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Partial recharge strategies for the electric vehicle routing problem with time windows

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ABSTRACT

The Electric Vehicle Routing Problem with Time Windows (EVRPTW) is an extension to the well-known Vehicle Routing Problem with Time Windows (VRPTW) where the fleet consists of electric vehicles (EVs). Since EVs have limited driving range due to their battery capacities they may need to visit recharging stations while servicing the customers along their route. The recharging may take place at any battery level and after the recharging the battery is assumed to be full. In this paper, we relax the full recharge restriction and allow partial recharging (EVRPTW-PR), which is more practical in the real world due to shorter recharging duration. We formulate this problem as a 0–1 mixed integer linear program and develop an Adaptive Large Neighborhood Search (ALNS) algorithm to solve it efficiently. We apply several removal and insertion mechanisms by selecting them dynamically and adaptively based on their past performances, including new mechanisms specifically designed for EVRPTW and EVRPTW-PR. These new mechanisms include the removal of the stations independently or along with the preceding or succeeding customers and the insertion of the stations with determining the charge amount based on the recharging decisions. We test the performance of ALNS by using benchmark instances from the recent literature. The computational results show that the proposed method is effective in finding high quality solutions and the partial recharging option may significantly improve the routing decisions.

1. Introduction

Electric vehicles (EVs) move with electric propulsion and can be used in a variety of transport needs such as public transportation, home deliveries from grocery stores, postal deliveries and courier services, and distribution operations in different sectors. Although EVs enable zero- or low-emission logistics services, operating an EV fleet has several drawbacks such as: (i) low energy density of batteries compared to the fuel of combustion engined vehicles; (ii) limited number of public charging stations; and (iii) long recharging times (Touati-Moungla and Jost, 2012). Battery swap may remedy the last; however, swapping raises additional issues in battery design and compatibility, battery degradation, ownership, and swap station infrastructure. Under these limitations, routing an EV fleet arises as a challenging combinatorial optimization problem in the Vehicle Routing Problem (VRP) literature.

The Electric Vehicle Routing Problem with Time Windows (EVRPTW) was introduced by Schneider et al. (2014) as an extension to the Green Vehicle Routing Problem (GVRP) of Erdoğan and Miller-Hooks (2012). GVRP concerns "green"

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vehicles which run with biodiesel, liquid natural gas, or CNG, and have a limited driving range. Hence, the vehicles may need refueling along their route. Refueling is fast; however, the stations for these fuels are scarce. EVRPTW is a variant of the classical VRPTW where the fleet consists of EVs that may need to visit stations to have their batteries recharged in order to continue their route, as in GVRP. On the other hand, the recharging operation may take a significant amount of time, especially when compared to relatively short refueling times of liquid fuels. Recharging may take place at any battery level and the recharge time is proportional to the amount charged. After the recharge the battery is assumed to be full. The number of stations is usually small and the stations are dispersed in distant locations, which increases the difficulty of the problem. In this paper, we relax the full recharging (FR) restriction and allow partial recharging (PR) which is more practical in the real world due to shorter recharging duration. When the vehicle visits a station near the end of its route, FR may not be needed for the vehicle to return to the depot. A similar situation may exist between two consecutive recharges. Saving from recharging time may allow the vehicle to catch the time window of an otherwise unvisited customer, thus, may improve the solution.

In the PR scheme, the recharge quantity is associated with a continuous decision variable. We refer to this problem as EVRPTW and Partial Recharges (EVRPTW-PR) and formulate it as 0–1 mixed integer linear program. Note that determining the recharge quantities brings significant difficulties to the problem. Since the problem is intractable for large instances, we propose an Adaptive Large Neighborhood Search (ALNS) approach to solve it efficiently. ALNS is based on the destroy-and-repair framework where at each iteration the existing feasible solution is destroyed by removing some customers and recharging stations from their routes and then repaired by inserting the removed customers to the solution along with stations when recharging is necessary. Several removal and insertion algorithms are applied by selecting them dynamically and adaptively based on their past performances**.** The new solution is accepted according to the Simulated Annealing criterion. Our approach combines the removal and insertion mechanisms presented in Ropke and Pisinger (2006a, 2006b), Pisinger and Ropke (2007) and Demir et al. (2012) with some new mechanisms designed specifically for EVRPTW and EVRPTW-PR. Our computational tests show that the proposed ALNS is effective in finding good quality solutions and improves some of the best-known solutions in the literature. Furthermore, our results reveal that the PR scheme may substantially improve the routing decisions.

The contributions of this study can be summarized as follows:

- We extend EVRPTW to a PR scheme, which is more general and practical, and present the mathematical programming formulation of the problem.
- We propose an effective ALNS method to solve the EVRPTW and EVRPTW-PR. The proposed method introduces new removal and insertion mechanisms to tackle the more complex problem structure of VRPs where the fleet consists of EVs.
- We validate the performance of the proposed method using the EVRPTW instances of Schneider et al. (2014) and improve the best-known solutions of four problems.
- We show that the PR scheme may improve the solutions obtained with the FR scheme substantially.

The remainder of the paper is organized as follows: Section 2 reviews the related studies in the literature. Section 3 describes the problem and formulates the mathematical model. The proposed ALNS method is presented in Section 4. Section 5 provides the computational study and discusses the results. Finally, concluding remarks and future research directions are given in Section 6.

2. Related literature

There are relatively few studies on route optimization of AFVs. Artmeier et al. (2010) studied this problem within a graph-theoretic context and proposes extensions to general shortest path algorithms that address the problem of energy-optimal routing. They formalize energy-efficient routing in the presence of rechargeable batteries as a special case of the constrained shortest path problem and present an adaption of a general shortest path algorithm that respects the given constraints. Wang and Shen (2007) developed a model that minimizes the number of tours and total deadhead time hierarchically. The driving range of the vehicle is limited but the charging durations, time windows and vehicle capacities are not considered. A multiple ant colony algorithm was proposed to solve the problem.

Conrad and Figliozzi (2011) introduced the Recharging VRP (RVRP), a new variant of the VRP where the EVs are allowed to recharge at selected customer locations. The model has dual objectives: the primary objective minimizes the number of routes or vehicles whereas the secondary objective minimizes the total costs associated with the travel distance, service time and vehicle recharging. The latter is a penalty cost incurred at each recharge. The EV is charged while servicing the customer and the charging time is constant. The battery level departing from a customer depends on the choice of full charge or partial charging. In the partial charge case the battery is charged to a specified level such as 80% of battery capacity. Conrad and Figliozzi (2011) used an iterative construction and improvement procedure to solve this problem but did not provide its details.

Wang and Cheu (2012) investigated the operations of an electric taxi fleet. Their model minimizes total distance traveled under the recharging constraints and maximum route time. The battery is consumed at a given rate per distance and can be replenished at the recharging stations. Charging times are constant and after charging the battery becomes full. They con-

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