

Research on the Effect of Path Optimization on Supply and Demand Coordination in the Fresh Food Cold Chain

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Abstract. The fresh food cold chain is characterized by significant demand fluctuations, high product perishability, and numerous supply chain nodes, posing substantial challenges to supply-demand coordination. Traditional research on route optimization has primarily focused on logistics efficiency factors such as transportation time, cost, and product loss, while relatively limited attention has been paid to the value of supply chain coordination. From a supply chain coordination perspective, this study analyzes route optimization factors—including transportation time, cost, product loss, and dynamic demand—based on theories of supply chain coordination, information sharing, and the bullwhip effect. It further explores how these factors enhance supply-demand alignment and supply chain collaboration efficiency. Research has found that route optimization can, on the one hand, directly improve the alignment between supply and demand by enhancing logistics operational efficiency, reducing product loss, and boosting a company's effective supply capacity; on the other hand, it can connect various supply chain participants through information sharing, promote the coordinated allocation of inventory and logistics resources, and enhance the overall responsiveness of the supply chain. It offers valuable insights for optimizing supply chain coordination in fresh food enterprises.

Keywords: Supply chain coordination, Demand-supply coordination, Path optimization

1. Introduction

With the development of e-commerce for fresh food and modern cold chain logistics, transportation efficiency and product quality have become increasingly important. Fresh cold chain products face volatile demand, high perishability and time sensitivity and complex multi-node transportation processes [1-3]. These characteristics pose greater challenges to supply-demand balancing, highlighting the critical role of effective supply chain coordination. Recent research has shown that route optimization can improve the efficiency of fresh cold chain distribution. The case study considering traffic, temperature, and humidity constraints reduced average product loss by 4.8 percentage points through optimized routing [4]. To address these challenges, route optimization has become a significant research area in cold chain logistics. Existing studies have incorporated factors such as transportation time, cost, environmental impact, and product quality into vehicle routing and cold chain optimization problems [5, 6]. A recent literature review further indicates that research on cold chain vehicle routing increasingly considers multiple operational objectives and constraints [7].

However, most current studies regard path optimization as an independent logistics decision, and rarely analyze how path optimization acts as an intermediary to link upstream and downstream to achieve supply and demand coordination, lacking an analysis at the mechanism level of action.

Therefore, this paper focuses on the role of route optimization in promoting supply-demand coordination within fresh food cold chain supply chains. Rather than merely examining how transportation routes can be optimized, this study re-evaluates the value of cold chain route optimization from the perspective of supply chain coordination and analyzes how it enhances supply-demand alignment and coordination efficiency. Specifically, by integrating a literature review with theoretical analysis, this paper develops an analytical framework to explore the relationship between route optimization and supply chain coordination. By expanding the perspective of cold chain route optimization from logistics efficiency to supply chain coordination, this paper provides practical insights for fresh food enterprises seeking to improve their supply chain coordination and operational efficiency.

2. Theoretical basis

Supply chain coordination theory focuses primarily on how decisions and objectives can be aligned among supply chain participants to enhance overall supply chain performance [8]. In fresh food cold-chain supply chains, suppliers, logistics companies, distributors, and retailers are typically independent decision-makers who often adjust their operations to maximize individual profits, resulting in divergent operational goals. Suppliers may prioritize production efficiency and order volume stability, logistics providers focus more on transportation efficiency, resource utilization, and energy consumption costs specific to cold-chain operations, while retailers emphasize the stability of upstream product supply, timely order fulfillment, delivery speed, and customer satisfaction. These differing objectives can easily lead to inefficient resource allocation and imbalances between supply and demand. For fresh food cold chains, coordination is even more critical due to the high sensitivity of perishable products to transit time and quality. Poor transportation decisions not only increase logistics costs but also cause delivery delays and product spoilage, thereby affecting downstream inventory levels and product availability. Therefore, supply chain coordination requires integrating logistics decisions with upstream supply and downstream demand. From this perspective, route optimization plays a crucial role in improving supply chain coordination. By more rationally allocating transportation resources and optimizing delivery routes, route optimization enables better alignment between logistics capacity and actual supply-demand conditions, thus enhancing coordination efficiency.

