JOINT OPTIMIZATION OF COLD-CHAIN PICK-UP VEHICLE ROUTING AND CARGO ALLOCATION FOR FRESH AGRICULTURAL PRODUCTS
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生鲜农产品冷链集货车辆路径与货物配载联合优化研究

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ABSTRACT
As a bridge connecting agricultural production and consumption, the circulation of agricultural products has the function of connecting supply and demand, guiding production and promoting consumption. However, the development of rural logistics in China is slow, and most logistics centers still rely on experience to plan the pick-up vehicle routing, resulting in long transport time and high cost. In order to improve the efficiency of pick-up and reduce transportation costs, a joint optimization model of cold-chain pick-up vehicle routing and cargo allocation for fresh agricultural products was proposed in this study. Soft time window constraint and three-dimensional loading constraints were considered, and the lowest pick-up cost was used as optimization goals in this model. In addition, adaptive large neighborhood search algorithm (ALNS) and heuristic depth-first search algorithm (HDFS) were combined to solve the model. A case study of Kunming International Flower Auction Center was conducted to compare the schemes of pick-up vehicle routing before and after optimization. Results demonstrate that the pick-up cost after optimization decreases by 9.6 %, the number of vehicles decreases by one, the total volume utilization rate of vehicles increases by 23 %, and the total load utilization rate of vehicles increases by 15 %. This study provides a model reference and solution method for enterprise operators to formulate schemes of pick-up vehicle routing quickly and reasonably.

摘要
农产品流通作为连接农业生产和消费的桥梁，具有连接供需、引导生产、促进消费的功能。然而，中国农村物流发展缓慢，大多数物流中心仍然依靠经验来规划取货车辆路线，导致运输时间长，成本高。为了提高提货效率，降低运输成本，本文提出了一种生鲜农产品冷链集货车辆路径与货物配载联合优化模型。该模型考虑了软时间窗约束和三维装载约束，以最低集货成本为优化目标。此外，结合自适应大邻域搜索算法(ALNS)和启发式深度优先搜索算法(HDFS)对模型进行求解。以昆明国际花卉拍卖中心为例，对比优化前后的集货车辆路径方案。结果表明，优化后的集货成本降低 9.6%，车辆数量减少 1 辆，车辆总容积利用率提高 23%，车辆总载重利用率提高 15%。本研究为企业运营者快速合理地制定集货车辆路线方案提供了模型参考和解决方法。

INTRODUCTION
The circulation of agricultural products has the function of connecting supply and demand, connecting urban and rural areas, guiding production and promoting consumption *(Takahashi., 2003; Ma et al., 2023)*. As the main way of fresh agricultural products circulation, cold chain logistics can not only greatly reduce the circulation loss of agricultural products and promote the increase of farmers' income, but also effectively improve the international competitiveness of China's agricultural products and comprehensively support and drive the development of agricultural modernization (*Lv et al., 2014; Rahmanifar et al., 2024)*. However, China's cold-chain logistics started late, and there are problems such as large loss, low efficiency and high cost, which cannot meet the current social cold-chain logistics needs. Most agricultural products logistics centers still rely on experience to dispatch transport vehicles, which is easy to cause problems such as excessive consumption of agricultural products, high transportation cost and low transportation efficiency. Based on this, scholars all over the world did many studies on the vehicle routing problem for fresh agricultural products, usually establishing a mathematical model with the lowest transportation cost as the goal, and designing algorithms to solve it. Sun et al. solved the optimization problem of distribution vehicle routing for fresh agricultural products with ant colony algorithm *(Sun et al., 2017)*.

Li et al. were concerned with the impact of the decaying factor on the total distribution cost and proposed a multi-objective VRP optimization model for multiple fresh products *(Li et al., 2019).* Jiang et al. proposed a multi-item packaging strategy that integrates different categories of fresh agricultural products according to food cold-chain temperature, and established an optimization model of vehicle routing that integrates multi-item packaging and sorting distribution *(Jiang et al., 2020).*

Xie pointed out that the exploration of "the first kilometer" is an indispensable step in the circulation of fresh agricultural products *(Xie, 2022)*. At present, on the optimization of cold chain transport path of fresh agricultural products, scholars' research focuses on the "last kilometer" distribution and transportation, and few pay attention to the collection transportation. At present, most scholars focus on the delivery vehicle routing problem for fresh agricultural products, and few pay attention to the pick-up vehicle routing problem. Zhu et al. proposed an optimization model of vehicle routing for agricultural products aiming at minimizing delivery cost, but this model did not include vehicle type variables *(Zhu et al., 2021)*.

Lin et al. used the improved genetic algorithm to solve the vehicle routing problem of agricultural products, but it could not solve the multi-vehicle distribution problem *(Lin et al., 2022)*. Fernando et al. established an optimization model of vehicle routing for agricultural products in the retail mode, but it is not suitable for multi-vehicle distribution *(Fernando et al., 2024)*. Varas et al. built an optimization model of vehicle routing with time window, but did not consider the road traffic conditions in the transportation process *(Varas et al., 2024)*. Lehmann et al. studied the pick-up vehicle routing problem, but did not consider the impact of traffic conditions on actual driving *(Lehmann et al., 2024)*. Ni et al. established an optimization model of vehicle routing for agricultural products based on low-carbon perspective, but set vehicle speed as a fixed value *(Ni et al., 2024)*.

Liu et al. introduced soft time window function and carbon emission parameters to build an optimization model of vehicle routing aiming at the lowest distribution cost and carbon emission, but the model did not conform to the actual driving conditions of vehicles *(Liu et al., 2023)*. Vehicle routing optimization or cargo allocation optimization cannot solve the problems of chaotic cargo handling, high empty driving rate and detour at the same time. Considering vehicle routing problem and vehicle filling problem at the same time is more conducive to improving vehicle space utilization, reducing transportation costs, and avoiding safety problems triggered by overload and other situations. Sbai et al. studied the vehicle routing problem with two-dimensional loading constraints, but did not consider three-dimensional loading constraints *(Sbai et al., 2022)*.

Pinto et al. proposed a multi-starting algorithm to solve the vehicle routing problem with two-dimensional loading constraints, and verified the effectiveness of the algorithm through case tests, but the algorithm could not solve the vehicle routing problem with three-dimensional transfer constraints (*Pinto et al., 2021)*. Ji et al. proposed an optimization model of vehicle delivery routing with two-dimensional loading constraints, but this model could not solve the vehicle routing problem with three-dimensional loading constraints *(Ji et al., 2021)*. Ines et al. introduced two-dimensional loading constraints to construct a dynamic optimization model of vehicle routing, but the model was not completely consistent with the actual loading of cargo *(Ines et al., 2021)*.

