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Route Optimization in Cold Chain Logistics from a Green Perspective: A Literature Review

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Abstract: Rapid global economic development and growing environmental concerns have made green logistics and cold chain logistics optimization prominent research topics in management science and engineering. Although cold chain logistics safeguards the quality and safety of perishable products, its high energy consumption and emissions create substantial environmental pressures. This review synthesizes recent domestic and international research on green logistics and low-carbon principles, vehicle routing problems incorporating carbon emissions, cold chain distribution routing, integrated inventory and distribution optimization in cold chains, and solution algorithms. Drawing on 45 representative studies, it summarizes major findings and areas of agreement in carbon emission modeling, multi-objective optimization, time-dependent traffic constraints, deterioration modeling, and algorithm design. It identifies gaps in multi-temperature joint distribution, vendor-managed inventory, deterioration modeling using the three-parameter Weibull distribution, and carbon emission estimation based on total vehicle energy consumption. Future research directions are proposed in four areas: research scope, modeling methods, algorithm design, and practical implementation. The review provides a theoretical foundation and practical guidance for subsequent research in green cold chain distribution routing.

Keywords: Green logistics; Cold chain logistics; Vehicle routing problem; Carbon emissions; Integrated inventory and distribution optimization.

1. Introduction

Green logistics and cold chain logistics are important components of modern logistics systems and contribute to sustainable economic and social development. Green logistics seeks to minimize the environmental impacts of logistics activities throughout the logistics process by adopting environmentally friendly technologies and strategies to reduce carbon emissions and improve resource efficiency. Cold chain logistics, by contrast, focuses on the transportation and storage of perishable products, ensuring their quality and safety through continuous temperature control. Rising consumer spending and the rapid expansion of fresh food e-commerce have increased demand for cold chain logistics. However, the high energy consumption and emissions of refrigerated vehicles have made this sector a priority for carbon mitigation in the logistics industry. Reducing the environmental impacts of cold chain operations while maintaining product quality has therefore become a major concern for both researchers and practitioners.

The vehicle routing problem (VRP) is central to modeling green cold chain distribution. Conventional VRPs seek to minimize transportation distance or cost, whereas green VRPs incorporate environmental factors, including carbon emissions and fuel consumption, into the objective function, giving rise to low-carbon VRPs. The distinctive requirements of cold chain logistics also necessitate consideration of refrigeration temperature, delivery time, product deterioration losses, and customer satisfaction, leading to more complex multi-objective optimization models. Zhou et al. developed a green VRP model for cold chain distribution and designed a solution algorithm, providing a representative framework for green cold chain routing [1]. Zhou et al. assessed the green development of cold chain logistics for fresh agricultural products from a regional perspective, revealing spatial disparities [2]. At the operational level, Wang et al. incorporated the effects of refrigeration temperature and delivery time on mold growth into a cold chain distribution model with temperature decisions [3]. Wu et al. introduced the concept of customer time tolerance and formulated a multi-objective cold chain optimization model [4].

Despite substantial progress, several limitations remain. First, most green and low-carbon logistics studies focus on conventional VRPs, and systematic research on green cold chain distribution remains limited. Second, cold chain distribution studies generally adopt conventional VRP modeling approaches, with insufficient consideration of distinctive features such as multiple temperature zones and refrigeration energy consumption. Third, integrated inventory and distribution optimization typically addresses single-temperature, single-product scenarios, with little systematic analysis of multi-temperature joint distribution. Fourth, carbon emissions are often estimated using simplified distance- or load-based models rather than detailed approaches based on total vehicle energy consumption.

