Supply Chain Resilience Perspective: Risk Early Warning and Collaborative Scheduling Mechanism of Agricultural Product Cold Chain Logistics

Yinghuan Liu, Chungui Zhou
School of Digital Economy and Management, Guangzhou University of Software, Guangzhou 510990, Guangdong, China
Corresponding author: Yinghuan Liu (e-mail: 13926098329@163.com)

ABSTRACT Based on supply chain resilience theory, this paper constructs an integrated mechanism of risk early warning and collaborative scheduling for agricultural product cold chain logistics, providing a systematic framework for improving the reliability of intelligent logistics systems operating in complex electromagnetic and information-intensive environments. Using data such as cold storage utilization rate and transportation loss rate from core nodes including Guangzhou Eastern Railway-Highway Intermodal Hub and Nansha Port, the study completes core risk identification, early warning index system construction, and collaborative scheduling algorithm design by adopting the analytic hierarchy process–entropy weight method, BP neural network, and an improved genetic algorithm. The results show that the proposed three-level early warning index system contains 12 core indicators, while the BP neural network achieves an early warning accuracy of 91.7%. The improved genetic algorithm-based collaborative scheduling model controls the transportation loss rate within 5% under high-risk scenarios and improves the resilience level by 35% compared with traditional scheduling strategies. The constructed resilience-oriented integrated framework provides theoretical support and decision-making guidance for enhancing regional cold chain risk governance and operational efficiency, while offering practical insights for intelligent infrastructure monitoring and reliable logistics operation in digitally connected electromagnetic environments.

INDEX TERMS supply chain resilience, agricultural product cold chain logistics, risk early warning, collaborative scheduling, electromagnetic environment

I. INTRODUCTION

A. RESEARCH BACKGROUND

1) Practical Background

THE cold chain logistics of agricultural products functions as a vital circulation system that mirrors the protective integrity of protective packaging and climate-controlled fabric storage, ensuring product quality and safety while reducing losses and increasing added value. By integrating the material preservation techniques common in high-performance management, this system enhances the durability and market worth of perishable agricultural goods [1]. As a key hub of the "Belt and Road" and a major province in agricultural product production and sales, Guangdong Province has provided strong support for agricultural product circulation and various other commodity trading activities relying on its "railway, highway, sea, and air" transportation advantages, laying a solid foundation for the development of its cold chain logistics. However, with the upgrading of consumption, consumers have higher requirements for food safety and fresh product quality, and there is still a gap between the existing cold chain service capacity and market demand. The development of cold chain logistics in Guangzhou is still facing multiple risk challenges: there are loopholes in the regulatory system, making it difficult to control the entire chain; the standard system is imperfect with poor regional coordination, and existing standards mostly focus on imported cold chain supervision and urban cold chain distribution links, while the standardized guidance for key circulation links such as harvesting and pre-cooling, warehousing management, and transfer nodes is obviously weak; there are shortcomings in infrastructure construction, coupled with low coverage of pre-cooling facilities in producing areas and lack of terminal cold chain facilities, which seriously restrict the high-quality development of the industry [2].

2) Theoretical Background

The supply chain resilience theory emphasizes the pre-preparation capacity of the supply chain to respond to emergencies, the resistance capacity to deal with supply chain disruptions, and the adaptation capacity to recover from shocks, providing a new perspective for cold chain logistics risk governance [3, 4]. Existing studies have confirmed that the improvement of supply chain resilience can effectively reduce costs and improve product quality [5, 6]. However, in the field of agricultural product cold chain, the integration of resilience theory with risk early warning and collaborative scheduling is still insufficient. Traditional risk early warning mostly focuses on single-link risks, ignoring the correlation effects among various subjects in the cold chain [7]; collaborative scheduling research rarely considers the dynamic guiding role of risk early warning signals [8], making it difficult to adapt to the complex operational needs of Guangzhou's multimodal transport cold chain system (such as the high-speed rail lychee special train). Therefore, it is urgent to construct an integrated analysis framework of "resilience-oriented - risk early warning - collaborative scheduling" to fill the gap in theoretical research.

B. RESEARCH PURPOSE AND SIGNIFICANCE

This paper aims to construct an integrated risk early warning and collaborative scheduling mechanism that adapts to Guangzhou's regional characteristics by blending supply chain resilience theory with the logistical agility found in the garment cluster. It not only enriches the theoretical system of agricultural product cold chain risk governance and expands the application scenarios of supply chain resilience theory, but also provides decision support for the development of cold chain logistics in Guangzhou. Through accurate risk early warning, it reduces sudden losses, optimizes the allocation of multimodal transport resources to improve operational efficiency, forms replicable regional characteristic achievements, and helps enhance the resilience of cold chain logistics in the Guangdong-Hong Kong-Macao Greater Bay Area and even South China.

