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A Vehicle Routing Problem with Flexible Time Windows

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ABSTRACT

In this paper, we introduce the Vehicle Routing Problem with Flexible Time Windows (VRPFlexTW), in which vehicles are allowed to deviate from customer time windows by a given tolerance. This flexibility enables savings in the operational costs of carriers, since customers may be served before and after the earliest and latest time window bounds, respectively. However, as time window deviations are undesired from a customer service perspective, a penalty proportional to these deviations is accounted for in the objective function. We develop a solution procedure, in which feasible vehicle routes are constructed via a tabu search algorithm. Furthermore, we propose a linear programming model to handle the detailed scheduling of customer visits for given routes. We validate our solution procedure by a number of Vehicle Routing Problem with Time Windows (VRPTW) benchmark instances. We highlight the costs involved in integrating flexibility in time windows and underline the advantages of the VRPFlexTW, when compared to the VRPTW.

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1. Introduction

Carrier companies are faced with the daily challenge of delivering goods to customers in a cost-effective manner. Often, these companies must adhere to customer service requirements. In this environment, customer service requirements are mainly reflected by the Vehicle Routing Problem with Time Windows (VRPTW). This problem can be observed in bank deliveries, postal deliveries, and school bus routing (see Hashimoto et al. [19]). Given a set of customers, the VRPTW consists of finding least cost routes such that each customer is visited within a predetermined time window by a single vehicle. Furthermore, a vehicle must deliver a quantity not exceeding its capacity, the vehicle should also start and end its route at a given depot. The vehicle is permitted to arrive before the opening of the time window, and wait at no cost until service becomes possible, but it is not permitted to arrive after the time window closes (see Bräysy and Gendreau [4]).

The definition of the VRPTW implies that time windows are treated as hard constraints, the relaxation of which may lead to reducing the total distance traveled while using fewer vehicles. A form of time window relaxation is considered in the Vehicle Routing Problem with Soft Time Windows (VRPSTW). This problem assumes that some or all customer time windows are soft and can be violated by paying appropriate penalties (see Balakrishnan [1]). The penalty structure associated with soft time windows essentially allows serving a customer at any point of the planning horizon. This mechanism is due to the penalty policies, which dictate that early arriving vehicles must wait or incur a penalty, while any late arrival is permissible at a cost. Therefore, when compared to the VRPTW, the VRPSTW operates on a much larger feasible solution space.

In several real-world situations, time window constraints can be violated to a certain extent. Therefore, in this paper we aim to assess the operational gains obtained by employing a fixed relaxation of the time window constraints. Namely, we study the Vehicle Routing Problem with Flexible Time Windows (VRPFlexTW), in which vehicles are allowed to deviate from customer time windows by a given tolerance. This flexibility enables savings in the operational costs of carriers, since customers may be served before and after the earliest and latest time window bounds, respectively. As time window violations affect customers satisfaction, they are penalized. Furthermore, as in the VRPTW we allow early arriving vehicles to wait at no cost until the earliest allowable service time is reached. The VRPFlexTW is distinct from the VRPSTW in that the former considers a restriction on the feasible time window violation. Therefore, when compared to the VRPSTW, the VRPFlexTW operates on a smaller feasible solution space.

The main contributions of this paper are threefold:

1. We introduce and model the VRPFlexTW.
2. To produce high-quality solutions, we develop an effective solution procedure which comprises three phases: (i) initialization, (ii) improving, (iii) scheduling.
3. We conduct a series of numerical experiments on benchmark instances, and assess the operational gains of using flexible time windows.

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The remainder of this paper is organized as follows. The relevant literature is reviewed in Section 2. Section 3 introduces the model. The solution procedure is then described in Section 4. This is followed by computational results provided in Section 5 and by conclusions given in Section 6.

2. Literature review

The daily distribution task faced by many freight transports is captured by the Vehicle Routing Problem (VRP). In its classical definition, the VRP minimizes the total travel cost incurred by a set of homogeneous vehicles that deliver customer demands. Each customer is to be visited by a single vehicle, each vehicle starts and ends its route at a depot and delivers a quantity not exceeding its capacity. The VRP has been widely studied for over 50 years (see, e.g., Laporte [24]). In an attempt to better link the VRP to realistic applications, a number of extensions have been proposed in the literature (see, e.g., Toth and Vigo [32], and Golden et al. [18]). One of the most extensively studied variants of the VRP is the VRPTW, in which time windows ensure that each customer must be visited within a given interval. Over the years, a number of exact and heuristic solution procedures have been proposed for the VRPTW. Bräysy and Gendreau [4] review the literature on route construction and local search algorithms for the VRPTW. The authors also survey metaheuristics for the same problem (see Bräysy and Gendreau [5]). Baldacci et al. [3] provide a recent review of mathematical formulations, relaxations and exact methods for the VRPTW.

