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A review on the electric vehicle routing problem and its variations

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Abstract: *As an important extension of the traditional Vehicle Routing Problem (VRP), the Electric Vehicle Routing Problem (EVRP) has attracted much attention of scholars. In this paper, we systematically summarize the literature on EVRP at home and abroad, and provide a detailed summary of the research on EVRP considering time windows, different recharging options and capacitated stations. Then, a variety of solving methods are introduced, including exact methods and heuristic methods. Finally, this study also provides some prospects for the future development trends of EVRP.*

Keywords: *Electric vehicle Routing, Time windows, Recharging technologies, Capacitated stations, Solving algorithm*

1. Introduction

In recent years, with the rapid development of the economy, the consumption of fossil energy has also increased rapidly, resulting in increasingly prominent issues such as the destruction of the natural environment, energy demand gap and global warming. The realization of "carbon neutrality" development has become very urgent. The Paris Agreement reached in 2015 requires all contracting parties to enhance their ability to respond to climate change, especially to reduce greenhouse gas emissions generated by human activities. In September 2020, China proposed the goal of "striving to reach the peak of carbon dioxide emissions before 2030 and striving to achieve carbon neutrality before 2060". The "14th Five-Year Plan" also proposed to reduce urban energy consumption and accelerate the promotion of green and low-carbon development under the "dual-carbon" strategy goal. According to data from the United Nations Environment Programme, greenhouse gas emissions from sea, land, and air transportation account for about 14% of the total global emissions, with land transportation being the main source, accounting for about 10%. However, due to the sustained growth in passenger and freight volume, carbon emissions from transportation still maintain a strong upward trend. Therefore, promoting the use of new energy vehicles to reduce reliance on fossil fuels is an inevitable way to reduce greenhouse gas emissions. Among them, pure electric vehicles can achieve true zero emissions through renewable energy generation technologies such as wind, water and solar power, which has gradually attracted the attention of governments, energy companies, and automobile manufacturers around the world.

As electric vehicles are widely put into use in realistic logistics and transportation scenarios, research on Electric Vehicle Routing Problem (EVRP) and its extensions have been gradually enriched. The EVRP is a variant of the classic Vehicle Routing Problem (VRP) that considers the limited range of electric vehicles and the availability of charging stations. The objective is to find optimal routes for electric vehicles to service a set of customers while minimizing the total distance traveled and the charging time. This literature review will summarize the current research on EVRP from three aspects: Electric Vehicle Routing Problem with Time Windows, Electric Vehicle Routing Problem with Multiple Recharging Options and Electric Vehicle Routing Problem with Capacitated Stations.

2. Electric Vehicle Routing Problem with Time Windows

EVRP was originally proposed as Green Vehicle Routing Problem (GVRP) by Erdoğan and Miller-Hooks [1], who assumed a single-fleet of hybrid electric vehicles that could replenish energy through refueling or recharging during their journey. The conventional charging station distribution proposed in this study has practical significance, but assuming a fixed charging time has some deviation from reality. Schneider et al. [2] extended GVRP to EVRP with time windows, establishing a path optimization model that simultaneously considers time windows, cargo volume constraints, and charging during travel. They

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assumed that the charging time is a linear function of energy consumption, rather than a fixed constant, and designed a hybrid algorithm combining variable neighborhood search and taboo search to solve the problem. Goeke and Schneider [3] studied the effect of driving distance, vehicle speed, and load on battery consumption and constructed an EVRP model with nonlinear discharge and time windows. This model is more in line with actual vehicle power consumption and was solved using an adaptive large neighborhood search algorithm with local search. Hiermann et al. [4] allowed vehicles to be fully charged multiple times, establishing a mixed-fleet EVRP model with time windows. They used a branch-and-price algorithm to solve small-scale examples and designed a hybrid heuristic algorithm combining local search and labeling method to solve large-scale examples. Schiffer and Walther [5] combined route optimization and location selection while considering partial charging strategies. They constructed a synchronous decision-making model for electric vehicle routing problem with time windows and charging station location problem.

Montoya et al. [6] first introduced a nonlinear charging function into EVRP and designed a hybrid heuristic algorithm to solve the problem. This study showed that ignoring nonlinear charging may result in higher costs or infeasible solutions. Subsequently, Froger et al. [7] constructed two new mixed-integer linear programming models for the problem proposed by Montoya, namely, arc-based and path-based models. They also designed an exact labeling algorithm to find the best charging decision for a given path. In addition, Pelletier et al. [8] introduced an uncertain energy consumption model into EVRP and assumed that vehicles only could be charged at the warehouse, not during the journey. To solve large-scale problems, they designed a two-stage heuristic algorithm. Zang et al. [9] compared the effects of different battery depreciation methods on EVRP with time windows, mainly studying nonlinear depreciation functions based on discharge depth, and developed a column generation algorithm that depends on a specific labeling method for solving the problem. Wang et al. [10] referred to the actual transportation scenario and proposed a multi-vehicle type and multi-cycle EVRP with time windows. They constructed a path-based mathematical model to solve small-scale instances and designed a hybrid heuristic algorithm combining variable neighborhood search and labeling method to solve large-scale instances.

