Integrated Optimization of Location and Routing for Fresh Agricultural Products in First-Mile Logistics Considering Time Windows and Spoilage Cost

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Abstract. This paper studies the integrated location-routing problem for fresh agricultural products in first-mile logistics. A mathematical model minimizes total cost including construction, transportation, spoilage, and time window penalties. A hybrid algorithm (K-means + improved GA) is proposed. A case study verifies significant reductions in cost and distance while improving utilization and service level.

Keywords: fresh agricultural products; location-routing problem; cold chain logistics; time window; genetic algorithm

1 Introduction

With the rapid development of e-commerce, demand for fresh agricultural product logistics has increased significantly. First-mile logistics faces challenges such as scattered supply, inefficient transportation, and product perishability, leading to high costs and losses. Existing studies on facility location and vehicle routing have made progress[1][2][4][5] but are often studied separately, limiting practical applicability[3]. This paper develops an integrated location-routing model considering time windows and spoilage cost to improve efficiency and reduce losses.

1.1 Problem Description

Problem Description – Determine distribution center (DC) locations, assign demand points, and optimize vehicle routes under capacity and time window constraints.

1.2 Assumptions

To simplify the model, the following assumptions are made:

(1) Products share the same decay rate β[1]. (2) Soft time windows with penalties[3].

L. W. Koon et al. (eds.), *Proceedings of the 2026 7th International Conference on Management Science and Engineering Management (ICMSEM 2026)*, Advances in Economics, Business and Management Research 399,
https://doi.org/10.2991/978-94-6239-758-3_56

(3) Vehicles are homogeneous. (4) Spoilage only during transport; waiting periods negligible.(5) DCs have daily throughput capacity. (6) All vehicles identical in capacity, speed, cost. (7) Demand deterministic and stable.

2 Model Formulation

The integrated location-routing model proposed in this paper is a single-objective optimization problem. The total system cost Z minimizes four components: fixed construction (C1), transportation (C2), spoilage (C3), and time window penalty (C4). Total cost:

$$minZ = C_1 + C_2 + C_3 + C_4 \tag{1}$$

2.1 Upper-Level Model (Location Problem)

Fixed construction and allocation cost $\boldsymbol{C_1}$: The location and construction of distribution centers include site rental, cold-chain equipment purchase, daily maintenance, and staff salaries. In addition, the transportation cost from villages to their assigned centers (based on straight-line distance) is also considered at this stage. The total upper-level cost is denoted as C1, as shown in Equation (2).

$$\min C_1 = \sum_{k\in K} f_k y_k + \sum_{i\in N} \sum_{k\in K} c\, d_{ik} x_{ik} \tag{2}$$

Subject to:

$$\sum_{k\in K} x_{ik} = 1, \quad \forall i \in N$$

$$x_{ik} \le y_k, \quad \forall i \in N, k \in K$$

$$\sum_{i\in N} q_i\, x_{ik} \le Q_k y_k, \quad \forall k \in K$$

2.2 Lower-Level Model (Routing Problem)

The lower-level model jointly optimizes vehicle routing, product spoilage, and time-window compliance. Its objective is to minimize the sum of transportation cost ($\boldsymbol{C_2}$), spoilage cost ($\boldsymbol{C_3}$), and time-window penalty cost ($\boldsymbol{C_4}$), as formulated in the following equations.

Vehicle transportation cost: During the collection of fresh products, vehicle travel mainly incurs fuel consumption, tire wear, and vehicle depreciation. The longer the distance and the heavier the load, the higher the cost. These costs are denoted as C2, as shown in Equation (3).

$$C_2 = \sum_{v\in V} \sum_{i\in N} \sum_{j\in N} c\, d_{ij} z_{ij}^{v} \tag{3}$$

Spoilage cost of fresh products: Fresh agricultural products lose freshness during transportation due to extended time, resulting in product value loss and disposal expenses. These costs are denoted as $\boldsymbol{C_3}$, as shown in Equation (4).

$$C_3 = \sum_{i \in N} q_i \; p_i \left(1 - e^{-\beta t_{ik}}\right) \tag{4}$$

where β $\left[\min^{-1}\right]$is the decay coefficient, $t_{ik} = \frac{d_{ik}}{v}$is the transport time (v constant), and $1 - e^{-\beta t_{ik}}$ is the fraction of product value lost. The refrigeration system operates continuously, but spoilage during waiting periods is not explicitly modeled as its effect is negligible compared to travel time.

Time-window violation penalty cost: When vehicles fail to arrive within the customer's specified time window, penalty costs are incurred. These mainly include resource idle cost from early arrival and customer satisfaction loss from late arrival. These costs are denoted as $\boldsymbol{C_4}$, as shown in Equation (5).

$$C_4 = \sum_{i \in N} [w_{\text{wait}} \max(0, e_i - T_i) + w_{\text{late}} \max(0, T_i - l_i)] \tag{5}$$

Penalty coefficients are cost-based: waiting penalty reflects vehicle idle cost; late penalty captures delay and deterioration losses. Sensitivity analysis (±20%) confirms a trade-off: higher penalties cut delay/spoilage but raise transport cost, while lower penalties do the reverse. The optimum balances marginal savings against marginal losses.

