Location Optimization of Agricultural Cold Chain Logistics Centers under Demand and Distance Fluctuations: A Case Study of Henan Province

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Abstract: The perishable nature of fresh agricultural products and consumer focus on freshness make efficient cold chain logistics vital for farmer income. Henan, a major agricultural province, faces significant logistics load surges due to high output and dispersed harvests. Optimizing cold chain logistics center layout to meet dynamic demand and alleviate load fluctuations is crucial for improving farmer income. This study addresses this challenge by developing a mathematical model for optimizing the location of cold chain logistics centers in Henan Province. The model explicitly incorporates fluctuations in cold storage demand and real-world uncertainties. Using data from 18 cities in Henan, the study investigates the impact of varying model parameters on optimal center location. The findings provide theoretical and methodological insights to support the scientific planning of new agricultural cold chain logistics infrastructure in the province.

Keywords: Henan Province；Cold chain logistics center location；Demand and Distance Fluctuations；Agricultural products；Case study

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1 INTRODUCTION

Logistics industry development is crucial for enhancing circulation efficiency, optimizing resource allocation, and promoting economic growth. Since the early 21st century, the Chinese government has prioritized logistics development, issuing numerous policy documents.To further advance agricultural cold chain logistics in Henan Province, the provincial government has introduced relevant policies.To date, Henan has designated 16 provincial-level cold chain logistics demonstration zones across two batches, with four cities selected as national cold chain logistics bases.

Agricultural products are highly perishable, requiring prompt transfer post-harvest to maximize freshness and minimize spoilage. Varying maturity cycles cause seasonal cold storage demand fluctuations, leading to abrupt logistics network load shifts. Consequently,optimizing the location of cold chain logistics centers is critical to, the key challenge is optimizing spatial distribution to accommodate product-specific time windows and demand fluctuations, reducing losses.

This study aims to address the following research questions:

What cost components and formulation should the location model incorporate?

How to quantitatively represent demand volatility and time sensitivity?

Which parameter variations should sensitivity analysis cover?

How to empirically validate the model?

Motivated by this, the research focuses on locating centers in Henan, examining seasonal output impact on logistics volumes.Adopting a total cost minimization objective,we investigate optimal strategies under demand volatility and product-specific time windows to mitigate delays or resource idling from load variations.The model ’ s cost function encompasses land leasing, fixed/variable facility costs, and transportation. Constraints include time windows and allocation rules. Crucially, the model accounts for real-world uncertainties.

2 LITERATURE REVIEW

Logistics centers are critical infrastructure. Optimal location facilitates efficient flows, enhances regulation, and reduces costs.This section mainly focuses on the “Cold Chain Logistics and Fresh Agricultural Product Logistics” content.Research on agricultural product logistics originated with Growell (1901)[1], who identified key factors influencing distribution costs.Studies have addressed challenges in China's “Internet Plus” fresh agricultural logistics (Li Zhiyong, 2020[2]; Wang Honglei, 2021[3]; Guo Xiaowei et al., 2021[4]; Gu Lingling et al., 2021[5]). He (2020)[6] revealed the complexity of fresh agricultural logistics ecosystems through analyzing micro-level stakeholder behaviors and macro-system evolution, aiming to enhance coordination and performance.Qi Yuxuan et al. (2021)[7] used neural networks to predict stable logistics demand trends during pandemics. Zhang et al. (2021)[8] proposed a bilevel programming model solved via cloud-based particle swarm optimization. Ge Chunyue (2021)[9] introduced clustering algorithms to accelerate system optimization. Zhuang Xiaoyun (2021)[10]combined set-covering theory with TOPSIS to evaluate sites based on natural conditions, transportation, and operating environments.

3 MODELS

3.1 Problem Description and Assumptions.

The agricultural cold chain logistics center location problem involves determining the optimal locations for centers and the assignment of demand points (farmers) to centers, aiming to minimize the total logistics network cost. Building upon the classic facility location problem, this study incorporates:

Uncertainties during transportation.Unit transportation cost (α) and speed (V_{ij}) are subject to variation due to road conditions and weather. We simulate these fluctuations by applying ±δ% deviations to baseline unit transportation cost (α) and speed (V_{ij}).

Fluctuations in cold storage demand. We simulate demand (D_i) fluctuations by applying ±γ% deviations to baseline yield data.

Product-specific arrival time requirements.We impose differentiated maximum transportation time limits (h_{ij}^{p}) for each product type p.

To facilitate analysis, we make the following assumptions:

Each farmer's cold storage demand is served by exactly one center.

The temperature inside cold chain transport vehicles remains constant during transit.

The cold storage demand quantity Di of each farmer is known.

The land rent R at each candidate location for logistics centers is identical.

3.2 Model Formulation.

3.2.1Sets and indices:

N={1,2,⋯ ,n}	Set of farmer demand points.
M={1,2,⋯ ,m}	Set of candidate locations for logistics centers.

