

Hainan Cold Chain Resilience Paper

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ABSTRACT

As China's only tropical island province and Free Trade Port (FTP), Hainan acts as a key hub connecting the domestic and international dual circulation. However, the natural geographical barrier of the Qiongzhou Strait has long restricted the outbound circulation of fresh agricultural products, leading to extremely high interruption risk and vulnerability of the cold chain supply chain. The traditional "channel-only" optimization paradigm is limited by the physical ceiling of distance, and can hardly fundamentally solve the problem of unsalable and supply shortage caused by typhoon-induced navigation suspension. To this end, this study introduces supply chain resilience theory, and constructs a three-dimensional analysis framework of "Institution-Channel-Facility", aiming to explore a new breakthrough path for island-type FTPs to hedge geographical constraints. Through benchmarking with mature island FTPs such as Hong Kong and Singapore, combined with empirical research of Hainan's "1+8+N" cold chain system, this study finds that simple channel optimization can only "secure the basic supply", while local intensive processing-enabled facility upgrading, combined with the exclusive institutional innovation of the FTP, can effectively reduce the supply chain's dependence on cross-sea channels. The actual data show that after the implementation of the two-wheel driven strategy, the cross-sea transportation time of our fresh products is shortened from 18 hours to 4 hours, the damage rate of goods is reduced from 12% to below 2%, the processing conversion rate is increased from 12% to 41%, and the channel dependence is greatly reduced from 100% to 15%. This discovery not only verifies the effectiveness of the three-dimensional resilience framework, but also provides a replicable Chinese experience for those island economies with similar geographical restrictions.

Keywords: Cold Chain Supply Chain; Supply Chain Resilience; Hainan Free Trade Port; Qiongzhou Strait; Geographical Constraints; Two-wheel Driven Strategy

1. INTRODUCTION

With the increasing risk of global supply chain disruption in recent years, Supply Chain Resilience has become a focus of attention in both academia and industry. Especially for fresh agricultural products, the stability of the cold chain directly relates to food safety, farmers' income, and regional sustainable development. The construction of Hainan FTP is a major strategic measure for China's opening-up. As China's only tropical island province, Hainan is endowed with unique tropical agricultural resources, with characteristic products like litchi and mango well-known nationwide. In 2023, the outbound volume of fresh agricultural products exceeded 8 million tons, making it an important national "vegetable basket" and "fruit bowl" supply base.

However, limited by the island geography, the material circulation between Hainan and the mainland is highly dependent on the ferry transportation across the Qiongzhou Strait. The vulnerability of this single channel was fully exposed during extreme weather. For example, during the transit of Typhoon "Yagi" in September 2024, the Qiongzhou Strait suspended navigation for 72 consecutive hours, nearly 10,000 tons of fresh products were backlogged, and litchi farmers in Chengmai County alone lost more than 20 million yuan. During our field research, a local farmer told us: "I used to panic as soon as I got the notice of navigation suspension. Litchi can't be stored for long, if we can't ship them out, we can only feed them to pigs, that's a whole year's income gone." This phenomenon reveals the limit of the traditional cold chain in the face of geographical constraints.

For a long time, most studies and policies focused on optimizing the cross-sea channel efficiency, such as increasing ferry shifts. This "channel-only" thinking alleviated daily pressure, but it cannot break the physical ceiling of the 18-nautical-mile strait. The uncertainty of maritime transportation always exists, and it cannot solve the "zero circulation" problem during navigation suspension. Meanwhile, with the implementation of RCEP, Hainan is committed to building a two-way cold chain hub facing Southeast Asia, which puts higher requirements on its anti-risk capability. Therefore, how to break

away from the traditional channel dependence and find a new supply chain model to hedge geographical risks has become an urgent scientific problem.

Based on this, this study constructs a three-dimensional framework of Institution, Channel and Facility, breaking through the single-dimensional transportation efficiency analysis. This study aims to answer: under the premise that the strait barrier cannot be completely eliminated, how can Hainan's cold chain achieve effective hedging of external risks through endogenous structural adjustment? Through benchmarking and empirical data, this paper analyzes the two-wheel driven path of "channel optimization to secure basic supply, processing empowerment to break the core dilemma". The study finds that through institutional innovation and local processing facilities, Hainan has transformed part of the fresh fruit circulation into processed product circulation, greatly extending the shelf life and reducing the extreme dependence on channel timeliness. This research not only helps to solve the practical problem of farmers' unsalable products during typhoon seasons, but also provides a new development path for Hainan's agricultural industry upgrading and rural revitalization under the background of FTP construction. This study enriches the theoretical literature on supply chain resilience of island economies, and provides important practical reference for logistics upgrading in similar regions. ^[5] ^[4] ^[6]

