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The green vehicle routing problem: A heuristic based exact solution approach

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ABSTRACT

This paper develops a simulated annealing heuristic based exact solution approach to solve the green vehicle routing problem (G-VRP) which extends the classical vehicle routing problem by considering a limited driving range of vehicles in conjunction with limited refueling infrastructure. The problem particularly arises for companies and agencies that employ a fleet of alternative energy powered vehicles on transportation systems for urban areas or for goods distribution. Exact algorithm is based on the branch-and-cut algorithm which combines several valid inequalities derived from the literature to improve lower bounds and introduces a heuristic algorithm based on simulated annealing to obtain upper bounds. Solution approach is evaluated in terms of the number of test instances solved to optimality, bound quality and computation time to reach the best solution of the various test problems. Computational results show that 22 of 40 instances with 20 customers can be solved optimally within reasonable computation time.

1. Introduction

Today's competitive economic environment requires strategic and operational decisions for companies in order to optimize and manage their logistic processes more efficiently. One of the most important operational decision concerns the design of vehicle routes since it offers great potential to reduce the costs and to improve the service quality.

The classical vehicle routing problem (VRP) aims at routing a fleet of vehicles on a given network to serve a set of customers under specified supply and demand related constraints. Minimizing the total distance traveled by all vehicles or minimizing the overall travel cost are the typical objectives of the VRP and usually the cost is computed as a linear function of distance. Since its introduction by Dantzig and Ramser [1], the VRP and its variants have been studied extensively by researchers. Many heuristics have been developed in recent years for several variants of the VRP (see [2–5]). For a recent coverage of the state-of-the-art models and solution algorithms, the reader is referred to the survey by Cordeau et al. [6], Golden et al. [7] and Laporte [8], and to the books by Golden et al. [7] and Toth and Vigo [9].

The classical VRP assumes that the vehicle fuel tank capacity is unlimited and the fuel amount in the tank is always sufficient to serve all customers in any possible route. However, in real-life, vehicles need to refuel their tanks to continue and complete their tour. This situation is frequently encountered in the case of companies or agencies having alternative energy powered fleets (i.e., natural gas, electricity, ethanol) in which routes have to be planned taking additional difficulties associated with the limited refueling infrastructure into account. The alternative energy powered fleet operations (or more generally green logistics concept) have emerged as one of the latest extensions of the VRP literature in recent years. For example, many studies suggest that there are several opportunities for reducing carbon dioxide (CO_2) emissions by extending the traditional VRP objectives to account for wider environmental and social impacts rather than just economic costs [10–12]. These studies are motivated by the activities of the transportation industry which has significant negative impacts on the environment, economy and human health. These impacts include increased resource consumption, toxic effects on ecosystems and humans, increased air and noise pollution, and also the climatic effects induced by greenhouse gas (GHG) emissions. GHG and in particular CO_2 emissions are the most concerning ones as they have direct effects on human health, e.g., pollution, and indirect ones, e.g., climate change. Growing concerns about such hazardous effects of transportation on the environment call for revised planning approaches to road transportation by explicitly accounting for

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such negative impacts. Juan et al. [13] studied the fleet size and mix vehicle routing problem with multiple driving ranges in which the total distance that each vehicle type can travel is limited. This problem arises in the routing of electric and hybrid-electric vehicles which can only travel limited distances due to the limited capacity of their batteries. A mathematical model is formulated and a multi-round heuristic is developed. The method is based on a biased randomized algorithm which can be used alone to create alternative fleet choices whenever the feasibility of the prespecified fleet configuration is not guaranteed. A set of benchmark instances were created to analyze how distance-based costs increase when considering "greener" fleet configurations. The method performed well on all benchmark instances and many different alternative solutions offer competitive distance-based costs while using fewer long- or medium-range vehicles than normally required. More recently, Koç et al. [14] studied the fleet size and mix pollution-routing problem where the objective is a linear combination of vehicle, fixed cost, fuel cost and CO_2 emissions, and driver cost. The authors formally defined the problem, presented a mathematical model and developed a hybrid evolutionary metaheuristic. For a further coverage of green issues at the operational level the reader is referred to the book chapter of Eglese and Bektaş [15] and to the surveys of Demir et al. [16] and Lin et al. [17].

Erdogan and Miller-Hooks [18] introduced the green vehicle routing problem (G-VRP). The problem design least-cost delivery routes from a depot to a set of geographically scattered customers within a pre-specified time limit and without exceeding the vehicle's driving range that depends on fuel tank capacity to minimize the total distance traveled and/or total cost. In the G-VRP, vehicles have limited fuel tank capacity and are allowed to refuel when needed. The vehicles may be refueled at a limited number of fuel stations (FSs) which are available in the service area and at the depot node. In practice, the G-VRP is encountered, particularly, when the vehicle fleet includes the alternative fuel vehicles (AFVs). The authors proposed a mathematical formulation, and developed two construction heuristics; the Modified Clarke and Wright Savings heuristic and the density-based clustering algorithm, and a customized improvement technique.

