of the existing studies have neglected the consideration of the loss of fresh agricultural products. For farmers with small and scattered demand for refrigeration, the LRP of origin-based cold storage is more complicated and requires further studies. Therefore, this study aims at the new scenario of "the first kilometer" origin-based cold storage service for scattered farmers, considering multiple factors such as cold storage capacity, fuel consumption, vehicle load, time window constraints, and fresh agricultural product loss and establishes an origin-based cold storage LRP model. The decision variables include the location of the cold storage, the farmers served by the cold storage, and the routing of farmers served by refrigeration trucks. The objective function is the system total cost after considering the above factors, such as the cold storage location (construction and operation), transportation, damage, refrigeration, and penalty costs. Moreover, a hybrid whale algorithm is designed to support the model.

The main innovations and contributions are as follows: (1) Focusing on "the first kilometer" origin-based cold storage as the research object, the LRP of the origin-based cold storage is studied; (2) the loss of fresh agricultural products in different environments during transportation is considered in detail, and the minimum loss cost is optimized as the objective function; (3) considering the time window constraints of farmers, the actual high requirements of farmers for the timeliness of fresh agricultural products after being picked must be meet; and (4) according to the characteristics of the model, a hybrid whale algorithm is designed. By designing chromosomes that can express all decision information and developing corresponding initialization and search strategies, the integrated optimization of location and routing is realized. Finally, through the practical case and sensitivity analyses, the validity of the model and algorithm is verified, and the influence of the change in cold storage capacity and farmers' demand on the results is analyzed, providing management significance and practical enlightenment for the cost reduction and efficiency increase of cold storage operators in the producing area.

The remainder of this study is organized as follows: "Literature review" section reviews the existing related literature. In "Model development" section introduces the origin-based cold storage location and routing optimization model of fresh agricultural products. In "Algorithm design" section describes a hybrid whale algorithm and presents its effectiveness verification through standard instances. In "Practical case application" section presents the actual data as a practical case to verify and puts forward relevant suggestions. In "Conclusion" section concludes the study and outlines future works.

Literature review

Regarding the origin-based cold storage LRP of fresh agricultural products in this study, the research work is summarized in the following three aspects:

(1) Cold chain of fresh agricultural products.

Nowadays, the logistics industry is rapidly developing, and the cold chain logistics of agricultural products has become the focus of the industry. Therefore, some scholars have studied this problem. For instance, Chunrong and Katarzyn[6] studied the optimization of the cold chain distribution route of urban agricultural products from the perspective of low carbon. They proposed the joint distribution mode of agricultural products under low carbon to reduce the circulation level of agricultural products and the impact of cold chain distribution activities on the environment. When Liu and Hou[7] studied the distribution of fresh agricultural products in urban areas, they optimized the freshness of the agricultural products at delivery, the maximum distribution distance, and the limited cold chain logistics budget as three-objective functions. The results indicated that the ability to accurately predict and control the freshness through the distance range can reduce the occurrence of customer complaints about the quality of the delivered products. Zhu et al.[8] studied the problem of "the first kilometer" cold chain logistics network design of fresh agricultural products under government subsidies. They designed effective solutions to this problem, providing management inspiration for managers. Tao[9] took the necessity of sinking the cold chain logistics service network of agricultural products as the starting point. Focusing on Jiangsu as an actual case, she analyzed the problems existing in the sinking of Jiangsu agricultural products cold chain logistics service network into rural areas. In addition, she proposed countermeasures to solve the problems, which promoted the development of cold chain logistics for Jiangsu agricultural products. Moreover, Zhang and Ding[10] determined that the cold chain logistics of fresh agricultural products in China presents the origin paradox of "the cold chain of origin is weak, the policy support is increased, the farmers do not use the cold chain, which leads to the origin weaker." The mechanism and internal reasons of the origin cold chain paradox are systematically analyzed, and the countermeasures and suggestions to promote the development of the origin cold chain are put forward. Furthermore, Xie[11] constructed a cold chain logistics mode of fresh agricultural products from "the first kilometer" to "the last kilometer". In addition, the links in this mode were analyzed. Hence, establishing a combined distribution network of production warehouse and sales warehouse is important to realize the standardization and scale of the agricultural product supply chain.

(2) LRP

LRP has always been one of the popular topics in academic research. LRP has been applied to emergency rescue[12,13], reverse logistics[5,14], green logistics[15,16], electric vehicle charging facility layout[17,18], medical waste recycling[19,20], and other fields. Peng[21] considered multiple fuzzy factors and introduced a customer fuzzy time window with variable coefficients, and established a multiobjective set allocation integrating a multilevel LRP model. She proposed an archive-type multiobjective simulated annealing improvement algorithm based on master–slave parallel framework embedded tabu search to solve the model. The experimental results demonstrate the preciseness and reference significance of the multilevel LRP model with multiple fuzzy factors. Wang et al.[22] discussed the problems of large greenhouse gas emissions in "the last mile" logistics distribution activities of rural logistics and the shortage of electric vehicles with respect to endurance mileage and carrying capacity. The planning problem of county-rural three-level logistics distribution network considering dynamic and static carbon emissions and oil-electric hybrid fleet configuration was studied, and an innovative two-stage hybrid algorithm was proposed to address it.

In addition, there are some scholars studying the LRP of fresh product cold chain industry. For instance, Zhang et al.[23] focus on the fresh cold chain prewarehouse as the research object and proposed a new comprehensive cost calculation method of carbon emissions. They analyzed the prewarehouse mode under the background of energy conservation and emission reduction. Ding and Chen[24] began by constructing a fresh logistics network and studied the spatial layout of the nodes of fresh and cold chain distribution centers. The decision-making factors have three aspects: node location, routing planning, and inventory control. Considering that the demand is difficult to determine, an integrated optimization model of the location-routing-inventory under fuzzy random demand is constructed. Fu and Tang[25] proposed applying a "high-speed rail + cold chain logistics" as a mode to transport fresh agricultural products. Focusing on high-speed rail freight, the LRP model of cold chain logistics distribution centers for fresh agricultural products with the lowest total cost and the best routing was constructed. Liu et al.[26] constructed a bi-objective model of cold chain logistics LRP based on the lowest logistics comprehensive cost and carbon emission by focusing on the cold storage self-pickup cabinet facilities of fresh e-commerce in the "to cabinet" mode as the research object.

The above research objects are all conducted in urban areas. There are few research results on the LRP of fresh agricultural products cold chain industry in rural areas. Most scholars studied from the LAP or VRP. For instance, Liang et al.[2] studied the LAP of cold storage with the goal of improving the satisfaction of e-commerce farmers. Ma and Wang[1] considered the loss of fresh agricultural products in "the first kilometer" process in the study of precooling station location, and considered the number, location, type, and capacity of precooling stations as decision variables. Wang et al.[27] focus on the postharvest grading and precooling of fresh agricultural products as the research object. In addition, they comprehensively considered unique collaborative scenarios such as the optimal precooling time of fresh agricultural products and the service order of precooling after grading. The collaborative scheduling optimization model of mobile hierarchical precooling resources is constructed. Zhang et al.[28] used the maximum coverage model to rationally plan the locations of precooling stations in concentrated areas of agricultural production bases in Xinxiang City, Henan Province. Moreover, they combined the entropy weight method to improve the traditional maximum coverage model to optimize the location layout of precooling stations. Ge and Zhang[29] predicted the collection demand of farmers, proposed a proactive scheduling strategy, and optimized the logistics collection routing of fresh products based on this strategy. Li et al.[30] combined the characteristics of agricultural product production and precooling in villages and towns in China. In addition, they proposed a coordinated precooling mechanism that comprehensively applied two precooling modes of fixed facilities and mobile facilities. Moreover, they constructed a multitype precooling facility LRP model for agricultural products in villages and towns. Considering the maximum pre-cooling delay time, an improved genetic algorithm (GA) was designed to solve the model according to its characteristics. The research results have important theoretical significance and practical value for the optimization of multitype precooling service network layout in villages and towns in China.

(3) Algorithms for the LRP.

LRP is a combination of two NP-hard problems: LAP and VRP. At present, many scholars have applied various heuristic algorithms to solve LAP and VRP. For instance, Ricardo et al.[31] used computational recursive switching techniques to optimize the placement of fixed-point vaccination sites. Moreover, they compared the predicted participation with the best-placed vaccination sites with the actual locations used in previous activities, providing the best solution by minimizing the average walking distance or maximizing the expected participation algorithm. Quan et al.[32] proposed an improved differential search algorithm by combining a learning strategy and a dynamic Cauchy mutation strategy to solve the pollution VRP of logistics distribution in an open medical consortium. Yilin et al.[33] used solutions based on deep neural networks and non-DNN solutions (sweep algorithm) to solve the VRP, and compared the results, indicating that deep reinforcement learning can provide more efficient solutions for decision-makers.

For the solution of the LRP, most scholars use a two-stage method to reduce the complexity of the problem[34,35]. In the process of solving the LRP, if the facility location problem and the VRP are solved separately, the problem will lose the essence of the overall optimization. Therefore, this study will solve the LRP of the origin-based cold storage of fresh agricultural products from the perspective of joint optimization. LRP is a NP-hard problem, and most scholars use heuristic algorithms to solve it, such as GA[30,36], particle swarm optimization algorithm[37,38], ant colony algorithm[39,40], neighborhood search algorithm[41,42], and so forth.

The whale optimization algorithm (WOA)[43] was used by some scholars to solve the LAP or VRP owing to its few parameters, simple structure and strong search ability. For instance, Hui et al.[44] designed an improved genetic whale optimization algorithm that combines the crossover and mutation ideas of GA, and proposes a whale individual position update mechanism under a hybrid strategy. The algorithm is used to solve the VRP of ship segment transportation task. Pham et al.[45] combined WOA with gray wolf optimization algorithm and proposed a hybrid whale optimization algorithm to solve VRP. Xiao et al.[46] and Cai and Du[47] used the WOA to solve the VRP of AGV and unmanned vehicles. Moreover, Liang et al.[48] utilized the WOA to solve the LAP of electric vehicle charging facilities.

(4) Research gap.

By studying the literature on the three research directions, namely, cold chain of fresh agricultural products, LRP, and algorithms for the LRP, there are some research gaps: (1) In the field of cold chain logistics of agricultural products, there has been an extensive qualitative analysis of the operation mode, management strategy, and policy support of cold chain logistics. However, quantitative research on "the first kilometer" of agricultural product cold chain is relatively scarce. This link is directly related to the initial quality of agricultural products and the efficiency of the subsequent supply chain. The existing literature rarely considers the loss of agricultural products, which is an important problem to be solved upstream of agricultural products. Therefore, it is important to quantitatively analyze the process of fresh agricultural products from the field to the cold storage, such as the time and cost-effectiveness of precooling, packaging, loading, and other links, and to consider the perishable characteristics of fresh agricultural products. (2) With respect to LRP, although the existing literature has widely discussed the LRP optimization strategies in different application scenarios, the research objects of cold chain logistics of fresh agricultural products are mainly concentrated in urban areas; hence, the attention to rural areas is insufficient. The construction of cold chain logistics facilities and the optimization of service networks in rural areas are of great significance for improving the overall efficiency of agricultural product supply chain and ensuring food safety. Therefore, future research should pay more attention to the LRP of cold chain logistics in rural areas. In addition, in the existing research on LRP, few studies have focused on "the first kilometer" origin-based cold storage as the research object. As the key node of cold chain logistics of fresh agricultural products, the location and routing decision of cold storage directly affect the preservation effect and logistics cost of fresh agricultural products. Therefore, it is an important direction of future research to study the LRP optimization model of cold storage and consider location decisions under various constraints. (3) With respect to algorithm research, the whale algorithm, as a new optimization algorithm, has achieved initial results in the application of LAP or VRP; however, there are few studies on joint optimization problems. In addition, the whale algorithm has some drawbacks in practical applications, such as the local optimal solution problem and the limitation of convergence speed. Therefore, it is an important direction of future research to improve the computational efficiency and optimization performance of the algorithm by introducing new heuristic strategies, improving the search mechanism of the algorithm or combining with other optimization algorithms.