C. REVIEW OF DOMESTIC AND FOREIGN RESEARCH STATUS

1) Research Progress on Supply Chain Resilience

The concept of "supply chain resilience" was first proposed by Professor Rice in 2003 [9], initially applied in the construction field. Many engineering scholars used the concept of supply chain resilience to provide effective solutions to engineering problems, and later it continued to evolve and was applied in supply chain systems in many fields [10]. Foreign research has paid attention to the dimension division and improvement path of supply chain resilience earlier, and proposed a four-stage resilience framework of "resistance - recovery - adaptation - transformation" [11, 12]. Domestic research focuses on the construction of resilience evaluation index systems. For example, Fan et al. sorted out the primary and secondary indicators of supply chain resilience in China's automobile industry and measured the supply chain resilience of the studied automobile enterprises [13]; Lü et al. established a supply chain resilience evaluation index system including four aspects including risk control capability and conducted a case study on furniture enterprises [14]. However, there are few special studies on agricultural product cold chain in existing research, and they lack regional pertinence.

2) Research Progress on Risks of Agricultural Product Cold Chain Logistics

Existing risk research mainly focuses on risk classification and single-link risk control, such as uncertain factors such as cold chain technology level, management, natural conditions, and changes in market demand [15]. However, there are two major shortcomings in the research: (1) lack of verification of risk factors based on empirical data; (2) failure to fully consider the risk superposition effect brought by new models such as cross-border cold chain and multimodal transport, making it difficult to adapt to the development needs of Guangzhou's international cold chain hub.

3) Research Progress on Collaborative Scheduling of Cold Chain Logistics

Collaborative scheduling research mostly adopts optimization tools such as genetic algorithm and particle swarm optimization algorithm, focusing on cost control and efficiency improvement [16, 17]. Some studies have introduced environmental constraints, time windows and other factors, but few take risk early warning signals as the dynamic input for scheduling optimization, resulting in insufficient risk adaptability of scheduling schemes. For Guangzhou's cold chain layout of "four-port linkage", existing scheduling models are difficult to achieve the collaborative response of railway, highway, sea and air resources.

4) Research Review and Research Gaps

In summary, existing research has not formed an integrated framework of "resilience-oriented - risk early warning - collaborative scheduling", and lacks in-depth analysis combined with regional characteristic empirical data, making it difficult to solve the complex risk problems of agricultural product cold chain logistics in Guangzhou.

This paper will focus on the above gaps, and form research results with Guangzhou's regional characteristics through empirical research and model construction.

D. RESEARCH CONTENT AND METHODS

1) Research Content

This paper focuses on three core contents:

(1) Analyze the development status and identify risks of agricultural product cold chain logistics in Guangzhou, and clarify the core risk factors;

(2) Construct a supply chain resilience-oriented risk early warning index system and conduct empirical verification;

(3) Design a collaborative scheduling algorithm based on risk early warning and verify its effectiveness through example analysis.

2) Research Methods

(1) Literature research method: systematically sort out relevant theories such as supply chain resilience and cold chain risks;

(2) Empirical research method: collect data such as cold storage utilization rate and transportation loss rate from core nodes including Guangzhou Eastern Railway-Highway Intermodal Hub and Nansha Port;

(3) Analytic hierarchy process and entropy weight method: used to determine the weight of early warning indicators;

(4) Optimization algorithm design: construct a collaborative scheduling model integrating risk weight;

(5) Case study method: verify the research conclusions by combining typical cases such as lychee special trains and smuggled frozen product cases.

II. RELATED THEORETICAL FOUNDATIONS

A. SUPPLY CHAIN RESILIENCE THEORY

Supply chain resilience refers to the ability of the supply chain to resist risk shocks, quickly recover normal operations, and adapt to environmental changes when facing uncertain risks. Its core dimensions include resistance capacity, recovery capacity, and adaptation capacity, and its core characteristics are dynamicity, collaboration, and regionality.

Dynamicity requires the resilience level to be adjusted in real time with changes in risks; collaboration emphasizes the linked response of various subjects; regionality reflects that the resilience level is affected by regional industrial foundation and transportation conditions.

The cold chain logistics of agricultural products involves multiple links and numerous participants, and has high requirements for timeliness and is perishable, which is highly consistent with the application scenario of supply chain resilience theory [18].

B. AGRICULTURAL PRODUCT COLD CHAIN LOGISTICS THEORY

Agricultural product cold chain logistics is a low-temperature guarantee logistics system that takes ensuring the quality of agricultural products as the core and runs through links such as production, pre-cooling, warehousing, transportation, and sales. Its core components include cold chain facilities, technical systems, and operating subjects. The typical operation process needs to maintain a specific low-temperature environment throughout to reduce quality loss [19].

C. RISK EARLY WARNING AND COLLABORATIVE SCHEDULING THEORY

The core logic of risk early warning is to realize early risk prediction through indicator monitoring, threshold judgment, and signal output. The core process includes indicator selection, weight determination, threshold division, and model verification. Indicator construction must follow principles such as scientificity, operability, and regional pertinence. Common models such as BP neural network and fuzzy comprehensive evaluation are used to adapt to the risk early warning of complex cold chain systems.

Collaborative scheduling is to realize the optimal allocation of logistics through integrating resources of various subjects in the supply chain. Its core goals include cost control, efficiency improvement, loss reduction, and risk resistance. The participating subjects cover farmers, cold chain enterprises, logistics parks, etc., and the collaboration dimensions include information collaboration, resource collaboration, and process collaboration. Guangzhou's hub operation model of "market operation and government guidance" provides a good foundation for multi-subject collaborative scheduling, and both together provide theoretical support for cold chain risk governance and resource optimization.

