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Analysis of Optimization Paths of Yichun Agricultural Product Cold Chain Logistics Anti-Risk Network from the Perspective of Air-Ground Collaborative Distribution

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Abstract: This paper examines the improvement of Yichun's agricultural product cold chain logistics anti-risk network from the perspective of air-ground collaborative distribution. The enabling mechanism of air-ground collaborative distribution for cold chain logistics anti-risk capability is systematically elaborated from three aspects: the spatiotemporal complementary advantages of air-ground collaboration, the mechanism for reducing cold chain interruption probability, and network resilience enhancement. On this basis, it is proposed that Yichun should advance the spatial layout optimization of air-ground collaborative distribution nodes, intelligent dispatching optimization based on risk perception, and whole-chain temperature control and emergency response optimization under multimodal transport collaboration, to construct an air-ground integrated, dynamically adaptive cold chain logistics anti-risk network architecture, providing theoretical reference and practical pathways for enhancing regional agricultural product cold chain logistics resilience.

Keywords: Air-ground collaborative distribution; Agricultural product cold chain logistics; Anti-risk network; Path optimization

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1. Introduction

Yichun City is a major agricultural product production area in Jiangxi Province, with characteristic agricultural products such as selenium-enriched chili peppers and selenium oranges having formed a certain industrial scale, and cold chain logistics infrastructure construction is gradually advancing. Currently, the city has laid out 28 large-scale cold chain logistics projects with a total cold storage capacity of approximately 600,000 cubic meters. However, the traditional cold chain logistics system remains vulnerable to external shocks such as natural disasters and market fluctuations. Air-ground collaborative distribution combines unmanned aerial vehicle air transportation with ground cold chain vehicles, providing new ideas for solving the "first mile" and "last mile" challenges of agricultural product cold chain. This paper explores improvement pathways for Yichun's agricultural product cold chain logistics anti-risk network from the perspective of air-ground collaborative distribution, aiming to provide a reference for enhancing regional cold chain logistics resilience.

2. Enabling mechanism of air-ground collaborative distribution for cold chain logistics anti-risk capability

2.1. Spatiotemporal complementary advantages and risk buffering function of air-ground collaboration

Risks in cold chain logistics systems are multidimensional, with natural disasters, extreme weather, and market fluctuations all capable of causing chain ruptures. Traditional ground cold chain relies on refrigerated vehicles as the sole transportation tool, with spatial accessibility constrained by roads and temporal controllability restricted by traffic and terrain. Air-ground collaboration combines unmanned aerial vehicles with refrigerated vehicles to form a three-dimensional distribution system, functionally surpassing traditional distribution models [1].

Unmanned aerial vehicles possess the capability to overcome geographical obstacles. Yichun is located in the mountainous western Jiangxi region, with complex terrain in areas such as Tonggu and Wanzai, where traditional cold chain vehicles have low passage efficiency and agricultural products from remote production areas have long faced difficulties in reaching external markets. Drones can achieve point-to-point direct access, bypassing ground transportation bottlenecks. The cruising speed of drones is considerably faster than that of ground vehicles, substantially reducing in-transit time for emergency deliveries.

The risk buffering function of air-ground collaboration lies in path redundancy design and flexible switching between transportation modes. When ground roads are interrupted due to disasters, drones can be deployed for transportation; when airspace conditions are unsuitable for flight, ground networks complete the delivery. The dual-mode switching mechanism provides crucial risk buffering for the system, effectively reducing systemic risks caused by failures in a single transportation mode.