Chi et al. studied the vehicle routing problem with three-dimensional loading constraints, but did not consider the gravity center constraints *(Chi et al., 2023)*. Che et al. built an optimization model of vehicle routing with three-dimensional loading constraints, but the model lacked gravity center constraints *(Che et al., 2023)*. Wang et al. established an optimization model of vehicle routing aiming at the lowest operating cost and the least number of vehicles used on the premise of three-dimensional loading constraints, but the proposed loading scheme could not guarantee the safe running of vehicles *(Wang et al., 2021)*. Wei et al. proposed an optimization model of multi-vehicle routing with three-dimensional loading constraints, which aims at minimizing delivery cost, but the proposed model did not meet the requirements of safe vehicle driving *(Wei et al., 2014)*.

In summary, the existing studies did not consider the realistic constraints in detail, and the applicability of the model is not high. Therefore, it is an urgent problem to establish an optimization model of pick-up vehicle routing for fresh agricultural products, which is suitable for the actual situation and has good applicability. Thus, a joint optimization model of pick-up vehicle routing and cargo allocation for fresh agricultural products is proposed in this study. Soft time window constraint and three-dimensional loading constraints are considered in this model. In addition, ALNS algorithm and HDFS (Hadoop Distributed File System) are combined to solve the model.

MATERIALS AND METHODS

Problem Description

In this study, the collection vehicle routing problem for fresh agricultural products can be specifically described as: within one identified production area, a collection center with different models of refrigerated transport vehicles performs collection operations at multiple collection points.

Agricultural products are packaged into cuboids of certain specifications, and consider the loading position and loading sequence of cargo. Under certain practical constraints, a vehicle routing scheme is obtained which minimizes the pick-up cost.

Model Assumptions

Before establishing the optimization model of pick-up vehicle routing for fresh agricultural products, the following assumptions need to be satisfied:

(1) The pick-up center grasps the coordinates of each pick-up point, the quantity of various agricultural products and other data, and the data remains unchanged.

(2) In the process of pick-up, consider road congestion, but do not consider vehicle failure, fuel exhaustion and other situations.

(3) Each pick-up point must be serviced once and only by one vehicle, and the vehicle has reached the best refrigeration temperature when leaving the pick-up center.

(4) The vehicle compartment and each piece of cargo are simplified into cuboids, and all kinds of cargo can be mixed.

Modeling

To make the model closer to the actual situation, the road congestion index is introduced to reflect the actual driving time of vehicles in this study. The actual driving time of vehicle in a certain road section is the product of the time that the vehicle passes the road section at an average speed and the road congestion coefficient corresponding to the period. The actual travel time of vehicle k from point *i* to point *j* is calculated by the following formula.

$$t_{ij}^{k} = \frac{d_{ij}}{v_0^k}\varepsilon_{ij}^{u} \tag{1}$$

where: d_{ij} is the distance between pick-up point *i* and pick-up point *j*, v_0^k is the average travel speed of vehicle *k*, ε_{ij}^u is the congestion coefficient of road section (*i*, *j*).

Vehicle fixed cost

Vehicle fixed cost mainly includes the depreciation cost caused by each start-up of the vehicle. Vehicle fixed cost can be expressed as:

$$C_g = \sum_{k=1}^{K}\sum_{j=1}^{n} f_k x_{0j}^k \tag{2}$$

where: f_k is the fixed cost for starting vehicle *k*, x_{0j}^k is the decision variable, $x_{0j}^k = 1$ indicates that vehicle *k* leaves the pick-up center to pick-up point *j*, otherwise $x_{0j}^k = 0$.

Vehicle transportation cost

In the actual driving process, there is a very complex nonlinear relationship between fuel consumption and speed, road condition and load, which is difficult to quantify accurately. Therefore, vehicle transportation cost is expressed as the product of the driving cost per unit distance and the driving distance, and the two cases of no-load driving and load driving of the vehicle are considered respectively. Vehicle transportation cost can be expressed as:

$$C_t = \sum_{k=1}^{K}\sum_{i=1}^{n} C_1^k d_{0i} x_{0i}^k + \sum_{k=1}^{K}\sum_{j=0}^{n}\sum_{i=1}^{n} C_2^k d_{ij} x_{ij}^k \tag{3}$$

where: C_1^k is the transportation cost per kilometer of vehicle *k* when unloaded-driving, C_2^k is the transportation cost per kilometer of vehicle *k* when loaded-driving, d_{0i} is the distance from pick-up center to pick-up point *i*, d_{ij} is the distance from pick-up point *i* to pick-up point *j*, x_{ij}^k is the decision variable, $x_{ij}^k=1$ indicates that vehicle *k* goes to pick-up point *j* after serving pick-up point *i*, otherwise $x_{0j}^k=0$.

Vehicle refrigeration cost

Vehicle refrigeration cost is divided into two parts, one is the refrigeration cost of maintaining the low temperature inside the carriage, and the other is the refrigeration cost caused by opening the door. Vehicle refrigeration cost can be expressed as:

$$C_z=\sum_{k=1}^{K}\sum_{j=0}^{n}\sum_{i=0}^{n}P_k t_{ij}^k x_{ij}^k+\sum_{k=1}^{K}\sum_{i=1}^{n}P_k' y_i^k \tag{4}$$

where: P_k is the refrigeration cost of vehicle *k* per hour, P_k' is the refrigeration cost of vehicle *k* when opening the compartment door one time, t_{ij}^k is the travel time of vehicle k from pick-up point *i* to pick-up point *j*, y_i^k is the decision variable, $y_i^k=1$ indicates that pick-up point *i* is served by vehicle *k*, otherwise $y_i^k=0$.

Cargo damage cost

Cargo damage cost is mainly divided into two parts, one is the corruption cost of fresh agricultural products caused by respiration, and the other is the damage cost incurred by loading cargos. Cargo damage cost can be expressed as:

$$C_s=\sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{i=1}^{n}P_r Q_i^r\left(1-e^{\alpha_r\left(t_k-t_i^k\right)}\right)y_i^k+\sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{j=1}^{n}\sum_{i=1}^{n}P_r Q_i^r \alpha_r' x_{ij}^k \tag{5}$$

where: P_r is the unit price of type *r* agricultural product, Q_i^r is the weight of agricultural product *r* at pick-up point *i*, α_r is the decay rate of type *r* agricultural product, α_r' is the spoilage rate of type *r* agricultural product, t_k is the arriving time of vehicle *k* to the pick-up center, t_i^k is the arriving time of vehicle *k* to pick-up point *i*.

