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The trade-off between fixed vehicle costs and time-dependent arrival penalties in a routing problem

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ABSTRACT

This paper introduces the vehicle routing problem with soft time windows (VRPSTW) in which problem definition differs from ones previously defined in literature. Branch-and-price approach is employed, resulting in a set partitioning master problem and its new subproblem. Novel techniques are consequently developed to solve this new subproblem. Experimental results report the comparisons of these solution techniques under the branch-and-price framework. The VRPSTW solutions have further been compared to the state-of-the-art literature, signifying the superiority of the VRPSTW on this issue.

1. Introduction

Much attention has been paid to urban freight transport (commodity movement), which is a significant issue in urban planning. As urban freight transport can generate some serious problems in urban areas and it mainly affects the profit of logistics distributors, effective tools for optimizing urban freight transport are thus required (Ando and Taniguchi, 2006; Taniguchi and Kakimoto, 2003; Taniguchi et al., 1999). One of such tools is the Vehicle Routing Problem (VRP). The aim of the VRP is to design an optimum cost set of delivery routes to supply all customer requirements subject to side constraints (Laporte, 1992, 2009). Since the VRP has emerged in the literature, various extensions to the basic VRP have been proposed in order to represent different characteristics of practical problems.

An important extension is the VRP under time window constraints that involves additional time requirements from customers. Each customer, indexed by i, requests to be serviced by a single delivery vehicle at his location within his specified time window $[a_i, b_i]$. The problem addressed here is the so-called VRP with hard time windows (VRPHTW). A vehicle can arrive at customer location before time window, but it needs to wait at no cost until the beginning of time window to start service. Any visit and service after time window is infeasible (Braysy and Gendreau, 2005a,b). It is however obvious that the VRPHTW has weaknesses when applying it to real-life situations, that is, managing vehicles to service all customers within time windows is very difficult in practice, and it is likely to receive very high costs due to use of many vehicles. To avoid these drawbacks, Qureshi et al. (2009, 2010) partially relaxed time window constraints by introducing time-dependent late arrival penalties to the problem. The problem is then described as the VRP with semi-soft time windows (VRPSSTW). In the VRPSSTW, a vehicle is allowed to visit and serve a customer later than his time window, however a time-dependent late arrival penalty must be taken into consideration if the delayed service occurs. The vehicle still has to

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wait to start service until a_i without cost if it arrives too early. Qureshi et al. (2009, 2010) also introduced the maximum allowable late arrival time at each customer to be visited (represented by b_i') by considering a trade-off between fixed vehicle cost and late arrival penalty.

The numerical experiments reported in Qureshi et al. (2009) show that the VRPSSTW can decrease number of vehicles used in the solution (as compared to the VRPHTW). The overall costs could consequently be reduced. In addition, total waiting time of vehicles, although not considered as main objective, is also reduced. Nevertheless, there still exists a significant amount of waiting time in the VRPSSTW solution. This amount of waiting time is meaningful in practice. First of all, waiting time implies non-profitable time of logistics distributor and firm's resources are also being underutilized. Spending too long time in waiting not only causes the loss of opportunity to generate more profits but also incurs extra costs such as vehicle/labor operating cost, maintenance cost, and parking fee. Secondly, it might contribute to traffic and environmental related problems such as traffic congestion due to waiting at inappropriate place, and air pollution if the vehicle waits in engine on state.