In summary, this study aims to fill the forementioned research gaps. Through in-depth research on the LRP of cold storage in rural areas and considering the loss of agricultural products, as well as the improvement of WOA, the theory and practice of LRP of cold storage in fresh agricultural products in rural areas are promoted, with the main innovations and contributions are as follows: (1) Focusing on "the first kilometer" origin-based cold storage as the research object, the LRP of the origin-based cold storage is studied; (2) the loss of fresh agricultural products in different environments during transportation is considered in detail, and the minimum loss cost is optimized as the objective function; (3) considering the time window constraints of farmers, the actual high requirements of farmers for the timeliness of fresh agricultural products after being picked must be meet; and (4) according to the characteristics of the model, a hybrid whale algorithm is designed. By designing chromosomes that can express all decision information and developing corresponding initialization and search strategies, the integrated optimization of location and routing is realized. Finally, through the practical case and sensitivity analyses, the validity of the model and algorithm is verified, and the influence of the change in cold storage capacity and farmers' demand on the results is analyzed, providing management significance and practical enlightenment for the cost reduction and efficiency increase of cold storage operators in the producing area.

Model development

Problem description

This study focuses on "the first kilometer" origin-based cold storage service for scattered farmers as the research object, and studies the LRP of origin-based cold storage with a time window. Figure 1 presents the location and routing optimization diagram of the origin-based cold storage. In a rural area, there are several alternative cold storage points with known locations and several farmer services points with known locations, refrigeration demands and service time window requirements. From the cold storage operator's perspective, at least one suitable location is selected from the alternative cold storage points to construct the cold storage. Under the condition of satisfying the load capacity and time window limit, the collection routing planning of each refrigerated truck was conducted, and the loss of fresh agricultural products was subdivided into each link of the transportation process for calculation and optimization as one of the objective functions. Finally, the total system costs of the origin-based cold storage are reduced, and the refrigeration demand of fresh agricultural products at multiple farmer service points within the origin-based cold storage is met.

Model assumptions

In order to facilitate the analysis of origin-based cold storage LRP, the following assumptions are made:

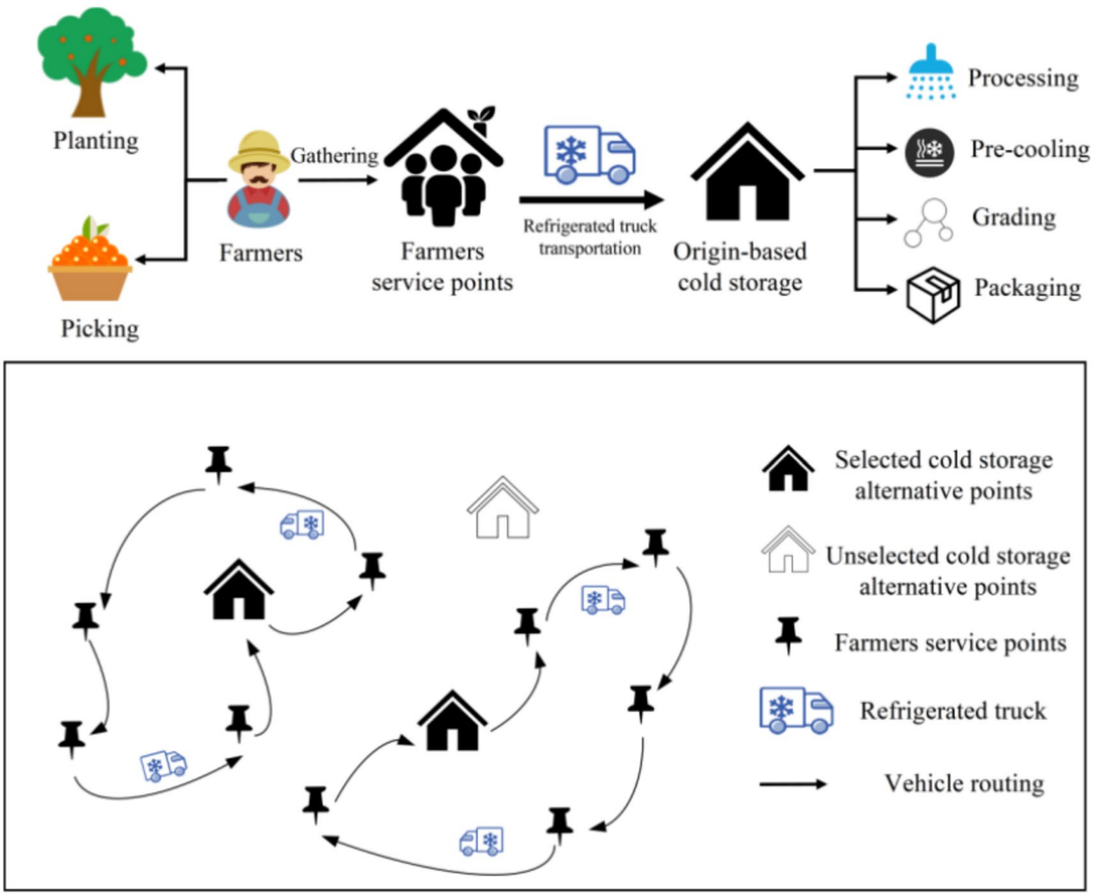


Fig. 1. Location and routing optimization diagram.

(1) The location of the farmer service points (hereinafter referred to as the service points), the alternative points of the origin-based cold storage, and the refrigeration demands are determined, and each service point can only be served by one cold storage.
(2) The origin-based cold storage cannot meet the large demand of service points without restriction, so the origin-based cold storage has a capacity limit.
(3) The speed of a vehicle during transportation is determined and fixed. Each vehicle can start from only one origin-based cold storage and return to the original cold storage after serving all the service points on the route.
(4) Each route is served only by a single vehicle, and any service point only has one vehicle through.
(5) The load of the vehicle in any route arc is less than or equal to the vehicle capacity.

This study sets the following parameters and variables, as shown in Table 1.

Model construction

According to the problem description and model assumptions, the cold storage operator should select at least one of the alternative points of the cold storage to construct the origin-based cold storage, which needs to consider factors such as distance, demands, and loss of fresh agricultural products. Simultaneously, the service relationship between cold storage and service points is determined, and the reasonable planning of the collection routing is conducted to meet the needs of all service points. Finally, the model with the minimum total system costs of cold storage is constructed. The total system costs of origin-based cold storage are location, transportation, damage, refrigeration and penalty costs.

Location Costs C_1: Location costs of the origin-based cold storage are composed of construction costs and operation costs. The location costs C1 in this model can be expressed as:

$$C_1 = \sum_{m=n'+1}^{n'+m'} X_m \left(C_s + 30pPC_o\right) \tag{1}$$

Transportation Costs C_2: Transportation costs are the costs spent in collecting fresh agricultural products. These include fixed and variable costs. The fixed costs are the purchase and maintenance costs of the

Type	Symbol	Description
Assembly	N	Set of farmers service point, N = {n|1, 2, …, n′}
	M	Set of origin-based cold storage alternative points, M = {m|n′ + 1, n′ + 2, …, n′ + m′}
	C	All points including origin-based cold storage alternative points and farmer service Points in the producing area, C = N ∪ M; the line between any two points is (i, j); i, j ∈ C; i ≠ j
	K	Set of refrigerated vehicle, K = {k|1, 2, …, k′}
	R	Set of types of goods collected, R = {r|1, 2, …, r′}
Variable	X_m	0–1variable, X_m equals 1 when alternative point m is selected as the origin-based cold storage, otherwise equals 0
	$X_{i,j}^k$	0–1variable, $X_{i,j}^k$ equals 1 when vehicle k from point i drive to point j, otherwise equals 0
	X_i^m	0–1variable, X_i^m equals 1 when the service point i is met by alternative cold storage m, otherwise equals 0
Parameters	C_s	Construction costs of origin-based cold storage
	C_o	Operating costs of origin-based cold storage
	Vol	Storage capacity of origin-based cold storage
	Cap	Capacity of refrigerated truck
	F_c	Purchase costs of refrigerated truck
	F_w	Maintenance costs of refrigerated truck
	F_x	Fuel consumption costs per unit distance of refrigerated truck
	d_{ij}	Distance between point i and point j
	Q_i^r	The volume of goods r at point i
	P_r	The unit price of goods r
	∂_1^r	The corruption rate of goods r in the process of transportation
	∂_2^r	The corruption rate of goods r in the process of opening the door
	t_i	The service time of point i
	$t_{i,j}$	The time of vehicle from point i to point j
	v	Vehicle running speed
	P_{zl}	Refrigeration costs per unit time
	Q_1	The heat transfer from outside the carriage to inside
	Q_2	The heat Q2 transfer into the carriage through solar radiation
	Q_3	The heat transfer into the carriage when opening the door
	U	Heat transfer coefficient of refrigerated compartment from outside to inside
	S	Exterior area of the carriage body
	Sc	Refrigerated trucks door area
	To	The temperature outside the carriage, often take the highest temperature of the environment
	T_i	The temperature inside the carriage
	ΔT	The temperature difference between inside and outside of refrigerated truck carriage, $\Delta T = T_o - T_i$
	t	Product cooling time
	S_i	The time when the vehicle arrives at point I; $S_j = S_i + t_i + t_{ij}$
	S_0	The time when the vehicle starts from the cold storage
	(E_i, L_i)	Time window required by point i
	ε	Penalty costs earlier than the time window
	ϕ	Penalty costs later than the time window
	p	Number of months for picking and harvesting in a year
	P	Operation accounting period

Table 1. The meaning table of parameters and variables.

transportation vehicle, and the maintenance costs are the maintenance and repair costs of vehicle. The variable costs under constant speed are vehicle fuel costs, which are proportional to distribution distance.

$$\text{The fixed costs} = \sum_{k=1}^{k'} (F_c + F_w P) \tag{2}$$

$$\text{The variable costs} = \sum_{k=1}^{k'} \sum_{i=1}^{n'} \sum_{j=1}^{n'} F_x d_{ij} X_{i,j}^k 30pP \tag{3}$$

$$C_2 = \sum_{k=1}^{k'} \left[F_c + F_w P + \sum_{i=1}^{n'} \sum_{j=1}^{n'} F_x d_{ij} 30pPX_{i,j}^k \right] \tag{4}$$

Damage Costs C_3: Owing to the perishable nature of fresh agricultural products, with the extension of time and the influence of external heat, temperature in the carriage of transport vehicles changes, and the quality of fresh agricultural products will decline, which is irreversible. Therefore, there will be certain damage costs associates with the transportation process. Fresh agricultural products will possibly two types of damage during transportation. The first is the damage caused by time accumulation during transportation, and the second is the damage caused by the sudden increase of temperature, such as by opening the door when the transport vehicle is at the service point, reducing the freshness of the agricultural products.

This study introduces the corruption function of fresh agricultural products to measure the costs of damage: $\varphi(t) = \varphi_0 e^{-\partial t}$;

In the formula: $\varphi(t)$ is the quality of fresh agricultural products at time t; φ_0 is the initial quality of fresh agricultural products; ∂ is the corruption rate, and its value is related to the characteristics of the product itself, so the corruption part of the fresh product quality is $\varphi_0\left(1 - e^{-\partial t}\right)$.