Information sharing theory emphasizes the importance of timely and accurate information exchange among supply chain participants [9, 10]. In fresh food cold-chain logistics, information sharing is particularly vital for transportation and delivery decisions. Route optimization is not an isolated process detached from supply and demand data; rather, it heavily depends on real-time or near-real-time information such as orders, inventory levels, delivery requirements, vehicle availability, and demand fluctuations. When suppliers, logistics providers, and retailers share such information promptly and accurately, transport routes can be dynamically adjusted according to actual supply and demand conditions. Thus, information sharing provides a critical foundation for route optimization. More comprehensive information sharing enables logistics companies to detect demand changes earlier and adjust delivery sequences, vehicle assignments, and transportation routes accordingly, reducing unnecessary travel and waiting time.

The bullwhip effect refers to the phenomenon where small fluctuations in downstream market demand are progressively amplified as they move upstream through the supply chain due to

independent decision-making by each participant [11, 12]. The bullwhip effect is highly relevant to fresh food cold-chain supply chains, as demand volatility directly affects inventory and transportation planning. The bullwhip effect holds significant relevance for fresh food cold-chain supply chains, as demand volatility directly impacts inventory and transportation planning. When demand information is delayed or inaccurate, upstream enterprises may overreact to perceived changes, leading to either stockpiling or shortages. For perishable goods, this issue becomes more severe under the inherently unstable demand patterns of cold-chain logistics, further exacerbating supply-demand imbalances and increasing product loss and operating costs. Route optimization can help mitigate the operational impact of demand fluctuations by improving the responsiveness of the logistics system. Faster delivery and stronger transport responsiveness reduce a company's reliance on excessive safety stock and improve inventory turnover efficiency, thereby mitigating the impact of demand fluctuations on supply chain operations. Therefore, route optimization cannot directly eliminate the bullwhip effect, but it can help reduce the impact of demand volatility on inventory, transportation, and supply-demand alignment by enhancing the responsiveness and flexibility of the logistics system.

Together, these three theories provide a foundation for linking route optimization with supply chain coordination. Coordination theory emphasizes the alignment of different participants, information sharing theory highlights the importance of timely supply and demand information, and bullwhip effect theory explains the need for rapid responses to demand fluctuations. These perspectives support the subsequent analysis of how route optimization can improve supply-demand matching and supply chain coordination in fresh food cold chains.

3. Influencing factors of path optimization

3.1. Time

Transportation time is one of the most fundamental considerations in vehicle route optimization, with the core objective being to meet customer demand under limited transportation resources while minimizing total delivery time. For perishable cold-chain logistics, the importance of time becomes even more pronounced, particularly due to the need to accommodate customer time windows. If a vehicle arrives too early, it may result in unnecessary waiting time and reduce the efficiency of vehicle and delivery resource utilization; if it arrives after the time window, customer satisfaction may decline, further disrupting downstream order processing and delivery scheduling. For highly perishable and time-sensitive fresh products, delivery delays can prolong the product's dwell time within the transportation and supply chain network, increasing the risk of product spoilage and value depreciation [2, 5]. Therefore, controlling transportation time not only affects transport costs and delivery efficiency but also directly impacts product quality and supply timeliness. Consequently, optimizing cold-chain routes cannot focus solely on minimizing travel distance or transit time; it must comprehensively consider customer time windows, vehicle loading and departure times, and the timeliness of delivery responsiveness to improve alignment between transportation resources and actual demand. In practice, the impact of route optimization on transportation time can be evaluated using indicators such as average delivery time, delay time, and time-window satisfaction rate. These indicators provide a practical basis for evaluating whether route optimization improves the timeliness and responsiveness of cold-chain distribution.