2.2. Mechanism of air-ground collaborative distribution in reducing cold chain interruption probability

Cold chain interruption represents the primary risk encountered in agricultural product cold chain logistics, essentially constituting fractures in the temperature control chain across temporal and spatial dimensions. The mechanism by which air-ground collaborative distribution reduces cold chain interruption probability can be elaborated from three aspects [2]. Air-ground collaborative distribution must satisfy several key assumptions: unmanned ground vehicles can carry multiple drones with sufficient payload capacity; unmanned ground vehicles have adequate range and only move between docking points; drones are constrained by range and payload but have free flight trajectories; drones can take off and land multiple times at the same or different docking points with rapid battery exchange; drones can serve multiple customers. These operational prerequisites provide the technical feasibility foundation for temperature control continuity in air-ground collaboration within cold chain logistics.

First, reducing temperature control exposure risk by shortening in-transit time. The quality deterioration of fresh agricultural products exhibits a significant cumulative time effect; the longer the transit time, the greater the risk of quality loss. Research results indicate that when the fresh agricultural product damage rate decreases from 0.3h to 0.1h, total system costs can be reduced by 10.43%. Air-ground collaborative distribution relies on rational division of labor between rapid drone transportation and refrigerated trunk line transport, substantially reducing delivery time for the "first mile" and "last mile," thereby lowering the probability of cold chain interruption from the source.

Second, achieving seamless temperature control connection throughout the entire transportation process. Most cold chain interruptions occur at transfer points between different transportation modes, the so-called "chain breakage points." Air-ground collaborative distribution requires technology to maintain uninterrupted temperature control between drone landing points and ground cold chain containers, namely rapid, seamless transfer from the flight cabin to the ground cold chain container. The adoption of standardized interface technology and automated docking equipment ensures continuous temperature maintenance for cold chain cargo during air-ground handover, improving upon the temperature control vacuum zones that exist in traditional multimodal transport.

Third, establishing a dynamic risk prediction system based on real-time perception. The air-ground collaborative distribution system relies on IoT sensors, 5G communication, and BeiDou positioning technology to collect and transmit real-time data on temperature, humidity, location, and other aspects throughout the entire cold chain process. When environmental parameters exceed set thresholds, the system immediately detects anomalies and issues graded alerts. This "perception-judgment-response" closed-loop model transforms cold chain interruption risk from post-event handling to pre-event early warning and in-process intervention, substantially reducing the actual probability of cold chain interruption occurrence.

2.3. Path for enhancing the resilience of anti-risk networks under the airspace-ground coordination model

Network resilience refers to the capability of a logistics system to maintain functionality and recover rapidly after being subjected to shocks. The air-ground collaborative distribution model enhances the overall performance of cold chain logistics anti-risk networks from three aspects: structural resilience, operational resilience, and recovery resilience.

In terms of structural resilience, air-ground collaborative distribution incorporates drones as new transportation nodes into traditional cold chain logistics networks, breaking away from the previous single hub-and-spoke topology and creating a composite network system of "ground backbone network + aerial branch network." The multimodal, multi-path network structure endows the system with higher fault tolerance in the event of single-point failures; that is, when any node or path malfunctions, the system can switch transportation modes or replan routes to ensure basic functionality [3].

In terms of operational resilience, air-ground collaborative distribution requires establishing data interoperability and task coordination mechanisms between air and ground dispatching systems. Utilizing intelligent dispatching algorithms, the system can dynamically adjust delivery routes and capacity arrangements based on real-time information regarding road conditions, weather status, vehicle conditions, drone endurance, and other factors. This dynamic adaptability enables the cold chain logistics system to rapidly alter operational strategies when external environments change, ensuring continuity and stability of service quality.

In terms of recovery resilience, the rapid response characteristic of air-ground collaborative distribution provides strong support for post-disaster cold chain logistics recovery. When major emergencies cause partial paralysis of ground cold chain networks, drones can rapidly establish temporary aerial distribution channels, ensuring timely delivery of emergency supplies and high-value agricultural products, thereby securing valuable time windows for comprehensive system recovery.

These three mechanisms empower the cold chain system in three aspects: spatial structure, operational decision-making, and emergency guarantee, and Yichun City's optimization path should be developed based on these foundations.