The damage costs of time accumulated =

$$\sum_{r=1}^{r'} \sum_{i=1}^{n'} \sum_{j=1}^{n'} \sum_{k=1}^{k'} P_r Q_i^r \left(1 - e^{-\partial_1^r t_{i,j}}\right) X_{i,j}^k 30pP \tag{5}$$

The damage costs of opening the door =

$$\sum_{r=1}^{r'} \sum_{i=1}^{n'} \sum_{j=1}^{n'} \sum_{k=1}^{k'} P_r Q_i^r \left(1 - e^{-\partial_2^r t_i}\right) X_{i,j}^k 30pP \tag{6}$$

$$C3 = \sum_{r=1}^{r'} \sum_{i=1}^{n'} \sum_{j=1}^{n'} \sum_{k=1}^{k'} P_r Q_i^r 30pP \left[\left(1 - e^{-\partial_1^r t_{i,j}}\right) + \left(1 - e^{-\partial_2^r t_i}\right) \right] X_{i,j}^k \tag{7}$$

Refrigeration Costs C_4: Refrigerated carriages will bear heat load during products transportation; hence, it will produce refrigeration costs. These costs are generated during the transportation process, from the origin-based cold storage to the product consolidation task. The refrigeration costs are determined by the heat Q_1 transfer from the outside to the inside of the carriage and the heat Q_3 transfer into the carriage when opening the door.

$$Q_1 = US(T_0 - T_i)t \tag{8}$$

The simplified formula $Q_2 = \beta Q_1$ is often used in the actual calculation of the heat Q_2 transfer into the carriage through solar radiation, where β is a scale factor, β = 0.1 in the area with general sunshine intensity, and β = 0.2 in the area with strong sunshine intensity.

The heat Q_3 transfer into the carriage when opening the door is generated by convection of cold and hot air during loading. Because the cold and hot air are in direct contact, there is no heat transfer coefficient U, and the heat transfer area is the area of the door S_c.

$$Q_3 = S_c(T_0 - T_i)t \tag{9}$$

The refrigeration costs in transportation process =

$$\sum_{i=1}^{n'} \sum_{j=1}^{n'} \sum_{k=1}^{k'} P_{zl}(1+\beta)US\Delta T t_{i,j} 30pPX_{i,j}^k \tag{10}$$

The refrigeration costs of door opening process =

$$\sum_{i=1}^{n'} \sum_{k=1}^{k'} P_{zl} S_c \Delta T t_i 30pPX_i^k \tag{11}$$

$$C4 = \sum_{i=1}^{n'} \sum_{k=1}^{k'} P_{zl} \Delta T 30pP \left[\sum_{j=1}^{n'} (1+\beta)USt_{i,j} X_{i,j}^k + S_c t_i X_i^k \right] \tag{12}$$

Penalty Costs C_5: The vehicle should reach the service points within a certain time period to ensure the quality of fresh agricultural products, and the penalty costs will be incurred before or after the farmer's service time window.

$$C5 = 30pP\left[\varepsilon\sum_{i=1}^{n'} max(E_i - S_i, 0) + \phi\sum_{i=1}^{n'} max(S_i - L_i, 0)\right] \tag{13}$$

Based on Eqs. (1)–(13), the optimization model of origin-based cold storage system is as follows:

$$\mathrm{MinC} = C_1 + C_2 + C_3 + C_4 + C_5 \tag{14}$$

Subject to

$$\sum_{m=n'+1}^{n'+m'} X_m \geq 1 \tag{15}$$

$$\sum_{i=1}^{n'} X_i^m = 1, \quad \forall m \in M \tag{16}$$

$$\sum_{k=1}^{k'}\sum_{i=1}^{n'} X_{i,j}^k = 1, \quad \forall j \in N \tag{17}$$

$$\sum_{r=1}^{r'}\sum_{i=1}^{n'} X_i^m Q_i^r \leq Vol, \quad \forall m \in M \tag{18}$$

$$\sum_{i=1}^{n'}\sum_{j=1}^{n'} X_{i,j}^k Q_i^r \leq Cap, \quad \forall k \in K \tag{19}$$

$$X_{i,i}^k = 0, \forall i \in C, \forall k \in K \tag{20}$$

$$\sum_{i=n'+1}^{n'+m'} X_{i,j}^k = 0, \quad \forall j \in M,\ \forall k \in K \tag{21}$$

$$\sum_{i=1}^{n'} X_{i,j}^k = \sum_{i=1}^{n'} X_{j,i}^k, \quad \forall j \in N,\ \forall k \in K \tag{22}$$

$$\sum_{j=n'+1}^{n'+m'}\sum_{i=1}^{n'} X_{i,j}^k \leq 1, \quad \forall k \in K \tag{23}$$

$$E_i \leq t_i \leq L_i, \quad \forall i \in N \tag{24}$$

$$X_m \in \{0,1\}, \quad \forall m \in M \tag{25}$$

$$X_{i,j}^k \in \{0, 1\}, \quad \forall i,j \in C,\ \forall k \in K \tag{26}$$

$$X_i^m \in \{0, 1\}, \quad \forall i \in N,\ \forall m \in M \tag{27}$$

In the above formula, constraint formula (14) indicates the minimum total system costs of the origin-based cold storage; constraint formula (15) indicates to build at least one origin-based cold storage; constraint formula (16) indicates that each service point is serviced by only one origin-based cold storage; constraint formula (17) indicates that each service point can only have one delivery vehicle to serve it; constraint formula (18) indicates that the total amount of agricultural products received by each origin-based cold storage does not exceed its maximum storage capacity; constraint formula (19) indicates that the total amount of agricultural products loaded by each refrigerated truck is less than the maximum capacity of the vehicle; constraint formula (20) indicates that there is no routing between the same origin-based cold storage and service points; constraint formula (21) indicates that there is no routing between different cold storages; constraint formula (22) indicates the balance constraint of vehicle entry and exit, and the vehicles arriving and leaving at each service point are the same; constraint formula (23) indicates that each vehicle has at most one service routing; constraint formula (24) indicates the service time window constraint; constraint formulas (25)–(27) are decision variable.

Algorithm design

WOA

The WOA simulates the unique search method and hunting mechanism of humpback whales, including three important phases: encircling prey, bubble-net attacking and searching for prey.

Encircling prey

The search range of the whale is the global solution space, and it is necessary to determine the location of the prey in order to surround it. Since the position of the optimal solution in the search space is unknown, the WOA algorithm assumes that the current optimal candidate solution is the target prey or close to the optimal solution. After defining the optimal whale position, other whales will attempt to update their position to the optimal whale. The position update formula is expressed by Eq. (29):

$$D = \left|C \cdot X^{*}(t) - X(t)\right| \tag{28}$$

$$X(t+1) = X^{*}(t) - A \cdot D \tag{29}$$

where A and C are coefficient vectors, X*(t) is the current optimal solution, X(t) is the individual, t is the current iteration number, | | is the absolute value.

The vector A and C are calculated as follows:

$$A = 2a \times r_1 - a \tag{30}$$

$$C = 2 \times r_2 \tag{31}$$

where a decreases linearly from 2 to 0 in the iterative process, r1 and r2 are random vectors in [0,1].

The selection of this phases depends on the parameter A and the probability p of the predator–prey mechanism, where p is a random number with a range of [0, 1]. For each individual, if $p < 0.5$ and $|A| < 1$, the location is updated by encircling prey.

Searching for prey

In order to ensure that all whales can fully search in the solution space, WOA updates the position according to the distance between whales to achieve the purpose of random search. Therefore, when $p < 0.5$ and $|A| \geq 1$, the search individual will swim to the random whale. The position update formula is shown in Eq. 33:

$$D^{''} = |C \cdot X_{rand}(t) - X(t)| \tag{32}$$

$$X(t+1) = X_{rand}(t) - A \cdot D \tag{33}$$

Bubble-net attacking

When $p \geq 0.5$, the bubble-net is used for predation. The position update between the humpback whale and the prey is expressed by the logarithmic spiral equation. The position update formula is shown in Eq. (35):

$$D' = \left|X^{*}(t) - X(t)\right| \tag{34}$$

$$X(t+1) = D' \times e^{bl} \times cos(2\pi l) + X^{*}(t) \tag{35}$$

where D′ is the distance between the current search individual and the current optimal solution, b is the spiral shape parameter, the range of l is a random number uniformly distributed in [− 1, 1].

Hybrid whale optimization algorithm (HWOA)

Chromosomes coding

When solving the LRP, a chromosome represents a feasible solution, and the encoding of the solution directly determines the difficulty and quality of the algorithm. In this study, natural number coding is used in the design of chromosome coding. When generating the initial solution of cold storage location and vehicle distribution routing, a routing is randomly generated first, and segmentation points with a label of 0 are inserted. Moreover, the routing is divided into several segments to indicate the opening of several cold storages. Afterward, the precise code of the cold storage is randomly selected at the beginning and end of each routing segment for insertion, and the preinserted segmentation points are deleted to represent a complete initial solution.

The initial decoding of 3 alternative origin-based cold storage points and 10 service points are used as example. Values 1–10 represents the service point, 11–13 represents the alternative origin-based cold storage points, as shown in Fig. 2. The first step is to initialize the coding of the service point service order, in which the shadow part marks the location of the segmentation point. The second step is to randomly select the cold storage code and fill it into the complete vehicle routing, in which the shadow part represents the cold storage coding position. As shown in the Fig. 2, in the candidate cold storage 11–13, cold storage 11 and 13 were opened.

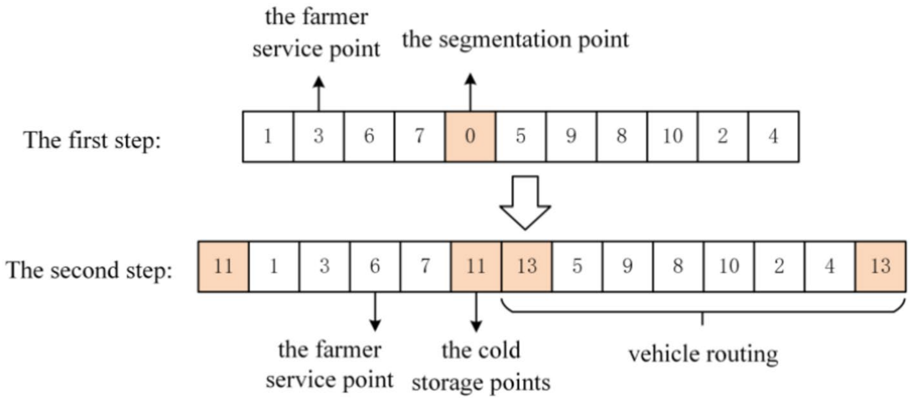


Fig. 2. Chromosome coding diagram.

Initializing the population

Reasonable population initialization improves the convergence efficiency of the algorithm. In the initial population, the diversity of the population is increased by combining random generation with a heuristic algorithm. Taking population 100 as an example, 70 individuals were randomly generated, and the other 30 individuals were randomly generated first. The nearest neighbor method was then used to optimize the service routing. To make the individuals in the population feasible, it is necessary to judge the individual constraints, and adjust the part of the gene if constraints are not met.

When the population is initialized, it mainly involves the cold storage capacity constraint (the total amount of agricultural products received by each origin-based cold storage does not exceed its maximum storage capacity) and the time window constraint (the time to reach each service point shall not exceed the time window limit of this service point). Therefore, after the chromosome sequence is randomly generated, the above constraints are checked in turn for each service routing. First, the capacity constraint is determined. If the constraint is not satisfied, the service point exceeding the capacity range is moved to the next cold storage service routing and the chromosome is updated. Afterward, the time window constraint is determined. The service points in the routing are reordered according to the left time window size. Figure 3 presents the specific process.

Improved search strategy

In the improved search operation, the crossover and mutation operators in the GA are introduced to ensure the diversity of feasible solutions. The crossover operation is realized by 2-opt exchange. In the genes of the chromosome representing the service point, two service point positions are randomly selected for exchange and their fitness values are calculated. The number of exchanges conducted on each chromosome n is 1/5 of the number of service points. By repeatedly conducting exchanges, the offspring with the best fitness value is selected. Figure 4 shows the cross-operation process with several service points of 20.