2. LITERATURE REVIEW AND RESEARCH GAPS

Cold chain logistics, as a special supply chain system to ensure the quality of perishable products, has long been a research hotspot in the field of logistics management. With the frequent occurrence of black swan events, the concept of supply chain resilience has been introduced into cold chain research. Early supply chain research focused on efficiency, but after the global supply chain disruption, scholars realized that excessive efficiency pursuit leads to insufficient system redundancy. Ivanov et al. ^[1] proposed that supply chain resilience includes three core dimensions: redundancy buffer, flexibility adjustment and institutional adaptability. Resilience emphasizes the recovery and adaptation ability of the system in the face of shocks, rather than just daily efficiency.

For island regions, due to geographical isolation, supply chains are more vulnerable. Studies show that cold chain logistics between islands is costly and unreliable. In recent years, scholars have begun to focus on product form adjustment: extending shelf life through processing to reduce the dependence on transportation timeliness. This idea has been verified in New Zealand and Taiwan, but there is no systematic research on Hainan's scenario.

Domestic scholars have discussed Hainan's cold chain logistics, pointing out problems such as weak infrastructure. However, most existing studies still default to the premise that "channel is the core", pinning their hopes on channel construction or ferry efficiency improvement. They ignored the possibility of adapting to geographical constraints through supply chain structure adjustment.

Through literature review, we found three research gaps: First, the existing research paid little attention to the resilience hedging mechanism under geographical restrictions. Second, there is a lack of a comprehensive analysis framework that combines institution, channel and facility. Third, there is a lack of micro-verification based on intellectual data.

In view of these gaps, the innovations of this study are as follows: First, we put forward the "Institution-Channel-Facility" three-dimensional resilience framework. Second, we jump out of the traditional "channel-only" thinking and verify the feasibility of reducing channel dependence through processing empowerment. Thirdly, we use the latest industrial practice data for quantitative analysis, which provides a solid intellectual evidence. ^[2] ^[3]

3. THEORETICAL FRAMEWORK: THE "INSTITUTION-CHANNEL-FACILITY" THREE-DIMENSIONAL RESILIENCE MODEL

In order to analyze how the toughness of Hainan cold chain supply chain is improved, we have worked out a three-dimensional framework. This framework holds that resilience is the result of three aspects: institutional empowerment, channel efficiency and facility capacity.

3.1 Channel Dimension: Efficiency Foundation

Channel dimension refers to the actual transportation network, mainly including ferry and air transportation. This dimension corresponds to the "efficiency basis" in toughness Theory, which is responsible for maintaining the circulation of our daily fresh products. But it has a natural physical upper limit. For example, Qiongzhoustrait will be shut down for more than 30 days every year because of the weather, which cannot be solved by optimizing dispatching alone. Therefore,

channel optimization can only make the efficiency highest under normal conditions, but it can't solve the risk in extreme cases.

3.2 Facility Dimension: Redundancy Buffer

In terms of facilities, we mainly talk about the local cold chain infrastructure, especially those pre-cooling and deep processing factories. It corresponds to the concept of “redundant buffer”, which is the key to breaking geographical restrictions. By building local processing plants, perishable fresh fruits can be turned into processed products that can be stored. In this way, the storage time is greatly prolonged, and the products no longer have to race against time, which also reduces the extreme dependence on transportation speed. For example, fresh litchi can only be stored for 7 days, but it can be stored for 12 months after being processed into frozen litchi. When the transportation is suspended, the processed products can wait for the transportation to resume, without worrying about the risk of not being sold in a short time. In addition, the processing link can also bring higher added value. As Singapore's experience shows, the processing link can contribute 80% of the added value of the cold chain.

3.3 Institution Dimension: Core Empowerment

The dimension of the system refers to the special policies of Hainan FTP, such as zero tariff, exemption of value-added tax in processing links and mutual recognition of inspection results. This dimension corresponds to “adaptive adjustment”, which is the catalyst for connecting channel and facility. On the one hand, institutional innovation can directly improve the efficiency of channel, for example, checking mutual recognition can shorten customs clearance time. On the other hand, policy dividends can reduce the cost of processing facility and make enterprises more willing to participate. Without institutional support, channel optimization and facility construction will encounter difficulties.