3. Optimization paths for Yichun agricultural product cold chain logistics anti-risk network

3.1. Spatial layout optimization of air-ground collaborative distribution nodes

Yichun City has achieved phased progress in agricultural product cold chain logistics infrastructure construction. Currently, the city has laid out 28 large-scale cold chain logistics projects in the commercial circulation sector, with total cold storage capacity (including under construction) of approximately 600,000 m³ and storage volume of 250,000 tons, of which 25 projects have been put into operation. In 2021, 429 origin cold storage and preservation facilities were newly built, renovated, or expanded, adding approximately 234,000 m³ of storage capacity. The Jiangxi Supply and Marketing (Wanzai) Cold Chain Logistics Industrial Park project has a total investment of 1.11 billion yuan, expected to be completed and put into use in August 2025; the Shanggao County Rural Cold Chain Logistics Distribution Center has a total construction area of 42,239.5 square meters. These various facilities constitute the ground skeleton of Yichun's cold chain logistics network. However, similar to provinces in central and western China such as Guizhou, although Yichun's cold chain logistics infrastructure has initially taken shape, total supply remains insufficient compared with the actual demand driven by continuous growth in fresh agricultural product output, and spatial distribution is somewhat imbalanced. Referencing data from neighboring provinces, the cold chain circulation rate for fruits and vegetables in central and western regions generally stands at only 18–19%, far below the national average of 35%, and Yichun faces the same bottleneck. The supply gap in cold chain facilities and low circulation rates directly constrain the effectiveness of air-ground collaborative distribution node layout optimization, requiring focused resolution in subsequent planning.

Based on this foundation, optimizing the spatial layout of air-ground collaborative distribution nodes requires addressing three main issues. First, scientifically determining the site selection for drone takeoff-landing points. Takeoff-landing points should be selected at geometric centers among main agricultural production areas, cold chain logistics parks, and major consumption zones, considering flight airspace conditions, electromagnetic environment, and ground connection convenience. The Selenium-Enriched Chili Pepper Industrial Park in Shanghu Township, Gao'an City has established a relatively mature cold chain logistics operation foundation, where freshly harvested chili peppers can be rapidly sorted and packaged before being distributed nationwide through cold chain logistics, possessing practical conditions for constructing drone takeoff-landing points. Tonggu County has established agricultural product e-commerce cloud warehouses relying on cold chain logistics parks, achieving one-stop services including warehousing, sorting, packaging, and shipping, which can serve as nodes for air-ground collaborative distribution.

Second, establishing a standardized interface system for air-ground connection. The connection between drone landing points and ground automated guided vehicles (AGVs) should employ unified automatic docking protocols and standard interface technologies. When Yichun City constructs new or renovates and expands cold chain logistics projects, drone takeoff-landing zones and air-ground connection operation areas should be reserved in the early stages to prevent cost and efficiency losses caused by later modifications.

Third, improving the hierarchical arrangement of multiple distribution centers. Research indicates that there exists a nonlinear relationship between the number of consolidation centers and total system costs, requiring systematic optimization of site selection and quantity arrangement. Yichun City has already formed a "1+4+N" logistics network structure with the central urban area as the core and Zhangshu, Fengcheng, Gao'an, and Shanggao as supporting nodes. The layout of air-ground collaborative distribution nodes should be refined on this basis, adding drone takeoff-landing points at the township level to unblock the "first mile" for agricultural products leaving villages.

3.2. Intelligent dispatching optimization for cold chain distribution based on risk perception

Yichun features complex terrain, with mountainous and hilly areas in Tonggu, Wanzai, and other regions, where traditional cold chain distribution faces high uncertainty in the face of disasters such as heavy rain, mountain floods, and freezing damage. Intelligent dispatching represents an important pathway for enhancing anti-risk capability.

