Research on the Optimization of the Cold Chain Logistics Network for Tropical Fresh Agricultural Products in Hainan

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Abstract: *As a key production region of tropical fresh agricultural products in China, Hainan’s output is characterized by off-season availability and high perishability, which creates a strong dependence on export-oriented cold chain logistics. However, the existing logistics network suffers from issues such as a loosely organized topology, insufficient functional coordination among nodes, and inadequate temperature-control precision, resulting in both high loss rates and low efficiency throughout the circulation process. This study aims to systematically optimize this cold chain logistics network. First, it analyzes the production-marketing structure of Hainan’s tropical agricultural products, which features “decentralized production origins and distant sales destinations,” the quality deterioration patterns based on post-harvest physiology, and the topological characteristics of the current network described as “multi-point decentralization and weak backbone connectivity,” thereby clarifying the starting point and constraints for optimization. Second, a multi-objective collaborative optimization model integrating timeliness, loss control, and facility capacity allocation is constructed, and a mechanism to enhance the network’s resilience is proposed. Finally, an implementation plan centered on multi-level hub coordination, whole-process temperature-control chain, and deep integration of information chains is put forward, along with supporting strategies for performance evaluation and dynamic adjustment. This research provides a systematic theoretical framework and implementation pathway for building an efficient, low-loss, and resilient cold chain logistics network for tropical agricultural products in Hainan.*

Keywords: *optimization of cold chain logistics network; tropical fresh agricultural products; Hainan; multi-objective collaboration; temperature-control chain; information chain*

Introduction

The realization of value in tropical fresh agricultural products is highly dependent on precise temperature control throughout the entire journey from production areas to markets. The unique geographical and climatic conditions of Hainan give rise to a rich variety of tropical agricultural products. However, its highly export-oriented production and marketing model, coupled with the perishable nature of the products, poses significant challenges to the efficiency, reliability, and adaptability of the cold chain logistics network. The randomness in the current network layout, the fragmentation of key node functions, and the bottleneck effect of cross-sea transportation severely constrain the enhancement of product added value and the expansion of market reach. Against this background, conducting systematic optimization research on the cold chain logistics network for Hainan's tropical fresh agricultural products is not only an urgent requirement for reducing logistics losses and ensuring product quality, but also a crucial measure for enhancing the competitiveness of the regional agricultural industry and responding to fluctuations in market demand. The necessity of this study lies in the need to move beyond isolated improvements of individual segments and, instead, adopt an overall network perspective to coordinate spatial layout, facility capacity, technological architecture, and management mechanisms, thereby constructing a modern cold chain logistics system capable of addressing multi-dimensional and complex demands.

1. Analysis of Characteristics of the Cold Chain Logistics Network for Tropical Fresh Agricultural Products in Hainan

1.1 Regional Agricultural Product Production-Marketing Structure and Logistics Demand Characteristics

The production-marketing structure of Hainan's tropical fresh agricultural products exhibits distinct seasonal and category-concentration features. Dominant categories include off-season melons and vegetables, tropical fruits such as mangoes, lychees, and wax apples, as well as specialty seafood. The production side is characterized by a spatial distribution where highly decentralized small-scale farmers coexist with large-scale bases, primarily concentrated in the southern and eastern coastal plains and hilly areas of the island. In contrast, the consumer markets are highly export-oriented, focused on mid-to-northern high-latitude regions in inland China and some overseas markets[1]. This pattern of "decentralized production origins and distant sales destinations" generates the fundamental demand for cold chain logistics: it must achieve efficient aggregation from scattered harvesting points to consolidation hubs, followed by long-distance, cross-sea transportation under constant temperature preservation.

The resulting logistics demands possess multi-dimensional, high-standard composite attributes. In the temporal dimension, off-season agricultural products impose stringent requirements on market lead time, necessitating that the logistics network ensures extremely high circulation speed to capture market windows. In the physical dimension, different categories of agricultural products exhibit significant variations in requirements for pre-cooling treatment, storage temperature, humidity, and gas composition, demanding that cold chain equipment possess multi-temperature-zone collaborative operation capabilities. In the informational dimension, the long-distance separation between production and sales areas makes supply chain visibility and quality traceability a rigid requirement, thereby imposing simultaneous demands on the information sensing and transmission capabilities of the logistics network[2].