Time window penalty cost

Time window penalty cost can be expressed as:

$$C_f=\sum_{k=1}^{K}\sum_{i=1}^{n}\eta_1 max\left(E_i-t_i^k,0\right)+\eta_2 max\left(t_i^k-L_i,0\right) \tag{6}$$

Time window penalty cost function is as follows:

$$C_f(t_i^k)=\begin{cases}M, & t_i^k<e_i \quad or \quad t_i^k>l_i\\ \eta_1(E_i-t_i^k), & e_i<t_i^k<E_i\\ \eta_2(t_i^k-L_i), & L_i<t_i^k<l_i\\ 0, & E_i<t_i^k<L_i\end{cases} \tag{7}$$

where: $\left[E_i,L_i\right]$ is the ideal time window of pick-up point *i*, there is no penalty cost for arriving at collection point *i* within this time period. e_i is the earliest time for pick-up point *i* to accept the operation, and l_i is the latest time for point *i* to accept operation. Pick-up operation earlier than the earliest time or later than the latest time will not be allowed. If operation occurs in $\left[e_i,E_i\right]$ or $\left[L_i,l_i\right]$, there will be a certain penalty cost. η_1 is the penalty coefficient for early arrival, η_2 is the penalty coefficient for late arrival.

Optimization model setting

Based on the above analysis, the following model is established.

$$MinZ_1=C_g+C_t+C_z+C_s+C_f \tag{8}$$

The constraints are as below:

$$\sum_{t=1}^{T}Q_t z_t^k\le Q_k,\quad k=1,2,3,\cdots,K \tag{9}$$

$$\sum_{t=1}^{T}V_t z_t^k\le \mathrm{V}_k,\quad k=1,2,3,\cdots,K \tag{10}$$

$$\sum_{k=1}^{K} y_i^k = 1, \quad i = 1,2,3,\cdots,n \tag{11}$$

$$\sum_{k=1}^{K}\sum_{j=0}^{n} x_{ij}^k = 1, \quad i = 1,2,3,\cdots,n \tag{12}$$

$$\sum_{k=1}^{K}\sum_{i=0}^{n} x_{ij}^k = 1, \quad j = 1,2,3,\cdots,n \tag{13}$$

$$\sum_{k}^{K} z_t^k = 1, \quad t = 1,2,3,\cdots,T \tag{14}$$

$$\sum_{i=1}^{n} x_{0i}^k = \sum_{i=1}^{n} x_{i0}^k \le 1, k = 1,2,3,\cdots,K \tag{15}$$

$$XR_t^k \le L_k, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{16}$$

$$YR_t^k \le W_k, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{17}$$

$$ZR_t^k \le H_k, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{18}$$

$$XL_t^k \ge 0, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{19}$$

$$YL_t^k \ge 0, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{20}$$

$$ZL_t^k \ge 0, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{21}$$

$$\left[\left(XL_t^k - XR_t^k\right) - L_t\right]\left[\left(YL_t^k - YR_t^k\right) - L_t\right] = 0, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{22}$$

$$\left[\left(XL_t^k - XR_t^k\right) - W_t\right]\left[\left(YL_t^k - YR_t^k\right) - W_t\right] = 0, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{23}$$

$$ZL_t^k - ZR_t^k = H_t, k = 1,2,3,\cdots,K, t = 1,2,3,\cdots,T \tag{24}$$

$$\frac{\sum_{t=1}^{T} Q_t GX_t^k z_t^k}{\sum_{t=1}^{T} Q_t z_t^k} \in \left[GX_{k1}, GX_{k2}\right], k = 1,2,3,\cdots,K \tag{25}$$

$$\frac{\sum_{t=1}^{T} Q_t GY_t^k z_t^k}{\sum_{t=1}^{T} Q_t z_t^k} \in \left[GY_{k1}, GY_{k2}\right], k = 1,2,3,\cdots,K \tag{26}$$

$$\frac{\sum_{t=1}^{T} Q_t GZ_t^k z_t^k}{\sum_{t=1}^{T} Q_t z_t^k} \in \left[GZ_{k1}, GZ_{k2}\right], k = 1,2,3,\cdots,K \tag{27}$$

where: Q_t and V_t are the weight and volume of cargo *t*, Q_k and V_k are the rated load and volume of vehicle *k*, L_t, W_t and H_t are the length, width and height of cargo *t*, L_k, W_k and H_k are the length, width and height of vehicle *k*, $\left[GX_{k1}, GX_{k2}\right]$, $\left[GY_{k1}, GY_{k2}\right]$ and $\left[GZ_{k1}, GZ_{k2}\right]$ are the range of gravity center in length, width and height direction of vehicle *k*, $\left(GX_t^k, GY_t^k, GZ_t^k\right)$ is the gravity center coordinates of cargo *t* in compartment of vehicle *k*, $\left(XL_t^k, YL_t^k, ZL_t^k\right)$ and $\left(XR_t^k, YR_t^k, ZR_t^k\right)$ are the left upper corner coordinates and right rear lower corner coordinates of cargo *t* in compartment of vehicle *k*, $z_t^k = 1$ is the decision variable, $y_i^k = 1$ indicates that cargo *t* is loaded by vehicle *k*, otherwise $y_i^k = 0$.

Equation (8) is objective functions, indicating the minimum total cargo cost, the maximum vehicle load utilization rate, the maximum vehicle volume utilization rate and the minimum number of vehicles used respectively. Equation (9) indicates that the total weight of agricultural products on each routing shall not exceed the maximum carrying weight of vehicles. Equation (10) indicates that the total volume of agricultural products on each routing shall not exceed the maximum carrying volume of vehicles. Equation (11) indicates that each collection point can be served once. Equation (12) and (13) indicate that each collection point can only be served once by one vehicle. Equation (14) indicates that each cargo is loaded and is only loaded by one vehicle.

Equation (15) indicates that each vehicle must return to the pick-up center after completing operation. Equation (16), (17), (18), (19), (20) and (21) indicate that the cargo shall not exceed the compartment. Equation (22), (23) and (24) indicate that the cargo shall not be placed on a diagonal. Equation (25), (26) and (27) indicate that the total gravity center of the cargo is within the gravity center of the carriage.

Algorithm Design

ANLS and HDFS are combined to solve the model, the former is used to generate the scheme of pick-up vehicle routing, and the latter is used to generate and test the scheme of cargo allocation. The essence of ALNS is to adaptively select a group of better damage operators and repair operators to deal with the current solution by examining the "historical performance" of different neighborhood search operators, and increase the probability of obtaining the optimal solution. The essence of HDFS is to search the current valid space and invalid space of the carriage, merge them according to the space merging rules, generate a larger valid space, and fill the cargo to be filled to the highest matching effective space. Repeat the above operations until the cargo cannot be filled or all cargo is loaded.