The literature was retrieved primarily from China National Knowledge Infrastructure (CNKI), Web of Science, and ScienceDirect using search terms including "green logistics," "cold chain logistics," "vehicle routing optimization," "low-carbon emissions," and "integrated inventory and distribution optimization." The search covered 2013–2025. Following preliminary screening of titles, abstracts, and keywords and further assessment of thematic relevance, 45 representative studies were selected, comprising 27 Chinese-language and 18 English-language publications. Before 2017, research primarily concerned the theoretical foundations of green logistics and conventional VRPs. Between 2018 and 2020, low-carbon principles were increasingly incorporated into VRPs, and the distinctive features of cold chain distribution began to receive attention. Since 2021, green cold chain distribution routing has become an increasingly prominent research topic, with substantial growth in multi-objective

optimization, time-dependent traffic, and integrated inventory and distribution optimization. The remainder of this article is organized as follows. Section 2 reviews five research themes. Section 3 synthesizes areas of agreement, discusses limitations, and identifies research gaps. Section 4 proposes future research directions, and Section 5 concludes.

2. Literature Review

2.1. Green Logistics and Low-Carbon Principles

Green logistics is an approach to logistics management guided by environmental protection and sustainable development. It reduces the adverse environmental effects of logistics operations through environmentally friendly technologies and strategies. On the one hand, green logistics uses emerging technologies to reduce carbon emissions and minimize environmental harm. On the other hand, it emphasizes the efficient allocation and utilization of resources to realize their full potential. Its ultimate objective is to establish a logistics system that is closely integrated with the ecological environment, enabling their coordinated development.

Researchers have developed multidimensional indicator systems and conducted empirical assessments of green logistics development. Zhang et al. applied a cloud PDR multi-criteria decision-making method to assess green logistics development across Chinese provinces and identify major barriers [5]. Liu et al. examined the principal challenges facing green logistics in China in the context of green industry development and proposed strategies for industrial upgrading and transformation [6]. Drawing on sustainable development theory, Niu et al. developed an indicator system for evaluating green logistics in port enterprises, encompassing warehousing, transportation, packaging, loading, unloading, and material handling [7]. Xue et al. analyzed trends in green logistics from a theoretical perspective, providing a basis for the development of the modern green logistics industry [8]. Di examined the role of green logistics in promoting economic development and the potential environmental hazards of conventional logistics models [9]. Yang investigated the development of green logistics systems at multiple levels, with particular attention to logistics chains and infrastructure [10]. Focusing on packaging in logistics distribution, Chen identified problems with existing packaging practices and proposed the concept of shared express delivery boxes, discussing their sustainability, economic viability, and safety [11].

As the low-carbon economy has gained prominence, low-carbon principles have increasingly been incorporated into operational decisions in logistics systems. Sharma et al. used partial least squares structural equation modeling to investigate how green logistics influences circular economy practices in the Industry 4.0 era, informing strategies for improving the environmental performance of the logistics sector [12]. Based on a subsidy model for green supply chains, Long et al. examined how green preferences affect consumers' willingness to pay when green logistics costs are shared among manufacturers, retailers, and consumers, finding that cost sharing helps consumers accept higher prices for green logistics services [13]. Ling et al. investigated product competition between two green manufacturers in a pollution-sensitive market and found that government subsidy rates are not necessarily positively associated with product greenness, providing insights for differentiated subsidy policies [14].

Overall, the literature has established a broad range of indicators and methods for assessing green logistics development across regions, ports, and enterprises. The application of low-carbon principles to supply chain coordination and policy incentives has also been extensively examined. Nevertheless, existing studies primarily focus on macro-level assessments of green logistics and supply chain strategy design. Less attention has been devoted to the environmental performance of energy-intensive cold chain logistics and the operational integration of low-carbon principles into specific routing decisions.

2.2. Vehicle Routing Problems Incorporating Carbon Emissions

VRPs that incorporate carbon emissions are central to operational decision-making in green logistics. Unlike conventional VRPs, which minimize transportation distance or cost, low-carbon VRPs incorporate environmental factors such as carbon emission costs and fuel consumption into the objective function through multi-objective or integrated single-objective formulations.