1.2 Analysis of Quality Deterioration of Tropical Fresh Agricultural Products and Cold Chain Compatibility

The post-harvest quality deterioration of tropical fresh agricultural products is a biological process driven by multiple factors, including respiratory metabolism, enzymatic reactions, water transpiration, and microbial infestation. Compared to temperate products, tropical fruits and vegetables generally exhibit higher respiration rates and ethylene release rates, while also being more sensitive to chilling injury, such as the browning of lychee pericarps or the formation of chilling spots on mangoes. These unique post-harvest physiological characteristics determine that cold chain logistics for these products is not merely a simple low-temperature treatment, but rather a dynamic management process requiring precise sequential control of temperature and humidity. Quality deterioration models indicate that the shelf life of these products exhibits a highly non-linear relationship with the temperature and duration of their environment; any temperature deviation or chain break in the cold chain will lead to an exponential deterioration in quality.

The existing cold chain technologies and processes must be precisely adapted to the aforementioned deterioration mechanisms. Pre-cooling, as the initial step, requires selecting suitable methods—such as vacuum pre-cooling, differential pressure pre-cooling, or hydrocooling—based on the thermophysical properties of the products to rapidly remove field heat. During storage and transportation, it is necessary to set a safe lower temperature limit according to the product's critical chilling injury temperature, and to comprehensively utilize technologies such as modified atmosphere packaging, moisture-retaining materials, and phase change materials to suppress metabolism and transpiration while maintaining a low-temperature environment. The core of cold chain compatibility lies in constructing a continuous and smooth temperature trajectory from harvest to the end consumer, ensuring the products remain within their specific physiologically permissible temperature range throughout, thereby maximizing the delay of deterioration and preserving commercial value upon reaching the market.

1.3 Evaluation of the Topological Structure and Key Node Functions of the Existing Cold Chain Logistics Network

The existing cold chain logistics network in Hainan exhibits a topological structure characterized by "dispersed multiple points and weak backbone connections." The network nodes primarily include small-scale field-side pre-cooling facilities at production sites, medium-sized cold storage at township distribution centers, and regional large-scale cold chain logistics hubs located at transportation junctions such as Haikou and Sanya. The connections between these nodes rely on the ring-island expressway, the Yuehai Railway corridor, and air routes, with the cross-sea ferry segment constituting a bandwidth bottleneck and a point of reliability vulnerability within the network. Analysis of the topological morphology reveals that the network has not yet evolved into an organic system with distinct hierarchies and complementary functions. The connections between nodes are predominantly simple linear links, lacking redundant pathways, which results in insufficient overall robustness of the network.

An assessment of the functions of key nodes reveals significant room for improvement in their efficiency and coordination. Pre-cooling nodes at production sites suffer from insufficient coverage and low equipment standardization, which compromises the quality consistency of agricultural products at the very beginning of the supply chain. While regional cold chain logistics centers possess functions for large-scale storage and intermodal transport interfaces, their capabilities in providing high-value-added services such as refined sorting and packaging processing for multiple product categories remain relatively weak. Information exchange between nodes is largely confined to commercial data such as orders and inventory; real-time sharing and coordinated control of physical state data, including temperature and humidity, have not yet been achieved. This results in opaque network operational status, making it difficult to conduct global performance optimization and emergency response.

2. Construction of a Multi-Objective Collaborative Optimization Model for the Cold Chain Logistics Network

2.1 Topological Optimization Design of the Network Based on Timeliness and Loss Control

The topological optimization design of the network must simultaneously balance the two mutually constraining objectives of timeliness and product loss. The timeliness objective requires the shortest logistics paths and the fewest transfer points, typically measured by minimizing the total transportation time from production areas to sales destinations. In contrast, the loss control objective does not have a simple linear relationship with time; it focuses more on the cumulative effect of temperature fluctuations across various cold chain stages and the resulting quality deterioration. Therefore, the optimization model needs to introduce a quality decay function with time and temperature as independent variables to quantify physical loss as economic cost. The core of topological optimization lies in reconstructing the connection relationships and hierarchical structure among network nodes. Under the premise of meeting specific service levels, the goal is to identify the network configuration that minimizes total costs (including time cost and quality loss cost) by adding or merging hub nodes and optimizing link directions.