Correlation degree damage operator

The principle of the damage operator is to randomly select a pick-up point for destruction, calculate the correlation degree between the pick-up point and the remaining pick-up points, and carry out descending order to destroy the first n pick-up points, and put all the damaged pick-up points into the virtual request library. The correlation degree between pick-up point *i* and *j* is calculated by the following formula.

$$R(i,j)=\varphi_1 d_{ij}+\varphi_2\left(\left|\sum_{r=1}^{R}Q_i^r-\sum_{r=1}^{R}Q_j^r\right|\right)+\varphi_3\left(\left|\sum_{r=1}^{R}V_i^r-\sum_{r=1}^{R}V_j^r\right|\right)+\varphi_4 \tag{28}$$

where φ_1, φ_2, φ_3 and φ_4 respectively are the distance, weight difference, volume difference and weight coefficient of the routing between pick-up point *i* and *j.*

Worst damage operator

The damage operator is designed to destroy the pick-up points that have the greatest impact on the current cost, thus reduce the pick-up cost of the entire transportation network. Its principle is to calculate the added value of the cost after the destruction of each pick-up point, select the point with the largest added value to destroy, and put it into the virtual request library. Repeat the destruction operation until n pick-up points are destroyed.

Random routing damage operator

The damage operator is designed to take into account random factors and reduce the possibility of the algorithm falling into local optimality. The principle is to select a routing with the largest pick-up cost, randomly destroy a pick-up point on the routing, and update the pick-up routing at the same time. Repeat the destruction operation until n pick-up points are destroyed, and place all the damaged pick-up points into the virtual request library.

Longest time damage operator

The principle is to calculate the added value of the pick-up time after each collection point is destroyed, and select the pick-up point with the largest added value into the virtual request library. Repeat until there are no pick-up points in the virtual request library.

Shortest time repair operator

The principle of the repair operator is to randomly select a pick-up point from the virtual request library and insert it into the appropriate position (the incremental travel time before and after the insertion is minimal). Repeat until there are no pick-up points in the virtual request library.

Shortest distance repair operator

The principle of the repair operator is to randomly select a pick-up point from the virtual request library and insert it into the appropriate position (the total mileage incremental before and after insertion is minimal). Repeat until there are no pick-up points in the virtual request library.

Lowest cost repair operator

The principle of the repair operator is to insert the destroyed pick-up points into the routing one by one with the smallest incremental cost until there are no pick-up points in the virtual request library.

Regret repair operator

The principle of the repair operator is to calculate the regret value of all the pick-up points in the virtual request library, and insert the pick-up point with the largest regret value into the appropriate position each time (the increment of the pick-up cost is the smallest before and after insertion). Repeat until there are no pick-up points in the virtual request library. The formula for calculating regret value is as follows:

$$c_i^* = \Delta F_{i,xi2} - \Delta F_{i,xi1} \tag{29}$$

where: $\Delta F_{i,xi1}$ is the cost increment after the pick-up point *i* is inserted into the appropriate position. $\Delta F_{i,xi2}$ is the cost increment after the pick-up point *i* is inserted into the second-appropriate position.

Operator selection mechanism

In each iteration process, the roulette choice method is used to call one damage operator and one repair operator to enhance the robustness of the algorithm. There are *n* damage operators, and the probability of damage operator α being called in the *s*th iteration is calculated as follows:

$$p(\alpha_s) = \frac{w_{\alpha,s-1}}{\sum_{i=1}^{n} w_{i,s-1}} \tag{30}$$

where: $w_{\alpha,s-1}$ is the weight of the damage operator α in the *s*th iteration.

Operator scoring mechanism

The score of the operator directly reflects the "historical performance" of the operator in the algorithm iteration process, and the specific scoring mechanism is as follows:

(1) If the candidate neighborhood solution obtained by a group of operators is better than the current solution, and better than the global optimal solution, then each operator is added *p1* score.

(2) If the candidate neighborhood solution obtained by a group of operators is better than the current solution, but not better than the global optimal solution, then each operator is added *p2* score.

(3) If the candidate neighborhood solution obtained after a group of operators is inferior to the current solution, but accepted by the acceptance criteria, then each operator is added *p3* score.

Operator weight adjustment mechanism

With the increase of the number of algorithm iterations, some operators that are suitable to be called in the early stage may not be suitable in the subsequent stage. Therefore, the operator weights should be dynamically adjusted according to the "historical performance" of operators to guide the operator invocation in the next stage. The weight update formula is as follows:

$$w_{i,s} = (1-\delta) w_{i,s-1} + \delta \frac{s_{i,s}}{t_i} \tag{31}$$

where: $w_{i,s}$ is the weight of the operator *i* in the *s*th iteration. $s_{i,s}$ is the score of operator *i* in the *s*th iteration. t_i is the number of times the operator *i* is called. δ is the reaction coefficient, with values from 0 to 1.

Acceptance criteria

In the process of searching for the global optimal solution, blindly accepting the optimal solution will narrow the neighborhood structure and cause the algorithm to fall into a local loop, and properly accepting the inferior solution will make the algorithm jump out of the local optimal. Therefore, the Metropolis criterion is adopted to accept the inferior solution with a certain probability to improve the searching ability of the algorithm. The probability of accepting the inferior solution is calculated as follows:

$$p = e^{-\frac{|f(x') - f(x)|}{\varphi T_0}} \tag{32}$$

where: $f(x)$ is the objective function value of the current solution. $f(x')$ is the objective function value of the inferior solution. T_0 is the initial temperature of the simulated annealing algorithm. φ is the annealing coefficient.

Basic steps of algorithm

Step 1): Generate the initial solution of the pick-up routing scheme and set the initial parameters.

Step 2): Determine whether the initial solution satisfies the termination condition. If the termination condition is reached, go to step 3; if not, go to step 10.

Step 3): Generate the initial solution of the cargo allocation scheme.

Step 4): Determine whether there is any cargo that are not loaded in the cargo set. If there is cargo that is not loaded, go to step 5; if not, go to step 19.

Step 5): Select a group of cargo from the cargo set for loading.

Step 6): Determine whether there is any cargo that are not unloaded in this cargo group. If there is cargo that is not loaded, go to step 7; if not, go to step 4.

Step 7): Select a cargo from this cargo group for loading.

Step 8): Determine whether the effective space set is empty. If it is empty, go to step 9; if not, go to step 20.

Step 9): Determine whether the invalid space set is empty. If it is empty, go to step 10; if not, go to step 22.

