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Algorithm and Application in Vehicle Routing Problem: A Review

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Abstract: This paper systematically reviews the latest research developments in Vehicle Routing Problems (VRP). It examines classical VRP models and their classifications across different dimensions, including load capacity, operational characteristics, optimization objectives, vehicle types, and time constraints. Based on literature retrieval results from the Web of Science database, the paper analyzes the current state and trends in VRP research, providing detailed explanations of VRP models and algorithms applied to various scenarios in recent years. Additionally, the article discusses limitations in existing research and provides perspectives on future development trends in VRP research. This review offers researchers in the VRP field a comprehensive overview while identifying future research directions.

Keywords: Vehicle routing problem; VRP; Delivery route optimization; Logistics planning

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1. Introduction

The Vehicle Routing Problem (VRP) has been a central challenge in operations research and logistics for over six decades, its origins tracing back to Dantzig and Ramser's seminal work in 1959 [1]. While the initial formulations focused on simple cost minimization, the explosive growth of e-commerce, urban logistics, and the increasing complexity of supply chains have transformed VRP into a far more multifaceted and critical area of study. No longer are we solely concerned with minimizing distance; modern VRPs demand the simultaneous optimization of multiple, often conflicting, objectives. These include considerations of time windows, diverse vehicle types and capacities, environmental impact (carbon emissions, fuel efficiency), dynamic demand fluctuations, real-time traffic conditions, and even fairness in workload distribution. The integration of big data analytics and advances in artificial intelligence further amplify both the opportunities and challenges inherent in contemporary VRP research [2].

This review critically examines the evolution of VRP research, offering a seasoned perspective on both its theoretical advancements and practical implementations. We will analyze the diverse classifications of VRP models based on load capacity, operational characteristics, objective functions, vehicle heterogeneity, time constraints, and other crucial factors. Drawing on extensive literature analysis, including a review of recent publications from the Web of Science database, we will highlight key breakthroughs in algorithm design and their application in diverse real-world settings. Furthermore, we will identify persistent challenges, limitations of current methodologies, and promising avenues for future research that are crucial to addressing the growing complexity and sophistication demanded by the modern logistics landscape. This paper aims to provide both established researchers and newcomers with a comprehensive and insightful understanding of the current state-of-the-art and future directions in VRP.

2. Vehicle routing problem

VRP, a cornerstone of operations research and transportation science, formally emerged in 1959 with Dantzig and Ramser's seminal work on optimizing fuel tanker routes. This initial formulation, focusing on minimizing transportation costs from a single depot to multiple delivery points, has since evolved dramatically. The problem's inherent complexity and its crucial role in optimizing logistics efficiency have spurred decades of research, leading to a rich landscape of VRP variants. These variants arise from incorporating a multitude of real-world constraints and objectives beyond simple cost minimization, reflecting the nuanced challenges faced in modern logistics and supply chain management. Understanding these variations, categorized along several key dimensions as detailed below, is essential for effective problem modeling and algorithm design. The classical VRP model describes a scenario where a single distribution center serves multiple user nodes, with the core objective of minimizing transportation costs through route optimization. As research has progressed, scholars have systematically categorized the VRP across various dimensions:

Table 1. Classification of VRP

Dimension	Classification	Description	Example
Load Capacity	Non-full load	Vehicles may not be fully loaded on each route	Delivering small packages across a city; not every vehicle is full
	Full load	Vehicles must be fully loaded before departure (or close to full)	Transporting large, bulky goods where each vehicle requires a full load
Operational Characteristics	Pure loading	Only loading operations at customer locations	Picking up goods from multiple suppliers
	Pure unloading	Only unloading operations at customer locations	Delivering goods to multiple customers from a central warehouse
	Mixed loading-unloading	Both loading and unloading operations occur at customer locations	Picking up goods from some locations and delivering to others
Optimization Objective	Single-objective	Minimizing a single objective (e.g., total distance, cost, time)	Minimizing the total travel distance for all vehicles
	Multi-objective	Optimizing multiple conflicting objectives (e.g., cost & time, cost & emissions)	Minimizing total cost while minimizing total delivery time and CO^2 emissions
Vehicle Homogeneity	Homogeneous vehicles	All vehicles have the same characteristics (capacity, speed, cost)	A fleet of identical delivery vans
	Heterogeneous vehicles	Vehicles have different characteristics (capacity, speed, cost)	A fleet with different sized trucks and vans