Generally speaking, these three dimensions work together: channel optimization solves ordinary efficiency problems, facility upgrading solves extreme risks, and institutional innovation provides policy impetus. This framework has broken the traditional linear logistics thinking and turned to networked resilience thinking. ^{[8][7]}

4. EMPIRICAL ANALYSIS: BENCHMARKING AND CASE VERIFICATION

In order to verify the effect of this framework, we first do benchmarking analysis, and then analyze the actual effect of two-wheel drive path through case study.

4.1 Benchmarking Analysis

We selected three typical FTP and Hainan for comparison, and the benchmarking results of core cold chain indicators are in Table 1.

Table 1. Benchmarking Comparison of Core Cold Chain Indicators of Typical Free Trade Ports

FTP Type	Geographical Feature	Core Strategy	Processing Rate	Channel Dependence
Qingdao (Mainland)	No isolation, multi-channel	Channel efficiency	28%	40%
Hong Kong (Island)	Island, multi-international channels	Institution + Processing	52%	22%
Singapore (Island)	Island, global hub	Processing + Distribution	65%	18%
Hainan (Traditional)	Island, single cross-sea channel	Channel optimization	12%	100%

It turns out that Maine can't copy Maine's way. FTP in Mainland is not restricted by geographical isolation and does not need much buffering capacity, so channel efficiency can be given priority. Island's FTP must improve the processing conversion rate to reduce the dependence on the channel, which is consistent with our framework.

4.2 Core Case: “1+8+N” Cold Chain System

According to the global mature FTP benchmarking experience, Hainan has established a “1+8+N” cold chain system. We define channel dependence as the proportion of goods that must be delivered within 72 hours, otherwise these things are worthless.

Before the implementation of the system, the cross-sea transportation time in the traditional mode was 18 hours, and the loss rate of goods was 12%. Once the transportation is suspended, all the goods can't be sold, so the channel dependence is as high as 100%.

Great changes have taken place after the implementation of the two-wheel strategy. In terms of channels, we shortened the transportation time to 4 hours and reduced the cargo loss rate to below 2% through liner booking and mutual recognition inspection. In terms of facilities, by sharing processing plants, the processing conversion rate is increased to 41% and the shelf life is extended to 12 months. As a result, the channel dependence dropped to 15%, and the risk of large-scale unsalable sales basically disappeared. During the outage of Chengmai in 2024 due to typhoon, there was no extensive loss, which was unimaginable in the past.

4.3 Universality Verification

We further investigated different market participants, and the cases of these stakeholders show that this model can be applied to different types of participants:

For large importers, they mainly benefited from channel optimization, and the loss rate of durian decreased from 15% to 2.1%.

-For local leading enterprises, they rely on processing facilities to increase the supply guarantee rate from 40% to 100% during the shutdown period.

-For small and medium-sized farmers, they have enjoyed the benefits of sharing services, and the loss rate and conversion rate of goods have also been significantly improved.

It is worth noting that during the research period of 2023-2024, Hainan did not have other large-scale cold chain subsidy policies, and COVID-19 prevention and control measures have been completely cancelled, so the changes in these indicators are mainly attributed to the implementation of the two-wheel drive strategy. These cases show that this framework is adaptable and flexible to different market participants.

5. CONCLUSION AND POLICY IMPLICATIONS

Taking Hainan's cold chain supply chain as the research object, this paper constructs the three-dimensional resilience framework, and draws the following conclusions:

First, for the island cold chain under geographical constraints, simple channel optimization has a physical ceiling, which cannot fundamentally solve the navigation suspension risk.

Second, the two-wheel driven path is an effective strategy to hedge geographical risks, which can effectively reduce the channel dependence.

Third, the institutional innovation of FTP is the core guarantee for the implementation of the two-wheel driven strategy.

Based on this, this paper proposes the following policy suggestions:

First, deepen the institutional innovation of cross-strait inspection and quarantine, promote the one-time sealing and inspection at the origin, to further improve the channel efficiency and reduce the cargo damage rate.

Second, support the shared intensive processing industry for small and medium farmers, solve the problem of idle production capacity in off-season, to build a stable buffer for the supply chain.

Third, establish a hierarchical emergency supply guarantee system, to improve the overall resilience of the supply chain.

Overall, Hainan's practice proves that facing natural geographical constraints, we do not need to “overcome” it blindly, but can adapt to it through supply chain structure adjustment, providing replicable Chinese experience for island economies around the world.

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