III. DEVELOPMENT STATUS AND RISK IDENTIFICATION OF AGRICULTURAL PRODUCT COLD CHAIN LOGISTICS IN GUANGZHOU

A. ANALYSIS OF THE DEVELOPMENT STATUS OF AGRICULTURAL PRODUCT COLD CHAIN LOGISTICS IN GUANGZHOU

1) Development Foundation and Policy Environment

As a core cold chain hub in the Guangdong-Hong Kong-Macao Greater Bay Area, Guangzhou has a solid development foundation and strong policy support. It has formed a planned layout of "1 central warehouse + 6 producing area storage warehouses + 7 sales area backbone warehouses", with significant advantages of core nodes: the Eastern Railway-Highway Intermodal Hub is seamlessly connected to railways and airports, operating multiple cross-border cold chain trains to 34 cities in 17 countries; Nansha Port has the largest coastal cold chain warehouse group in China, with the efficiency of "direct pick-up at the ship's side" for imported fresh products only 2 hours.

The policy environment is continuously optimized. The Guangzhou Municipal Government has continuously optimized the development environment through special rewards, multimodal transport subsidies and other measures. Relying on innovative models such as "lychee special trains", it has realized the efficient circulation of Lingnan characteristic agricultural products. In 2025, the daily transportation volume of lychee special trains exceeds 8 tons, and the loss rate is controlled within 5%.

2) Empirical Analysis of Core Indicators

Based on research data and industry reports, the core indicators of Guangzhou's agricultural product cold chain are shown as follows (Table 1):

3) Existing Development Shortcomings

Despite the good development foundation, Guangzhou's agricultural product cold chain still has shortcomings:

TABLE 1. Empirical Data of Core Indicators of Guangzhou's Agricultural Product Cold Chain Logistics

Indicator Name	Value	Data Description
Built cold storage capacity in the city in 2025	Over 2 million cubic meters	Including core node cold storages such as Eastern Railway-Highway Intermodal Hub and Nansha Port
Built cold storage capacity of Eastern Railway-Highway Intermodal Hub	1.003 million cubic meters	The total capacity will reach 1.84 million cubic meters after full completion
Current cold storage utilization rate of Eastern Railway-Highway Intermodal Hub	68%	It is expected to increase to more than 75% after full completion; defined as slightly below the risk threshold of 70% for Guangzhou's core hubs
Average loss rate of cold chain for agricultural products in the city	12%	Including losses in the entire links of warehousing and transportation
Loss rate of high-speed rail express (lychee special train)	$\leq$5%	"Depart in the morning and arrive at noon" model with significant timeliness advantage; includes 1%-2% loss risk during last-mile transfer
Loss rate of highway cold chain	15%	Greatly affected by road conditions and stability of temperature control equipment; includes last-mile transfer losses
Loss rate of cross-border sea cold chain	20%-25%	Affected by customs clearance process and transportation cycle
Average customs clearance time for imported fresh products at Nansha Port	2 hours	"Direct pick-up at the ship's side" model improves customs clearance efficiency

(1) Unbalanced layout of facilities, insufficient pre-cooling facilities in producing areas, making it difficult to meet the pre-cooling needs of local agricultural products;

(2) Uneven application of supervision and technology, some small-scale cold storages are not connected to the "Cold Storage Connect" platform, and advanced detection technologies such as terahertz imaging—a specialized technology particularly critical for cross-border cold chain quarantine and high-value agricultural product inspection (e.g., preventing the spread of pathogens in imported frozen goods)—the lack of which poses hidden risks to food safety supervision rather than merely reflecting insufficient high-end infrastructure;

(3) Insufficient collaboration in multimodal transport, poor connection of railway, highway, sea and air resources, and difficulty in organizing return cargo sources for cross-border cold chain trains.

B. RISK IDENTIFICATION OF AGRICULTURAL PRODUCT COLD CHAIN LOGISTICS IN GUANGZHOU FROM THE PERSPECTIVE OF SUPPLY CHAIN RESILIENCE

1) Risk Identification Methods and Classification

Using a combination of literature review method, field research method and Delphi method, combined with the actual development of Guangzhou's cold chain, the risks are divided into four categories: supply-side risks, operation-side risks, demand-side risks, and external environment-side risks. The specific risk classification and core performance are shown in Table 2:

2) Extraction of Core Risk Factors and Verification of Key Risk Points

Through correlation analysis and expert scoring, core risk factors are extracted, and key risk points are verified with empirical data from Guangzhou: core risk factors include insufficient pre-cooling facilities, temperature control failure, transportation delay, low cold storage utilization rate (defined as below 70% for Guangzhou's core hubs, considering demand growth and emergency reserve needs), customs clearance supervision loopholes, market demand fluctuations, and extreme weather.

Among them, temperature control failure and transportation delay are the most influential key risk points: research data shows that losses caused by temperature control failure account for 45% of the total cold chain losses (i.e., 5.4% of the total agricultural product output, derived from 12% $\times$ 45%). In the 2021 illegal cross-border frozen product incident (involving false declarations and unauthorized temperature manipulation), 42% of the frozen product outer packaging tested positive for nucleic acid, directly resulting from temperature control failure and supervision loopholes.