In this study, four search mechanisms are used in the mutation process: routing gene reversal, routing gene insertion, location gene insertion, and location gene mutation. The first two mechanisms work on the routing gene, and the latter two mechanisms work on the location gene. The probability of selecting each mutation operator is equal.

Routing gene reversal: Randomly select two positions i and j ($i \neq 1$ and $i < j$) representing the service point from the coding arrangement of the solution, and then insert the chromosome fragments between the two service points into the original position after reverse arrangement, as shown in Fig. 5a.

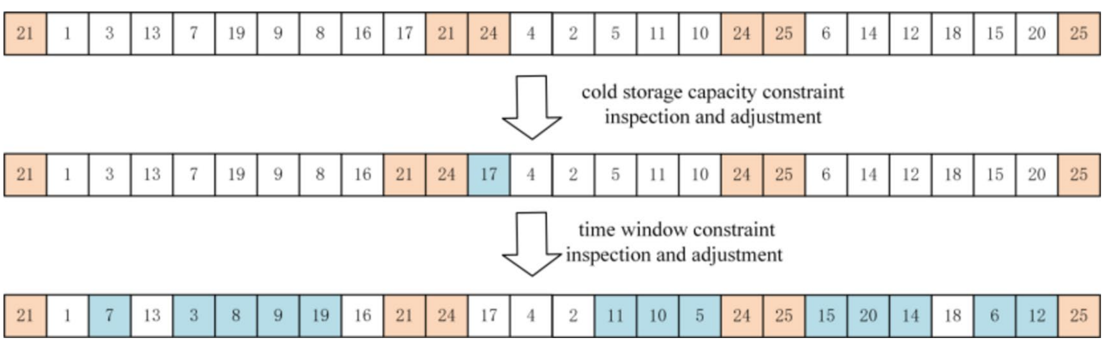


Fig. 3. Initializing the population diagram.

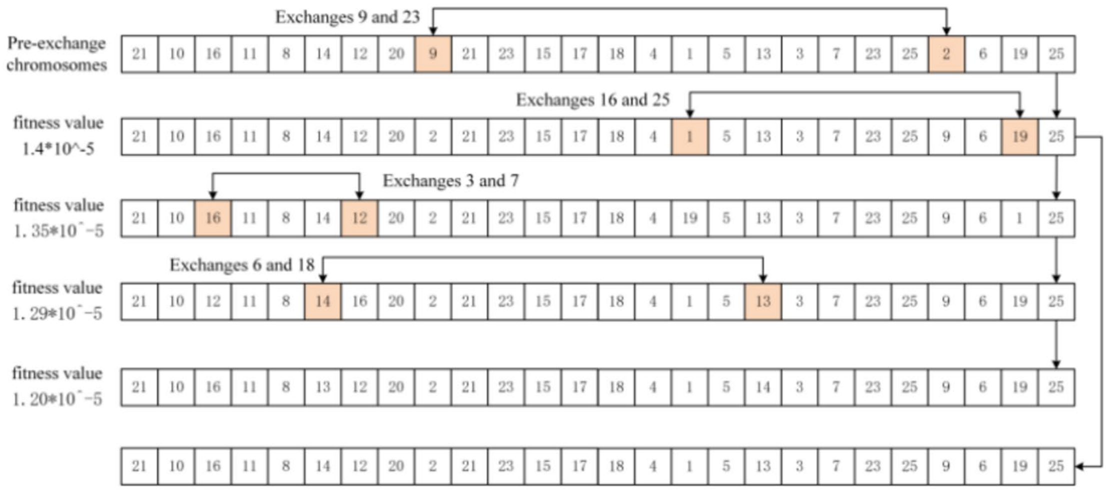


Fig. 4. Crossover operation process.

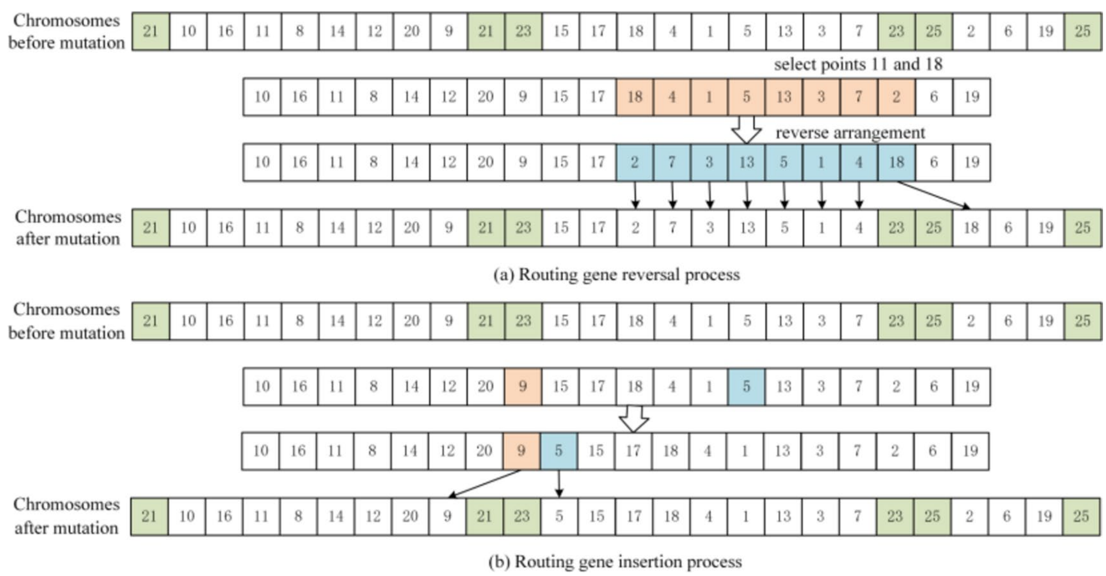


Fig. 5. Routing gene mutation operation process.

Routing gene insertion: Randomly select two positions i and j ($i \neq 1$ and $i < j$) representing the service point from the encoding arrangement of the solution, and then insert the element at the j position into the following position of the i element, as shown in Fig. 5b.

Location gene insertion: Because the location genes in the middle position of the chromosome are always connected, the two connected location genes in the middle position are divided into a group, then a group is randomly selected from the grouping of the location genes, then a service point i is randomly selected from the service points of the two cold stores, and then this group of location genes is inserted behind the i element, as shown in Fig. 6a.

Location gene replacement: After extracting the location gene of the chromosome, cold storage i is randomly selected from the open cold storage, and then a cold storage j is randomly selected from the unopened cold storage. Replace i with j and insert it back to the original location of i, as shown in Fig. 6b.

Local search strategy

To better improve the optimization ability of the algorithm, the population is evaluated after optimization, and the top 10% of the individuals in the population perform iterative local search operations to evaluate the offspring obtained by the search. Finally, the roulette wheel selection is utilized to select a certain number of excellent individuals from the offspring and put them back into the original population. When performing a local search, the population needs to readjust the coding strategy first. The vehicle routing extracted by each individual is used as a new chromosome. Figure 7 presents the specific adjustment operation of a chromosome, in which each row presents the routing of a vehicle.

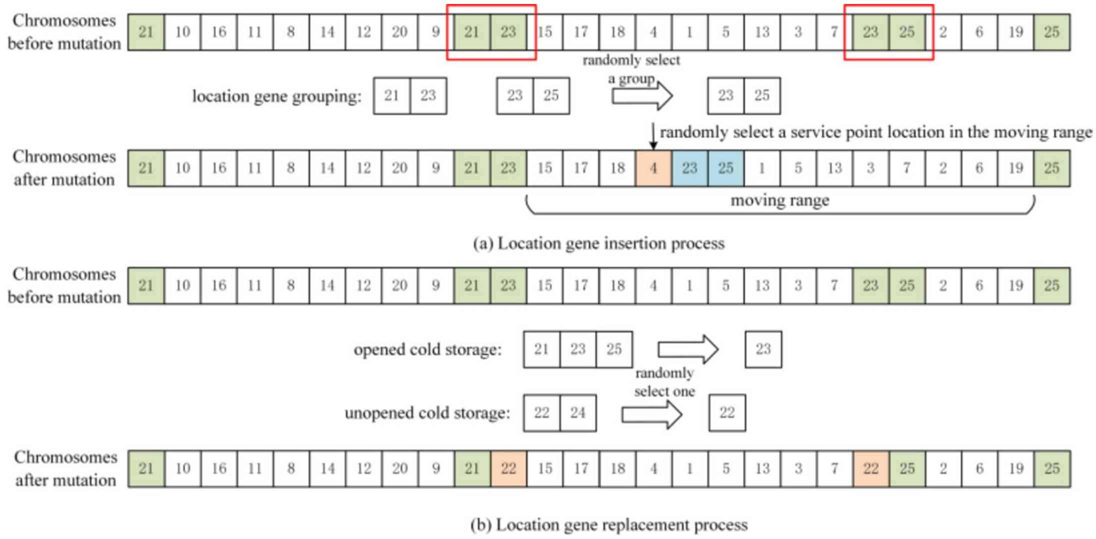


Fig. 6. Location gene mutation operation process.

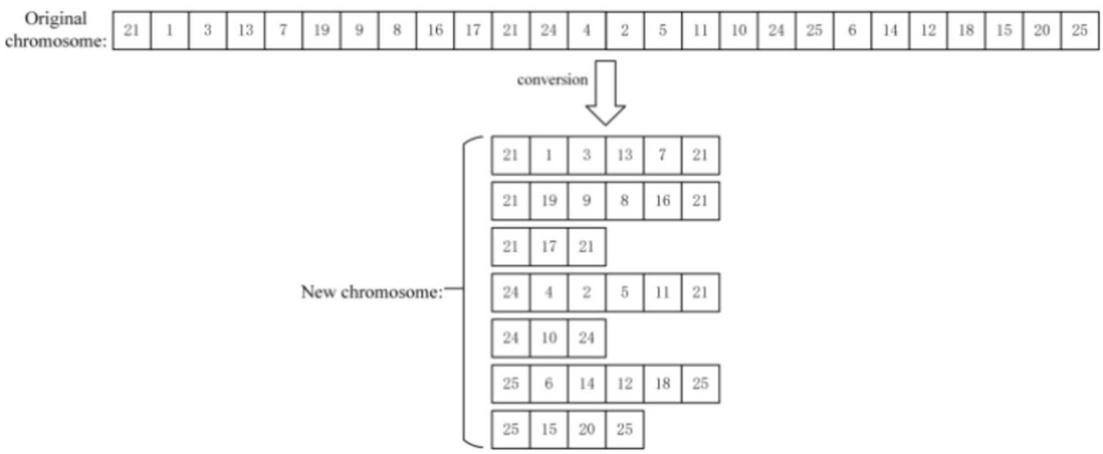


Fig. 7. Readjustment of chromosome coding strategy process.

In the local search, this study adopts three kinds of neighborhood operations. (1) First is the multisequence exchange neighborhood operation, as shown in Fig. 8a. The process can be described as follows: first select two parents P1 and P2; the child inherits 1/3 of the total routing of the parent P1. The remaining unserved points are arranged according to the service order of the parent P2. Afterward, the unserved points are assigned to the cold storage to generate a new vehicle routing and then inserted into the child. When the cold storage is allocated, it is first allocated from the open cold storage. When the open cold storage cannot meet the demand of the service point, a new cold storage is opened. (2) Second is the exchange neighborhood operation, as shown in Fig. 8b. The process can be described as follows: randomly select two service points in two different routings from the total routing of the parent, and replace the position. (3) Third is the mutation neighborhood operation, as shown in Fig. 8c. The process can be described as follows: 1/3 of the routing was randomly selected from the total routing of the parent, and a cold storage was reselected to replace the cold storage of the original routing.