Apparently, the VRPSSTW could cope with the drawbacks of the VRPHTW, yet they are addressed only partially. Both the VRPHTW and the VRPSSTW still generate significant amount of waiting time of vehicles. Therefore, in addition to optimization of total routing costs, our aim is to also simultaneously minimize total waiting time of all vehicles. The problem considered in this paper is called the VRP with soft time windows (VRPSTW). Early arrival penalties, in addition to late arrival penalties, are also introduced to the problem. Indeed, a vehicle is possible to arrive and service after time window with taking late arrival penalty into account. On the other hand, if the vehicle arrives early, it must wait to begin the service until a_i with taking early arrival penalty (or waiting cost) into account. However, the vehicle is not permitted to wait if it arrives within time window or later so that the service must start immediately. This matter is important in the proposed VRPSTW characteristics since the objective is to minimize total waiting time as well as total routing costs (and the corresponding late arrival penalties). For the sake of both objectives, any unnecessary waiting, i.e. whether within time window or later, is definitely not optimal and it needs to be avoided. In general, types (such as linear and non-linear) of penalties might vary from one customer to another, depending on importance, priority, and criticality. However, in this paper, both early and late arrival penalties are assumed to be linearly proportional to the early and late arrival time of vehicles, respectively. To prevent too long waiting time and delayed time which are impractical, the maximum limits of early arrival time and late arrival time at each customer $[a_i', b_i']$ are also imposed. Therefore, it becomes infeasible to visit a customer beyond maximum limits of either early arrival time or late arrival time. Fig. 1 shows time-dependent arrival penalty functions of the three variants of the VRP under time window constraints (i.e. the VRPHTW, the VRPSSTW and the VRPSTW, respectively).

In combinatorial optimization problem perspective, the VRPSTW is much harder to be solved to optimality than the VRPHTW and the VRPSSTW. The main difficulty of solving the VRPSTW is that time-dependent arrival penalties, i.e. both early and late arrival penalties, are considered. Because time-dependent arrival penalty function is not a non-decreasing function, consequently the cost function along a route traversed by a vehicle is also not a non-decreasing function as well. This makes the problem more complicated. Besides, due to taking early arrival penalty into account, the vehicle does not necessarily depart as early as possible. Departure time from depot of each vehicle must therefore optimally be determined.

Through the years, a great number of research papers has been dedicated to the VRPHTW (see e.g. Alvarenga et al., 2007; Azi et al., 2007, 2010; Baldacci et al., 2011; Fisher et al., 1997; Kallehauge et al., 2006; Kohl and Madsen, 1997; Potvin and Rousseau, 1993). On contrary, a few cases have studied on the soft time window variants. These include the work of Balakrishnan (1993), where servicing a customer before or after time window is possible with taking appropriate penalties. However, the vehicle could decide to wait (not more than a maximum limit) without penalty instead of premature service with early penalty due to economical reasons or exceeding the allowed maximum penalty. Simple constructive heuristics were used in his work to provide the solution to the corresponding problem. Some effective heuristics and metaheuristics such as nearest-neighbor heuristic (Ioannou et al., 2003), tabu search (Chiang and Russell, 2004), and local search approaches (Hashimoto et al., 2006; Ibaraki et al., 2005) were further exploited to solve similar problems. The VRPSTW of Gendreau et al. (1999) and Taillard et al. (1997) allow late services with late penalties, while waiting of vehicles could be possible at no cost in case of early arrival. Their soft time window settings are implicitly equivalent to the VRPSSTW of Qureshi et al. (2009,

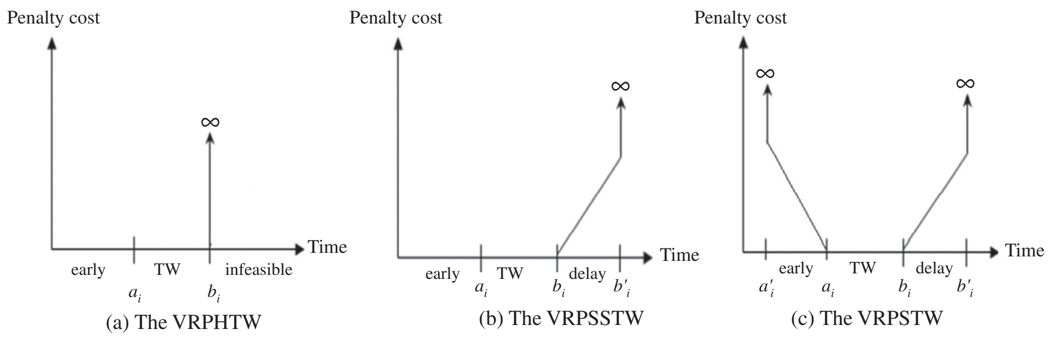

Fig. 1. Linear penalty functions for different variants of the VRP under time window constraints.