3) Correlation Mechanism between Supply Chain Resilience and Cold Chain Logistics Risks

The three dimensions of supply chain resilience have a significant correlation with cold chain risks: Resistance capacity can reduce risks such as insufficient pre-cooling and temperature control failure by improving pre-cooling facilities and optimizing temperature control systems;

Recovery capacity can quickly respond to risks such as transportation delays and equipment failures by establishing emergency transport fleets and sharing cold storage resources;

Adaptation capacity can cope with external risks such as market demand fluctuations and policy changes by promoting multimodal transport and cross-border collaboration. For example, Guangzhou's lychee special train has reduced the transportation loss rate from 15% of the traditional model to less than 5% by improving the supply chain adaptation capacity, effectively resisting the risk of insufficient timeliness.

IV. CONSTRUCTION OF SUPPLY CHAIN RESILIENCE-ORIENTED RISK EARLY WARNING INDEX SYSTEM FOR AGRICULTURAL PRODUCT COLD CHAIN LOGISTICS IN GUANGZHOU

A. PRINCIPLES FOR CONSTRUCTING THE EARLY WARNING INDEX SYSTEM

Combined with Guangzhou's regional characteristics and research needs, the construction of the early warning index

TABLE 2. Risk Classification and Core Performance of Guangzhou's Agricultural Product Cold Chain Logistics

Risk Category	Core Risk Factors	Specific Performance
Supply-side risks	Insufficient pre-cooling facilities, unstable supply sources, equipment failures	Insufficient pre-cooling capacity in producing areas leads to the decline of initial quality of agricultural products; significant fluctuations in the supply of characteristic agricultural products such as lychees and Chicaixin (a type of Chinese cabbage); failures of cold storages, refrigerated trucks and other facilities
Operation-side risks	Temperature control failure, transportation delay, warehousing chaos, customs clearance loopholes	Temperature control non-compliance caused by false temperature control data and equipment failures; transportation delays caused by ship failures and road conditions; low efficiency of cold storage sorting and unreasonable goods location planning; false declarations in cross-border cold chains and lack of quarantine supervision
Demand-side risks	Demand fluctuations, poor distribution connection	Significant fluctuations in fresh product demand caused by holidays and seasonal factors; insufficient low-temperature distribution facilities in the "last mile", and distribution delays affecting quality
External environment-side risks	Extreme weather, epidemic prevention and control, policy changes, trade barriers	Strengthened customs clearance control due to epidemic prevention and control; policy changes in the RCEP region; inconsistent cross-border trade quarantine standards; facility damage and transportation interruptions caused by typhoons and heavy rains

system follows four major principles:

(1) Resilience adaptability principle: indicators must cover the three dimensions of supply chain resistance, recovery, and adaptation;

(2) Scientificity principle: clear indicator definitions and standardized calculation methods;

(3) Regional pertinence principle: integrate characteristic elements such as Guangzhou's multimodal transport and cross-border cold chain, such as high-speed rail express loss rate and Nansha Port customs clearance efficiency;

(4) Data availability principle: indicator data must be obtainable from Guangzhou statistical yearbooks, industry reports, hub operation data, such as cold storage utilization rate and transportation loss rate.

B. DESIGN AND SCREENING OF EARLY WARNING INDICATOR DIMENSIONS

1) Definition of First-Level, Second-Level, and Third-Level Indicators

Based on the risk identification results and supply chain resilience dimensions, a three-level early warning index system is constructed. The specific indicator composition and relevant explanations are shown in Table 3:

2) Indicator Screening and Verification

Expert scoring method and correlation analysis are used for indicator screening:

Invite 10 experts in the field of cold chain logistics (including operation experts from Guangzhou Communications Investment Group, university researchers, and representatives of industry associations) to score the importance of indicators, and delete indicators with a score lower than 3 points (on a 5-point scale); Conduct correlation analysis on the remaining indicators and delete redundant indicators with a correlation coefficient greater than 0.8.

Finally, 12 third-level indicators are retained, all of which pass the correlation test (correlation coefficient is less than 0.8), and the expert scores are all higher than 4 points, meeting the screening requirements.

C. DETERMINATION OF INDICATOR WEIGHTS AND DIVISION OF EARLY WARNING LEVELS

1) Combined Weighting

The analytic hierarchy process (AHP) and entropy weight method are used for combined weighting, taking into account both expert experience and data objectivity:

First, calculate the subjective weight through the analytic hierarchy process, invite experts to make pairwise comparisons of the importance of each indicator, and construct a judgment matrix;

Second, calculate the objective weight through the entropy weight method, and calculate the information entropy and weight of each indicator based on the indicator data of Guangzhou from 2020 to 2024; Finally, determine the combined weight using the weighted average method, the formula is:

$$\begin{aligned} \text{Combinedweight} = 0.5 \times \text{Subjectiveweight} \\ + 0.5 \times \text{Objectiveweight} \end{aligned} \tag{1}$$

The weight calculation results show that the second-level indicator of operation-side risks has the highest weight (0.42), among which the temperature control compliance rate (0.15), transportation delay rate (0.12), and cold storage utilization rate (0.08) are the three third-level indicators with the highest weights, highlighting the core status of operation-side risks; among the regional characteristic indicators, the high-speed rail express loss rate has a weight of 0.06, and the customs clearance efficiency has a weight of 0.05, reflecting the characteristic needs of Guangzhou's multimodal transport and cross-border cold chain.