Step 10): Determine whether the weight update condition is met. If it is met, go to step 11; if not, go to step 12.

Step 11): Update operator weight.

Step 12): Update annealing temperature.

Step 13): Select a repair operator and a damage operator.

Step 14): Determine whether the new solution is accepted. If it is accepted, go to step 15; if not, go to step 18.

Step 15): Set the new solution to the current solution.

Step 16): Determine whether the current solution is better than the optimal solution. If it is better than the optimal solution, go to step 17; if not, go to step 18.

Step 17): Set the current solution to the optimal solution.

Step 18): Update operator score, and go to step 2.

Step 19): Determine whether the loading scheme is feasible. If it is feasible, output loading scheme; if not, go to step 24.

Step 20): Determine whether there is a suitable valid space after merge. If there is a suitable valid space, go to step 21, if not, go to step 10.

Step 21): Place the cargo, and go to step 6.

Step 22): Make space merge.

Step 23): Determine whether there is a suitable valid space after merger. If there is a suitable valid space, go to step 21; if not, go to step 10.

Step 24): Determine whether the adjusted loading scheme is feasible. If it is feasible, output loading scheme; if not, go to step 10.

RESULTS

Case Introduction

Kunming International Flower Auction Center is selected as an example. The enterprise is a comprehensive industrial service platform, which mainly focuses on flower auction and integrates flower market information service, technical service and logistics service. At present, 43 cold chain transportation lines have been established in Yunnan Province, involving more than 460 cargo collection stations, covering the main production areas of Yunnan flowers, and solving the difficult problem of flower farmers' flowers transportation from origin to market.

According to the statistics, the main types of fresh cut flowers in a planting area are Brushed gerbera (R1), Blue demon (R2), Peach snow mountain (R3), Corolla (R4), Maria (R5) and Cappuccino (R6). To facilitate loading, the cargo collection center issues packing boxes for each farmer, and the farmer treats each variety of fresh cut flowers into cuboids cargos of different specifications in advance (10 bundles for one cargo). The relevant information about each variety of fresh cut flowers is shown in Table 1.

The parameters such as rated volume, rated load and size of the three types of refrigerated trucks in the pick-up center are shown in Table 2. The penalty coefficients for early and late arrival are set 1.0 yuan per minute and 1.5 per minute. The locations of pick-up points and center were processed with two-dimensional coordinates. The time window, location, type and quantity of goods at each collection point are shown in Table 3. Baidu Map intelligent transportation network is used to predict the road traffic congestion index of a certain area throughout the day, and the road congestion index of the area on the same day is shown in Table 4.

Table 1

Information on each variety of fresh cut flowers

	R1	R2	R3	R4	R5	R6
Packing specifications (cm)	100*60*60	100*60*50	100*50*50	100*45*45	100*36*36	100*30*25
Weight of each package (kg)	40	30	25	20	18	16
Volume of each package (m^3)	0.36	0.3	0.25	0.2025	0.1296	0.075
Spoilage rate	3%	2%	3%	4%	2%	3%
Decay rate	4%	5%	6%	5%	7%	4%
Unit price(yuan/kg)	7	12	14	10	13	16

Table 2

Vehicle parameters

	A	B	C
Fixed cost for starting vehicle one time (yuan/time)	20	30	35
Transportation cost per kilometer when unloaded-driving (yuan/km)	2.3	3.4	4.0
Transportation cost per kilometer when loaded-driving (yuan/km)	5.0	5.5	6.2
Refrigeration cost per hour (yuan/h)	20	30	40
Refrigeration cost when opening the compartment door (yuan/time)	30	40	50
Length (m)	4.2	6.2	8.2
Width (m)	1.4	1.8	2.2
Height (m)	1.8	2.0	2.4
Rated load (kg)	2530	3620	6240
Rated volume (m^3)	10.584	22.32	43.296

Table 3

Information on each pick-up point

Points	XY(km)	Type and quantity of cargo	$[E_i, L_i]$	$[e_i, l_i]$
0	(30,35)	/	/	/
1	(30,35)	6*R1+5*R2+2*R3+4*R4+6*R5+10*R6	5:00-8:30	5:00-11:00
2	(44,37)	6*R1+4*R2+2*R3+3*R4+7*R5+9*R6	6:00-9:00	5:30—12:00
3	(40,43)	5*R1+4*R2+0*R3+6*R4+5*R5+11*R6	5:30-9:00	5:00-11:00
4	(35,57)	2*R1+1*R2+1*R3+2*R4+2*R5+4*R6	6:30-10:00	5:30-11:30
5	(29,64)	7*R1+3*R2+3*R3+3*R4+8*R5+12*R6	6:00-9:30	5:00-12:00
6	(61,42)	4*R1+2*R2+3*R3+3*R4+7*R5+6*R6	5:00-8:30	5:00-11:30
7	(53,58)	7*R1+1*R2+0*R3+4*R4+5*R5+12*R6	7:40-10:40	5:40-11:50
8	(42,67)	7*R1+1*R2+0*R3+4*R4+5*R5+12*R6	7:00-9:00	6:00-11:00
9	(39,80)	1*R1+3*R2+0*R3+0*R4+3*R5+4*R6	8:30-10:30	7:00-11:30
10	(37,108)	4*R1+3*R2+1*R3+3*R4+3*R5+4*R6	5:40-8:00	5:40-9:50
11	(90,30)	1*R1+3*R2+0*R3+1*R4+1*R5+4*R6	6:00-9:00	5:00-11:00
12	(93,36)	4*R1+5*R2+1*R3+6*R4+5*R5+8*R6	6:00-9:30	5:00-11:10
13	(80,40)	8*R1+5*R2+0*R3+6*R4+9*R5+11*R6	5:00-8:30	5:00-10:10
14	(80,56)	5*R1+4*R2+3*R3+1*R4+6*R5+8*R6	6:00-9:00	5:00-11:20
15	(70,65)	7*R1+5*R2+1*R3+0*R4+7*R5+6*R6	6:00-10:00	5:00-11:10
16	(60,79)	4*R1+4*R2+1*R3+7*R4+1*R5+7*R6	7:00-9:30	5:30-10:50
17	(59,102)	3*R1+4*R2+2*R3+0*R4+10*R5+11*R6	6:00-10:00	5:00-11:40
18	(121,35)	3*R1+2*R2+1*R3+0*R4+1*R5+3*R6	5:00-8:30	5:00-10:10
19	(115,50)	2*R1+2*R2+1*R3+2*R4+4*R5+6*R6	5:30-9:00	5:00-11:10
20	(110,58)	5*R1+4*R2+3*R3+6*R4+3*R5+10*R6	6:00-8:00	5:00-10:20
21	(92,70)	4*R1+5*R2+0*R3+6*R4+9*R5+7*R6	7:00-9:30	6:00-10:50
22	(76,94)	4*R1+5*R2+0*R3+4*R4+1*R5+10*R6	7:30-10:30	6:30-12:10
23	(57,128)	6*R1+3*R2+1*R3+2*R4+10*R5+8*R6	6:40-8:40	5:40-10:50
24	(41,140)	3*R1+2*R2+1*R3+2*R4+0*R5+4*R6	8:00-11:00	7:00-12:30