3.2. Transportation cost and product quality

In optimizing transportation routes for general goods, factors such as vehicle activation cost, transportation cost, time window penalties, and carbon emissions are typically considered, with some studies further examining how changes in vehicle load affect transportation costs. These cost factors also apply to perishable cold-chain transportation [6, 7]. However, because of the specific temperature control requirements of cold-chain logistics, refrigeration energy consumption must also be considered. Particularly during deliveries to retailers and end customers, where individual orders tend to be small, refrigerated vehicles often carry multiple types of fresh products simultaneously—each with different temperature sensitivity levels [5]. Thus, route optimization must not only account for customer delivery sequences but also integrate product temperature requirements, loading configurations, and transport distances into comprehensive decision-making to minimize unnecessary refrigeration energy use. Moreover, fresh products face higher risks of loss during transportation. Compared with non-perishable goods, fresh products are more vulnerable to temperature fluctuations, transit time, and mechanical damage during loading and unloading, which can reduce product quality and market value or even make the products unsellable. The economic and quality impacts of route optimization can be evaluated using indicators such as total logistics cost, cargo loss rate, and temperature exceedance rate. In a recent fresh-food distribution case, route optimization reduced total logistics costs by 15.3% and average product loss by 4.8 percentage points [4]. These measures illustrate how route decisions can affect both transportation efficiency and the effective supply of fresh products.

3.3. Dynamic demand

Demand for fresh products is highly dynamic and susceptible to influences such as holidays, consumer preferences, and weather conditions [13]. As a result, the volumes, locations, and requirements of cold-chain deliveries may vary significantly across delivery cycles. Traditional static route planning typically relies on relatively fixed order information, making it difficult to maintain efficient resource allocation when demand shifts. Therefore, route optimization must be based on dynamic demand data, enabling timely adjustments to fleet size, delivery sequences, and transportation routes in response to order changes throughout each delivery cycle [14]. This dynamic adjustment primarily refers to re-planning routes before dispatch or between different delivery cycles, rather than requiring frequent mid-trip rerouting. By synchronizing route planning with evolving demand patterns, transportation resources can be better aligned with actual demand, enhancing delivery efficiency and supply chain responsiveness. These factors are closely interrelated in fresh cold chain route optimization. Reducing transportation time may increase transportation costs, while cost minimization may lead to longer delivery times and higher product loss. Meanwhile, responding to dynamic demand may require additional route adjustments and transportation resources. Therefore, these factors cannot be optimized simultaneously, and route planning requires trade-offs based on overall supply and demand objectives to achieve better supply chain coordination.

4. Optimization effect of path optimization on supply and demand coordination

4.1. The improvement of efficiency in supply and demand coordination

In the fresh cold-chain supply chain, supply-demand matching involves not only alignment between product supply and market demand but also coordination among supply timing, location, product quality, and actual customer needs. Chapter 3 analysis indicates that factors such as transportation time, transport cost, product loss, and dynamic demand all affect the operational efficiency of cold-chain logistics. Therefore, path optimization is not merely about reducing vehicle travel distance; rather, it aims to enhance logistics system efficiency by rationally allocating transportation resources, thereby strengthening supply capacity and improving overall supply-demand matching in the supply chain.

Path optimization improves the timeliness of product delivery by reducing transportation time and minimizing unnecessary waiting periods. Well-designed delivery routes can shorten driving distances, eliminate redundant trips, and reduce idle waiting times, enabling limited transportation resources to fulfill more orders within a given timeframe while maintaining the required freshness and delivery speed for perishable goods. For fresh products, shorter transit times mean not only higher logistics efficiency but also reduced dwell time during transportation, ensuring faster and more timely delivery to end customers. When market demand has already emerged, prompt delivery helps prevent temporary supply-demand gaps caused by delayed product availability, bringing actual supply closer to real-time demand. Path optimization reduces product loss during transportation, thereby enhancing effective supply capacity. Fresh products are highly vulnerable to factors such as transit times, temperature control, and loading/unloading operations. Even if an order is delivered successfully, significant quality deterioration upon arrival diminishes its practical supply value. By shortening transit times, optimizing delivery sequences, and eliminating unnecessary transport steps, path optimization minimizes product damage, ensuring that more items reach customers in saleable condition. Thus, improvements in logistics efficiency through path optimization directly translate into stronger effective supply capabilities.

