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

Zhu Zheng*

Hainan Vocational University of Science and Technology, Haikou, 571126, China
**Corresponding author: zhengzhu821@163.com*

Abstract: *Hainan is a key production base for tropical fresh agricultural products in China, but its production is seasonal and the products are highly perishable; therefore, an export-oriented cold chain logistics system has been established. The structure of the current logistics network is loose, the coordination function among nodes is weak, and there is no special temperature control; thus, there are high losses and low efficiencies in the circulation process. This paper will put forward some improvements to the cold chain logistics network. First, analyze the production-marketing structure of tropical agricultural products in Hainan, which is a model of "decentralised production origin and distant sales destination", the pattern of quality deterioration according to post-harvest physiology, and the topological features of the current network, described as "multi-point decentralisation and weak backbone connectivity", to determine the starting point and constraints for optimisation. Second, a multi-objective cooperative optimisation model for timeliness, loss control and facility capacity allocation has been built, and a way to improve the resilience of the network has also been put forward. Finally, an implementation plan has been issued to build multi-level hubs, construct an all-round temperature-control chain, improve the integration of the information chain, provide support for performance evaluation and dynamic adjustment, etc. Present the general theoretical system and construction path of an efficient, low-loss and stable cold chain logistics network for tropical agricultural products in Hainan.*

Keywords: *Optimisation of Cold Chain Logistics Network, Tropical Fresh Agricultural Products, Hainan, Multi-objective Collaboration, Temperature-controlled Chain, Information Chain*

Introduction

To maintain the quality of tropical fresh agricultural products at all times during distribution, it is necessary to keep them at a low temperature. Hainan has good geography and a favorable climate, so many kinds of tropical agricultural products can be grown here. Given that it is a large-scale exporter and the products are perishable, there are serious problems in the efficiency, reliability and adaptability of the cold chain logistics network. Random layout of the current network, fragmentation of core node functions and the bottleneck effect of cross-sea transportation all limit the increase in product added value and the expansion of the market. Therefore, based on the above analysis, systematic optimisation research of the cold chain logistics network for tropical fresh agricultural products in Hainan is needed to reduce logistics losses and ensure product quality; at the same time, it will boost the competitiveness of the region's agricultural industry and meet the changing demands of the market. The reason for this study is that we need to move beyond the problem of improving only one part and consider the whole network. Therefore, we will coordinate the spatial layout, facility capacity, technological architecture and management mode of the entire cold chain logistics system to meet all the various and high demands of modern society.

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

1.1 Production-and-Distribution Structure of Regional Agricultural Products and Characteristics of Logistics Demand

The production-and-sales structure of tropical fresh agricultural products in Hainan has some seasonality and category concentration. The main products are off-season melons and vegetables, tropical fruits such as mangoes, lychees and wax apples, other seafood products, etc. The production side has a high degree of decentralisation in the form of small-scale farmers and large-scale bases, and the main areas are the southern and eastern coastal plains and hilly areas of the island. The consumer market is relatively export-oriented, and its main areas are in the mid- and north-high latitudes of inland China and some places abroad[1]. The model of "decentralised production and distant sales markets" has given rise to a basic demand for cold chain logistics; that is, products need to be collected efficiently from all over the country at central collection points, and then long-distance and cross-sea transport in a cool environment must be carried out.

The resulting logistics demand has many good compound attributes. Off-season agricultural products have a short market lead time, so the logistics network needs to be very agile to meet the demand of this market period. The various categories of agricultural products have different requirements for pre-cooling treatment, storage temperature and humidity, gas composition, etc., so the cold chain equipment needs to be able to operate in multiple temperature zones at the same time. Due to the long-distance separation of the production and sales areas, supply chain visibility and quality traceability have become necessary conditions, and at the same time, the demand for information sensing and transmission in the logistics network has also risen[2].

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

A decline in the post-harvest quality of tropical fresh agricultural products is a biological phenomenon caused by all sorts of reasons, such as respiration and metabolism, enzymes, water loss, microorganisms, etc. Tropical fruits and vegetables generally have a higher respiration rate and ethylene emission rate than temperate products, are also more susceptible to chilling injury; for example, there is browning of lychee pericarps and the appearance of chilling spots on mangoes. Given that these products have certain post-harvest physiological conditions, cold chain logistics need to keep the temperature low, and both the temperature and relative humidity must be in a narrow range at all times. Models of quality deterioration show that the shelf life of these products is very sensitive to changes in temperature and the length of time they have been under various conditions; therefore, any increase in temperature or a break in the cold chain will lead to a rapid decline in quality.