Carbon emission modeling forms the foundation of low-carbon VRPs. Luo et al. developed a mathematical optimization model for green transportation routing in many-to-many interregional logistics under both traffic and weather constraints, aiming to minimize the combined cost of carbon emissions and fuel consumption [15]. For many-to-many supply–demand matching, Zhou et al. formulated a green VRP for cross-docking distribution that minimizes the sum of carbon emission and fuel costs [16]. Recognizing that travel distance and actual vehicle load substantially affect carbon emissions, Pu et al. formulated a multi-depot VRP minimizing logistics costs and travel distance and developed a mixed-integer programming model [17]. Fu et al. proposed a collaborative logistics model in which customers, vehicles, and logistics centers are shared. Their computational experiments demonstrated that minimizing total costs under such a model can reduce travel distance and carbon emissions [18]. Yan et al. formulated a split-delivery VRP incorporating carbon emissions and designed a corresponding solution algorithm [19]. These studies indicate that emission modeling has evolved from simplified distance-based approaches to more detailed formulations incorporating vehicle load, speed, and traffic conditions. However, most models focus on fuel consumption during vehicle operation and insufficiently account for refrigeration system energy consumption and associated emissions.

Low-carbon VRPs generally involve a trade-off between economic and environmental costs and are thus commonly formulated as multi-objective optimization problems. Gil et al. reviewed heuristic and hybrid techniques that address both vehicle routing and environmental concerns, analyzing features and problem components associated with emissions and providing a systematic reference for green VRP algorithm design [20]. Tang et al. formulated a multi-objective nonlinear programming model minimizing travel distance and carbon emissions, solved it using an improved ant colony optimization algorithm, and demonstrated its superiority over commonly used algorithms for similar problems through numerical analysis [21]. Li et al. investigated green vehicle routing in cold chain distribution with greenhouse gas emissions and assessed the effects of maximum vehicle load on costs and emissions [22]. Pareto optimization and

weighted-sum methods are widely used to address conflicts between economic and environmental objectives. Metaheuristics such as ant colony optimization, particle swarm optimization, and genetic algorithms, together with their improved variants, remain prevalent solution approaches. Nevertheless, algorithms tailored to the specific structure of low-carbon VRPs warrant further development.

In practice, vehicle speeds vary over time with traffic conditions, substantially affecting routes and carbon emissions. Bai et al. incorporated road network complexity and time-dependent traffic into a cold chain routing model, using an improved nondominated sorting genetic algorithm to minimize carbon emissions and distribution costs [23]. By incorporating real-time traffic conditions into low-carbon routing, their study provides a basis for dynamic route optimization in urban cold chain distribution. Time-dependent low-carbon VRPs are more complex than static problems because route selection and departure times must be determined jointly. Further research is needed on real-time traffic data acquisition, dynamic route reoptimization mechanisms, and the time-dependent modeling of carbon emissions.

2.3. Cold Chain Distribution Routing Optimization

Cold chain distribution routing extends conventional VRPs by incorporating the distinctive requirements of cold chain products, including temperature control, time sensitivity, and quality deterioration.

A defining characteristic of cold chain distribution is the high sensitivity of products to temperature and time. To address the susceptibility of fresh fruit to mold growth under varying refrigeration temperatures and delivery durations, Wang et al. developed a nonlinear transportation and distribution model with temperature decisions and order substitution, examining how total distribution costs can be reduced while safeguarding product quality [3]. Wu et al. introduced and quantified the concept of time tolerance, formulated a multi-objective cold chain logistics model that maximizes customer time tolerance while minimizing logistics costs, and solved it using an improved multi-objective plant growth simulation algorithm [4]. These studies highlight three distinctive features of cold chain distribution: temperature control directly affects product quality losses; delivery times are subject to stringent time windows; and quality losses must be balanced against costs. However, existing models generally simplify the dynamic evolution of temperature, often assuming fixed temperatures or linear deterioration.

Cold chain distribution must control costs and emissions while satisfying customer requirements regarding delivery time and product quality. Consequently, customer satisfaction is an important optimization objective. Ma et al. formulated a total-cost minimization model and used grey whitening weight functions to model courier satisfaction. They found that accounting for courier satisfaction increases total logistics costs but also improves both customer and courier satisfaction [24]. Wang et al. classified customers into service tiers and developed a routing model that jointly considers customer satisfaction and cold chain logistics costs [25]. Customer satisfaction is commonly quantified using time-window deviations, product freshness, and service levels. However, existing research predominantly measures satisfaction in terms of delivery time, with limited consideration of perceived product quality, delivery flexibility, and systematic modeling of customer heterogeneity.

