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Exploration on Practical Application of Cold-Chain Logistics Distribution in Real Road Networks from the Perspective of Dynamic Vehicle Routing Problems

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ABSTRACT

This paper investigates the application of cold-chain logistics distribution in real road networks through the framework of dynamic vehicle routing problems (DVRP). It does not offer new empirical data, but gathers previous research on vehicle routing, dynamic routing models and cold chain distribution to explore how dynamic VRP formulations can support decision-making under real-time information, traffic fluctuations and temperature-control constraints. Based on taxonomies of DVRP variants, classification studies of vehicle routing problems and specific models for perishable products and multi-compartment refrigerated vehicles have been conducted, and this paper explores how logistics practitioners can adapt the dynamic VRP framework to real road conditions, such as time-dependent travel times, congestion, and heterogeneous customer requirements. Cold-chain distribution in practice is expected to integrate routing optimisation with risk management for product quality, customer satisfaction and environmental performance, and dynamic VRP approaches offer a practical, albeit not exhaustive, path to explore these trade-offs. Therefore, the application should be based on a well-defined problem, integrated with monitoring technology, and have realistic expectations for the limits of optimisation models.

KEYWORDS

Dynamic Vehicle Routing; Cold-chain Logistics; Real Road Networks; Perishable Products; Time-dependent Travel Times; Customer Satisfaction.

1. INTRODUCTION

Cold-chain logistics has gradually been integrated into the supply chain for perishable goods, such as fresh food and medicine, and other temperature-sensitive products. Control the cost of maintaining product quality by organising the storage, transportation and distribution of products reasonably.

It is very difficult to route refrigerated trucks to the urban and rural distribution areas according to actual road conditions, fluctuating traffic, delivery time windows and strict temperature requirements in practice. Given the uncertainty and real-time changes, the operator must ensure service stability, product quality and economic viability simultaneously.

Dynamic Vehicle Routing Problems (DVRP) offer a way to model routing decisions when the information of customer requests, travel time or other factors changes over time. This paper studies how to apply the dynamic VRP approach to real road networks for cold chain logistics distribution. It is a problem of concept and modelling, not new empirical data; it extends the previous research on vehicle routing and cold chain logistics to explore opportunities and constraints.

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2. VEHICLE ROUTING PROBLEMS AND DYNAMIC VRP PERSPECTIVE

Vehicle Routing Problems (VRP) are the basic types of models for freight distribution. Toth and Vigo present a general introduction to VRP variants, including the classical capacitated VRP, VRP with time windows, multi-depot VRP, and many other models that add additional operational constraints [1]. Their work shows that routing problems in practice often have multiple interacting features, such as heterogeneous fleets, time-dependent travel times and service-level requirements.

Braekers, Ramaekers and Van Nieuwenhuyse have classified vehicle routing problems in a review, and pointed out how different problem characteristics have been studied and which variants are most applicable to industrial applications [2]. They have added cold-chain logistics, environmental constraints and customer satisfaction to the VRP formulation in recent years [2]. The above development shows that VRP is a flexible model that can meet the particular requirements of refrigerated distribution.

Dynamic Vehicle Routing Problems (DVRP) are extensions of the static VRP that consider changes in time. Psaraftis, Wen and Kontovas have conducted research on DVRP for the past thirty years and developed a taxonomy based on problem type, logistical environment, objective function and the characteristics of dynamism and stochasticity [3]. Dynamic routing is employed in many areas to this day, such as dial-a-ride services, courier operations and real-time freight distribution.

Ritzinger, Puchinger and Hartl have combined surveys of dynamic and stochastic VRP, and indicated that many real-world routing problems involve both the arrival of dynamic information and uncertainty in demand or travel time [4]. Considering the cold-chain logistics in a real road network, the above analysis suggests that models incorporating time-dependent conditions and dynamic decisions should be used instead of static, deterministic VRP formulations.

3. COLD-CHAIN LOGISTICS AND VRP FOR PERISHABLE PRODUCTS

The distribution of perishable goods adds extra constraints to those of a general VRP. Osvald and Stirn's study of fresh vegetable distribution has formulated a VRP with time windows and time-dependent travel times, explicitly modelling perishability as a cost factor [5]. The algorithm considers the effect of driving time and delivery time on product degradation, and thus routing decisions can significantly impact waste and total distribution costs [5].