Algorithm process
In summary, Fig. 9 presents the overall process of the hybrid whale algorithm, and the specific steps are as follows:

(1) Initialize the algorithm parameters such as the initial population number N, the maximum number of iterations (Gmax), and so forth.
(2) Initialize the whale population according to the initialization strategy, evaluate the fitness value of each whale individual, and identify the optimal individual as the global optimal individual (Xbest).
(3) Determine whether the maximum number of iterations is reached. If it is not satisfied, proceed to step 4. If it is satisfied, generate the current optimal solution, and the algorithm ends.
(4) The iteration process begins, and the individuals in the population are traversed in turn. A random number p between 0 and 1 is generated. If $p < 0.5$, then proceed to step 5; otherwise, proceed to step 6.

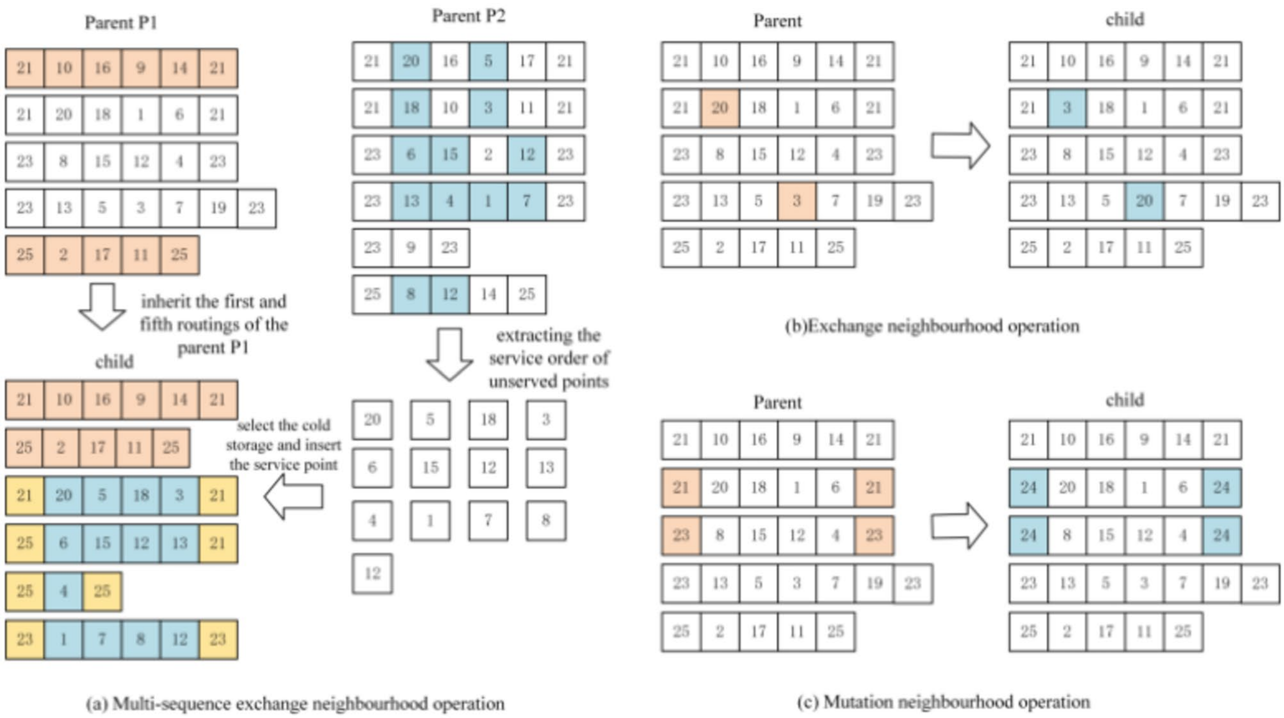


Fig. 8. Three neighbourhood operation example processes.

(5) If |A|< 1, the current individual performs cross-operation and replaces the current individual with the offspring. If |A|≥ 1, the globally optimal individual performs a crossover operation and replaces the current individual with its offspring.
(6) The current individual performs a mutation operation and replaces the current individual with the offspring.
(7) Evaluate the population, identify the current optimal individual, and replace if it is better than the global optimal individual; the individuals with the top 10% fitness value in the population were selected as population 2.
(8) Population 2 performs local search operations to obtain a new population, finds the current optimal individual of the new population, and replaces if it is better than the historical global optimal individual.
(9) After the iteration process is completed, the roulette wheel selection is used to select the corresponding number of excellent individuals and put them back to the original population.
(10) Repeat the above steps until the algorithm reaches the termination condition and generates the result.

Verify the efficiency of the algorithm

Taguchi method parameter setting

The algorithm is very sensitive to the setting of parameters, and different parameter values can determine the effectiveness of the algorithm. Therefore, we need to determine the reasonable parameter values before running the algorithm. HWOA contains two main parameters, which are population number N and the maximum number of iterations Gmax. In this study, the experimental method of Taguchi design is used to optimize the parameters to determine their values. The target value of Taguchi method is divided into three groups: 'the smaller the better', 'the larger the better' and 'nominally the best'. The objective function of this study is to minimize the cost, select the type of 'the smaller the better', and the corresponding signal-to-noise (SN) ratio is shown in (36).

$$S/N = -10 \times \log_{10}\left(\sum_{t=1}^{n} F_t^2/n\right) \tag{36}$$

In the formula, n is the number of executions of the algorithm at each parameter level, and Ft is the response value, that is, the objective function value of the t-times experiment. The N and Gmax are set to four levels respectively. The four levels of N are: 100, 200, 300, 400. The four levels of iterations are 100, 300, 500, 700. The two can form a total of 16 combinations L16 (4^2). Under each parameter combination, HWOA uses the standard LRP example 50–5–1a proposed by Prins et al.[49] to run independently for 10 times, and the calculated experimental values are analyzed by Taguchi design. The analysis results are shown in Table 2, and the corresponding mean and SN ratio are shown in Figs. 10 and 11.

It can be seen from Fig. 10 that when N is 300 and Gmax is 300, the SN ratio is the largest. Similarly, in Fig. 11, when the N is 300 and Gmax is 300, the date means is the smallest. Therefore, according to the Taguchi experimental analysis, N is set to 300, and Gmax is 300.

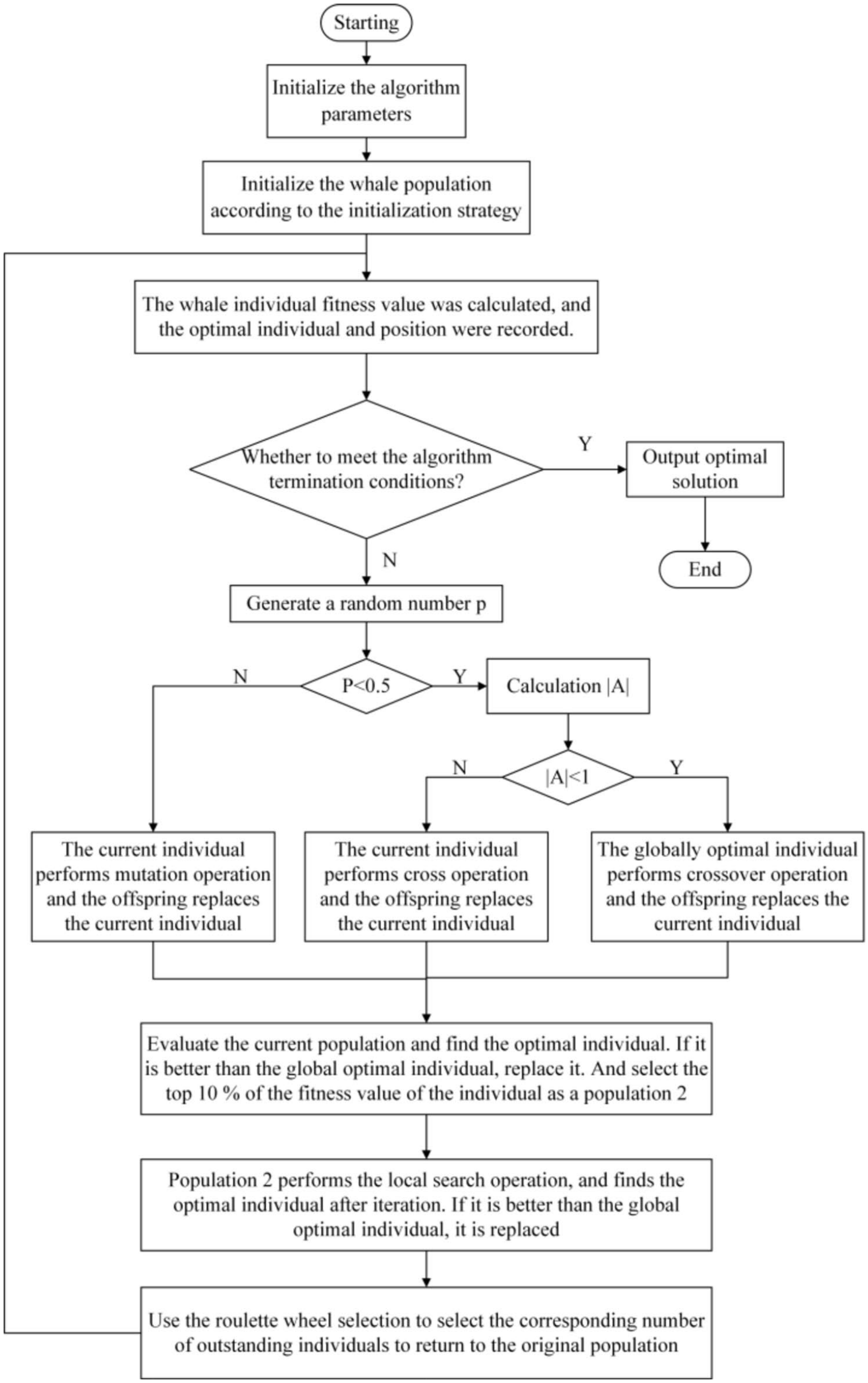


Fig. 9. Hybrid whale algorithm flowchart.

Instances verification

To test the performance of HWOA to solve the LRP, this study utilized the standard LRP instances proposed by Prins et al.[49] to conduct simulation experiments. Eight test datasets are selected from them, and the parameters are set according to the original dataset. At the same time, the algorithm is compared with WOA and GA. In this study, MATLAB R2022a under Windows 11 system is used to code the HWOA and the experiment of related instances.

N	Gmax	SN ratio	Date means	Standard deviation	Logarithmic standard deviation
100	100	− 100.922	110,890	8735.26	9.07512
100	300	− 100.154	101,652	5605.92	8.63158
100	500	− 100.349	103,782	8644.71	9.0647
100	700	− 100.333	103,729	6428.44	8.76849
200	100	− 100.288	103,277	4641.37	8.44276
200	300	− 100.273	103,103	4490.18	8.40965
200	500	− 100.465	105,136	9239.8	9.13128
200	700	− 100.246	102,713	6037.76	8.70579
300	100	− 100.552	106,427	5549.04	8.62138
300	300	− 99.997	99,795	6247.43	8.73992
300	500	− 100.191	101,950	7866.53	8.97037
300	700	− 100.166	101,655	7826.16	8.96523
400	100	− 100.515	105,951	6153.11	8.72471
400	300	− 100.276	102,957	7925.18	8.9778
400	500	− 100.206	102,074	8566.05	9.05556
400	700	− 100.009	100,062	3111.17	8.04275

Table 2. Taguchi design analysis results.