Urban cold chain distribution faces constraints such as vehicle access restrictions, speed limits, and traffic congestion. Accordingly, conventional shortest-distance routes are not necessarily optimal in urban settings. Zhao et al. incorporated congestion into distribution routing and argued that, under congested urban traffic conditions, routes should minimize travel time rather than distance while accounting for economic and environmental costs [26]. Yao et al. analyzed distribution costs using real-time road condition information and proposed static transfer points to reduce costs and improve customer satisfaction [27]. From an environmental perspective, Liu et al. developed an urban transportation network routing model, represented real-time traffic using an urban traffic state index, and employed an improved particle swarm optimization algorithm to minimize emissions and delivery time [28]. Chen et al. analyzed the spatiotemporal dynamics of urban delivery vehicle speeds, constructed a speed matrix for dynamic travel-time calculation, and incorporated vehicle carbon emissions into the operating cost function [29]. Research on cold chain distribution under urban traffic constraints has advanced, and the advantages of shortest-time over shortest-distance routing have been widely recognized. Nevertheless, real-time traffic data availability, the computational efficiency of dynamic reoptimization, and coordination among multiple participants in urban cold chain distribution warrant further investigation.

2.4. Integrated Inventory and Distribution Optimization in Cold Chains

In cold chain logistics systems, inventory and distribution decisions are interdependent. Optimizing either in isolation is unlikely to achieve system-wide optimality, making their joint optimization an important research area.

Accurately modeling deterioration rates is critical to inventory models for perishable cold chain products. Wang et al. developed a retailer replenishment and pricing model under uncertainty to maximize profit in a cold chain system with Weibull-distributed deterioration [30]. Kouki et al. examined cost-minimizing parameters for a perishable inventory system with fixed product lifetimes, fixed lead times, and stochastic demand [31]. Wang et al. formulated a three-echelon refrigerated logistics optimization model incorporating product freshness; sensitivity analysis revealed a positive relationship between system profit and freshness [32]. Zou et al. introduced a quality effort parameter to quantify product quality and enterprise profit and derived the manufacturer's optimal production quantity and optimal inventory levels at each echelon under Weibull-distributed deterioration [33]. Most existing studies use the two-parameter Weibull distribution to characterize cold chain product deterioration, while some incorporate additional measures such as quality effort and freshness. Nevertheless, most assume that deterioration begins immediately upon storage. This assumption overlooks shelf-life characteristics under specific storage conditions, and the two-parameter Weibull distribution cannot adequately capture deterioration processes involving a distinct initial shelf-life period.

Integrated inventory-routing optimization jointly addresses inventory replenishment and vehicle routing decisions and is central to coordinated supply chain optimization. Wang et al. formulated a VRP incorporating food safety risk coefficients and time windows for perishable foods to minimize

distribution costs and solved it using an improved whale optimization algorithm [34]. Govindan et al. examined a multi-objective inventory-routing problem for perishables, introduced a two-echelon location-routing problem with time windows, and designed a multi-objective hybrid solution algorithm [35]. From a green perspective, Soysal et al. investigated inventory and transportation costs in an inventory-routing problem involving multiple suppliers and customers and analyzed horizontal collaboration among suppliers of perishable products. Their findings indicate that horizontal collaboration reduces both costs and carbon emissions [36]. Integrated inventory-routing research has progressed from simple single-distribution-center settings to more complex multi-echelon supply chains and multi-supplier collaboration. Nevertheless, most studies address single-temperature, single-product scenarios, leaving integrated inventory-routing optimization for multi-temperature joint distribution underexplored.