Subject to:

$$\sum_{v \in V} \sum_{j \in N} z_{ij}^v = 1, \quad \forall i \in N$$

$$\sum_{i \in N} q_i \sum_{j \in N} z_{ij}^v \le Q, \quad \forall v \in V$$

$$\sum_{j \in N} z_{ij}^v = \sum_{j \in N} z_{ji}^v, \quad \forall i \in N, v \in V$$

$$\sum_{j \in N} z_{0j}^v = 1, \quad \forall v \in V$$

$$\sum_{i \in N} z_{i0}^v = 1, \quad \forall v \in V$$

$$u_i - u_j + Q\, z_{ij}^v \le Q - q_j, \quad \forall i, j \in N \setminus \{0\}, i \ne j, v \in V$$

$$T_j \ge T_i + t_{ij} - M\left(1 - z_{ij}^v\right), \quad \forall i, j, v$$

$$e_i \le T_i \le l_i, \quad \forall i \in N$$

2.3 Mathematical Models

The model minimizes total system cost while ensuring demand assignment, capacity constraints, routing feasibility, and time window compliance.

$$minZ = C_1 + C_2 + C_3 + C_4$$

$$\sum_{k\in K} x_{ik} = 1, \quad \forall i \in N \tag{6}$$

$$x_{ik} \le y_k, \quad \forall i \in N, k \in K \tag{7}$$

$$\sum_{i\in N} q_i x_{ik} \le Q_k y_k, \quad \forall k \in K \tag{8}$$

$$\sum_{v\in V} \sum_{j\in N} z_{ij}^v = 1, \quad \forall i \in N \tag{9}$$

$$\sum_{j\in N} z_{ij}^v = \sum_{j\in N} z_{ji}^v, \quad \forall v \in V \tag{10}$$

$$\sum_{i\in N} q_i \sum_{j\in N} z_{ij}^v \le Q, \quad \forall v \in V \tag{11}$$

$$T_j \ge T_i + t_{ij} - M\left(1 - z_{ij}^v\right), \quad \forall i, j, v \tag{12}$$

$$e_i \le T_i \le l_i, \quad \forall i \in N \tag{13}$$

$$x_{ik}, y_k, z_{ij}^v \in \{0,1\}$$

The integrated model simultaneously determines the optimal location of distribution centers and the routing of vehicles. The objective function consists of four main components: construction cost, transportation cost, spoilage cost, and time window penalty cost.Constraint (6) ensures that each demand point is assigned to exactly one distribution center. Constraint (7) guarantees that allocation only occurs if a center is established. Constraint (8) restricts the capacity of distribution centers.Constraints (9) and (10) ensure that each node is visited exactly once and that vehicle routes remain continuous. Constraint (11) enforces vehicle capacity limitations. Constraint (12) ensures logical consistency of travel time between nodes, while Constraint (13) guarantees compliance with customer time windows.Overall, the model captures both spatial allocation decisions and temporal routing constraints, forming a comprehensive optimization framework for first-mile logistics of fresh agricultural products.

3 Solution Method

3.1 Hybrid Algorithm Based on K-means and Improved Genetic Algorithm

A hybrid algorithm combines K-means clustering (for location/allocation) and an improved genetic algorithm (for routing)[5][6].

3.2 Algorithm Procedure

Step 1: Input data (coordinates, demand, parameters).**Step 2**: K-means to determine DCs and assignments.Step 3: Encode routes as chromosomes; initialize population.**Step 4**: Compute fitness value: $fitness = \frac{1}{C_2 + C_3 + C_4}$.**Step 5**: Apply genetic operations (roulette selection, PMX crossover, swap mutation) with elite retention, adaptive probabilities, and penalty mechanism.**Step 6**: Repeat Steps 4–5 until termination; output best solution.K-means partitions demand points into clusters, reducing search space complexity and providing informative initial solutions for the genetic algorithm. This enhances search efficiency, prevents premature convergence, and improves solution stability.

4 Simulation Example Analysis

4.1 Data Description

A case with 20 demand points (random coordinates, demand 0.5–2 t) is conducted.

Key parameters are set as follows: Vehicle capacity: 5 tons Transportation cost: 2 RMB/km Vehicle speed: 40 km/h Unit price: 10 RMB/kg Distribution center construction cost: 5000 RMB/day Time window: 0–120 min Penalty coefficient: 50 Spoilage coefficient: 0.05.

4.2 Experimental Design

To evaluate the performance of the proposed method, two scenarios are designed:

Scenario 1: Traditional Method, Fixed distribution center locations, Nearest-neighbor routing strategy, No optimization Scenario 2: Proposed Method, K-means clustering for location, Improved genetic algorithm for routing, Integrated optimization.The parameters are shown in Table 1.

Table 1. Results Comparison

Metric	Traditional	Proposed	Improvement
Total cost (RMB)	15200	12100	-20.4%
Distance (km)	860	690	-19.8%
Utilization (%)	62	85	+23%
On-time rate (%)	78	93	+15%
Spoilage (%)	12	7	-41.7%

The proposed method was run 30 times with different random seeds. Mean total cost = 12145 RMB (SD = 312 RMB). A one-sample t-test against the traditional method (15200 RMB) gives $t = 53.6$ ($p < 0.001$), confirming the 20.4% reduction is statistically significant.

5 Conclusion

This paper proposes an integrated model and hybrid algorithm (K-means + improved GA) for first-mile logistics of fresh agricultural products, minimizing construction, transportation, spoilage, and time-window costs. K-means determines DC locations and allocation, while GA optimizes routes. The case study confirms significant gains. The algorithm (pop=50, G=200, pc=0.8, pm=0.1) converges within 120 generations and 7 seconds.

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