Table 1 (Continued)

Dimension	Classification	Description	Example
Time Constraint	With time windows	Deliveries must be made within specified time windows	Delivering perishable goods with strict delivery timeframes
	Without time windows	No time constraints on deliveries	Delivering non-perishable goods with flexible delivery times
Demand Divisibility	Split delivery	Demand at a customer can be split among multiple vehicles	Delivering a large order in multiple trips
	Non-split delivery	Demand at a customer must be fulfilled by a single vehicle	Delivering a furniture set that must be transported together
Priority Constraint	With priority restrictions	Some customers have higher priority than others	Delivering urgent medical supplies before regular orders
	Without priority restrictions	All customers have equal priority	Delivering standard packages to customers
Route Closure	Open routes	Vehicles do not need to return to the depot	A one-way delivery route where vehicles are left at the final delivery point
	Closed routes	Vehicles must return to the depot after completing their routes.	Standard delivery routes where vehicles return to the warehouse.

Notably, practical applications often require consideration of multiple constraint combinations, resulting in more complex VRP variants. These theoretical classifications provide an important conceptual framework for subsequent research while reflecting the rich connotations and research value of VRP problems.

3. Research progress in vehicle routing problem

A comprehensive literature search was conducted in the Web of Science (WOS) database using the keyword "Vehicle routing problem" for full-text articles. As of January 2025, a total of 10,154 papers were retrieved. According to the citation report provided by WOS, these papers have been cited 196,168 times, with an average citation frequency of 19.32 times per paper. **Figure 1** shows the number of papers published and their corresponding citations from 2015 to January 2025. It is evident that since 2015, the quantity of VRP-related academic achievements has steadily increased with a rapid growth rate, while the number of citations has also shown year-on-year growth.

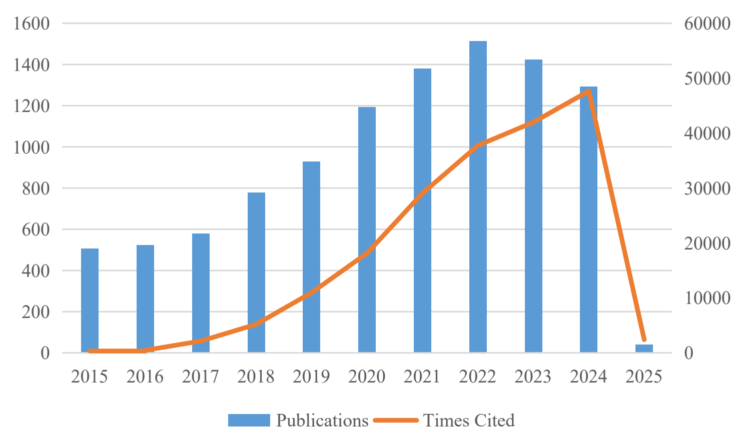

Figure 1. Number of papers and corresponding citation counts from 2015 to 2025

Based on **Figure 2**, through reviewing the relevant literature, we have observed that VRP problems have increasingly attracted attention from researchers in the computer science field, beyond the traditional domains of operations research and transportation. This paper systematically reviews the major research achievements in recent years from two aspects: VRP applications and model algorithm research.

Figure 2. Number of VRP-related papers in various research fields

3.1. Applications

The applications of VRP are expanding rapidly, driven by the increasing complexity of modern logistics and the availability of advanced computational tools. The following examples, drawn from recent literature, highlight both the breadth of VRP applications and the evolving sophistication of solution methodologies. However, it is essential to examine the limitations often present in reported findings critically. Many studies focus on specific scenarios, utilizing carefully selected datasets which may not fully capture the complexities of real-world operations. Furthermore, the benchmark problems often employed do not always provide a rigorous comparison across diverse algorithms and conditions. A more robust and standardized evaluation framework is crucial for future progress.