2) Division of Early Warning Levels and Thresholds

Combined with the indicator data of Guangzhou from 2020 to 2024 and expert judgment, the risk early warning levels are divided into four levels: low risk (0-0.3), medium risk (0.3-0.6), relatively high risk (0.6-0.8), and high risk (0.8-1.0).

The threshold of each indicator is calibrated through historical data, and the specific thresholds are listed in Table 3. For example, the low-risk threshold of cold storage utilization rate is 65%-85% (the current average utilization rate in Guangzhou is 68%, which is in the low-risk range), and the low-risk threshold of high-speed rail express loss

TABLE 3. Supply Chain Resilience-Oriented Risk Early Warning Index System for Guangzhou's Agricultural Product Cold Chain Logistics

First-Level Indicator	Second-Level Indicator	Third-Level Indicator	Indicator Definition	Calculation Method	Combined Weight	Early Warning Threshold (Low Risk)
	Supply-side risks (0.18)	Pre-cooling facility coverage rate	Pre-cooling facility guarantee capacity in producing areas	Pre-cooling facility capacity in producing areas / Agricultural product output	0.07	$\geq$30%
		Supply stability	Fluctuation degree of agricultural product supply	Fluctuation coefficient of daily average agricultural product supply	0.11	$\leq$15%
Supply chain resilience-oriented risk early warning total indicator	Operation-side risks (0.42)	Cold storage utilization rate	Actual use efficiency of cold storage	Actual storage capacity / Designed storage capacity	0.08	65%-85% (risk threshold defined as $\geq$70%)
		Temperature control compliance rate	Compliance degree of full cold chain temperature control	Temperature control qualified time / Total operation time	0.15	$\geq$95%
		High-speed rail express loss rate	Loss degree of high-speed rail cold chain transportation	High-speed rail transportation loss volume / Total transportation volume	0.06	$\leq$5% (including last-mile transfer loss)
		Highway cold chain loss rate	Loss degree of highway cold chain transportation	Highway transportation loss volume / Total transportation volume	0.05	$\leq$12% (including last-mile transfer loss)
		Customs clearance efficiency	Convenience of cross-border cold chain customs clearance	Average customs clearance time	0.05	$\leq$2 hours
		False declaration rate	Compliance degree of cross-border cold chain declaration	Number of false declaration batches / Total number of declaration batches	0.03	$\leq$1%
	Demand-side risks (0.20)	Demand fluctuation coefficient	Fluctuation degree of market demand	Fluctuation range of daily average demand	0.12	$\leq$20%
		Terminal distribution connection rate	Punctuality degree of terminal distribution	Number of on-time distribution batches / Total number of distribution batches	0.08	$\geq$90% (including last-mile temperature control compliance)
	External environment-side risks (0.20)	Extreme weather occurrence rate	Frequency of extreme weather impact on cold chain	Number of days affected by extreme weather in a year	0.10	$\leq$15 days
		Cross-border policy change frequency	Number of changes in cross-border cold chain-related policies	Number of policy changes in a year	0.10	$\leq$3 times

rate is 0-5% (the actual loss rate of lychee special trains meets the low-risk requirements).

D. CONSTRUCTION AND EMPIRICAL VERIFICATION OF RISK EARLY WARNING MODEL

1) Selection and Construction of Early Warning Model

The BP neural network model is selected to construct the risk early warning model. This model has strong nonlinear fitting ability and is suitable for the complex risk relationship of the cold chain system. The input layer of the model is 12 third-level early warning indicators, the hidden layer is set to 2 layers (with 20 and 10 nodes respectively), and the output layer is the risk early warning level (low, medium, relatively high, high risk). The model training uses monthly indicator data of Guangzhou from 2020 to 2024 (a total of 60 groups), among which 48 groups are used for training and 12 groups are used for testing.

2) Empirical Verification Results

The actual data of Guangzhou from January to June 2025 are substituted for model verification. The results show that the accuracy of the model's early warning reaches 91.7%, among which all low-risk and high-risk cases are accurately identified, and there is 1 misjudgment each for medium-risk and relatively high-risk cases. Specifically, 5 days before the Nansha Port cherry delay case in March 2025, the model output a high-risk early warning, and the early warning signal was accurate; during the operation of the lychee special train in June 2025, the model output a low-risk early warning, which was consistent with the actual low-risk state of the loss rate within 5%.

The verification results show that the early warning model can effectively identify the core risks of Guangzhou's agricultural product cold chain and adapt to regional development needs.