3.2.2Parameters:

C	Total operating cost of the cold chain logistics network (Yuan).
C_f	Total construction cost of cold chain logistics centers (Yuan).
C_v	Total variable operating cost of cold chain logistics centers (Yuan).
C_t	Total transportation cost for fresh agricultural products (Yuan).
f	Fixed cost coefficient for logistics centers.
φ	Economies of scale exponent.(0< φ <1.a smaller value indicates stronger economies of scale.)
VC_j	Variable operating cost coefficient for a logistics center operating at candidate site j.(Yuan/t)
V_{ij}	Travel speed between demand i and site j.(km/h)
D_i	Cold storage demand quantity of farmer i.(t)
R	Land rent at candidate site.(Yuan)
d_{ij}	Distance from demand i and site j.(km)
α	Unit transportation cost for fresh agricultural products.(Yuan/km·t)
Vol_j	Capacity of cold chain logistics center j.(t)

h_{ij}^{p}	Maximum allowable requirement for agricultural productp from i to j .(hours)
F	Maximum number of centers to be established.

3.2.3Decision Variables:

Y_{ij}	1,if demand i is served by logistics center j.0,otherwise.
X_j	1,if a logistics center is established at candidate site j.0,otherwise.

3.3 Models.

The total operating cost of the cold chain logistics network studied here comprises the construction cost of the logistics centers, their variable operating costs, and the transportation cost for moving harvested agricultural products from farms to the cold chain logistics centers.

1. The total construction cost Cf includes land rental fees at the construction site and the cost of building the logistics centers.

$$C_f = \sum_{j=1}^{m}(RX_j + fVol_j) \tag{3.1}$$

2.The variable operating cost Cv includes costs for production factors such as electricity and water required for product refrigeration.

$$C_v = \sum_{i=1}^{n}\sum_{j=1}^{m} VC_j (Y_{ij} D_i)^{\varphi} \tag{3.2}$$

3.The agricultural product transportation cost Ct represents the total cost of transporting products from origins to cold chain logistics centers.

$$C_t = \alpha \sum_{i=1}^{n}\sum_{j=1}^{m} d_{ij} Y_{ij} D_i \tag{3.3}$$

The specific model is as follows:

$$\min C = \sum_{j=1}^{m}(RX_j + fVol_j) + \sum_{i=1}^{n}\sum_{j=1}^{m} VC_j (Y_{ij} D_i)^{\varphi} + \alpha \sum_{i=1}^{n}\sum_{j=1}^{m} d_{ij} Y_{ij} D_i \tag{3.4}$$

3.4 Subject to.

$$\sum_{j=1}^{m} Y_{ij} = 1, i = 1,2,\ldots,n \tag{3.5}$$

$$Y_{ij} \le X_j, j = 1,2,\ldots,m, i = 1,2,\ldots,n \tag{3.6}$$

$$Y_{ij} \frac{d_{ij}}{V_{ij}} \le h_{ij}^{\mathrm{p}}, j = 1,2,\ldots,m, i = 1,2,\ldots,n \tag{3.7}$$

$$\sum_{j=1}^{m} X_j = F \tag{3.8}$$

$$\sum_{i=1}^{n} Y_{ij} D_i \le Vol_j, j = 1,2,\ldots,m \tag{3.9}$$

$$X_j, Y_{ij} \in \{0,1\}, i = 1,2,\ldots,n; j = 1,2,\ldots,m, \tag{3.10}$$

Constraints (3.5) and (3.6) ensure each farmer is served by exactly one open center. Constraint (3.7) enforces the product-specific time window. Constraint (3.8) sets the number of centers to F. Constraint (3.9) is the capacity constraint.

Constraint (3.10) defines the binary variables. Sensitivity analysis is performed on key parameters (α ,V_{ij}, D_i) to transform uncertainties into analyzable scenarios. The model is solved using Lingo software.

4 CASE STUDY

4.1 Case Background

Henan is China's core grain area, major livestock hub, and cash crop region. 34 county-level cities specialize in distinct products and 16 provincial cold chain logistics demonstration parks.

4.2 Data Selection

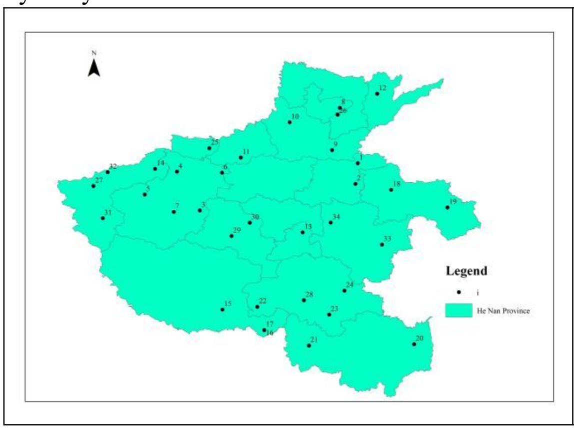
This study applies the model to optimize the location of centers serving the 34 agricultural counties (Fig 1) from among the 16 candidate parks (Fig 2). We examine how parameter variations affect optimal locations to inform park operations and future expansions.