Integrating green and low-carbon principles into cold chain inventory and distribution optimization has emerged as a recent research direction. Yang et al. examined inventory and distribution decisions jointly from the perspectives of a low-carbon economy and green logistics, analyzed costs incurred in product circulation, and proposed integrated optimization strategies to reduce environmental costs and increase system profit [37]. Zakaryaei et al. investigated a dynamic green VRP for perishable products under green traffic conditions, seeking to minimize total costs and carbon emissions while maximizing customer service levels [38]. Integrated optimization from a low-carbon perspective remains at an early stage. Although carbon emission costs have begun to be incorporated into joint inventory and distribution models, considerable scope remains for improving detailed emission estimation, designing multi-objective algorithms, and investigating how low-carbon strategies affect supply chain coordination.

2.5. Advances in Solution Algorithms

Green cold chain distribution routing problems are generally NP-hard. As problem size and the number of constraints increase, exact algorithms struggle to obtain optimal solutions within a reasonable computational time. Metaheuristics and their hybrid and improved variants have therefore become the predominant approaches to solving these problems.

Metaheuristics imitate natural phenomena or biological behavior to explore solution spaces efficiently and are well suited to complex combinatorial optimization problems. Belmecheri et al. developed a particle swarm optimization algorithm incorporating local search for a VRP with mixed linehauls and backhauls and demonstrated improved algorithmic performance through computational experiments [39]. Xie investigated vehicle routing with simultaneous pickup and delivery and applied ant colony optimization to multi-temperature cold chain distribution, achieving substantially faster convergence than the conventional algorithm [40]. Ren et al. formulated a minimum-cost routing model incorporating customer satisfaction and traffic congestion, introduced a knowledge-based ant colony algorithm that embeds a knowledge-guided mechanism, and verified its effectiveness through case analysis [41]. Wang et al. addressed distribution facility location using a two-stage heuristic, seeking to minimize distribution center location costs and vehicle distribution costs, and validated the model with specific data [42]. Wang et al. formulated a cold chain routing model with time windows and improved the intelligent water drops algorithm by incorporating a contraction factor and a set of suboptimal solutions. Simulation experiments demonstrated more accurate solutions and addressed limitations of the conventional algorithm [43]. Metaheuristics, including ant colony optimization, particle swarm optimization, genetic algorithms, and intelligent water drops algorithms, have been widely applied to green cold chain routing. These approaches differ in convergence speed, solution quality, and computational stability, and researchers typically select or adapt algorithms according to problem characteristics.

Individual metaheuristics may exhibit slow convergence or become trapped in local optima. Hybrid algorithms can improve solution performance by combining complementary strengths. Fang et al. incorporated energy conservation and emission reduction into routing optimization, combining the A* algorithm with ant colony optimization to address slow convergence during the initial search. Simulation and comparative experiments verified the effectiveness of the model and algorithm [44]. Yan et al. developed an improved particle swarm optimization algorithm with dynamic learning factors for a cost-minimizing routing model. Computational experiments showed that it improves computational efficiency while maintaining solution quality [19]. Utama et al. formulated a single-distribution-center green VRP minimizing distribution costs and developed a hybrid butterfly optimization algorithm that effectively reduces distribution costs [45]. Research on hybrid algorithms and improvement strategies indicates that algorithm integration and adaptive parameter adjustment can improve the efficiency and quality of solutions to green cold chain routing problems. However, most hybrid designs are based on empirical combinations rather than theoretical analyses of algorithmic complementarity, and their scalability to large instances remains to be established.

3. Synthesis of Existing Research and Research Gaps

The reviewed literature reveals five main areas of agreement. First, carbon emissions and fuel consumption are fundamental environmental costs in green VRPs and are closely related to travel distance, vehicle load, and speed. Second, cold chain distribution is subject to temperature sensitivity and time constraints, necessitating trade-offs among product quality losses, customer satisfaction, and distribution costs. Third, under congested urban traffic conditions, shortest-time routes are preferable to shortest-distance routes, and real-time traffic information is valuable for dynamic route optimization. Fourth, integrated inventory and distribution optimization can achieve system-wide supply chain optimality, while horizontal collaboration and joint distribution can reduce costs and emissions. Fifth, metaheuristics and their hybrid and improved variants are effective solution methods for these problems.