(1) Sustainable cold chain E-commerce fulfillment: Tsang *et al*. presented a noteworthy attempt to integrate order packaging optimization with vehicle routing in cold chain e-commerce [3]. Their JOSOPMDP model aims for sustainability by minimizing packaging materials. While addressing a significant contemporary issue, the model's real-world applicability hinges on the accuracy of its demand and packaging cost estimations, which are often challenging to obtain 1accurately.

(2) Medical waste transportation optimization: Anityasari *et al.* apply the Periodic Vehicle Routing Problem (PVRP) to medical waste collection in Surabaya [4]. Their work demonstrates the practical benefits of optimized routing for waste management. However, the generalizability of their findings to other contexts necessitates careful consideration of local infrastructure and regulations.

(3) Multi-objective time window VRP for E-commerce: Guo *et al.* utilize an improved Intelligent Water Drops algorithm for a Multi-objective Time Window Vehicle Routing Problem (MTWVRP) applied to

Suning.com's operations [5]. While showcasing algorithmic improvement, the study's reliance on a single case study limits the generalizability of performance claims. Robustness testing across a broader range of problem instances would strengthen these conclusions.

(4) Dynamic VRP for autonomous vehicles in agriculture: Andersen *et al.* tackle the challenging Dynamic Vehicle Routing Problem (DVRP) with dynamic nodes, focusing on autonomous vehicles in agriculture [6]. The findings on optimal detectability levels are valuable, but the context-specific nature of their problem demands careful consideration of transferability to other applications of DVRP.

(5) Capacitated VRP with fuzzy stochastic demand: Singh *et al.* addressed uncertainty in demand using fuzzy stochastic variables within a Capacitated Vehicle Routing Problem (CVRP) [7]. Their approach offers improved realism, yet the computational complexity of handling fuzzy uncertainty needs further investigation for larger-scale real-world applications.

(6) VRP with constraints in car-sharing: Feng and Xiao developed a Vehicle Routing Problem with Constraints (VRPC) for car-sharing, focusing on minimizing operational costs and maximizing user experience [8]. Their hybrid algorithm demonstrates improvement but lacks extensive comparative analysis against a wider range of state-of-the-art algorithms.

(7) Cold chain logistics VRP with travel time prediction: Bai *et al.* integrates data fusion technology for travel time prediction into a cold chain logistics VRP [9]. The use of real-time traffic data is a significant advance, yet the accuracy and robustness of the prediction model in diverse traffic conditions require further validation.

(8) Low-carbon VRP with time windows: Lou *et al.* incorporated carbon emission considerations into a VRP with time windows [10]. The inclusion of high-granularity time-dependent speeds is commendable, but the computational burden associated with high resolution needs further analysis, especially for large-scale deployments.

(9) Electric vehicle-drone coordinated delivery: Ma *et al.* address the novel challenge of coordinated delivery using electric vehicles and drones, considering carbon emissions [11]. This work highlights the growing interest in integrating different transportation modes, however, the practicality of this integrated approach depends on various operational factors, including drone regulations, infrastructure, and battery technology advancements, warranting further investigation.

In conclusion, while these studies offer valuable insights into diverse VRP applications, a critical assessment reveals a need for more rigorous validation methodologies, broader comparative analyses, and a deeper understanding of the limitations inherent in transferring research findings to practical implementation. Future research should prioritize the development of robust, generalizable solutions that address the full spectrum of real-world complexities.

3.2. Model algorithm research

This section reviews recent advancements in model algorithms for solving various VRPs. The research highlights the application of metaheuristics, including hybrid approaches that combine the strengths of different optimization techniques. Specific algorithms discussed include Improved Multi-directional Local Search (IMDLS), Student Psychology-Based Optimization combined with Ant Colony Optimization (SPBO-ACO), Dynamic Population Island Genetic Algorithm with Hybrid Genetic Search (DPIGA-HGS), and an Improved hybrid Fish-Ant Colony Optimization algorithm (IFACO). Additionally, the development of standardized validation methodologies for algorithm comparison is examined.