3. Electric Vehicle Routing Problem with Multiple Recharging Options

Against the backdrop of rapid development in battery technology and gradual improvement in charging infrastructure, research on EVRP with multiple recharging options can better reflect the actual situation of energy replenishment for electric vehicles. Specifically, the recharging methods include battery swapping and plug-in charging. And plug-in charging can be categorized as fast or slow based on the charging speed, and as complete or partial based on the charging strategy. Felipe et al. [11] were the first to introduce multiple recharging technologies such as fast charging, slow charging, and partial charging strategy in EVRP. In addition to determining the travel route, this study also decided on the charging method and energy replenishment. Desaulniers et al. [12] considered four charging strategies in the EVRP with time windows and developed corresponding exact algorithms for solving the problem. The research results indicated that allowing charging multiple times and partial charging can help reduce distribution costs and the number of vehicles. Keskin and Çatay [13] proposed an EVRP with time windows that integrates three charging technologies (slow, fast, and super-fast) as well as partial charging strategy. They developed a hybrid algorithm that combines adaptive large neighborhood search algorithm and exact algorithm to solve the problem. Macrina et al. [14] allowed electric vehicles to be partially charged at any charging station and considered an energy consumption model based on speed, acceleration, slope, and vehicle load. They proposed a mixed fleet EVRP with time windows and corresponding large neighborhood search algorithm.

It is worth noting that battery swapping has become an important choice for energy replenishment of electric vehicles and a research hotspot in the field of route optimization. Yang and Sun [15] proposed a problem of electric vehicle routing and battery swapping station location, which considered the construction cost of swapping stations and the battery replacement cost for vehicles, and solved it through a four-stage heuristic algorithm. However, they only focused on battery replacement technology and did not comprehensively study multiple charging technologies. Verma et al. [16] proposed a variant of the EVRP with time windows, in which each station can provide both charging and swapping options. However, they assumed that electric vehicles must leave the charging station with a full battery, ignoring the more realistic scenario of partial charging. Mao et al. [17] simultaneously considered multiple charging technologies, swapping options, and partial charging strategies. They constructed a model of EVRP with time windows and developed an embedded insertion heuristic algorithm and a local search-based ant colony algorithm for this problem. Li et al. [18] studied battery- swappable electric vehicles, and comprehensively considered battery capacity and swapping station constraints. They developed a mixed integer programming model for EVRP and solved it using an adaptive genetic algorithm.

4. Electric Vehicle Routing Problem with Capacitated Stations

Most existing research assumes that each charging station has a sufficient number of chargers, thus electric vehicles can be charged upon arrival at the station. However, the number of chargers in the station is usually limited in reality, and it is likely that vehicles will queue up and wait for charging. To address this practical problem, a variant of EVRP is proposed which considers the capacity restriction of stations. Through the literature review, we found that only two studies have considered this aspect. Bruglieri et al. [19] set a limited number of refueling pumps in each alternative fuel station in GVRP, constructed two hybrid integer linear programming models based on arc and path, and improved an exact cutting-plane algorithm for solving them. Froger et al. [20] studied EVRP with nonlinear charging functions, multiple charging technologies, en-route charging, and partial charging while considering the capacity constraint of charging stations. They limited the number of electric vehicles that can be charged simultaneously at each charging station based on the number of chargers. In addition, Zhang et al. [21] analyzed the capacity constraint of charging stations from different perspectives and proposed a multi-period flow-based charging location problem for electric vehicles. They established an optimization model to help decide the location of stations and the number of chargers during different time periods.

5. Solving Methods of Electric Vehicle Routing Problem

5.1. Exact Methods

Exact methods require the establishment of a precise mathematical model and data structure based on the problem, followed by a solution using commercial solvers. The advantage of the exact method is that the solution obtained is a global optimum, but the disadvantage is that the algorithm has a higher complexity, and the solving time increases exponentially with the problem size. The mainstream for solving EVRP includes dynamic programming, Branch and Bound, etc.