Later, research on cold-chain VRP has taken this approach. Chen, Liu and Langevin have studied a multi-compartment vehicle routing problem for cold-chain distribution, in which vehicles need to carry products at different temperatures in separate compartments [6]. The model shows the relationship between vehicle design and routing decisions and operating efficiency and temperature requirements [6].

Qin, Tao and Li propose a cold-chain vehicle routing optimisation problem that considers cost, customer satisfaction and carbon emissions simultaneously [7]. The above work shows that the routing decision can be based on multiple objectives, such as environmental performance and service quality, rather than solely on distance or time reduction [7]. The above studies have proposed VRP formulations for cold-chain logistics that consider perishability, temperature control and multiple objectives.

Literature reviews on vehicle routing in cold food supply chains have also shown that the proposed models generally incorporate transportation, quality and environmental cost factors [2][8][10]. Therefore, the routing decision should be regarded as part of the overall risk management plan that balances the interests of product quality, service level and long-term development, rather than being an independent optimisation problem.

4. DYNAMIC VRP IN REAL ROAD NETWORKS

Dynamic VRP formulations are more suitable for distribution in actual road networks that have congestion, accidents and varying travel speeds. Psaraftis and later research have added dynamic characteristics, such as time-varying travel times, real-time customer demands, and continuous information flow through telematics and communication systems [3,4]. These features are typical of urban cold chain distribution, and both traffic conditions and customer schedules are irregular.

Time-varying travel times and traffic congestion in the actual road network will affect the reliability of cold-chain delivery schedules. Research on time-varying networks and dynamic routing has shown that, by adding traffic information, one can improve on-time performance and reduce delays; however, this may also make the model more complex to formulate and solve [3, 9, 11]. Therefore, a problem in cold chain logistics is how to combine dynamic travel-time models with temperature-control requirements and service windows.

Liao and Hu have put forward an object-oriented evaluation system for dynamic VRP under real-time information to assess the performance of various algorithms in different operating environments [11]. Their work indicates that, in addition to the mean, the worst-case scenario and robustness of dynamic routing methods in real road networks should also be considered by practitioners [11].

Dynamically, the VRP method for cold chain operators needs to build a data collection and communication network for real-time GPS tracking, traffic information, and temperature monitoring systems in practice. Without particular data, the desired advantages of dynamic routing models in real road networks cannot be realised.

5. PRACTICAL CONSIDERATIONS IN COLD-CHAIN DISTRIBUTION ROUTING

Applying dynamic VRP ideas to cold chain logistics in real road networks needs to consider many practical constraints. Research on cold-chain VRP has shown that the routing decision should meet delivery time windows, vehicle capacity limits and temperature-control policies, as well as regulatory requirements and driver working hours [5-7]. Many of these constraints reduce the flexibility of dynamic rerouting for vehicles that are close to full capacity or have a tight time window.

Practical cold-chain distribution also has various customer demands. Some recipients need to receive the goods on time and are sensitive to temperature changes; others can wait longer. Multi-objective models of customer satisfaction indicators have shown that, by giving different weights to service levels, the optimal routing choice can be changed [7][10]. Dynamically, the routing algorithm should be adjusted based on the current demands for punctuality, freshness and cost in a particular business environment for dynamic Vehicle Routing Problems (VRPs).

The method of incorporating route optimisation into warehouse operations and inventory management in practice is also unknown. Research on inventory-routing problems for perishable products has shown that transportation and storage decisions are closely related and affect the whole system [2, 9, 10]. Dynamic routing in a real road network may need to be coordinated with loading procedures, cross-docking arrangements and temperature recovery times, thus limiting the frequency of route adjustments.

Therefore, the application of dynamic VRP in cold-chain logistics must be in line with the actual circumstances of operation. A model that does not consider the handling time, temperature recovery, etc., of customers will be theoretically efficient in terms of routing but not feasible in practice.