Based on the reasons for the decline mentioned above, the current cold chain technology and process need to be reformed. The first is pre-cooling, and among all the ways to reduce the temperature of a product quickly, some are more suitable, such as vacuum pre-cooling, differential-pressure pre-cooling and hydrocooling. Given that the critical chilling injury temperature of the product is low, a relatively high lower temperature limit should be set for storage and transportation, and all kinds of technologies need to be employed to reduce metabolism and transpiration in a cold environment, such as modified atmosphere packaging, moisture-retaining materials, phase change materials, etc. The general idea of cold chain compatibility is to keep the temperature of the product relatively stable from the time of harvest until it reaches the end consumer, and thus prevent changes that can harm the quality and extend its shelf life.

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

The structure of the current cold chain logistics network in Hainan is that of "many dispersed nodes and weak backbone links". The nodes in this network are mainly the small-scale field-side pre-cooling facilities at the production site, the medium-sized cold storage facilities in the township distribution centres, and the regional large-scale cold chain logistics hubs located at transportation junctions, such as Haikou and Sanya. Although all the nodes are connected by the ring-island expressway, the Yuehai Railway Corridor and air routes are not, and the cross-sea ferry section is a bandwidth bottleneck and a single point of failure in the network. Based on the analysis of topology, the network has not yet formed an organic system with clear hierarchy and division of labour. Most of the connections among the nodes are single linear links, and there are no other paths; therefore, the whole network is not very stable.

Analysis of the function of the main links shows that their efficiency and cooperation need to be improved. The pre-cooling nodes at the production site have poor coverage and lack equipment uniformity, so the quality of agricultural products at the beginning of the supply chain will be uneven.

Although the regional cold chain logistics centres have the functions of large-scale storage and intermodal transportation connections, they have not yet developed strong high-value-added services such as refined sorting and packaging processing for all kinds of products. Most of the information exchanged among nodes is of a commercial nature, such as orders and inventory; real-time sharing and coordinated control of physical state data, including temperature and humidity, have not been realised yet. Therefore, we do not know the actual operating conditions of the network and cannot solve the problem in time.

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

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

The Design of the topology for the network should achieve both the aim of high speed and the goal of low product loss simultaneously. First of all, it needs to be timely, so a short logistics route with few transfers should be chosen to reduce the total transportation time from the production base to the market. At the same time, the goal of loss control is not directly related to time in a simple linear way; rather, it takes into account the total effect of temperature fluctuations at all times in the cold chain and the resulting decline in quality. Therefore, the optimisation model should add a quality decay function that is a function of both time and temperature to show that the loss of quality is an economic cost. First, we will introduce the concept of connected nodes and a hierarchy among them. Given that the demand is for good service quality, a network plan will be built to reduce the total cost (the sum of time cost and quality loss cost) by adding or deleting hub nodes and changing the direction of links.

Therefore, the following mixed-integer programming model will be used to introduce spatiotemporal cost functions. Network nodes are the production areas, potential hub locations and sales markets, and the directed edges are the transportation routes. The decision variables are the choice of hub location, the hierarchical affiliation of nodes, allocation of routes, and also the time and temperature sequences of product flow along these paths. The reasons are that the facility does not have space, time, cold chain facilities, etc. Based on the above model, it is possible to find the Pareto-optimal layout of key hubs and plan main circulation routes for various types of agricultural products to either reduce loss under a certain time constraint or increase speed at the cost of some loss. Therefore, the first is that the network should operate normally at the level of topology[3].

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

The capacity arrangement of the cold chain facility will directly determine the scale, type and efficiency of product handling in the network. The Capacity Configuration Problem is to set the parameters of the storage volume for cold storage facilities at all levels, as well as the types and processing speeds of pre-cooling equipment and the degree of automation of sorting and packaging lines. Based on an accurate analysis of the structure, flow and operating process of the product category, the optimised allocation should have no capacity bottlenecks or idle resources at any time. A flexible arrangement of facility capacity is needed to meet the different demands for various agricultural products at different times, so modular and scalable Design, as well as shared-storage ideas, should be employed to improve the utilisation of facility resources.