Points	XY(km)	Type and quantity of cargo	$[E_i, L_i]$	$[e_i, l_i]$
25	(140,40)	1*R1+0*R2+0*R3+1*R4+2*R5+2*R6	8:50-11:50	7:30-13:00
26	(135,60)	2*R1+3*R2+3*R3+0*R4+6*R5+9*R6	9:00-12:00	7:50-14:00
27	(120,68)	6*R1+2*R2+0*R3+4*R4+6*R5+10*R6	8:00-11:30	7:00-13:30
28	(114,80)	6*R1+2*R2+0*R3+4*R4+5*R5+9*R6	8:20-10:20	7:20-12:10
29	(99,101)	6*R1+0*R2+3*R3+0*R4+8*R5+10*R6	10:40-11:50	8:40-13:40
30	(79,110)	3*R1+2*R2+1*R3+1*R4+3*R5+4*R6	11:00-12:00	9:50-14:00
31	(78,136)	1*R1+3*R2+0*R3+1*R4+5*R5+6*R6	9:30-12:30	8:30-13:20
32	(160,60)	2*R1+6*R2+2*R3+2*R4+4*R5+9*R6	10:00-12:00	8:50-14:10
33	(140,70)	2*R1+5*R2+1*R3+4*R4+8*R5+8*R6	9:00-11:10	8:00-12:50
34	(125,92)	3*R1+5*R2+2*R3+1*R4+6*R5+7*R6	9:00-11:40	7:50-13:10
35	(119,104)	3*R1+2*R2+0*R3+1*R4+3*R5+2*R6	8:00-11:25	6:30-13:30
36	(113,126)	6*R1+7*R2+0*R3+6*R4+5*R5+8*R6	8:50-10:40	7:20-11:50
37	(160,93)	7*R1+6*R2+3*R3+5*R4+5*R5+7*R6	8:30-11:50	6:50-13:40
38	(139,102)	6*R1+7*R2+1*R3+0*R4+6*R5+9*R6	11:40-13:00	9:50-14:20

Table 4

Congestion index predicted by Baidu map intelligent traffic network

Time period	Congestion coefficient	Time period	Congestion coefficient
[5:00-6:00)	1.00	[10:00-11:00)	1.39
[6:00-7:00)	1.25	[11:00-12:00)	1.31
[7:00-8:00)	1.76	[12:00-13:00)	1.42
[8:00-9:00)	1.74	[13:00-14:00)	1.55
[9:00-10:00)	1.49	[14:00-15:00)	1.52

Simulation Results

The original scheme of pick-up vehicle routing is shown in Table 5. Python software was used to complete the algorithm programming. As shown in Fig. 1, the adaptive mechanism in the algorithm guides the entire search direction to converge towards the optimization direction, gradually approaches the optimal solution, and reaches a stable state after about 870 iterations. The optimized vehicle routing scheme is shown in Fig. 2 and Table 6, and the visualization results of each vehicle's three-dimensional packing are shown in Fig. 3.

The original scheme requires seven vehicles to complete the pick-up operation, including three type A vehicle, 2 type B vehicles and 2 type C vehicles. The total cost is 10742 yuan, the total volume utilization rate is 60%, and the total load utilization rate is 55%. After optimization, six vehicles need to be dispatched to complete the pick-up operation, including 1 type A vehicle, 1 type B vehicle and 4 type C vehicles. The total cost is 9714 yuan, the total volume utilization rate is 83%, and the total load utilization rate is 70%.

The calculation results show that the cost of the optimized vehicle routing scheme reduces by 9.6% and the number of vehicles reduces by one compared with the original vehicle routing scheme. In addition, the total volume utilization rate and total load utilization rate of the vehicle increase by 23% and 15%. Three-dimensional diagram of cargo loading shows that cargo loading is not a process of neatly filling the carriage, and many gaps that cannot be utilized will be generated in actual placement. Therefore, it is necessary to consider the three-dimensional loading constraints when modeling. Under the background of market economy, the competition of cold-chain logistics enterprises is increasing day by day. Therefore, the optimization model of pick-up vehicle adopting soft time window constraints and three-dimensional loading constraints is more suitable for the actual situation. The effectiveness of the proposed model and algorithm is verified by comparing the schemes of pick-up vehicle routing before and after optimization.

Table 5

Original pick-up vehicle routing scheme

Routings	Vehicle types	Cost (yuan)	Volume utilization rate	Load utilization rate
0→15→8→3→13→6→7→2→27→20→0	C	1824	79%	62%
0→4→9→29→16→23→22→1→5→12→0	C	1910	76%	60%
0→36→24→10→11→37→17→0	B	1850	74%	62%
0→25→21→14→28→38→0	B	1735	75%	63%
0→18→35→34→0	A	1263	70%	61%
0→30→33→32→0	A	1155	68%	59%
0→19→26→31→0	A	1005	64%	51%

Note: The results in the table are rounded.