Despite these advances, several limitations remain. Regarding research scope, most green and low-carbon studies address conventional VRPs, while systematic research on green cold chain distribution is still at an early stage, with insufficient consideration of refrigeration energy consumption and multi-temperature vehicle configurations. Regarding modeling methods, carbon emissions are typically

estimated using simplified distance- or load-based models rather than detailed methods based on total vehicle energy consumption. Deterioration is usually modeled using a two-parameter Weibull distribution under an immediate deterioration assumption, which inadequately represents products with a distinct shelf-life period. Regarding problem extensions, integrated inventory and distribution optimization generally focuses on single-temperature, single-product scenarios, with limited attention to multi-temperature joint distribution and vendor-managed inventory. Regarding algorithm design, existing approaches mostly involve incremental improvements to conventional algorithms; more tailored algorithms and large-scale scalability assessments are needed.

These limitations reveal five research gaps. First, a systematic research framework for green cold chain distribution has yet to be established, as most studies adopt a single perspective rather than integrating low-carbon principles, cold chain characteristics, and operational decisions. Second, routing and integrated inventory and distribution optimization for multi-temperature joint distribution remain underexplored. The configuration of temperature zones, coordination of routes for products requiring different temperatures, and inventory management pose unresolved challenges. Third, methods for estimating carbon emissions based on total vehicle energy consumption are lacking; existing models cannot adequately represent combined emissions from propulsion and refrigeration. Fourth, relatively few studies investigate integrated cold chain inventory and distribution optimization under vendor-managed inventory. Fifth, the three-parameter Weibull distribution has received limited attention in modeling cold chain product deterioration rates.

4. Future Research Directions

To address these gaps, this review proposes future research directions in four areas.

Regarding research scope, systematic investigations of green cold chain distribution should be strengthened by integrating low-carbon principles throughout warehousing, transportation, and distribution. Particular attention should be paid to urban multi-temperature joint distribution, taking into account multi-temperature vehicle configurations, refrigeration energy consumption, and product quality losses.

Regarding modeling methods, carbon emission estimation for refrigerated transportation should be based on total vehicle energy consumption, jointly accounting for propulsion energy, refrigeration energy, and start-stop energy losses. Deterioration modeling should make greater use of the three-parameter Weibull distribution to capture the effects of shelf life and ambient temperature on deterioration and move beyond the assumption of immediate deterioration. The application of vendor-managed inventory to integrated cold chain inventory and distribution optimization should also be explored.

Regarding algorithm design, tailored metaheuristic and hybrid algorithms should be developed to exploit the specific structure of green cold chain routing problems. Greater attention should be devoted to theoretical analysis of algorithmic complementarity, and scalability should be assessed using large-scale computational instances. Dynamic route reoptimization driven by real-time traffic data also merits further investigation.

Regarding practical implementation, green cold chain distribution optimization models should be evaluated in actual enterprises, using case studies and empirical research to verify model effectiveness. Future studies should also examine the effects of policy incentives, such as carbon taxes and subsidies, on green cold chain distribution decisions, thereby providing a theoretical basis for low-carbon logistics policy.

5. Conclusion

This article systematically reviews cold chain distribution routing optimization from a green perspective. Based on 45 representative studies, it synthesizes major findings and areas of agreement across five themes: green logistics and low-carbon principles, VRPs incorporating carbon emissions, cold chain distribution routing optimization, integrated cold chain inventory and distribution optimization, and solution algorithms. It identifies limitations in research scope, modeling methods, problem extensions, and algorithm design, as well as five specific research gaps: the absence of a systematic research framework for green cold chain distribution; insufficient research on multi-temperature joint distribution; the lack of carbon emission estimation methods based on total vehicle energy consumption; limited application of vendor-managed inventory; and limited use of the three-parameter Weibull distribution. Future research directions are proposed in four areas: research scope, modeling methods, algorithm design, and practical implementation.

This review helps researchers develop a systematic understanding of the current state and emerging trends in green cold chain distribution routing, providing a theoretical basis and guidance for further research. Given the scope of the literature search and space limitations, it does not encompass all relevant studies. Future reviews could extend the search coverage and incorporate bibliometric analysis and knowledge mapping to provide a more detailed visualization of research hotspots and their evolution.

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