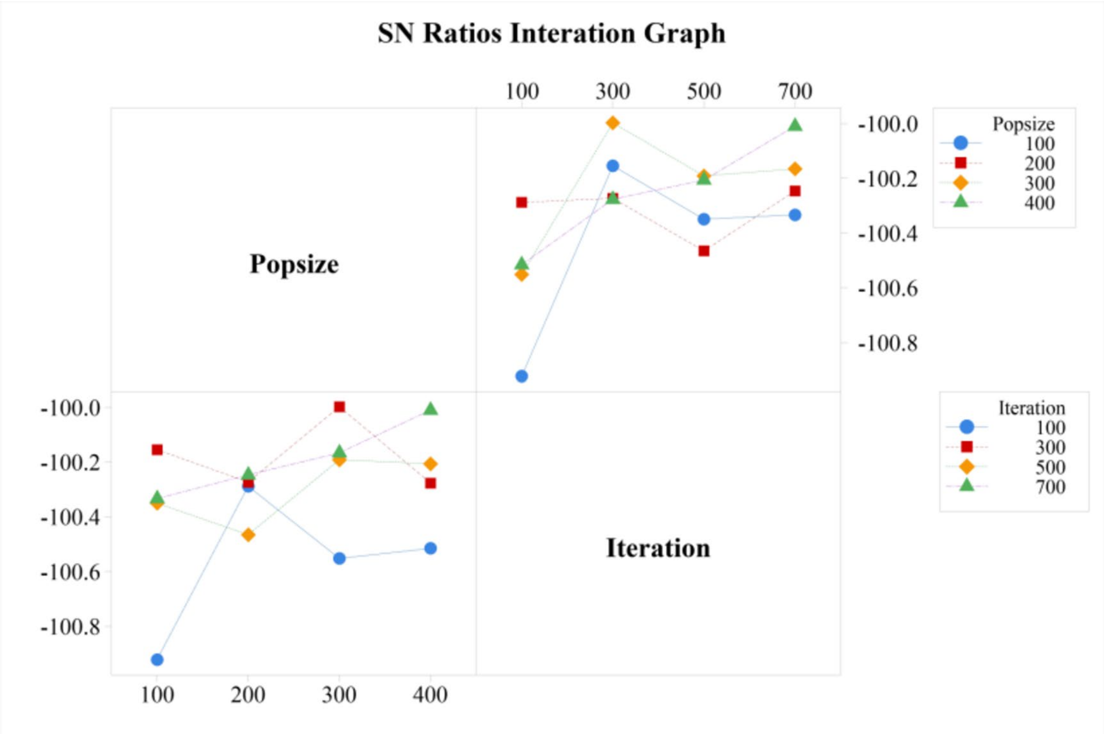


Fig. 10. SN ratio interaction diagram.

In this study, N and Gmax of the three algorithms are set to 300, and the coding methods of the three algorithms adopt the coding rules proposed in this study. The parameters of GA are set as follows: the selection probability is 0.8, the crossover probability is 0.5, and the mutation probability is 0.1. Because the original WOA cannot solve the discrete problem, the search strategy of this study is adopted. In the same computing environment, the comparison results of the optimal values of the three algorithms after 10 times of each group of instances are shown in Table 3.

As shown in Table 3, when solving small-scale instances, all three algorithms can find the optimal solution. WOA takes the least time, followed by GA, and finally HWOA. When solving medium-scale examples, WOA has the fastest calculation time, but the accuracy of the calculation results is the worst. The accuracy of GA calculation results is better than that of WOA, but the calculation time is the slowest. The proposed HWOA achieved the highest accuracy, and the calculation time is better than that of GA and worse than that of WOA. It can be seen that the WOA algorithm is highly competitive in solving small-scale examples using the change

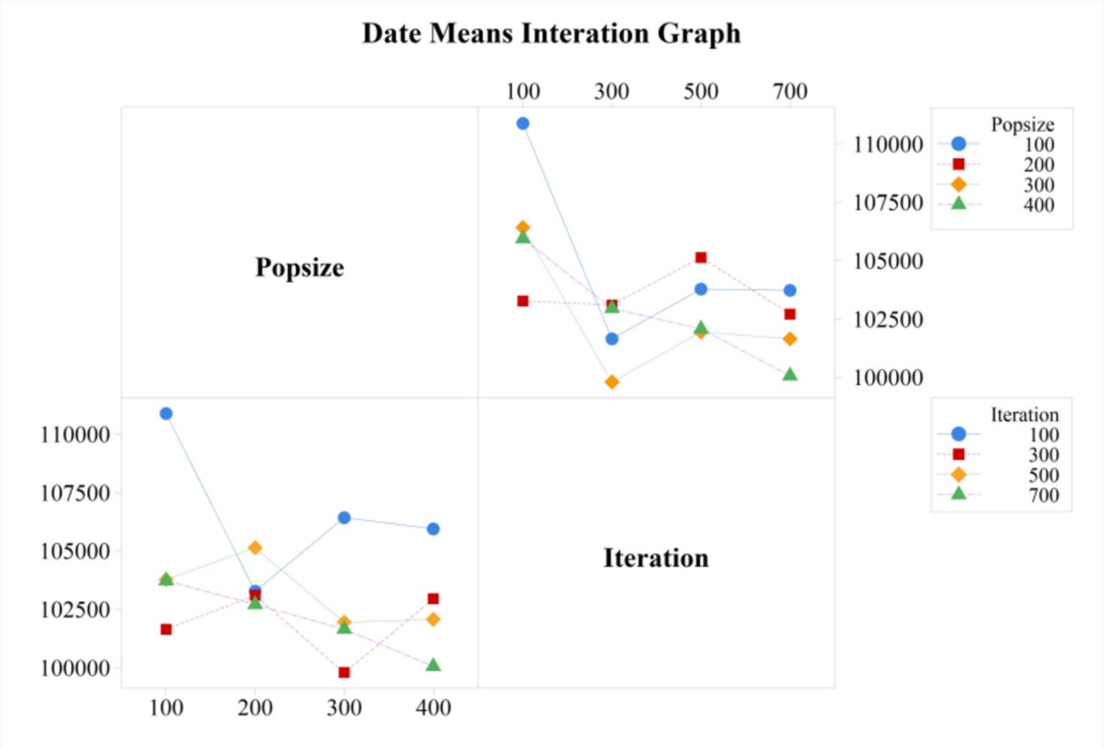


Fig. 11. Date means interaction diagram.

Instance	LB	BKR	HWOA			WOA			GA		
			Result	Gap_{BKR}	Computing time/s	Result	Gap_{BKR}	Computing time/s	Result	Gap_{BKR}	Computing time/s
20-5-1a	54793.00	54,793	54,793	0%	32.67	54,793	0%	24.17	54,793	0%	30.57
20-5-1b	39104.00	39,104	39,104	0%	32.57	39,104	0%	24.98	39,104	0%	27.40
20-5-2a	48908.00	48,908	48,908	0%	36.59	48,908	0%	24.57	48,908	0%	28.91
20-5-2b	37542.00	37,542	37,542	0%	30.61	37,542	0%	26.25	37,542	0%	25.93
50-5-1a	87109.64	90,111	90,111	0%	70.91	90,872	0.845%	56.59	90,632	0.578%	79.91
50-5-1b	61595.22	63,242	63,242	0%	67.63	64,761	2.402%	57.02	64,761	2.402%	80.72
50-5-2a	86055.01	88,293	88,304	0.012%	77.34	90,447	2.440%	65.39	88,506	0.241%	87.01
50-5-2b	65787.75	67,340	67,374	0.050%	76.40	68,042	1.042%	64.11	67,782	0.656%	87.06

Table 3. Experimental results of three algorithms.

rules in this study. However, as the size of the example increases, the accuracy of WOA decreases. Considering the accuracy of the calculation results, the calculation time of HWOA is within an acceptable range. Therefore, HWOA is suitable for solving medium-scale LRP.

Practical case application

Practical case introduction

Chenggu County, Hanzhong City, Shaanxi Province is the largest producer of citrus fruit in the northwest. At present, the citrus planting area is about 230,000 mu, the annual output is 320,000 tons, and the annual output value is exceeding 800 million yuan. However, the number and capacity of cold storages in local areas cannot meet the current citrus production. Therefore, this study takes the citrus planting belt in Chenggu County as the research object, and takes the village-level units with a total output of more than 150 tons as service points. A total of 35 service points were obtained, with a total demand of 8752.68 tons. There are 7 alternative cold storage points available. The number of farmer service points is 1–35, and the number of alternative cold storage points is 36–42. The location information of farmer service points and alternative cold storage points is shown in Fig. 12, and the specific information of each point is shown in Table 4.

Combined with existing literature[1,50,51] and the actual situation of Chenggu County, the basic data of the model are set as follows: the construction costs of the origin-based cold storage are 150,000 yuan, the operation costs of the origin-based cold storage are 50 yuan/day, the maximum storage capacity of the origin-based cold

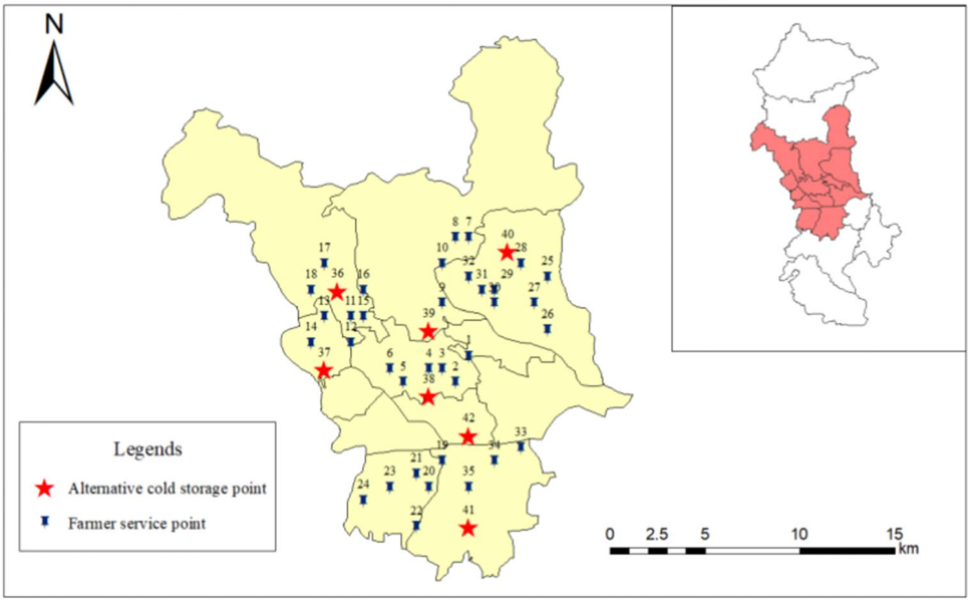


Fig. 12. Location distribution map of each point.

storage is 40 t, the operation accounting period is 5 years, the annual operation time is 6 months, the maximum load of the refrigerated truck is 8t, and the driving speed is set to 50 km/h. The relevant data settings such as purchase costs, maintenance costs and transportation costs of refrigerated trucks are shown in Table 5. The unit price of fresh agricultural products is 1.2 yuan/kg. The hourly loss rates of fresh agricultural products during transportation and door opening are 0.2% and 0.3%, respectively. The ambient temperature is set at 20 °C, the temperature in the refrigerated truck carriage is 4 °C. The heat transfer coefficient of the carriage is 0.7, and the sunshine intensity is 0.1. The penalty costs earlier than the time window are 30 yuan/h, and the penalty costs later than the time window are 50 yuan/h.

Practical case results and analysis

In this study, a total of 35 farmer service points and 7 alternative cold storage points in Chenggu County citrus planting belt are selected as datasets for calculation. This is a medium-scale LRP, and the proposed HWOA has been verified several times. It has strong competitiveness in solving medium-scale LRP. Therefore, according to the above parameter values, the HWOA is used to solve the problem on MATLAB2022a. The algorithm sets the population size to 300 and the maximum number of iterations to 500. When the optimal value does not change for 200 consecutive generations or the population chromosomes are completely consistent, the calculation is completed and the results are generated.