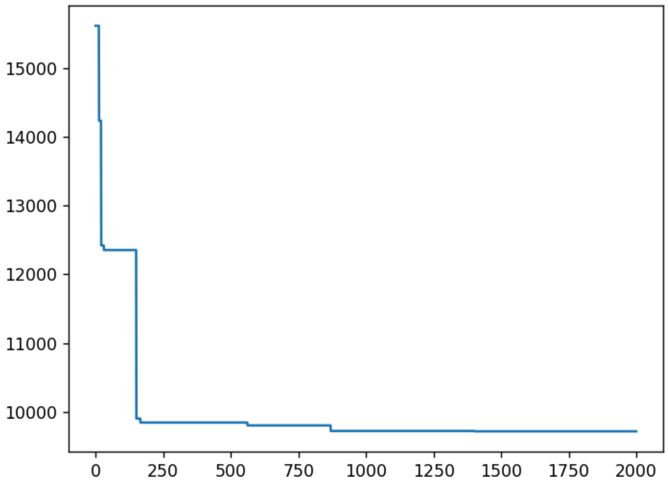


Fig. 1 - Pick-up cost iteration diagram

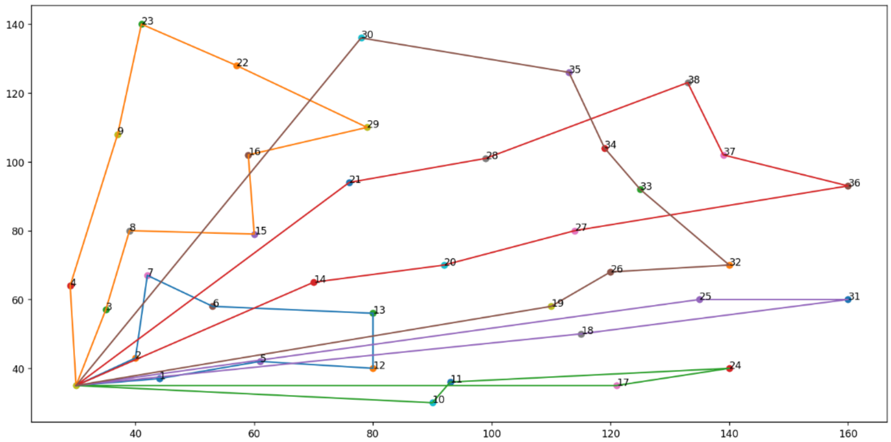


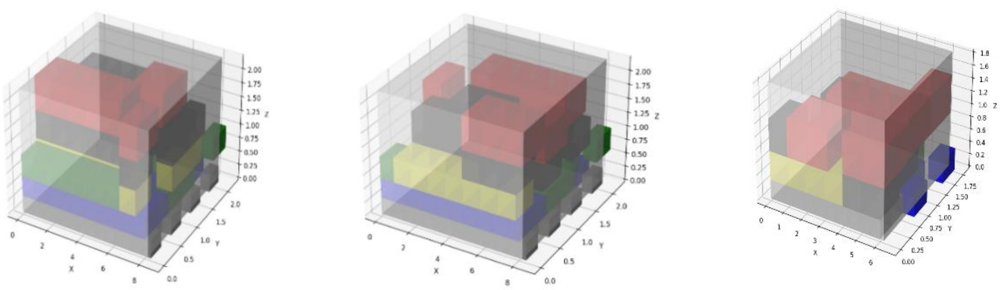
Fig. 2 - Pick-up vehicle routing diagram

Table 6

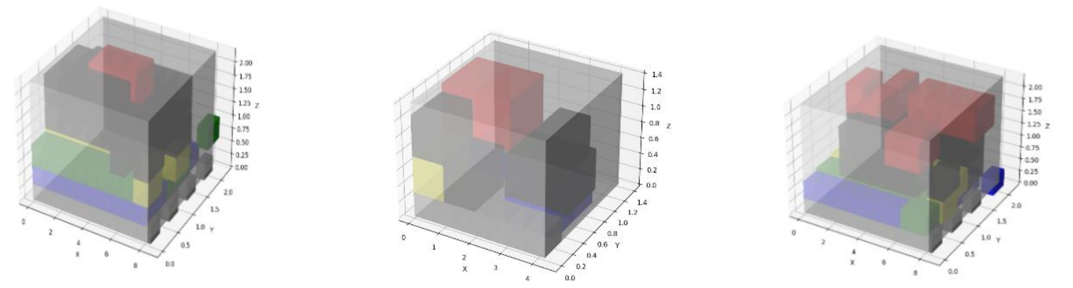
Optimization scheme of pick-up vehicle routing

Routings	Vehicle types	Cost(yuan)	Volume utilization rate	Load utilization rate
0→1→5→12→13→6→7→2→0	C	1547	84%	73%
0→4→9→23→22→29→16→15→8→3→0	C	1875	82%	72%
0→10→11→24→17→0	B	1796	87%	66%
0→21→28→38→37→36→27→20→14→0	C	1728	85%	72%
0→18→31→25→0	A	1113	78%	67%
0→30→35→34→33→32→26→19→0	C	1655	76%	52%

Note: The results in the table are rounded.



0→1→5→12→13→6→7→2→0 0→4→9→23→22→29→16→15→8→3→0 0→10→11→24→17→0



0→21→28→38→37→36→27→20→14→0 0→18→31→25→0 0→30→35→34→33→32→26→19→0

Fig. 3 - Three-dimensional diagram of cargo loading

CONCLUSIONS

To reduce pick-up time and cost, a joint optimization model of pick-up vehicle routing and cargo allocation for fresh agricultural products was constructed. ALNS and HDFS were integrated to solve the model. A case study of Kunming International Flower Auction Center was conducted to compare the schemes of pick-up vehicle routing before and after optimization. The following conclusions could be drawn:

(1) Compared with the original scheme, the total cost of the optimized scheme reduces by 9.6%, the number of vehicles used reduces by one, and the total volume utilization rate and total load utilization rate of the vehicle increase by 23% and 15%. The experimental results show that ALNS combined with HDFS has good sensitivity and can be applied to solve the proposed model in this study.

(2) The damage operators and repair operators are used to process the current solution, which enriches the diversity of the neighborhood structure, enhances the optimization ability of the algorithm, and helps the algorithm to avoid premature convergence and local optimal. A variety of operators designed according to the characteristics of the problem can even further solve the optimization problem of pick-up vehicle routing for large-scale fresh agricultural products, and provide more decision-making basis for enterprise operators.

The joint optimization of vehicle routing and cargo allocation is a very complex and systematic task. In this study, time limits and three-dimensional loading constraints are considered, which provides a reference for cold-chain logistics enterprises to optimize pick-up vehicle routing. However, the proposed model does not consider the impact of traffic accidents and weather conditions on vehicle driving and the change of pick-up point orders. Therefore, it is vital to construct a more realistic dynamic model in the future.

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REFERENCES

[1] Chi, J., & He, S. (2023). Pickup capacitated vehicle routing problem with three-dimensional loading constraints: model and algorithms. *Transportation Research Part E*, United Kingdom, *176,* 103208. http://dx.doi.org/10.1016/J.TRE.2023.103208

[2] Che, L., & Yang, Z. (2023). Optimization of cyclic pick-up path for simultaneous pick-up and delivery of auto parts under three-dimensional loading constraints (三维装载约束下汽车零部件同时取送的循环取货路径优化研究). *Journal of Chongqing Normal University (Natural Science)*, China, *40*(1), 61-72.