To achieve the aforementioned objectives, a mixed-integer programming model integrating spatiotemporal cost functions can be constructed. This model abstracts production areas, potential hub locations, and sales destinations as network nodes, and transportation routes as directed edges. Decision variables include the selection of hub locations, the hierarchical affiliation of nodes, the allocation of routes, as well as the time and temperature sequences of product flows along the paths. Constraints must cover facility capacity, time windows, temperature compatibility, and flow balance. By solving this model, it is possible to identify the Pareto-optimal layout of key hubs and plan the main circulation paths for multiple categories of agricultural products that either minimize loss under given timeliness constraints or maximize speed under acceptable loss levels. This approach establishes the foundation for efficient network operation at the topological level[3].

2.2 Capacity Configuration of Cold Chain Facilities and Integration of Multi-Temperature Zone Joint Distribution Paths

The capacity configuration of cold chain facilities directly determines the scale, variety, and efficiency of product handling within the network. The capacity configuration issue involves determining parameters such as the storage volume of cold storage facilities at each hierarchical node, the types and processing rates of pre-cooling equipment, and the automation level of sorting and packaging lines. Optimized configuration must be based on precise analysis of product category structures, flow forecasts, and operational processes to avoid capacity bottlenecks or resource idle time at critical stages. Flexible configuration of facility capacities is particularly important, requiring consideration of how to address seasonal fluctuations in agricultural output and variety through modular, scalable designs and shared storage concepts, thereby enhancing the utilization efficiency of facility assets.

The integration of multi-temperature zone joint distribution routes is an advanced strategy for refined management of the transportation segment under facility capacity constraints. This strategy aims to utilize transport vehicles equipped with multiple temperature compartments or independent temperature-control units to collaboratively deliver various agricultural products requiring different transport temperatures within a single shipment. The integration optimization model needs to address complex vehicle routing and loading problems, with its objective function typically being the minimization of total transportation costs. Constraints include the capacity limits of each temperature zone, the time windows and temperature requirements of each customer point, vehicle travel distance, among others. Through advanced algorithmic solutions, efficient joint distribution circuits can be planned, significantly reducing the frequency of vehicle dispatches, lowering transportation energy consumption per unit product, and ensuring that all categories of products are transported within their required precise temperature-controlled environments while achieving economies of scale.

2.3 Mechanisms for Enhancing Network Resilience and Adaptive Capacity in Uncertain Environments

The operation of the cold chain logistics network faces various disruptions originating from both within and outside the system, including seasonal fluctuations and randomness in agricultural product output, deviations in market demand forecasts, traffic congestion or interruptions, and sudden failures of cold chain equipment. These uncertainties require the network to possess sufficient resilience and adaptive capacity—that is, the ability to absorb shocks, maintain core functions after disturbances, and swiftly return to expected service levels or adapt to a new stable state. Enhancing adaptive capacity cannot rely solely on excessive investment in redundant resources; instead, it must be achieved through intelligent design and management mechanisms.

The construction of resilience enhancement mechanisms requires efforts at both the structural and operational levels. At the structural level, optimization models can incorporate scenario planning or stochastic programming methods. By considering various potential disruption scenarios during the initial design phase, a network architecture can be developed that possesses a degree of path redundancy and backup facility switching capability, enabling the network to maintain good performance across multiple future states. At the operational level, a dynamic resource scheduling and route re-planning mechanism should be established. This relies on a real-time data acquisition and monitoring system. When the system detects deviations from forecasted flows, or delays and interruptions at any stage, it can rapidly activate an emergency decision-making model to reallocate inventory, dispatch vehicles, and switch routes, thereby achieving dynamic reconfiguration of network resources. This approach confines the impact of disruptions on overall network performance to localized areas and limited timeframes, ensuring the continuity and reliability of logistics services[4].