V. DESIGN OF COLLABORATIVE SCHEDULING ALGORITHM FOR AGRICULTURAL PRODUCT COLD CHAIN LOGISTICS IN GUANGZHOU BASED ON RISK EARLY WARNING

A. CORE OBJECTIVES AND CONSTRAINTS OF COLLABORATIVE SCHEDULING

1) Core Objectives

The core objectives of collaborative scheduling are multi-objective optimization, including:

(1) Resilience improvement objective: maximize the supply chain's resistance, recovery, and adaptation capabilities;

(2) Loss reduction objective: control the total transportation and warehousing loss rate within the early warning threshold;

(3) Cost control objective: minimize the total cost of cold chain transportation, warehousing, and sorting;

(4) Efficiency improvement objective: maximize the cold storage utilization rate and transportation punctuality rate.

The weight of each objective is adjusted to prioritize thermal stability: the loss reduction objective (including temperature control compliance) is weighted at 0.45 (increased from 0.35), the resilience improvement objective at 0.30, the cost control objective at 0.15 (decreased from 0.20), and the efficiency improvement objective at 0.10 (decreased from 0.15), reflecting the core role of temperature control in risk mitigation.

2) Constraints

The constraints of the scheduling algorithm include:

(1) Cold storage capacity constraint: the actual storage capacity of each hub's cold storage does not exceed the designed storage capacity;

(2) Transportation resource constraint: the transportation capacity of high-speed rail, highway, and sea transportation does not exceed the maximum capacity, such as the daily maximum transportation volume of lychee special trains is 8 tons;

(3) Risk threshold constraint: the temperature control compliance rate is not less than 95%, and the transportation loss rate does not exceed the low-risk threshold of the corresponding mode;

(4) Time window constraint: the total time from the producing area to the terminal market for fresh products does not exceed the quality preservation time, such as the preservation time of lychees is not more than 48 hours.

(5) Last-mile distribution constraint: the temperature fluctuation during the last-mile transfer (from urban distribution centers to retail terminals) shall not exceed $\pm 2°C$, and dedicated low-temperature vehicles must be used to avoid cold chain breaks.

B. CONSTRUCTION OF GUANGZHOU'S REGIONAL CHARACTERISTIC COLLABORATIVE SCHEDULING MODEL

Combined with Guangzhou's advantages of "four-port linkage" and multimodal transport, a collaborative scheduling model of "hub coordination + multimodal transport + risk response" is constructed:

Take Guangzhou Eastern Railway-Highway Intermodal Hub and Nansha Port as the core coordination nodes, and integrate resources of pre-cooling centers in producing areas and distribution centers in sales areas; Dynamically select transportation modes according to risk early warning signals - prioritize low-cost highway cold chain under low-risk conditions;

Adopt the "highway + high-speed rail" intermodal mode under medium-risk conditions to improve timeliness; Activate emergency response under high-risk conditions, and dispatch shared cold storages and emergency transport fleets. For example, in response to high-risk signals of cross-border cold chains, the scheduling system automatically prioritizes the "direct pick-up at the ship's side" mode at Nansha Port to shorten the customs clearance time.

To enhance replicability, the model can be adapted for inland regions by replacing port-specific "direct pickup" with inland dry port multimodal transport coordination mechanisms, and adjusting cold storage utilization thresholds based on regional demand density.

C. DESIGN AND OPTIMIZATION OF RESILIENCE-ORIENTED COLLABORATIVE SCHEDULING ALGORITHM

1) Selection of Basic Model and Algorithm

The improved genetic algorithm is selected as the basic algorithm for collaborative scheduling. The genetic algorithm has strong global search ability and is suitable for multi-objective optimization.

The core steps of the algorithm include: coding design (adopting real number coding, the coding length is the number of transportation paths + the number of cold storage allocations), initial population generation (randomly generating 100 feasible scheduling schemes), fitness function construction (calculating the fitness value based on multi-objective optimization objectives and weights), selection operation (adopting roulette selection method), crossover operation (adopting single-point crossover), mutation operation (randomly adjusting transportation paths or cold storage allocations).

2) Algorithm Optimization and Process Design Introducing Risk Weight

Introduce risk weight to optimize the algorithm:

Determine the risk weight coefficient according to the risk level output by the early warning model (low risk 0.1, medium risk 0.3, high risk 0.5), and integrate it into the fitness function. The formula is:

$$\begin{aligned} \text{Fitness} = {} & 0.45(1-\text{Loss rate})(1-\text{Risk weight}) \\ & + 0.30\cdot\text{Resilience level}(1+\text{Risk weight}) \\ & + 0.15(1-\text{Cost ratio}) + 0.10\cdot\text{Punctuality rate} \end{aligned} \tag{2}$$

The algorithm process is designed as follows: first, input the early warning risk level and indicator data; second, generate initial scheduling schemes; third, iteratively optimize through the genetic algorithm and output the optimal scheme; finally, dynamically adjust according to the actual operation situation.

D. ALGORITHM VERIFICATION AND EFFECT ANALYSIS

1) Example Design

Select the cold chain route from Maoming lychee producing area in Guangzhou to Wuhan as a typical example. The route parameters are as follows:

The daily supply volume is 8 tons, and the preservation time of lychees is 48 hours;

The optional transportation modes are highway cold chain (loss rate 15%, cost 2 yuan/kg·km, time 24 hours) and high-speed rail express (loss rate 5%, cost 5 yuan/kg·km, time 8 hours);

Cold storage resources include Maoming producing area pre-cooling warehouse (storage capacity 50 tons), Guangzhou Eastern Railway-Highway Intermodal Hub cold storage (storage capacity 1.003 million cubic meters), and Wuhan sales area cold storage (storage capacity 30 tons);

The algorithm incorporates last-mile transfer risks by setting a temperature control penalty term for multi modal transport transfers, ensuring that the "highway + high-speed rail" mode accounts for the additional 1%-2% loss risk during terminal transfer;

Simulate three risk scenarios (low, medium, high) to verify the algorithm effect.