6. INTEGRATION OF DYNAMIC VRP WITH MONITORING AND CONTROL TECHNOLOGIES

Recently, some studies have proposed combining dynamic routing with monitoring and control technology for cold chain logistics. Digital cold chain systems are adding temperature sensors, data loggers and telematics to monitor the condition of products in real time [8-9]. Dynamically VRP algorithms are employed by the above systems to adjust routes and distribute loads in response to a temperature increase in advance.

Most vehicle routing models that consider real-time information assume timely and accurate access to traffic condition and delivery status data [3, 11]. The above models need stable communication links between vehicles, dispatch centres and customers in practice. Industrial IoT frameworks and intelligent logistics platforms aim to provide this connectivity and enable dynamic optimisation based on the latest road network information [9, 11].

Monitoring Technology can be used to determine the operating efficiency of a cold chain logistics route. In addition to the total cost, one can also determine whether different routes will have a different temperature profile and product quality under the regulations. Bibliometric analysis of cold-chain VRP research shows a trend of adding quality and environmental performance indicators to the routing objective [8, 10].

Integration of dynamic VRP with monitoring systems is also organisationally and technically difficult. Data quality problems, a lack of system interoperability and the need for staff training can all reduce the speed of adoption for dynamic routing frameworks. Therefore, the practical application will gradually introduce a testing mechanism for dynamic routing in a pilot project before extending it to the whole network.

7. OPPORTUNITIES AND LIMITATIONS OF DYNAMIC VRP FOR COLD-CHAIN LOGISTICS

Dynamic VRP considers the real-road network conditions of cold chain logistics distribution and has certain advantages and drawbacks. Dynamic Routing Models can be used to reduce delay, respond to traffic disruptions and improve vehicle utilisation in a dense urban area [3, 9, 11]. In conjunction with multi-objective formulations, they can support decision-making that balances cost, customer satisfaction and environmental performance [7][10].

Dynamic VRP approaches also consider uncertainty and real-time information explicitly, helping logistics planners determine which data sources and decision rules are most relevant to cold chain operations [3,4]. Organise the problem based on dynamic events and update policies, and then these models can provide a structure for designing dispatch strategies that adapt to changes in circumstances rather than using fixed plans.

At the same time, there are also deficiencies. Surveys of dynamic and cold-chain VRP show that many models are based on assumptions that are difficult to meet in practice, such as perfect information, instantaneous communication or unlimited computational resources [2][3][8]. Small and medium-sized cold chain enterprises without good IT facilities and optimisation knowledge will find it difficult to apply a high-end dynamic VRP algorithm.

Dynamic Routing Decisions can also be affected by human factors, such as driver acceptance, contract provisions and safety considerations. Based on the above case studies, although dynamic routing is theoretically superior, organisational constraints may cause some companies to select a stable-route structure. Therefore, dynamic VRP should be viewed as one of many ways to enhance cold-chain logistics and is not presented as an all-encompassing solution.

Currently, the application of dynamic VRP ideas in cold chain logistics is still in the exploration and adaptation stage. Pilot projects and targeted applications, such as dynamic rerouting in response to serious traffic accidents or temperature alarms, can offer practical benefits without the need for full-scale changes to the routing practice. The incremental approach will not promise the world; it will also avoid overstating the performance of optimisation models in complex road networks and cold chain operations.

8. SUMMARY

Cold-chain logistics distribution in the real road network needs to coordinate perishable products, temperature-control requirements and fluctuating traffic conditions. Dynamic Vehicle Routing Problems provide a good case study for the above problems, and their characteristics include time-varying conditions, real-time information and flexible decision rules.

The literature on VRP, dynamic VRP and cold-chain routing shows that many modelling tools are available for representing perishable product distribution, multi-compartment vehicles and multi-objective trade-offs. At the same time, the model should also meet the operating demands in practice, be supported by monitoring and communication technology, and consider organisational factors.

Given that dynamic VRP is being used, the application of cold-chain distribution in real road networks will require both technical and managerial support. Dynamic Routing Models can enhance performance, but they need to be combined with other measures for quality assurance, customer service and sustainability. Dynamic VRP is only a conceptual system at present and has not been realised as an independent solution for real-world application in cold chain logistics routing.

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