4.2. The improvement of supply chain collaboration efficiency

Unlike traditional studies that treat vehicle routing as an independent logistics decision, path optimization in fresh food cold-chain supply chains must integrate with suppliers' production capacities, logistics providers' transportation resources, and retailers' actual demand. Due to information asymmetry and conflicting objectives among different supply chain participants, optimizing just one segment's route may fail to maximize the overall supply chain efficiency. Therefore, the role of route optimization extends beyond improving logistics efficiency; it also promotes information sharing, inventory coordination, and optimal allocation of logistics resources by connecting supply, logistics, and demand sides, thereby enhancing overall supply chain collaboration. Route optimization facilitates information sharing among supply chain participants. Effective route planning requires data on supply capacity and inventory levels, carriers' available transportation resources, downstream order volumes, and delivery locations-information held by different entities such as suppliers, logistics companies, and retailers. When these parties share relevant information in a timely manner, logistics providers can adjust the number of vehicles, delivery sequences, and transport routes based on actual supply capacity and changing retail demand. Thus, route optimization effectively serves as a key medium for interconnecting information across different stakeholders, transforming fragmented data from various supply chain

nodes into concrete transportation decisions and improving the supply chain's responsiveness to demand fluctuations.

Route optimization enhances coordination between inventory and logistics. By improving inventory turnover efficiency, optimized routing lowers holding costs and strengthens alignment between supplied quantities and actual demand. Traditional inventory decisions often account for transportation uncertainties; when delivery times are long or reliability is low, retailers may increase safety stock to mitigate supply risks. However, with optimized routing, delivery times and transport reliability improve, enabling retailers to replenish inventory more accurately based on reliable logistics information, rely less on high safety stock, and thereby lower inventory carrying costs. At the same time, logistics companies can allocate delivery resources more efficiently according to inventory levels and order demands, creating a coordinated link between inventory and transportation decisions. As a result, route optimization integrates previously independent inventory and transportation management, reducing resource waste across supply chain stages.

Logistics companies should not select routes solely on the basis of internal metrics such as vehicle utilization or transportation costs; they must also consider supply capacity and actual retail demand. When a supplier has limited capacity, logistics providers can allocate transport resources accordingly. If retail demand suddenly increases, they can dynamically reconfigure routes by adding delivery resources or adjusting delivery priorities. In this context, route optimization becomes a collaborative decision rather than an isolated internal process. By integrating supply capacity, inventory status, order requirements, and transportation resources, the logistics system achieves a more precise connection between supply and demand.

5. Conclusion

The research first identifies that perishable cold chains are characterized by high demand volatility, strong product perishability, and numerous supply chain nodes, requiring logistics operations to consider not only traditional factors such as distance, time, and cost, but also product spoilage, customer time windows, and dynamic demand. Therefore, cold-chain route optimization essentially involves trade-offs among transportation time, cost, product loss, and dynamic demand under limited logistics resources. Further analysis shows that route optimization promotes supply-demand coordination in two ways. First, by reducing transportation time and waiting, inventory costs, and product loss, it improves logistics efficiency and effective supply capacity, enabling products to reach the right locations at appropriate times and quality levels, thereby improving supply-demand matching. Second, route optimization connects suppliers, logistics providers, and retailers by coordinating information on inventory, orders, and transportation resources. This enables delivery capacity to respond more effectively to demand changes and improves overall supply chain responsiveness and coordination efficiency. This study is mainly based on theoretical analysis and does not provide empirical quantitative validation of the impact of route optimization on supply-demand coordination. Future research could combine simulation, case studies, or empirical data to quantitatively examine the actual effects of route optimization on supply-demand matching and supply chain coordination. Such research would provide stronger empirical evidence for further validating and improving the proposed coordination mechanism.

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