A general way to divide the joint distribution paths of multiple-temperature zones is to keep them within the capacity limits of the facilities. First, vehicles with several temperature zones or independent temperature-control boxes should be used to carry different kinds of agricultural products at different temperatures at the same time. An Optimisation Model for Integration will be employed to solve many problems in vehicle routing and loading, and the goal is to reduce the total transportation cost. Constraints include the capacities of all temperature zones, the time window and temperature requirements of all customer areas, vehicle travel distance, etc. With the help of a good algorithm, a reasonably efficient joint distribution circuit can be constructed to reduce the number of vehicle dispatches, lower the transportation energy per unit of product, ensure that all kinds of products are transported in their necessary temperature-controlled environments, and achieve economies of scale.

2.3 Mechanisms for Strengthening Network Resilience and Adaptability in Unstable Environments

Most of the disturbances to the operation of the cold chain logistics network can be classified into internal and external factors; for example, seasonal changes and randomness in the production of agricultural products, deviations in market demand forecasts, traffic congestion or interruptions, and sudden failures of cold chain equipment are typical cases. Therefore, the network should be stable and flexible enough to handle all kinds of risks; that is to say, after a disturbance, it should still be able to operate normally and recover in a short time. To increase flexibility, we should not increase the amount of redundant resources but rather introduce an intelligent Design and Management System.

The Structure and Operating Mode of the Resilience-Promotion System also need to be set up. Some good models are based on scenario planning or stochastic programming. Based on all the possible disruption scenarios at the beginning of the design stage, a network structure will be built with some path redundancy and a switch-over backup option so that it can continue to operate normally even if there are many problems in the future. At the level of operation, there should be dynamic resource scheduling and route planning. It will be collected and recorded according to the actual circumstances. If the actual flow of goods is different from what was expected, or if there are any delays or other problems at any time, then the emergency decision-making model will be used to adjust inventory allocation and dynamically change vehicles and routes. Therefore, the impact of the disturbance on the operation of the entire network will be relatively small, and the logistics services will continue to run normally and stably[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

A Hierarchy of Hubs and a Division of Labour will be set up in the Network. Pre-processing centres for the field area need to be established in the main production areas, and regional consolidation and processing centres should be built at key links of the logistics corridor and inter-island circulation core hubs connected to major ports and airports. The first goal of the centre for field preprocessing is to rapidly cool and uniformly grade agricultural products after harvest. The technical conditions should be suitable for the thermal characteristics of the different products; for example, differential-pressure pre-cooling units can be used for leafy vegetables and vacuum pre-cooling units can be employed for flowers to reduce the field heat as much as possible and maintain the initial quality of the products. Regional consolidation and processing centres have many functions, such as collecting goods from all over, providing short-term cold chain storage, sorting and distributing them after processing, brand-labeling and primary processing, etc. There should be many temperature-zone storage areas and flexible sorting lines for a large number of different products. Most of the centres for inter-island traffic are only for long-distance, high-volume goods transport. They should have their own docks and fast-transfer systems for good connections with cross-sea ferries and air cargo containers, and be able to switch between all kinds of transportation efficiently.

Coordination of hubs at all levels should move away from the old way of linear transfer and build a cooperative network based on service capacity reservation and dynamic resource scheduling. At any time, the requirements of the downstream hubs for product categories, quantities, time windows and temperature zones can be broken down into a single operating platform and then distributed to production and dispatch instructions at the upstream hubs. For example, when the central hub finds out that an order for mangoes has been placed in North China, it will immediately issue sorting and packaging instructions to the relevant regional centres, automatically reserve the necessary field pre-cooling facilities and trunk-line cold chain transportation vehicles, and so on. According to the whole-system information and standardised operating container, coordination will be carried out to ensure that the flow of goods, information and funds at all levels is in harmony. Therefore, the distributed nodes will be arranged in a single intelligent virtual service cluster to reduce both the total inventory and the cycle time.