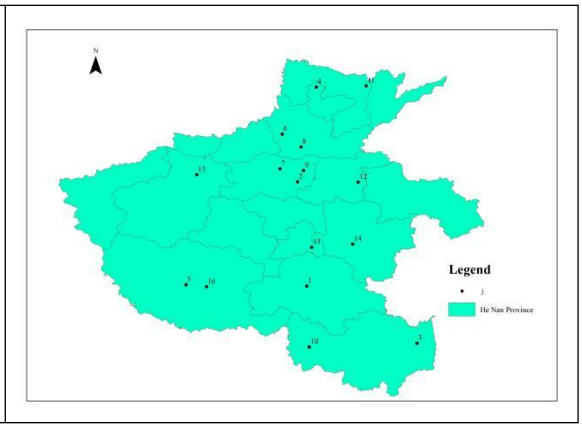
Distances dij between demand points and candidates were obtained via Amap API.

Demand quantities were sourced from county government agricultural reports.

Key parameters :f=5000(yuan); R=10000(Yuan); φ =0.5;VC_i=20(Yuan/t);α=200(Yuan/km·t); Baseline V_{ij}=60(km/h).

Preliminary experiments revealed a U-shaped total cost curve as the number of centers (F) increases. Minimum total costs occur at F=13, 15, and 16, with these values closely clustered. These three center counts are therefore the focus of the sensitivity analysis.





5 SENSITIVITY ANALYSIS

5.1 Impact of Demand Fluctuations.

Table1 shows the influence of demand variation (±50%) on minimum total cost (min C) for different numbers of centers (F=13,15,16).When the number was fixed, the stations selected changed under different demand scenarios (F=13,15); when the number was 16, station selection remained unchanged.As can be seen from the diagram, it is optimal to set up 15 cold chain logistics centers when all conditions are in a stable state; When demand decreases, it is optimal to have 13 cold chain logistics centers; When demand increases, it is optimal to set up 16 cold chain logistics centers. Adjusting the number of centers and the assignment of demand points to centers effectively reduces costs under demand fluctuations.

5.2 Impact of Product-Specific Time Constraints.

Table 2 presents the min C, optimal number of stations, and selected stations under different arrival times.Total cost increases by 3.17% (due to potentially shorter average distances),the spoilage rate significantly decreases from 5.33% to 3.61%, a reduction of 1.72 percentage points.This demonstrates that product-specific time windows effectively reduce spoilage and economic losses.

5.3 Impact of Transportation Distance Uncertainty.

Table1 shows the impact of distance variation (±50%) on minC. When the number was fixed, the stations selected changed under different distance scenarios (F=13,15); when the number was 16, station selection remained unchanged.When the number of logistics centers is 13, if the transportation distance is increased by 50%, the cost rises significantly, becoming the most expensive of all scenarios. However, as the number of logistics centers increases, the growth rate of total cost will be relatively slow, and when the number of logistics centers reaches 16, the increase in transportation distance has the least impact on the total cost.

Table 1 Candidate Site Variations Under Distance and Demand Fluctuations

(￥：×10^{11})

centers	distance change	min C	demand change	min C
13	0.5×	2.00	0.5×	2.18
	0.75×	3.14	0.75×	3.20
	1×	4.24	1×	4.24
	1.25×	5.30	1.25×	6.00
	1.5×	6.47	1.5×	6.80
15	0.5×	2.10	0.5×	2.38
	0.75×	3.21	0.75×	3.49
	1×	3.74	1×	3.74
	1.25×	5.20	1.25×	5.40
	1.5×	6.25	1.5×	6.50
16	0.5×	2.30	0.5×	2.59
	0.75×	3.33	0.75×	3.62
	1×	4.45	1×	4.45
	1.25×	5.26	1.25×	5.80
	1.5×	6.35	1.5×	6.10

Table 2 Details of different arrival time constraints

	F	min C(￥)	parks j
Uniform	13	4.25×10^{11}	1、2、4、5、7、8、9、10、11、13、14、15、16
Differentiated	15	4.11×10^{11}	1、2、3、4、5、6、7、9、10、11、12、13、14、15、16

6 CONCLUSIONS

This study developed a mathematical model to optimize the location of agricultural cold chain logistics centers in Henan Province.Key findings are:

The model integrates key cost components and constraints to minimize total network cost under uncertainty, analyzed via parameter sensitivity our province as the research object. It extends the classic facility location model by incorporating agricultural output fluctuations across seasons and the impact of climatic factors on product flow. Decisions on center location are made from a cost optimization perspective, considering the distinct arrival time requirements of different products to reduce spoilage and increase farmer income. Sensitivity analysis on environmental factors enhances the model's practical relevance.

Applying the model to 34 counties and 16 candidate parks in Henan revealed: The optimal number of centers adapts to demand levels (F=13 for low demand, F=15 for baseline, F=16 for high demand). Product-specific time windows significantly reduce spoilage compared to uniform time limits, though potentially increasing the number of centers needed. Increasing transportation distance raises costs, with the impact mitigated by having more centers. Decreasing distance favors fewer centers. The fuzzy environment is considered or not to directly affect the network layout of the optimal cold chain logistics center location and distribution, and the cost of the cold chain logistics center location network considering the fuzzy is much lower than that of the network layout without fuzzy consideration.

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