The VRPTW treats time windows as hard constraints. However, some practical applications imply that customer time windows can be treated as soft constraints, i.e., may be violated at a cost. This setting gives rise to the VRPSTW, which is significantly less studied than the VRPTW. The VRPSTW considers the existence of time windows, however it assumes that customers are available at any moment in time to receive their goods. Therefore, vehicles incur penalty costs for time window violations. As such, the VRPSTW is a special case of the VRPFlexTW, where the relaxation of time windows is unbounded, i.e., infinite flexible bounds. The majority of the literature on the VRPSTW considers a linear penalty function for time window deviations. Balakrishnan [1] develops three heuristics for the VRPSTW based on the nearest neighbor Clarke–Wright savings and space–time rules. Koskosidis et al. [23] propose a heuristic algorithm for the VRPSTW. Their algorithm decomposes the problem into an assignment component and a series of routing and scheduling components. Min [25] considers the VRPSTW for a single vehicle where the problem is solved for small-sized instances. Taillard et al. [30] propose a tabu search heuristic to solve the VRPSTW. Calvete et al. [6] consider a general medium-sized VRPSTW and propose a goal programming model. Aside from minimizing the operational cost and time window violations, the authors consider avoiding underutilization of vehicles and labor. The solution approach first computes feasible routes and then selects the set of best ones.

Ibaraki et al. [21] propose an efficient algorithm to deal with general time window constraints. The cost function considered for time window violations can be non-convex and discontinuous as long as it is piecewise linear. Furthermore, one or more time slots can be assigned to each customer. Building upon the model proposed in [21], Hashimoto et al. [19] define the travel time as a variable representing the difference between the starting times of services at two consecutive customers, and introduce its cost function.

A main difference of our model and those presented in the recent papers (e.g., Fagerholt [12], Chiang and Russell [7], Fu et al. [14], Figliozzi [13]) lies in the way of allowing time window violations. More specifically, our problem has a different structure in which vehicles are allowed to provide both early and late services with a penalty limit, and to wait in case of early arrival (until the enlarged lower bound) without any waiting time limit. Note that the most similar structure employed in [12] with a waiting time limit defined for the whole route (not separately for each customer) whereas the authors focus on a multi-ship pickup and delivery problem. Another algorithmic difference of our method between the recent algorithms is the application of a schedule optimization phase. In our paper, we apply a scheduling method in two ways: (i) as a last phase to improve the solution generated by the tabu search method and (ii) every iteration in the tabu search method as an improvement step. Moreover, we compare the computational results provided by our solution procedure for the classical VRPTW not only with the solutions obtained by the existing (meta)heuristic algorithms but also with the optimal/best-known solutions.

One of the underlying assumptions in VRPSTW is that the deviations from time windows are essentially unbounded, implying that any feasible VRP solution is feasible in the VRPSTW as well. The VRPFlexTW proposed in this paper bounds the lower and upper time window deviations, and hence allows a predetermined amount of flexibility in adhering to time windows. Qureshi et al. [26,27] develop a column generation based exact algorithm for the Vehicle Routing and scheduling Problem with Semi Soft Time Windows (VRPSSTW). This problem considers an upper bound on the tardiness time window deviation, and thus may be viewed as a special case of the VRPFlexTW. The solution approach is shown to be efficient on medium-sized instances. Tang et al. [31] study the VRP with fuzzy time windows where the authors consider the multi-objective problem of minimizing travel time and maximizing customer service level, similar to the VRPTW. The authors take into account a limited allowable deviation from time windows and solve their multi-objective model with a two-stage algorithm which yields Pareto solutions.

3. Model formulation

Formally, the VRPFlexTW can be represented by a connected digraph $G=(N,A)$ where $N=\{0,1,\ldots,n,n+1\}$ is the set of nodes and $A=\{(i,j)|i,j\in N, i\neq j\}$ is the set of arcs. Nodes 0 and $n+1$ correspond to the starting and ending nodes of each route, respectively (the central depot). Let $C=N\backslash\{0,n+1\}$ denote the set of customers. For each customer $i\in C$, we have a positive demand q_i, a time window $[l_i,u_i]$ and fractions p_i^l and p_i^u which are used to set the maximum allowed violations, leading to the flexible time window. The time window at the depot, $[l_0,u_0]$ (or equivalently $[l_{n+1},u_{n+1}]$), corresponds to the feasible scheduling horizon for each vehicle route. For each node i, a flexible time window $[l_i',u_i']$ is generated with respect to the length of the original time window, where $l_i'=l_i-p_i^l(u_i-l_i)$, and $u_i'=u_i+p_i^u(u_i-l_i)$. Additionally, Q represents the capacity given for each vehicle $v\in V$ where V denotes a homogeneous fleet.

Associated with each arc $(i,j)\in A$, t_{ij} and d_{ij} represent the travel time and the distance along that arc, respectively. Note that the service time at node i, z_i is included in t_{ij}. A fixed cost c_f is incurred for using a vehicle. Time window violations, i.e., serving a customer within $[l_i',l_i]$ or $[u_i,u_i']$ are penalized by c_e and c_d for one unit of earliness and one unit of delay, respectively. Moreover, c_t is the cost paid for one unit of distance. In the early servicing case, service at the customer starts between the flexible earliest time and the original earliest time. In the late servicing case, service takes place between the original latest time and the flexible latest time. Note that vehicles wait at customers (at least) until the flexible time window is reached if they arrive early, and they cannot serve after the customer flexible time window closes. Following the commonly used assumption in the classical VRPTW, we

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