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

First of all, in order to improve the network, a cooperative model should be established, and all changes in the digital information of the physical temperature-control device must be known in time. The foundation of the hardware for the whole process of temperature control is a group of environmentally controlled units that have been equipped with intelligent sensor nodes, such as mobile pre-cooling equipment at the production site, multi-temperature-zone-controlled trucks and refrigerated containers for trunk transportation, and miniaturised phase-change cold storage boxes for last-mile delivery at the sales destination. At the bottom is a kind of adaptive predictive temperature control algorithm. According to the product respiration model, the algorithm will dynamically adjust the cooling power and fan mode of different parts of the road in real time according to the traffic conditions on the road and the weather outside. Therefore, a good and healthy life can be provided for the people of a large city with a large population[5].

The Information Chain is the digital nervous system of the entire network, and it is based on the foundation of IoT platforms and edge computing. At all times, the sensors will gather environmental data and other information about the operating conditions of the equipment, as well as vibrations and shocks of the cargo, such as temperature and humidity, ethylene concentration, etc. Collect high-frequency data from many places in various forms, save it in the cloud data lake in real time via LPWAN, and so on. The first goal of the general idea of dual-chain synergy is to guide and regulate the actual flow of information in both directions. At the core of this is digital twin technology, and virtual models of all batches of goods, transport vehicles, and even the whole network have been created. According to the simulation and prediction model, we know in advance that there will be an external disturbance (e.g., a reduction in cooling capacity due to traffic congestion), so we can take preventive measures by increasing the power of the backup cooler or switching to a different transfer route. At the same time, based on a large amount of historical temperature-control data and the corresponding final-quality data, we will continuously improve the temperature-setting curve and the transportation-route algorithm to build a data-driven, self-optimising smart cold chain closed-loop system.

3.3 Evaluation of the Effect of Network Optimisation and Dynamic Adjustment Strategies

Based on the above, some objective data need to be collected to determine the results of the revised plan. The three kinds of deficiencies are operating efficiency, service quality and stability. The indicators of operating efficiency are network turnover time, facility utilisation rate, unit loss cost and energy consumption intensity. The first three indicators of service quality are order processing rate, timely delivery rate and quality of the final product at the terminal[6]. Durability is the carbon-emission intensity of a network and how often it is used. The above indicators are to be used together. Regularly collect the operating data, compare the changes in the indicators before and after optimisation, and then objectively evaluate the entire network and how effective the improvement in key areas has been.

Based on the feedback in the performance review, we need to modify some parts of the network according to the new developments at home and abroad. The two stages of continuous adjustment are the modification of parameters and the alteration of structure. Change the frequency of transport, safety stock, operating conditions for equipment, etc., in line with changes in the flow of goods. Structural Optimisation is more fundamental; if the evaluation shows that some paths will be permanently congested or certain nodes will not have enough capacity in the long run, then some reconstruction of the network structure should be considered. Add a micro-collection and distribution point, expand the service area of the distribution centre, introduce a new transportation cooperation model, etc. According to the above data and prediction models, changes will be made to the network structure and service capabilities in response to changes in demand for the agricultural product supply chain.

Conclusion

Based on the general analysis of the cold chain logistics network for tropical fresh agricultural products in Hainan, this paper will present all-round optimisation directions for the characteristics of the network, model construction and implementation plans. Research has shown that the main purpose of network optimisation is to solve the problem of multi-objective coordination; that is, to simultaneously optimise the problems of timeliness, loss and cost, and achieve physical integration through scientific functional division and coordinated operation of a multi-level hub system. Based on the above research, in order to improve the accuracy of network management and the intelligence of decision-making, cooperation among the physical temperature-control chain and the digital information chain needs to be strengthened. Given that the network has been changed, the new dynamic performance appraisal and adjustment plan will be revised. The next direction of research will be to improve the dynamic-robust optimisation algorithm for complex uncertainties, build a blockchain-based full-chain trustworthy traceability system, design and evaluate green cold chain networks with the goal of carbon neutrality, and promote the development of high intelligence, transparency and sustainability.

Fund Projects

2025 Hainan Provincial Philosophy and Social Sciences Planning Project, Project Title: Research on the Collaborative Optimization of Storage and Distribution for Fresh Agricultural Products in Hainan, Project Approval Number: HNSK (YB) 25-11

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.