5.1.1. Dynamic Programming

Dynamic programming [22] [23] is an algorithmic strategy for solving optimization problems by breaking down the problem instance into smaller, similar subproblems and storing the solutions to these subproblems to avoid redundant calculations. Essentially, it employs the divide-and-conquer approach and resolves redundancy. The implementation steps of dynamic programming are: first, divide the problem into several ordered or sortable stages based on the time or space characteristics of the problem. Then, use different states to represent the objective situation at each stage of the problem development, and the selection of the state should satisfy the property of no aftereffect. After that, keep the local solutions that may lead to the optimal solution and discard other local solutions through decision-making. Finally, solve the problems of each stage in sequence, and the solution of the last stage is the solution of the initial problem. Although methods such as relaxation process and feasibility rules can be introduced to reduce the state space, dynamic programming is still difficult to solve large-scale problems.

5.1.2. Branch and Bound

Branch and bound [24] [25] is a very important algorithmic approach in the field of integer programming and the origin of many mainstream algorithms [26]. The essence of this algorithm is still implicit enumeration, and its implementation steps are as follows: first construct a search tree for the solution space, and all solutions can be reached by traversing the search tree. Then construct the upper and lower bounds of the solution, with the upper bound generally being the previously obtained optimal solution and the lower bound being the optimal solution of the current search path without constraints. Then use backtracking to traverse the search tree and constantly update the upper and lower bounds. If the lower bound of the current solution has exceeded the upper bound, pruning is performed. Pruning can gradually narrow the range of solutions, and the solution obtained at the end of the traversal is the optimal solution. The branch and bound method has a high search efficiency, but a long iteration period, and it is difficult to model complex problems. Therefore, it is only suitable for small-scale vehicle routing problems.

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5.2. Heuristic methods

Heuristic method are approximate algorithms that can obtain optimal feasible solutions or satisfactory solutions within a reasonable time or a reasonable number of computations. The time complexity of such algorithms is much lower than that of exact methods, making them more feasible and effective in solving large-scale problems. Heuristic algorithms can be divided into traditional heuristic algorithms and modern heuristic algorithms. Traditional heuristic algorithms can quickly obtain satisfactory solutions through local search, but they are prone to getting stuck in local optima. Modern heuristic algorithms improve on traditional ones by adding randomized operators, including genetic algorithms, tabu search, etc.

5.2.1. Genetic Algorithms

Genetic algorithm [27] [28] is a random global search and optimization method developed from the biological evolution mechanism in nature. It simulates the phenomena of reproduction, hybridization, and mutation in natural selection and genetic processes. The implementation steps of this algorithm are as follows: first, initialize a population containing several individuals, each with a genome representing a feasible solution to the problem. Then, design a fitness function based on the characteristics of the problem and use it to calculate the fitness of each individual. Next, select individuals with better fitness to perform operations such as crossover and mutation to generate a new generation population. This process is repeated until a certain termination condition is met. The core of genetic algorithm lies in the design of crossover and mutation operators, and specific strategies for crossover and mutation need to be developed for different problems in order to maximize computational efficiency.

5.2.2. Tabu Search Algorithm

Tabu search algorithm [29] [30] uses the neighborhood selection method and is an extension of the local search algorithm. Traditional local search algorithms optimize the current solution by iteratively searching for better solutions in the neighborhood, which easily falls into local optima. Tabu search algorithm imitates the human memory function by using a tabu list to mark the already found local optimal solutions and the search process, then avoiding them in subsequent searches. The tabu list can avoid detours and is a key factor affecting the performance of the tabu search algorithm. Other factors that affect the performance include neighborhood, tabu tenure, candidate solutions, and aspiration criteria. Tabu search algorithm has fast convergence speed and high efficiency, but it depends heavily on the quality of the initial solution and its iterative process is based on a single solution rather than a population.

6. Conclusions

In order to alleviate the energy crisis and reduce air pollution, an increasing number of logistics companies are adopting electric vehicles for transportation. However, due to battery capacity limitations, electric vehicles often need to be charged or replaced batteries on the way to ensure smooth transportation services. Since 2012, the problem of electric vehicle routing has received widespread attention from the academic community. Scholars have combined the new features of electric vehicles with traditional vehicle routing problems to derive many variants, such as EVRP with time windows, EVRP with nonlinear charging functions, EVRP with partial charging strategy, EVRP with multiple charging options, EVRP with capacitated stations, etc. Finally, several exact and heuristic algorithms for solving EVRP were discussed, including dynamic programming, branch and bound, genetic algorithms, and tabu search algorithms.

Although we have seen important progress in EVRP research, there are still some limitations. Through a review of the literature, this paper summarizes possible directions for future EVRP research:

(1) Considering more factors that occur in actual situations, such as weather, traffic conditions and type of goods, and incorporating these factors into EVRP models for optimization.

(2) Considering collaboration between charging stations to optimize EVRP charging strategies, for example, through shared charging stations to replenish energy.

(3) Developing a more flexible routing model that allows electric vehicles to adjust their routes in real-time during transportation, thus responding to emergencies immediately.

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