First, a risk perception data system should be established. Relying on IoT, meteorological stations, and traffic information systems, real-time collection of road conditions, weather, temperature and humidity, vehicle parameters, and other data should be conducted to provide a foundation for intelligent dispatching. Jiangxi Province has already released the "Artificial Intelligence+" initiative, and Yichun should actively align with it.

Second, dynamic route optimization algorithms should be developed. Different strategies should be formulated according to regional risk characteristics: during heavy rain seasons, priority should be given to routes with high elevation and good drainage; during freezing weather, transportation to high-altitude mountainous areas should be ensured. Referencing collaborative models for refrigerated vehicles and drones, the lowest total cost criterion should be adopted based on factors including energy consumption, payload capacity, and cargo damage.

An air-ground capacity elastic allocation mechanism should be established. When the system perceives high risks, it automatically initiates contingency plans, switching from ground delivery to drone delivery or concentrating deployment to risk areas. Yichun's "15th Five-Year" plan proposes developing low-altitude transportation and unmanned intelligent logistics, providing policy support for intelligent dispatching.

3.3. Whole-chain temperature control and emergency response optimization under multimodal transport collaboration

Multimodal transport represents a high-incidence area for chain rupture risks. To maximize the effectiveness of air-ground collaborative distribution for Yichun's agricultural product cold chain logistics, optimization of the whole-chain temperature control and emergency response system should be advanced within the multimodal transport collaboration framework.

The key to temperature control optimization lies in maintaining temperature continuity at air-ground handover points. Yichun has already formed a cold chain logistics network relying on the Ganxi Agricultural and Sideline Products Wholesale Market, with surrounding important distribution centers, production-marketing area agricultural product circulation enterprises, processing and distribution centers, and retail terminals as key nodes. When introducing drone delivery, the technical challenge of seamless transfer between flight cabins and ground cold chain containers must first be addressed. Specific measures include: installing micro refrigeration units in drone cargo holds to maintain stable temperatures during flight; establishing pre-cooled buffer zones at ground connection points to complete temperature-controlled transitions during cargo transfer; and creating a real-time air-ground temperature control data sharing system to ensure traceability of temperature control throughout the entire chain.

The focus of emergency response optimization lies in establishing a graded emergency plan system. Different response procedures and resource allocation schemes should be formulated according to risk levels: for general risks (short-term traffic congestion), the intelligent dispatching system automatically adjusts delivery routes; for moderate risks (regional road interruptions), air-ground capacity conversion is activated; for major risks (large-scale natural disasters), city-wide cold chain logistics emergency dispatching is launched, deploying emergency transportation forces including drones and refrigerated vehicles. Yichun should rely on the special cold chain logistics joint conference mechanism to incorporate air-ground collaboration into the emergency management system.

Additionally, strengthening cold chain logistics talent cultivation is essential. Through “1+N” initiatives for talent recruitment, establishing industry-university-research platforms, and enhancing professional technical training for air-ground collaborative distribution, compound talents proficient in both cold chain logistics and drone operations should be cultivated to provide human resources support for anti-risk network optimization.

4. Conclusion

Air-ground collaborative distribution provides a feasible technical pathway for optimizing Yichun’s agricultural product cold chain logistics anti-risk network. Through systematic advancement in three aspects—collaborative air-ground node deployment, intelligent route automatic adjustment, and whole-chain temperature control risk prediction—the survivability and recovery capability of cold chain logistics networks in responding to various risk scenarios can be significantly enhanced. Future research may conduct quantitative analysis of cost-benefit outcomes of air-ground collaborative distribution under various risk conditions, explore the feasibility of technologies such as multi-drone collaborative dispatching and dynamic route replanning, and perform differentiated empirical analysis tailored to the cold chain demand characteristics of Yichun’s characteristic agricultural products (selenium-enriched chili peppers and selenium oranges), promoting deep integration of air-ground collaborative technology with regional agricultural industries, and supporting “Yichun Products Going National” and rural revitalization.

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