[3] Fernando, M. W., Thibbotuwawa, A., Perera, N., Nielsen, P., & Kilic, D. K. (2024). An integrated vehicle routing model to optimize agricultural products distribution in retail chains. *Cleaner Logistics and Supply Chain*, United Kingdom, *10*, 100137. http://dx.doi.org/10.1016/J.CLSCN.2023.100137

[4] Ines, S., & Saoussen, K. (2021). A novel adaptive genetic algorithm for dynamic vehicle routing problem with backhaul and two-dimensional loading constraints: a case in Tunisian Posta. *International Journal of Applied Metaheuristic Computing*, United States, *13*(1), 1-34. http://dx.doi.org/10.4018/IJAMC.2022010103

[5] Ji, B., Zhou, S., Samson, S., & Wu, G. (2021). An enhanced neighborhood search algorithm for solving the split delivery vehicle routing problem with two-dimensional loading constraints. *Computers & Industrial Engineering*, United Kingdom, *162,* 107720. http://dx.doi.org/10.1016/J.CIE.2021.107720

[6] Jiang, Y., Bian, Be, & Liu, Y. (2020) Integrated multi-item packaging and vehicle routing with split delivery problem for fresh agri-product emergency supply at large-scale epidemic disease context. *Journal of Traffic and Transportation Engineering (English Edition),* Netherlands, *8*(2), 196-208. http://dx.doi.org/10.1016/J.JTTE.2020.08.003

[7] Lv, D., Zhou, Q., Yang, M., & Chen, Q. (2014). Evaluation of AHP-based agricultural products circulation efficiency index. *BioTechnology: An Indian Journal*, India, *10*(18), 10305-10310.

[8] Li, S., Liu, Z., Fang, H., & Liu, L. (2019). Vehicle routing problem of fresh agricultural products considering decaying factors. *IOP Conference Series: Materials Science and Engineering*, United Kingdom, *688*(4), 044012. http://dx.doi.org/10.1088/1757-899X/688/4/044012

[9] Li, J., Liu, M., & Liu, P. (2021). Route optimization of multi-vehicle cold chain logistics for fresh agricultural products (生鲜农产品多车型冷链物流车辆路径优化). China, *Journal of China Agricultural University*, *26*(7), 115-123.

[10] Lin, Y., Zhao, X., & Shen, H. (2022). Research on route optimization of agricultural products transport vehicles based on improved genetic algorithm (基于改进遗传算法的农产品运输车辆路径优化研究). China, *Automation Application*, *12*, 5-8+14. http://dx.doi.org/10.19769/j.zdhy.2022.12.002

[11] Lehmann, J., & Winkenbach, M. (2024). A matheuristic for the two-echelon multi-trip vehicle routing problem with mixed pickup and delivery demand and time windows. *Transportation Research Part C*, United Kingdom, *160*, 104522. http://dx.doi.org/10.1016/J.TRC.2024.104522

[12] Liu, Z., Niu, Y., Guo, C., & Jia, S. (2023). A vehicle routing optimization model for community group buying considering carbon emissions and total distribution costs. *Energies*, Switzerland, *16*(2), 631. http://dx.doi.org/10.3390/EN16020931

[13] Ma, L., Chen, Z., & Li, Y. (2023). Research on the circulation strategy of agricultural products under extreme weather. *Journal of Physics: Conference Series*, United Kingdom, *2468*(1), 012153. http://dx.doi.org/10.1088/1742-6596/2468/1/012153

[14] Ni, C., & Katarzyna, D. (2024). Research on optimization of agricultural products cold chain logistics distribution system based on low carbon perspective. *International Journal of Information Systems and Supply Chain Management*, United States, *17*(1), 1-14. http://dx.doi.org/10.4018/IJISSCM.338220

[15] Pinto, L. F., Carlos, J. F., Augusto, G. H., Victoria, B. J. L., & Marko, B. (2021). A multi-start algorithm for solving the capacitated vehicle routing problem with two-dimensional loading constraints. *Symmetry*, Switzerland, *13*(9), 1697. http://dx.doi.org/10.3390/SYM13091697

[16] Rahmanifar, G., Mohammadi, M., Golabian, M., Sherafat, A., & Keshteli, M. H. (2024). Integrated location and routing for cold chain logistics networks with heterogeneous customer demand. J*ournal of Industrial Information Integration, Netherlands*, *38*, 100573. http://dx.doi.org/10.1016/J.JII.2024.100573

[17] Sun, M., & Pang, D. (2017). Vehicle routing optimisation algorithm for agricultural products logistics distribution. *International Journal of Applied Decision Sciences*, United Kingdom, *10*(4), 327-334. http://dx.doi.org/10.1504/IJADS.2017.087175

[18] Sbai, I., Krichen, S., & Limam, O. (2022). Solving the capacitated vehicle routing problem with two-dimensional loading constraints using a parallel VNS approach. *International Journal of Metaheuristics*, United Kingdom, *8*(1), 51-78. http://dx.doi.org/10.1504/IJMHEUR.2022.10052727

[19] Takahashi, T. (2003). The social meaning of the organic agricultural produce circulation channel formation by the organic farming management activities. *The Journal of Japan Society for Distributive Sciences*, Japan, *2003*(16), 51-57. http://dx.doi.org/10.14904/jsds1988.2003.51

[20] Varas, M., Baesler, F., Basso, F., Contreras, J. P., & Pezoa, R. (2024). A home hospitalization assignment and routing problem with multiple time windows, mandatory returns and perishable biological samples: a Chilean case study. *Computers & Industrial Engineering*, United Kingdom, *189*, 109951. http://dx.doi.org/10.1016/J.CIE.2024.109951

[21] Wang, Y., We,i Y., Jiang, Q., & Xu, M. (2021). Vehicle routing problem based on transportation resource sharing under three-dimensional loading constraints (三维装载约束下基于运输资源共享的车辆路径问题). *Computer Integrated Manufacturing Systems*, China, *29*(9), 3153-3170.
http://dx.doi.org/10.13196/j.cims.2023.09.025

[22] Wei, L., Zhang, Z., & Lim, A. (2014). An adaptive variable neighborhood search for a heterogeneous fleet vehicle routing problem with three-dimensional loading constraints. *IEEE Computational Intelligence Magazine*, United States, *9*(4), 18-30. http://dx.doi.org/10.1109/MCI.2014.2350933

[23] Xie, R. (2022). Discussion on the development of "the first one kilometer" of cold chain logistics of fresh agricultural products in China (中国生鲜农产品冷链物流"最先一公里"发展探讨). *Journal of Commercial Economics*, China, *2*, 114-117.

[24] Zhu, S., Fu, H., & Li, Y. (2021). Optimization research on vehicle routing for fresh agricultural products based on the investment of freshness-keeping cost in the distribution process. *Sustainability*, Switzerland, *13*(14), 8110. http://dx.doi.org/10.3390/SU13148110