The algorithm was run 30 times in the environment of Intel®Core™i5-13400F, and good results were obtained. Figure 13 presents the convergence of the optimal solution in 30 operations. It can be seen that the algorithm converges in about 100 generations and takes 102.0 s. Table 6 presents the optimal calculation scheme, and Fig. 14 presents the location and vehicle routing of the optimal scheme. Combining the results presented in Table 6 and Fig. 14, it can be concluded that under the current parameter value, Chenggu County should build origin-based cold storage at alternative points No. 39 and No. 42, respectively. Moreover, cold storage No. 39 needs to serve 26 farmers and invest on 5 refrigerated trucks; the No. 42 cold storage needs to serve 9 farmers and invest on 2 refrigerated trucks. The total system costs of cold storage are 40964.199 million yuan.

The origin-based cold storage capacity is directly related to the costs. The cold storage with a small storage capacity has small construction costs, and it can serve a small number of farmers. The cold storage with a large storage capacity has large construction costs, and it can serve a large number of farmers. Therefore, exploring the impact of cold storage capacity on the final result can provide a scientific basis for cold storage operators to make decisions.

The types and planting scales of fresh agricultural products in different regions vary. If the planting products are rare or the planting scale is small, the yield is small. On the contrary, if the planting products are more common or the planting scale is larger, the yield is larger. Moreover, even in the same area, the planting conditions and scales of different farmers are still different. Therefore, the refrigeration demand of farmers varies greatly, which has a direct impact on the final result.

In this study, the capacity of cold storage and the farmers' refrigeration demands are utilized as variables; both of them are reduced by 50% and 25%, increased by 25% and 50%. Four sets of data are generated respectively, and the results are recalculated. Comparing the four new results with the original results, the influence of capacity and demand on the layout of origin-based cold storage and the vehicle routing of refrigerated trucks is analyzed.

(1) The influence of origin-based cold storage capacity.

No	Latitude	Longitude	Demand (t)	Left time window (min)	Right time window (min)	service time (min)
1	107.27	33.18	0.9	520	777	10
2	107.26	33.16	1.0	580	882	10
3	107.25	33.17	2.9	661	876	10
4	107.24	33.17	1.1	646	1003	10
5	107.22	33.16	0.9	555	847	10
6	107.21	33.17	1.8	497	1001	10
7	107.27	33.27	1.0	610	948	10
8	107.26	33.27	1.7	624	992	10
9	107.25	33.22	1.8	588	917	10
10	107.25	33.25	1.5	519	1004	10
11	107.18	33.21	1.1	680	1001	10
12	107.18	33.19	1.1	488	793	10
13	107.16	33.21	1.2	684	831	10
14	107.15	33.19	1.3	605	868	10
15	107.19	33.21	0.9	511	806	10
16	107.19	33.23	1.3	622	808	10
17	107.16	33.25	2.6	536	971	10
18	107.15	33.23	0.9	665	1007	10
19	107.25	33.10	0.9	589	877	10
20	107.24	33.08	1.0	646	922	10
21	107.23	33.09	2.9	623	740	10
22	107.23	33.05	1.0	547	1014	10
23	107.21	33.08	1.3	498	720	10
24	107.19	33.07	0.9	582	908	10
25	107.33	33.24	1.0	718	783	10
26	107.33	33.20	0.9	529	797	10
27	107.32	33.22	0.9	650	747	10
28	107.31	33.25	1.1	519	899	10
29	107.29	33.23	1.8	559	774	10
30	107.29	33.22	0.9	591	805	10
31	107.28	33.23	1.0	565	761	10
32	107.27	33.24	2.1	498	889	10
33	107.31	33.11	1.4	601	763	10
34	107.29	33.1	2.2	627	790	10
35	107.27	33.08	2.3	553	932	10
36	107.17	33.23	0	480	1080	–
37	107.16	33.17	0	480	1080	–
38	107.24	33.15	0	480	1080	–
39	107.24	33.20	0	480	1080	–
40	107.3	33.26	0	480	1080	–
41	107.27	33.05	0	480	1080	–
42	107.27	33.12	0	480	1080	–

Table 4. Specific information for each point.

Refrigerated truck parameters	Value
Purchase costs	120,000 yuan
Maintenance costs	8000 yuan/year
Fuel costs per unit distance	1.2 yuan/km
Refrigeration costs per unit time	3 yuan/h
Exterior area of the carriage body	48.58 m^2
Refrigerated trucks door area	5.29 m^2

Table 5. Refrigerated truck parameters.

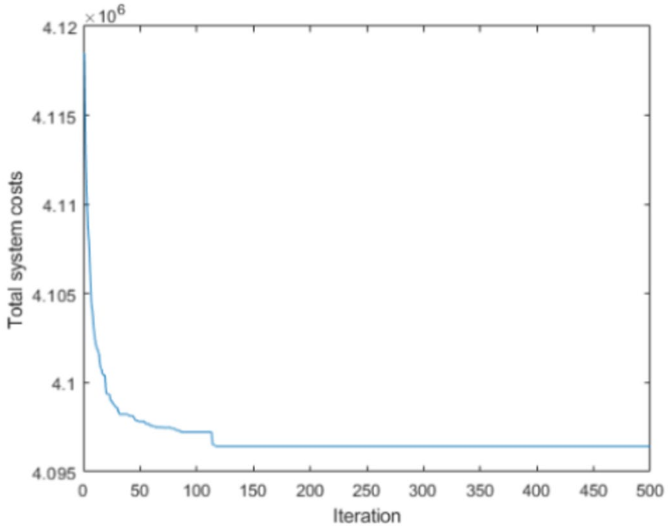


Fig. 13. Convergence curves of the HWOA.

Related costs/million yuan		Open cold storage number	Vehicle number	Vehicle routing
Location costs	390,000	39	1	39–10–8–7–32–31–39
Transportation costs	1121481.1		2	39–1–26–27–25–28–29–30–39
Damage costs	930.0		3	39–6–5–4–2–3–39
Refrigeration costs	2575625.3		4	39–17–18–13–14–12–39
Penalty costs	11383.5		5	39–9–16–11–15–39
Total system costs	4096419.9	42	1	42–20–22–24–23–21–42
			2	42–33–34–35–19–42

Table 6. The optimal calculation scheme for 30 times of case operation.

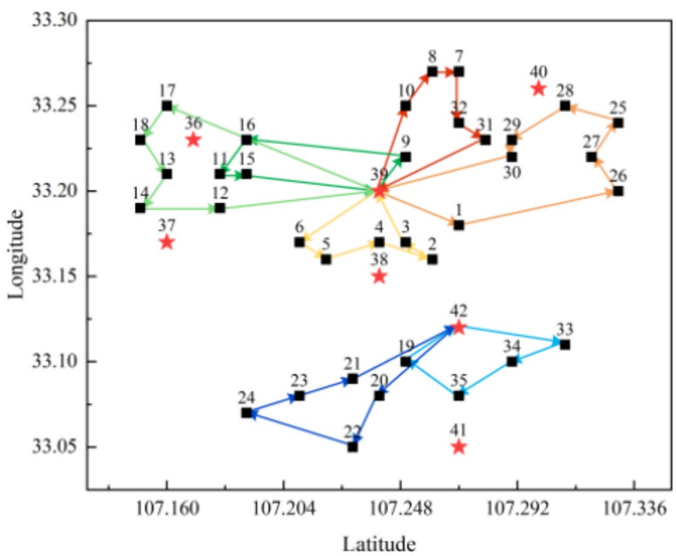


Fig. 14. Optimal scheme diagram.

Table 7 presents the impacts of four sets of data on cold storage capacity on various costs, and Fig. 15 presents the impacts on cold storage location and vehicle routing results. When the storage capacity is reduced by 50%, the construction costs and operation costs of a single cold storage are reduced by 50%. Moreover, the second row of Table 7 presents the costs of origin-based cold storage in each region, and Fig. 15a presents the LRP result. Furthermore, it is necessary to build three cold storages to meet the farmers' needs. With the increased number of cold storages, the related transportation costs from the farmers' service points to the cold storage reduced, and the total costs of building this cold storage are also less than the total costs of building the original cold storage; hence, the total costs are significantly reduced.

When the storage capacity is reduced by 25%, the construction and operation costs of a single cold storage are reduced by 25%. The third row of Table 7 presents the costs of origin-based cold storage in each part, and Fig. 15b presents the LRP results. In addition, it is necessary to build two cold storages to meet the farmers' needs. Moreover, the number of cold storages remains the same; however, the service relationship has improved, and there is no significant difference in the related transportation costs. Because the total costs of building this cold storage are less than the total costs of building the original cold storage, the total costs are reduced.

When the storage capacity increases by 25% and 50%, the construction and operation costs of a single cold storage increase by 25% and 50%. The fifth and sixth rows of Table 7 present the costs of origin-based cold storage

Ratio of change	Total system costs	Location costs	Transportation costs	Damage costs	Refrigeration costs	Penalty costs
Reduced by 50%	3997665.2	29.2500	1121316.2	929.7	2571535.8	11383.5
Reduced by 25%	3999389.7	29,2500	1121546.1	930.1	2573054.9	11358.5
original	4096419.9	390,000	1121481.1	930.0	2575625.3	11383.5
Increased by 25%	3952367.3	243,750	1121769.9	930.6	2574533.4	11383.5
Increased by 50%	4001117.3	292,500	1121769.9	930.6	2574533.4	11383.5

Table 7. The impact of changes in cold storage capacity on various costs.

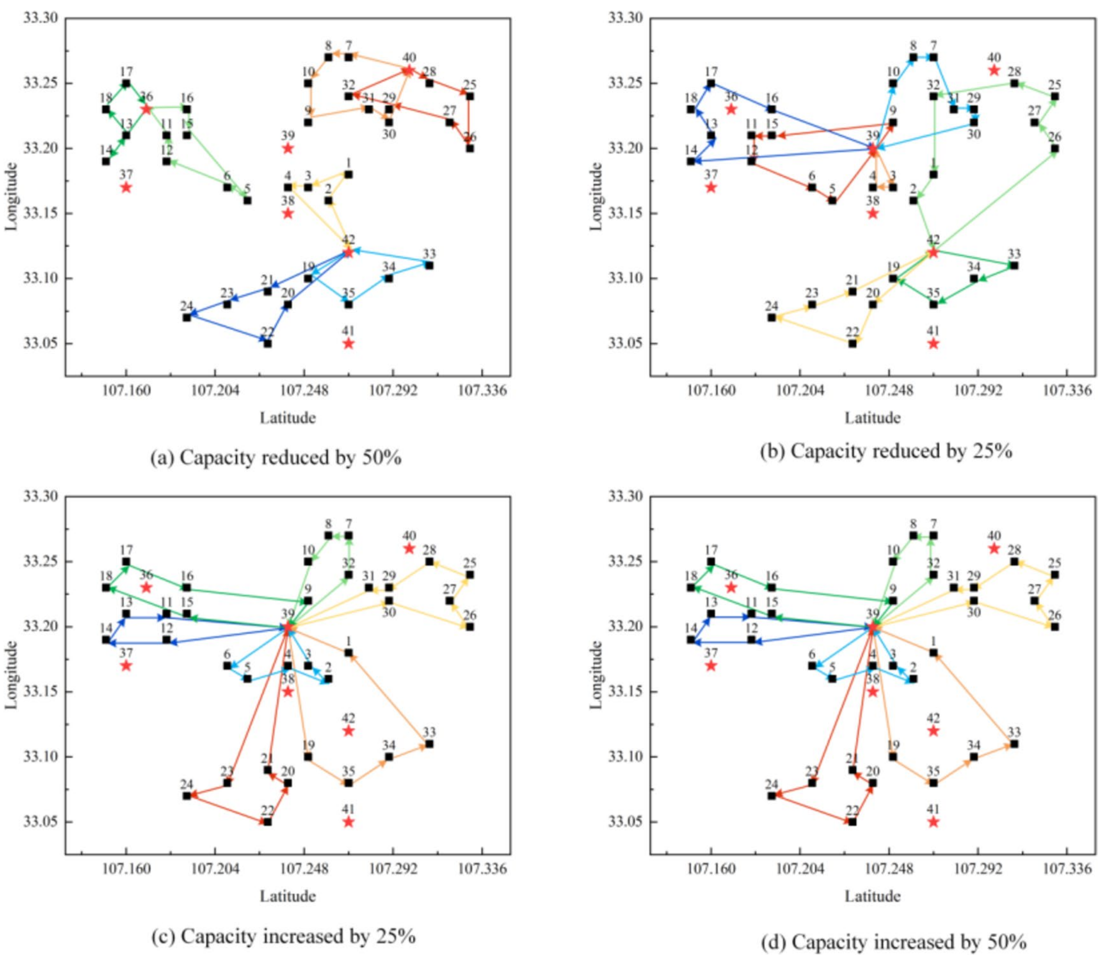


Fig. 15. The impact of changes in cold storage capacity on the location and vehicle routing results of the cold storage.