Feng *et al.* established the VRPTWRB model and conducted numerical studies on the rational selection of workload resources and fairness functions [12]. An Improved Multi-directional Local Search (IMDLS) algorithm was proposed to solve the model and approximate the Pareto frontier. The IMDLS algorithm restricts the archive size and adaptively determines the number of current solutions and search directions. Experimental results demonstrated that when considering time window constraints, using duration to evaluate workload resources is more appropriate than using distance; more sophisticated fairness functions can effectively identify high-quality non-dominated solutions with good fairness. The IMDLS algorithm outperformed existing multi-directional local search algorithms in terms of both efficiency and solution quality.

Li *et al.* proposed an integrated route planning method for autonomous vehicle delivery systems to improve the efficiency of urban "last-mile" delivery [13]. Experimental results demonstrated that this method significantly improved delivery efficiency and reduced total travel distance and time in real urban delivery scenarios.

Wei *et al.* introduced a hybrid metaheuristic algorithm (SPBO-ACO) combining Student Psychology-Based Optimization and Ant Colony Optimization for solving the Multi-Depot Vehicle Routing Problem with Time Windows for Electric Vehicles (MDVRPTW-EV) [14]. The algorithm integrates ACO's global search capability with SPBO's local search efficiency, employing strategies such as path length classification, strong-weak perturbation, and learning operators to enhance search efficiency and solution quality. Results demonstrated that the algorithm exhibits high scalability and stability and significantly reduced travel distances of electric loaders in industrial applications, proving its practicality.

Rezaei *et al.* proposed a novel hybrid metaheuristic algorithm called Dynamic Population Island Genetic Algorithm with Hybrid Genetic Search (DPIGA-HGS), combining the advantages of Dynamic Population Island Genetic Algorithm (DPIGA) and improved Hybrid Genetic Search (HGS) to solve the Capacitated Vehicle Routing Problem (CVRP) [15]. DPIGA is a specialized variant of island genetic algorithms that allows islands to lose their populations over time. Experimental results demonstrated that DPIGA-HGS outperformed existing state-of-the-art algorithms on multiple benchmark instances (including Uchoa, CMT, Golden, and LoggiBUD), achieving higher solution quality, finding more Best Known Solutions (BKS), and reducing both average and maximum solution gaps compared to BKS. The paper also included parameter tuning and analysis of the impact of the proposed multi-step restart mechanism.

Jastrzab *et al.* introduced a standardized validation methodology for vehicle routing algorithms, addressing the lack of unified and widely adopted algorithm validation methods in existing research [16]. The methodology consists of three main modules: a benchmark generator, a solver, and a post-processing module. The paper demonstrated the flexibility and effectiveness of this approach through experiments on the NP-hard Pickup and Delivery Problem with Time Windows (PDPTW), providing comprehensive performance comparison and analysis of different algorithms.

Hosseini *et al.* investigated the Green Cold Vehicle Routing Problem (GC-VRP), considering traffic congestion and variable speed. The author proposed a mixed-integer nonlinear programming model that incorporates variable vehicle speeds and the impact of traffic congestion during different time periods on travel times and fuel consumption [17]. A hybrid solution method combining Benders decomposition and Binary Particle Swarm Optimization (BPSO) algorithm was developed. Finally, numerical experiments and sensitivity analyses were conducted to validate the algorithm's effectiveness and the model's rationality.

Zhang *et al.* proposed an Improved hybrid Fish-Ant Colony Optimization algorithm (IFACO) to solve the

Vehicle Routing Problem with Time Windows (VRPTW) [18]. The algorithm integrates Artificial Fish Swarm Algorithm (AFSA) with Ant Colony Optimization (ACO). The paper designed three neighborhood search strategies (2-opt exchange, crossover, and insertion) to further enhance solution quality. Experimental results demonstrated that IFACO possesses strong search capabilities and good convergence when solving VRPTW problems of different scales, effectively avoiding local optima while outperforming several existing algorithms in terms of solution accuracy and efficiency.