Another problem that is closely related to the G-VRP is the VRP with satellite facilities (VRP-SF) in which replenishment of a vehicle is allowed from another facility different from the depot. Bard et al. [19] have formulated the VRP-SF as a mixed integer programming (MIP) formulation with capacity and tour duration limitation constraints. Vehicles with capacity limitations have the option to stop at satellite facilities to reload in order to serve customer demand at the nodes. In their formulation, dummy nodes are introduced to represent multiple stops at intermediate depots for reloading vehicles with goods for delivery process. The authors have also developed an exact solution procedure (B&C algorithm) for solving VRP-SF to optimality. Regarding the complexity of the problem, different heuristic/meta-heuristic approaches have been also proposed to solve larger VRP-SF instances [20–22].

Frade et al. [23] studied the location of electric-vehicle charging stations in the city of Lisbon. The authors used a maximal covering model, and the aim to minimize the level of service and the number of charging stations. Chen et al. [24] later studied the electric vehicle charging stations location problem where a parking-based assignment method is presented for the city of Seattle. Nie and Ghamami [25] developed a conceptual optimization model to investigate travel of electric vehicles along a long corridor. Cavadas et al. [26] later described a method to locate the electric charging stations in the city of Coimbra where the aim is to maximize the number of electric vehicles under a fixed budget for building the stations. More recently, Schneider et al. [27] introduced an extended version of the G-VRP by considering an electric vehicle fleet with time windows, recharging at stations and limited vehicle load capacity. The authors formulated the electric vehicle routing problem with time windows and recharging stations (E-VRPTW) as a MIP and employed a hybrid heuristic solution procedure that combines a variable neighborhood search algorithm with a Tabu Search heuristic. The authors have also improved the MIP formulation of Erdogan and Miller-Hooks [18] and used it to solve the set of small G-VRP benchmark instances with CPLEX. The algorithm is tested on a benchmark instances derived from the literature and on a newly generated benchmark instances. The results have shown that the proposed heuristic performed well and the hybridization mechanism had positive impacts on the solution quality. Schneider et al. [28] later studied the vehicle routing problems with intermediate stops (VRP-IS) in which stopping requirements at intermediate facilities may include replenishment/disposal and refueling/recharging stops. The authors have developed an adaptive variable neighborhood search algorithm to solve the VRP-IS instances. The algorithm is tested on several related VRP instances (G-VRP, E-VRPTW, etc.) in the literature and on the new benchmark instances. The authors reported that the proposed algorithm shows a satisfactory performance compared to the methods from the literature and is able to obtain numerous new best solutions. Felipe et al. [29] proposed constructive and local search heuristics within a simulated annealing framework to solve a variant of the G-VRP which considers multiple technologies and partial recharges. The authors tested their solution method on a newly generated benchmark instances, which indicate the efficiency of the algorithm.

This brief review shows that only several heuristic algorithms have already solved the G-VRP, which does not guarantee the optimality. We believe there exists merit for the development of a new solution approach based on simulated annealing heuristic and branch-and-cut (B&C) algorithm, which is capable of optimally solving the G-VRP. This is the main motivation of this paper. The contributions of this paper are as follows: we introduce an efficient and powerful new solution approach to solve the G-VRP. We develop a new mathematical formulation having fewer variable and constraints without network augmentation, and adapts a set of valid inequalities to strengthen the linear programming relaxation of the formulation. We propose a simulated annealing heuristic to improve initial solution and upper bounds found during the search process of the solution approach.

The rest of this paper is organized as follows. The problem description and a brief review of the literature are given in Section 2. Section 2.1 shows the formulation of Erdogan and Miller-Hooks [18]. Section 2.2 presents the proposed mixed integer programming formulation, and subsequently Section 3 introduces valid inequalities. The proposed solution approach is described in Section 4. Finally, Section 5 presents the result of computational experiment results, followed by conclusions in Section 6.

2. Problem definition and formulations

The G-VRP is defined on a complete directed graph $G=(N, A)$, where $N=\text{"0"} \cup N_c \cup F$ is the set of nodes, "0" corresponds to the depot, $N_c=\{n_1, n_2, \ldots, n_c\}$ is the customer nodes, $F=\{n_{c+1}, n_{c+2}, \ldots, n_{c+s}\}$ is the fuel stations, and $A=\{(n_i, n_j): n_i, n_j, \in N\}$ is the set of arcs that connect nodes in N. An unlimited number of homogeneous vehicle fleet is available at the depot to serve customers with fuel tank capacity Q (gallons) and fuel consumption rate r (gallons per mile). Each vehicle travels on the graph with constant speed sp (miles per hour). Each arc $(n_i, n_j) \in A$ is associated with a nonnegative distance d_{ij}, travel time t_{ij} associated with distance ($t_{ij}=d_{ij}/\text{sp}$) and also the triangular inequality holds ($d_{ij}+d_{jk} \geq d_{ik}$). Note that our formulation is also valid when the triangular inequality does not hold. Each node is associated with a service time p_i, which represents the service

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