in each part. Figure 15c,d present the LRP results. In both cases, one cold storage can be built to meet the farmers' needs, and the location and vehicle routing results of the cold storage remain the same. As the number of cold storages decreased, the related transportation costs increased, and the costs of building a single cold storage increased; however, the number of cold storages decreased. The costs of building a cold storage with a large storage capacity are less than the costs of building two original storage cold storages; the increasing transportation costs are less than the costs of reducing the number of cold storages, and the total costs are still reduced.

In summary, it is the best scheme to build one cold storage with a storage capacity of 50t in Chenggu County because the total system costs are still low. With the change of storage capacity, the final results accordingly change. Therefore, the scale and quantity of origin-based cold storage can be considered according to the local actual situation, and the construction scheme with the lowest costs can be sought.

(2) The impact of farmers' refrigeration demand.

Table 8 presents the impact of the four sets of data on farmers' demand on various costs, and Fig. 16 presents the impact on cold storage location and vehicle routing results. The second and third rows of Table 8 present the costs of LRP in each stage when the demand is reduced by 50% and 25%, and Fig. 16a,b presents the LRP results. Moreover, the construction of one cold storage can meet the farmers' needs. As the number of cold storages decreases, the number of refrigerated trucks decreases, the number of farmers served by one refrigerated truck increases, and the service relationship changes. The costs are reduced compared with the original, and the smaller the farmers' demands, the smaller the total costs.

The fifth and sixth rows of Table 8 present the costs of cold storage LRP in each stage when the demand increases by 25% and 50%. Figure 16c,d present the LRP results. The construction of two cold storages can meet the farmers' needs. Moreover, the number of cold storages remains the same, and the number of refrigerated trucks has increased. Except for the location costs (C_1), which remain the same owing to the same number of cold storages, the other costs have increased than those of the original; thus, the total costs have increased. The larger the demand, the greater the number of vehicles, and the higher the total cost.

To sum up, with the change of farmers' demands, only the change in cold storage location and vehicle routing can minimize the total minimum costs. When optimizing the LRP of cold storage in the region, it is necessary to predict the production and sales of local fresh agricultural products to make rational use of the layout of origin-based cold storage and improve the utilization rate of cold storage.

Conclusion

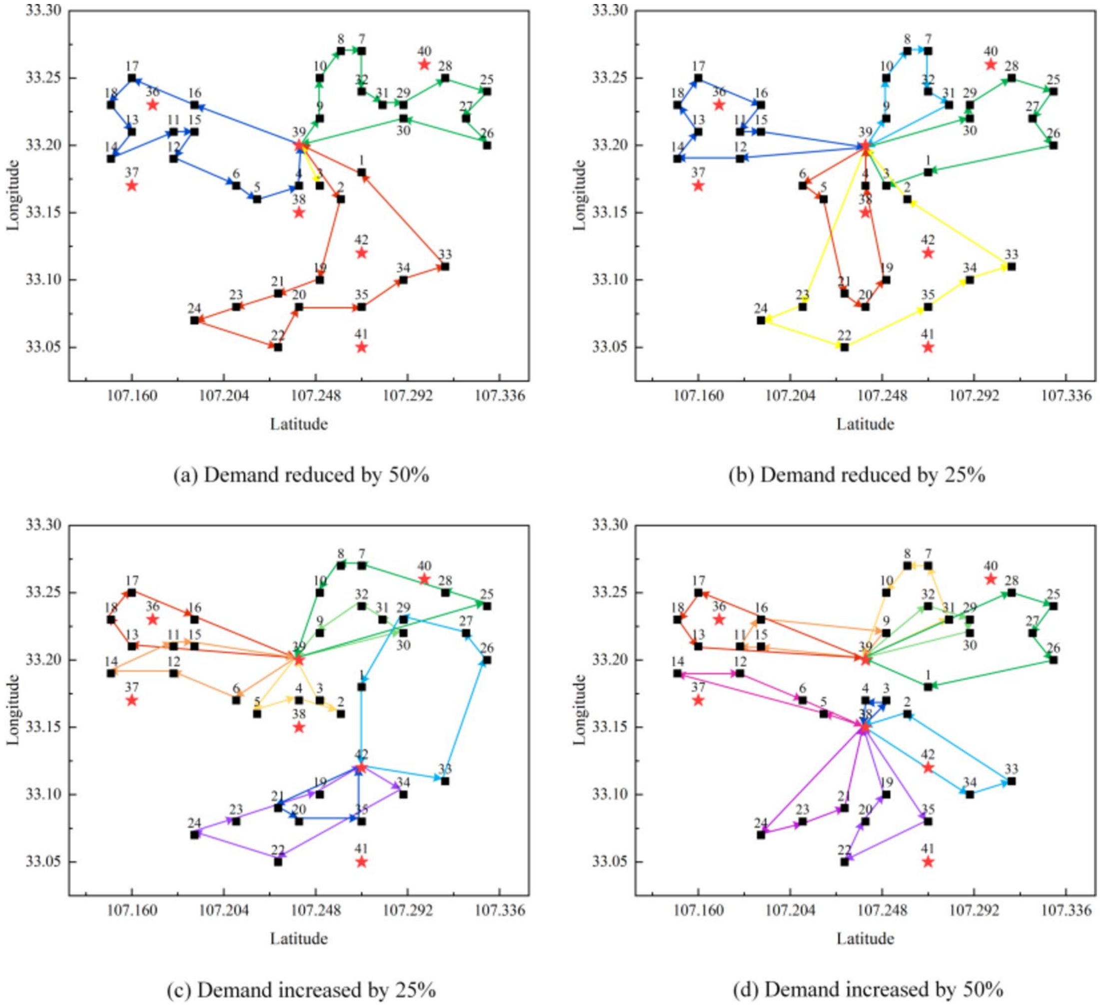
"The first kilometer" of the cold chain is the challenging and critical part of the upstream transportation of fresh agricultural products, as well as the key to ensuring the final product quality. In this study, considering the loss of fresh agricultural products during transportation to the origin-based cold storage after picking, the LRP of the cold storage of fresh agricultural products are studied. With the goal of minimizing the total system costs, the LRP model of the cold storage of fresh agricultural products is constructed, and HWOA is designed to solve the problem. The designed algorithm realizes the improvement of WOA, which is a better algorithm to solve such problems. Good results are obtained in different instances. In practical case, the location layout of origin-based cold storage for fresh agricultural products and the route planning for refrigerated trucks have been successfully implemented. Afterward, this study explores the impact of changes in cold storage capacity and farmers' cold storage demand on the total system costs and the location and vehicle routing results of cold storage. It provides theoretical references for cold storage operators in location selection and vehicle routing for serving farmers.

The results show that: (1) The algorithm designed in this study achieves the improvement of WOA. The results of different instances show that HWOA is suitable for solving medium-scale LRP and has good performance. (2) The change of cold storage capacity has an important influence on the results. With the increase of the proportion of cold storage capacity change from 0.5 to 1.5, the system total costs can be increased by 0.086%. After calculation, it is the best scheme to build a cold storage with a storage capacity of 50t in Chenggu County of Hanzhong City, and the system total costs are the lowest. (3) With the increase of farmers' demands for refrigeration, the number of cold storage and vehicles increases, and the total costs increase. As the proportion of farmers' demands for refrigeration increases from 0.5 to 1.5, the system total costs can increase by 34.034%.

Through the calculation and analysis, the following management implications are obtained: (1) When planning the origin-based cold storage, the demand for storage capacity should be accurately evaluated to avoid overinvestment or insufficient storage capacity. Considering the impact of changes in cold storage capacity on the total costs, it is recommended to establish a flexible storage capacity adjustment mechanism to adjust the

Ratio of change	Total system costs	Location costs	Transportation costs	Damage costs	Refrigeration costs	Penalty costs
Reduced by 50%	3418104.5	195,000	641268.7	464.8	2571222.5	10148.5
Reduced by 25%	3580403.6	195,000	801502.9	697.5	2572769.7	10433.4
Original	4096419.9	390,000	1121481.1	930.0	2575625.3	11,383.5
Increased by 25%	4259028.7	390,000	1281753.9	1163.2	2574428.1	11683.5
Increased by 50%	4581418.5	390,000	1601965.1	1396.4	2575823.5	12233.5

Table 8. The impact of changes in demand on various costs.



(a) Demand reduced by 50%

(b) Demand reduced by 25%

(c) Demand increased by 25%

(d) Demand increased by 50%

Fig. 16. The impact of changes in demand on the location and vehicle routing results of the cold storage.

storage capacity in a timely manner according to market changes and seasonal demand. (2) Strengthen the prediction of farmers' cold storage demand, and use historical data and market analysis to predict future demand changes and to achieve efficient resource allocation in advance. In addition, it is recommended to develop coping strategies in advance, such as the establishment of standby cold storage, a flexible vehicle scheduling system, and so forth, to cope with demand fluctuations. (3) Improve the efficiency of cold storage and vehicle use through technological upgrading and management innovation, and ensure that the cost is reduced as much as possible while meeting the demand. Farmers are encouraged to provide feedback to better understand changes in demand and improve services.

However, this study also has some limitations. First, the model assumes that the scale and capacity of the origin-based cold storage are fixed, and the scale of the origin-based cold storage is not optimized. Second, the model assumes that the farmers' demand is fixed, and does not consider farmers' uncertain demand in an actual situation. Third, the algorithm may encounter computational efficiency problems when dealing with large-scale data. Fourth, this study mainly focuses on the construction of theoretical models and algorithm optimization, and the replicability in practical applications must be further verified. Given the above limitations, we propose the following suggestions: First, future research can consider optimizing the scale of origin-based cold storage as a decision variable to more accurately determine the most suitable cold storage scale in the region. Second, considering the uncertain demand, the LRP model of fresh agricultural product cold storage with uncertain demand is constructed. Third, more efficient algorithms or parallel computing techniques can be explored to improve the ability to process large-scale data. Fourth, it is recommended to implement and test the model in actual cases to evaluate its performance in the real environment, and to adjust and optimize it based on feedback.

This study provides an innovative solution for the LRP of cold storage of fresh agricultural products, and provides a valuable reference for relevant enterprises and management departments. Future research should continue to deepen the exploration in this field to promote the continuous optimization and development of fresh agricultural product cold chain.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

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Author contributions
X.Z. and J.L. wrote the main manuscript text. F.X. and J.F. prepared practical case data and content review.

Competing interests
The authors declare no competing interests.

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