Several studies employ metaheuristic algorithms to tackle the complexities of VRPs. Genetic algorithms (GAs) remain a popular choice, as demonstrated by Rezaei *et al.* DPIGA-HGS algorithm, which incorporates a dynamic population island strategy and hybrid genetic search to improve solution quality and efficiency on benchmark instances. Lou *et al.* combine a Hybrid Genetic Algorithm with Adaptive Variable Neighborhood Search (HGA-AVNS) to address the VRP with time windows and carbon emission considerations. Ant Colony Optimization (ACO), known for its exploration capabilities, is utilized in Wei *et al.* SPBO-ACO hybrid algorithm, which incorporates Student Psychology-Based Optimization to enhance local search. The comparative effectiveness of these and other GA-based approaches should be investigated further using standardized benchmarks (as suggested by Jastrzab *et al.*).

4. Academic perspectives and personal analysis

The academic research on VRP primarily diverges into two main directions: practical application studies and model-algorithm research. One group of scholars emphasizes the importance of fundamental theory, arguing that VRP requires more solid theoretical support through the enhancement of mathematical models and algorithmic research. Another group of researchers focuses more on the feasibility and applicability of algorithms in real-world scenarios, advocating for the development of customized solutions that address practical needs.

In this analysis, the integration of theoretical model innovation and practical application is crucial for VRP research. On one hand, theoretical research needs to propose more efficient algorithms for complex scenarios (such as multi-objective, multi-constraint problems). On the other hand, the true value of VRP research can only be realized by combining industry requirements to design routing planning solutions that feature both robustness and real-time capabilities.

Overall, vehicle routing problem research shows a trend toward closer alignment with practical applications, adoption of more sophisticated modeling approaches, and development of more efficient algorithms. This development emphasizes both theoretical innovation and practical value, providing strong support for modern logistics management.

5. Existing challenges

Despite extensive research and numerous algorithms developed for Vehicle Routing Problems, several challenges remain unresolved. Firstly, existing studies often take an overly idealistic approach, primarily emphasizing single objectives such as cost minimization and route length optimization while neglecting conflicts between customer satisfaction and cost minimization. These conflicts arise from real-world factors such as travel delays and varying customer demands. Secondly, while research on single-constraint VRP is relatively mature, its application scope is limited, constraining practical implementation. Lastly, widely used heuristic algorithms generally suffer from limitations such as insufficient local search capabilities, slow convergence rates, and susceptibility to local optima, which restrict their effectiveness in solving complex VRP problems.

6. Future development trends

Based on ongoing technological advancements and evolving demands, this paper identifies the following trends in VRP research:

(1) Dynamic and real-time optimization: Future research will increasingly focus on routing problems in dynamically changing scenarios, such as real-time traffic conditions and order modifications. The development of real-time optimization algorithms, leveraging big data and Internet of Things technologies, will become a dominant trend.

(2) Intelligence and automation: Artificial intelligence, particularly deep learning and reinforcement learning, will play an increasingly crucial role in VRP. Intelligent algorithms, by simulating human decision-making processes, can plan routes more efficiently in large-scale complex networks.

(3) Green solutions and sustainable development: Against the backdrop of growing global environmental concerns, research will increasingly focus on green delivery problems, including electric vehicle route optimization and carbon emission reduction.

(4) Interdisciplinary research: VRP research will integrate with fields such as biology and sociology, for example, designing new algorithms through biological evolution simulation or optimizing distribution network structures through social network analysis.

7. Conclusion

This paper reviews the current state and development trends of VRP. Some researchers have achieved notable progress in model development and algorithm applications, while others have made significant contributions to theoretical framework construction and practical implementations. Looking ahead, VRP research will evolve towards dynamic optimization, intelligence, sustainability, and interdisciplinary integration. It is recommended that researchers, while exploring new algorithms, should emphasize their practical application potential to provide more scientific support for logistics transportation and urban development.

Disclosure statement

The author declares no conflict of interest.

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