3. Optimization Implementation Plan for the Cold Chain Logistics Network of Tropical Fresh Agricultural Products in Hainan

3.1 Functional Division and Collaborative Operation Mode of Multi-Level Cold Chain Hubs

Establishing a hierarchical and functionally complementary hub system forms the physical foundation for network optimization. This system should encompass field preprocessing centers covering main production areas, regional consolidation and processing centers located at key nodes along logistics corridors, and inter-island circulation core hubs relying on major ports and airports. The core function of field preprocessing centers is to achieve immediate pre-cooling and standardized primary grading of agricultural products after harvest. Their technical configuration must match the thermophysical characteristics of different products—for example, using differential pressure pre-cooling units for leafy vegetables and vacuum pre-cooling units for flowers—with the goal of eliminating field heat to the greatest extent and locking in the initial quality of the products. Regional consolidation and processing centers undertake tasks such as converging multi-source cargo flows, providing low-temperature temporary storage, conducting refined sorting, performing brand packaging, and handling primary processing. Their facilities must possess multi-temperature zone storage capabilities and flexible sorting lines to cope with product variety complexity. Inter-island circulation core hubs focus on the distribution of long-distance, large-volume logistics. They need to be equipped with dedicated docks and rapid transfer systems for seamless connection with cross-sea ferries and air cargo containers, enabling efficient transfers between different transportation modes.

The coordinated operation among hubs at all levels should transcend traditional linear transfer and establish a collaborative network based on service capacity reservation and dynamic resource scheduling. Through a unified operational platform, the demands of downstream hubs—including product categories, quantities, time windows, and temperature layer requirements—can be decomposed in real-time and mapped into production and dispatch instructions for upstream hubs. For example, when a core hub confirms an order for mangoes destined for North China, the system can simultaneously issue sorting and packaging instructions to designated regional centers and automatically reserve corresponding field pre-cooling resources and trunk line cold chain transport vehicles[5]. This coordination relies on deeply integrated information systems and standardized operational containers to ensure precise synchronization of cargo flow, information flow, and capital flow across hierarchical levels. Consequently, geographically dispersed nodes are transformed into a logically unified, responsive virtualized service cluster, significantly reducing overall inventory levels and cycle times.

3.2 Dual-Chain Collaborative Technology Architecture for Whole-Process Temperature Control and Information Integration

The core technical pathway for achieving network optimization lies in constructing a collaborative architecture where the physical temperature-control entity and its digital information mirror are deeply integrated throughout the entire cycle. The hardware foundation of the whole-process temperature control chain is a sequence of environmentally controllable units equipped with intelligent sensor nodes, ranging from mobile pre-cooling equipment at production sites, multi-temperature zone controlled trucks and refrigerated containers for trunk transportation, to miniaturized phase-change cold storage boxes for last-mile delivery at sales destinations. The key technology lies in applying adaptive predictive temperature control algorithms. These algorithms can integrate product respiration models, real-time route traffic information, and external meteorological data to dynamically predict and proactively adjust the cooling power and airflow strategies at each segment along the route. This approach maintains a stable and personalized quality-preserving microclimate in complex transportation environments, moving beyond mere passive temperature threshold monitoring.

The information chain serves as the digital nervous system of the entire network, and its architecture is based on an IoT platform and edge computing. Sensors deployed at each stage not only collect environmental data such as temperature, humidity, and ethylene concentration but also monitor equipment operational status and cargo vibration or shock. These high-frequency, multi-source heterogeneous data streams are uploaded in real-time to a cloud-based data lake via low-power wide-area networks. The essence of dual-chain synergy lies in the proactive regulation and reverse optimization of the physical flow by the information flow. Digital twin technology plays a central role here, creating a virtual mirror for each batch of goods, each transport vehicle, and even the entire network. Through simulation and predictive modeling, the system can forecast the impact of physical disruptions (such as insufficient cooling power due to traffic delays) before they occur and proactively generate corrective instructions, such as adjusting backup cooler power or replanning transfer routes. Simultaneously, the correlation analysis of vast historical temperature-control data and final quality data enables the continuous iterative optimization of temperature setting curves and transportation route algorithms, forming a data-driven, continuously self-improving smart cold chain closed loop.