2) Algorithm Verification Results and Effect Analysis

The algorithm verification results show that the optimized collaborative scheduling algorithm performs excellently under various risk scenarios. The comparison data between traditional scheduling and optimized scheduling under different risk scenarios are as follows:

Under low-risk scenarios, the algorithm selects the mode of highway cold chain as the main and high-speed rail express as supplementary, with a total loss rate of 10.2% and a total cost 18% lower than that of traditional scheduling;

Under medium-risk scenarios, the "highway + high-speed rail" intermodal mode is adopted, the total loss rate is reduced to 7.5%, and the punctuality rate is increased to 98%;

Under high-risk scenarios, emergency scheduling is activated, shared cold storages are used to store redundant supply sources, and high-speed rail special trains are dispatched for priority transportation. The total loss rate is controlled within 5%, 42% lower than that of traditional scheduling, and the resilience level is increased by 35%.

The results show that the algorithm can dynamically optimize the scheduling scheme according to the risk early warning signal, effectively reducing losses and improving resilience.

VI. CONCLUSION

A. RESEARCH CONCLUSIONS

Through systematic research, this paper draws the following core conclusions:

(1) Guangzhou's agricultural product cold chain logistics exhibits hub agglomeration and multimodal transport integration aligned with the city's expansive trade networks, yet faces challenges such as unbalanced facility layout and insufficient collaboration between logistics providers and agricultural stakeholders. The disconnect between the highly developed infrastructure of the manufacturing zones and the emerging cold chain requirements limits the potential for shared regional resource optimization. The core risks include temperature control failure, transportation delay, customs clearance supervision loopholes, etc., and the three dimensions of supply chain resilience have a significant correlation with risks;

(2) A risk early warning system including 12 third-level indicators is constructed. Among them, the operation-side risk has the highest weight, the temperature control compliance rate and transportation delay rate are the core early warning indicators, and the accuracy of the BP neural network early warning model reaches 91.7%, which can effectively identify the regional cold chain risks in Guangzhou;

(3) An improved genetic algorithm collaborative scheduling model integrating risk weight is designed, and a regional characteristic model of "hub coordination + multimodal transport + risk response" is constructed. Example verification shows that the algorithm can effectively reduce the loss rate (up to 42% reduction) and improve the resilience level (35% increase) under different risk scenarios. The model's replicability is enhanced by providing adaptive adjustments for inland regions, such as replacing port-specific mechanisms with dry port coordination.

B. POLICY RECOMMENDATIONS

Combined with the research conclusions, targeted policy recommendations are put forward:

(1) Optimize the facility layout, increase investment in pre-cooling facilities in producing areas, and improve the utilization rate and regional balance of hub cold storages;

(2) Strengthen risk supervision, promote the full connection of cold storages to the supervision platform, popularize advanced detection technologies and unify standards;

(3) Deepen multimodal transport collaboration, implement subsidy policies, and promote the "single bill system" to improve the efficiency of resource connection;

(4) Build an intelligent scheduling platform, integrate early warning and scheduling functions, and realize dynamic risk response;

(5) Strengthen cross-border cold chain cooperation, negotiate and unify the quarantine standards in the RCEP region, and improve the convenience of customs clearance.

AUTHOR CONTRIBUTIONS

Conceptualization –Yinghuan Liu and Chungui Zhou; methodology – Yinghuan Liu and Chungui Zhou; investigation – Yinghuan Liu and Chungui Zhou; writing-original draft preparation – Yinghuan Liu and Chungui Zhou. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research was supported by:

1. Scientific Research Project of Guangzhou Software College: Research on the High-quality Development Level and Path Optimization of Logistics Industry Driven by Digital Economy under the New Quality Productivity in the Yangtze River Delta of China (No. KY202433)

2. Quality Engineering Construction Project of Guangzhou Software College: Teaching and Research Office of Smart Logistics Technology Application Course Group (No. JYS202206)

3. Characteristic and Innovative Project for General Institutions of Higher Education of the Department of Education of Guangdong Province: Research on the Transformation and Upgrading Path of Traditional Commercial and Trade Wholesale Markets in Guangzhou—A Case Study of Traditional Agricultural Product Wholesale Markets (No. 2023WTSCX44)

4. 2024 Undergraduate University Curriculum Teaching and Research Office Construction Project of the Department of Education of Guangdong Province: "Teaching and Research Office of Digital and Intelligent Logistics Curriculum"

5. 2025 College Students' Innovation and Entrepreneurship Project of Guangzhou Software College: Research on Strengthening the High-quality Development of

Village-level Express Logistics Services under the Background of Rural Revitalization and Low-altitude Economy Strategies—A Case Study of Lianma Village, Taiping Town, Guangzhou (No. DCXM2025084)

ACKNOWLEDGEMENTS

Not applicable.

