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A scenario decomposition algorithm for strategic time window assignment vehicle routing problems

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A R T I C L E I N F O

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A B S T R A C T

We study the strategic decision-making problem of assigning time windows to customers in the context of vehicle routing applications that are affected by operational uncertainty. This problem, known as the Time Window Assignment Vehicle Routing Problem, can be viewed as a two-stage stochastic optimization problem, where time window assignments constitute first-stage decisions, vehicle routes adhering to the assigned time windows constitute second-stage decisions, and the objective is to minimize the expected routing costs. To that end, we develop in this paper a new scenario decomposition algorithm to solve the sampled deterministic equivalent of this stochastic model. From a modeling viewpoint, our approach can accommodate both continuous and discrete sets of feasible time window assignments as well as general scenario-based models of uncertainty for several routing-specific parameters, including customer demands and travel times, among others. From an algorithmic viewpoint, our approach can be easily parallelized, can utilize any available vehicle routing solver as a black box, and can be readily modified as a heuristic for large-scale instances. We perform a comprehensive computational study to demonstrate that our algorithm strongly outperforms all existing solution methods, as well as to quantify the trade-off between computational tractability and expected cost savings when considering a larger number of future scenarios during strategic time window assignment.

1. Introduction

The commitment to deliver (or pickup) goods within scheduled time windows is a common practice in several real world distribution networks. In many industries, these time windows are mutually agreed upon by the distributor and customer through long-term delivery contracts. For example, in a distribution network of retailers, it is common that deliveries to a retail store are always made on the same day of the week (at about the same time) for an entire year (Spliet and Gabor, 2015; Vercammen, 2016). Likewise, in maritime distribution of liquefied natural gas, a central planning activity is to design and negotiate contractual agreements of *annual delivery plans* that specify delivery dates and corresponding delivery quantities to customers (Zhang et al., 2015). From the customer's point of view, this is crucial for efficient inventory management and scheduling of personnel to process the delivery. From the distributor's point of view, it reduces the variability across repetitive deliveries and exposes efficiencies that add up to significant cost savings. Short- and medium-term contracts of similar nature can be also found in small-package shipping where, for instance, courier companies provide a delivery time

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window to customers receiving sensitive packages (Jabali et al., 2015). Other examples of applications where such operations are typical include, among others, attended home delivery in e-commerce businesses (Agatz et al., 2011) and internet installation services (Ulmer and Thomas, 2017).

Once a time window has been agreed upon and communicated to the customer, the distributor must attempt to meet it on an operational (e.g., daily) basis as well as possible. This is done by solving a Vehicle Routing Problem with Time Windows (VRPTW) to determine a delivery schedule that adheres to the agreed time windows. The assigned time windows strongly influence the structure of feasible delivery schedules and, hence, the daily incurred distribution costs. Therefore, a natural choice is to assign time windows based on the arrival times at customer locations in the optimal (i.e., minimum cost) vehicle routing schedule. However, this seemingly optimal decision may become highly suboptimal in the presence of operational uncertainty.

In reality, operational level information (such as customer demands or travel times) is often not known with certainty at the strategic level when time windows are to be decided. For example, the demand volume of a customer typically fluctuates per delivery. Similarly, travel times vary on a day-to-day basis (e.g., because of unpredictable traffic conditions). The true values of these operational parameters are not known far in advance, and often may become known only on the day of delivery before the vehicles are dispatched. This makes the strategic assignment of time windows a non-trivial task. Indeed, if one utilizes only nominal values of the uncertainty when assigning time windows, then it will often lead to situations in which the distribution costs are unacceptably high, since the nominal delivery schedule may no longer be feasible, let alone optimal, in such cases. Fortunately, with the increasing availability of data, distributors can readily obtain forecasts of uncertain operational parameters (e.g., as perturbations from their nominal values). It is possible to take advantage of this information and assign time windows in a way that will lead to low distribution costs in the long run. The goal of this paper is to study the problem of strategic time window assignment in the presence of operational uncertainty.

Our paper builds upon the work of Spliet and Gabor (2015), which introduced the Time Window Assignment Vehicle Routing Problem (TWAVRP). The TWAVRP consists of assigning time windows of pre-specified width within some exogenous time windows to a set of known customers. The exogenous time windows typically correspond to operating hours of the customer but may also arise from hours-of-work or other government regulations. The work of Spliet and Gabor (2015) studies the TWAVRP under situations in which the demand volume of the customers is unknown and subject to uncertainty. However, a finite set of "scenarios," each describing a possible realization of demand for every customer, is assumed to be given with known probability of occurrence. This information is used to formulate a two-stage stochastic program, in which the first-stage decisions are to assign time windows, while the second-stage decisions are to design vehicle routing schedules satisfying the assigned time windows, one for each of the demand scenarios. The objective is to minimize the total routing costs, averaged over the postulated scenarios. A similar modeling approach is followed in Spliet and Desaulniers (2015), with the only difference that the first-stage time windows are selected from a finite set of *a priori* constructed windows; this problem is referred to as the *discrete* TWAVRP to distinguish it from the original *continuous* TWAVRP. In this paper, we consider both cases, and we shall in fact allow also for the generalized case in which feasible time window assignments lie in a continuous set for some portion of the customer base and in a discrete set for the remaining portion.

Algorithms to solve the aforementioned stochastic programming models have been proposed in Spliet and Gabor (2015) and Dalmeijer and Spliet (2018) for the continuous version, and in Spliet and Desaulniers (2015) for the discrete version of the problem. The algorithms of Spliet and Gabor (2015) and Spliet and Desaulniers (2015) are based on branch-price-and-cut and can solve instances with 25 customers and 3 demand scenarios to optimality, while the algorithm of Dalmeijer and Spliet (2018) is based on branch-and-cut and can address instances containing 40 customers and 3 scenarios. Several heuristics have also been proposed in Spliet and Desaulniers (2015) for the discrete setting that can address instances containing up to 60 customers. Recently, Spliet et al. (2018) studied a variant of the TWAVRP with time-dependent travel times and proposed a branch-price-and-cut algorithm that can solve instances with 25 customers and 3 demand scenarios.

A problem that is closely related to the strategic TWAVRP is the Consistent Vehicle Routing Problem (ConVRP) (Groër et al., 2009), which is motivated in the context of operational level planning. The ConVRP aims to design minimum cost vehicle routes over a finite, multi-day horizon to serve a set of customers with known demands. The goal is to design routes that are *consistent* over time; this translates to satisfying any of the following requirements each time service is provided to a customer: *(i)* arrival-time consistency, wherein the customer should be visited at roughly the same time during the day, *(ii)* person-oriented consistency, in which the customer should be visited by the same driver, and whenever applicable, *(iii)* load consistency, for which a customer should receive roughly the same quantity of goods. We refer the reader to Kovacs et al. (2014) for an overview of this problem and its applications.

Conceptually, the assigned time windows in the TWAVRP (which are also referred to as the *endogenous time windows*) serve to satisfy the arrival-time consistency requirement of the ConVRP, which requires that every customer be visited at roughly the same time whenever service is requested. Formally, the ConVRP requires that the difference between the earliest and the latest arrival times at each customer location must differ by no more than some pre-specified constant bound, which is referred to as the *maximum allowable arrival-time differential*. This bound is analogous to the pre-specified width of the endogenous time window in the continuous TWAVRP, and this equivalence between the two problems has been previously acknowledged in Spliet et al. (2018) and Spliet and Gabor (2015).

The equivalence between the TWAVRP and the arrival-time ConVRP has two important consequences. First, we observe that, in the most general case, the ConVRP allows for the possibility that not all customers require service in all time