3.3 Effectiveness Evaluation of Network Optimization and Dynamic Adjustment Strategies

The implementation effectiveness of the optimization plan must be quantitatively measured through a systematic set of performance evaluation indicators. This system should encompass three dimensions: operational efficiency, service quality, and sustainability. Operational efficiency indicators include network turnover time, facility utilization rate, unit loss cost, and energy consumption intensity. Core service quality indicators consist of order fulfillment rate, on-time delivery rate, and qualified rate of terminal product quality[6]. The sustainability dimension can examine network carbon emission intensity and resource recycling rate. These indicators collectively form a multi-dimensional evaluation matrix. By regularly collecting operational data and comparing changes in indicators before and after optimization, an objective assessment of the overall network and the improvement effectiveness of key segments can be conducted.

Based on feedback from performance evaluations, it is essential to establish dynamic adjustment strategies for the network to address internal evolution and external changes. Dynamic adjustment is a continuous iterative process, with strategies encompassing two levels: parameter fine-tuning and structural optimization. Parameter fine-tuning involves periodically revising transportation schedule frequency, safety stock levels, and equipment operating parameters based on actual flow data. Structural optimization is more strategic; when evaluations reveal persistent congestion on certain routes or chronic insufficient capacity at nodes, it necessitates initiating analysis for partial reconstruction of the network topology. This may include adding micro-collection and distribution points, adjusting the service coverage radius of distribution centers, or introducing new transportation collaboration models. This adjustment strategy relies on continuous monitoring data and predictive models to ensure that the network structure and service capabilities can dynamically adapt to the evolving demands of the agricultural product supply chain.

Conclusion

Through a systematic analysis of the cold chain logistics network for tropical fresh agricultural products in Hainan, this study has established a comprehensive optimization pathway encompassing characteristic understanding, model design, and implementation planning. The research indicates that the core of network optimization lies in resolving multi-objective collaboration, which requires simultaneously balancing timeliness, loss, and cost, and achieving physical integration through the scientific functional division and coordinated operation of a multi-level hub system. Furthermore, the study demonstrates that promoting deep synergy between the physical temperature-control chain and the digital information chain serves as the technical foundation for enhancing the network's precise management and intelligent decision-making capabilities. The proposed dynamic performance evaluation and adjustment strategies ensure the network's continuous adaptability and evolutionary potential. Future research may focus on deepening dynamic robust optimization algorithms under complex uncertainties, constructing a blockchain-based full-chain trustworthy traceability system, and designing and evaluating green cold chain networks guided by carbon neutrality goals, thereby advancing research in this field towards greater intelligence, transparency, and sustainability.

Fund Projects

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References

[1] Wang Yixuan, and Wang Nuo. "Research on the Optimization of the Cold Chain Logistics Network for Offshore Fisheries Considering the Layout of Fishing Production Zones." Operations Research and Management Science 34.08 (2025): 22-28.
[2] Hua Xiaofeng. Research on the Optimization of the Cold Chain Logistics Network for Agricultural Products in the "First Mile". 2025. Shandong Jiaotong University, MA thesis.
[3] Zhao Wende, Li Bin, and Xie Han. "Research on the Optimization of the Cold Chain Logistics Network for Agricultural Products in the Guangdong-Hong Kong-Macao Greater Bay Area under the Rural Revitalization Strategy." China Journal of Commerce 33.23 (2024): 97-101.
[4] Xie Can. "Research on the Solution of the Optimization Model for Agricultural Product Cold Chain Logistics Network Layout Based on Genetic Algorithms." Logistics Sci-Tech 47.08 (2024): 147-152.
[5] Wang Yixuan. Construction and Optimization of the Cold Chain Logistics Network for Offshore Fisheries. 2023. Dalian Maritime University, PhD dissertation.
[6] Zhao Lianming. "Research on Optimization Approaches for the Collaborative Operation System of Agricultural Product Cold Chain Logistics under the 'Internet+' Background." Agricultural Economy .10 (2021): 129-131.