REFERENCES

[1] M. Zhang, J. Li, W. Feng, et al., "Review and Prospect of the Development Course of China's Agricultural Product Cold Chain Logistics," Preservation and Processing, vol. 25, no. 11, pp. 129-136, 2025.
[2] Y. Z. Ding, P. F. Ning, and K. K. Xie, "High-Quality Development Strategy of Agricultural Product Cold Chain Logistics in Guangdong Province," China Shipping Weekly, no. 43, pp. 63-65, 2025.
[3] S. Y. Ponomarov and M. C. Holcomb, "Understanding the Concept of Supply Chain Resilience," The International Journal of Logistics Management, vol. 20, no. 1, pp. 124-143, 2009, doi: 10.1108/09574090910954873.
[4] A. Abduwali, D. Mirkamili, and Z. N. Zhao, "Rural Digitalization and Grain Supply Chain Resilience: Theoretical Mechanism, Empirical Evidence and Policy Choice," Journal of Northwest A&F University (Social Science Edition), vol. 24, no. 04, pp. 83-90, 2024, doi: 10.13968/j.cnki.1009-9107.2024.04.09.
[5] S. Beshara, H. Fors, N. Harraz, et al., "Designing Supply Chain to Hedge Against Disruptions: A Review of Literature in General and Agro Food Supply Chains," IEOM Society International, Southfield, MI, USA, pp. 135-146, 2022.
[6] J. Jiang, X. Wang, and Y. Liu, "Research on the Performance Evaluation of Agricultural Products Supply Chain Integrated Operation," AIP Conference Proceedings, vol. 1834, no. 1, Art. no. 040008, 2017, doi: 10.1063/1.4981604.
[7] G. L. Zhao, "Literature Review on the Development Status and Countermeasures of Agricultural Product Cold Chain Logistics," Agriculture and Technology, vol. 41, no. 02, pp. 178-180, 2021, doi: 10.19754/j.nyyjs.20210130052.
[8] X. P. Wang, Y. Wang, Y. Li, et al., "Collaborative Scheduling Model and Algorithm for Post-Harvest Grading and Pre-Cooling Vehicles of Fruits and Vegetables," Journal of Systems & Management, vol. 33, no. 01, pp. 76-89, 2024.
[9] J. B. Rice and F. Caniato, "Building a Secure and Resilient Supply Network," Supply Chain Management Review, vol. 7, no. 5, pp. 22-30, 2003.
[10] D. Y. Zhao, "Research on Fresh Food Supply Chain Resilience Analysis and Dual-Objective Optimization," Tianjin University of Science and Technology, 2024, doi: 10.27359/d.cnki.gtqgu.2024.000733.
[11] S. Somers, "Measuring Resilience Potential: An Adaptive Strategy for Organizational Crisis Planning," Journal of Contingencies and Crisis Management, vol. 17, no. 1, pp. 12-23, 2009, doi: 10.1111/j.1468-5973.2009.00558.x.
[12] H. Adobor and R. S. McMullen, "Supply Chain Resilience: A Dynamic and Multidimensional Approach," The International Journal of Logistics Management, vol. 29, no. 4, pp. 1451-1471, 2018, doi: 10.1108/IJLM-04-2017-0093.
[13] X. M. Fan and M. Y. Lu, "Influencing Factors and Evaluation of Supply Chain Resilience of Automobile Enterprises Under the COVID-19 Epidemic," Industrial Technology & Economy, vol. 39, no. 10, pp. 21-28, 2020.
[14] Y. M. Lü, Z. Y. Shi, and P. F. Ning, "Analysis of Influencing Factors of Supply Chain Resilience Based on SWARA," China Market, no. 10, pp. 167-170, 2022, doi: 10.13939/j.cnki.zgsc.2022.10.167.
[15] G. Q. Wang, K. K. Xie, Y. Sun, et al., "Research on the Influencing Factors of Cold Chain Logistics Risks of Fresh Agricultural Products in Guangdong Province," Times Economic & Trade, vol. 21, no. 11, pp. 67-69, 2024, doi: 10.19463/j.cnki.sdjm.2024.11.032.
[16] R. Fang, "Research on Collaborative Scheduling Optimization of Multi-Equipment Across Systems in Sea-Rail Intermodal Transport," Tianjin University of Technology, 2025, doi: 10.27360/d.cnki.gtlgy.2025.001354.
[17] H. Chen, L. Q. Zhang, Y. F. Zhang, et al., "Intelligent Grid Load Collaborative Scheduling Based on Hybrid Particle Swarm Optimization," Electronic Design Engineering, vol. 32, no. 16, pp. 111-114+120, 2024, doi: 10.14022/j.issn16746236.2024.16.023.
[18] H. H. Hu, "Application of Supply Chain Resilience in Cold Chain Logistics and Risk Prevention Strategies," China Shipping Weekly, no. 14, pp. 71-73, 2025.
[19] P. F. Li, "Exploration on the Green Development of Agricultural Product Cold Chain Logistics," Shanxi Agricultural Economy, no. 21, pp. 126-128, 2025, doi: 10.16675/j.cnki.cn14-1065/f.2025.21.036.