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A Branch-and-Cut-and-Price algorithm for the Multi-trip Separate Pickup and Delivery Problem with Time Windows at Customers and Facilities

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ABSTRACT

We study the Multi-trip Separate Pickup and Delivery Problem with Time Windows at Customers and Facilities (MT-PDTWCF), arising in two-tiered city logistics systems. The first tier refers to the transportation between the city distribution centers, in the outskirts of the city, and intermediate facilities, while the second tier refers to the transportation of goods between the intermediate facilities and the (pickup and delivery) customers. We focus on the second tier, and consider that customers and facilities have time windows in which they can be visited. Waiting is possible at waiting stations for free or at customers and facilities at a given cost or penalty. Therefore, it is relevant to coordinate the arrivals of vehicles at facilities and customers with the corresponding time windows. The MT-PDTWCF calls for determining minimum (fixed, routing and waiting) cost multi-trip routes, for a given fleet of vehicles, to service separately pickup and delivery customers, while taking into account vehicle capacity and time windows both at customers and facilities. We propose the first exact algorithm for MT-PDTWCF, namely a Branch-and-Cut-and-Price algorithm. It is based on column generation, where the pricing problem is solved by a bi-directional dynamic programming algorithm designed to cope with the features of the problem. Subset-row and rounded capacity inequalities are adapted to deal with MT-PDTWCF and inserted in the Branch-and-Cut-and-Price algorithm. The performance of the proposed algorithm is tested on benchmark instances with up to 200 customers, showing its effectiveness.

1. Introduction

We address the *Multi-trip Separate Pickup and Delivery Problem with Time Windows at Customers and Facilities* (*MT-PDTWCF*), which arises in the context of two-tiered City Logistics systems (Cattaruzza, Absi, Feillet, & González-Feliu, 2017; Crainic, Errico, Rei, & Ricciardi, 2012; Crainic, Ricciardi, & Storchi, 2009). In these systems, the first tier refers to the consolidation and transportation of loads between the city distribution centers (CDCs), in the outskirts of the city, and intermediate facilities without storage or waiting areas, called *satellites*, located inside the city (or close to it), by using large-capacity vehicles. The second tier considers the delivery/pickup of goods between the satellites and the customers, by using smaller-capacity vehicles that can travel inside the city. The usefulness of two-tier City Logistics systems stands in reducing the nuisances caused by freight transportation in urban areas (Crainic et al., 2009): larger trucks transport freight to satellites using corridors surrounding the city, while only small vehicles enter the city center, and the coordination of the two tiers at satellites allows the reduction of traffic congestion.

In this paper, we focus on the second tier problem and consider that both customers and facilities have time windows, so that it is essential to coordinate the arrivals of vehicles at facilities and customers with the corresponding time windows. This class of problems has recently received significant attention (see, e.g., Crainic, Gajpal, & Gendreau, 2015b; Crainic, Nguyen, & Toulouse, 2016; Grangier, Gendreau, Lehuédé, & Rousseau, 2016; Guastaroba, Speranza, & Vigo, 2016; Nguyen, Crainic, & Toulouse, 2013; Nguyen, Crainic, & Toulouse, 2017), as environmental issues and traffic congestion have become more critical in every day life (Guastaroba et al., 2016).

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Before describing the features of the studied problem in more detail, we briefly outline the considered setting and the first tier problem. We deal with tactical planning, introduced in Crainic (2008) and Crainic et al. (2009), and called *day-before planning problem*, in which the following assumptions are made: (i) the CDCs and satellites are given, as well as their locations and the corridors that can be used to connect them; (ii) the number and capacity of the available large-capacity and smaller capacity vehicles are known; (iii) customer demands (and their characteristics such as amount of product, origin, destination and time window) are also known. The first tier problem calls for determining the departure times, routes and loads of the large-capacity vehicles from the CDCs to the satellites (delivery of inbound demand) and back (picked up outbound demand), while the second tier problem has to determine the routing of the smaller-capacity vehicles between the satellites and the customers, in order to deliver and pickup goods while respecting the time windows of customers and satellites. The two problems are clearly interrelated by the transfer of freight between vehicles that occurs at satellites during specified (short) time windows. Since satellites do not have any storage or waiting zone, not only customers must be served within their time windows, but also vehicles must coordinate at the satellites.

The first tier problem receives as input the description of the physical network, with the locations of CDCs and satellites and their possible connections, as well as the available fleet of large-capacity vehicles. Each inbound customer demand is associated with a CDC, has a time at which goods become available at the CDC, a quantity of product and a destination, i.e., a satellite or a customer location within the city when the first-tier problem addresses the customer-to-satellite allocation as well (Fontaine, Crainic, Jabali, & Rei, 2016). Symmetrically, outbound customer demand has a customer location or satellite as origin, a CDC as destination, a time when goods become available, and a volume to be moved. In addition, a set of services is considered. Each service originates at a CDC, visits a set of satellites and ends at a CDC: it represents the travel of a large-capacity vehicle for transporting freight from a CDC to one or several satellites and its return back to a CDC. It has an associated cost that includes the operating cost and a penalty for the inconvenience caused to traffic congestion by using the service. The goal of the first tier is to determine which services should be selected and operated by the large-capacity vehicles, and their schedule consisting of the departure time from the CDC and the departure time from each visited satellite, so that the cost is minimized. Constraints require to transport the demand between the CDCs and the satellites, and to respect the capacity of the large-capacity vehicles, and the capacity of the satellites in terms of number of vehicles that can be present at the satellite in the same period. Mathematical models for the first tier problem and its variants fall in the category of capacitated multicommodity fixed charge network design models (see Crainic & Sgalambro, 2014 and Crainic (2008) for more details).

Based on the service plan and schedule chosen for the first tier system, the amounts of goods delivered and picked up at satellites have been determined, and consequently the subsets of customers that each satellite will serve have been chosen. In addition, the time windows in which the satellites are active for freight transfer have been defined. Once the first tier solution has been determined, the second tier problem, that we call MT-PDTWCF, has to be solved. In MT-PDTWCF, a set of customers requiring the delivery of loads or having loads to be picked up is given. They must be served by a homogeneous fleet of vehicles that can perform *multi-trip* routes leaving from and going back to a single depot. Each delivery customer requires some loads, that must be received in a given hard *time window*, from a specific satellite that operates in a given hard *time window*. Similarly, each pickup customer has loads that must be picked up in a given hard time window and brought to a specific satellite in a given hard time window. We consider *separate* pickup and delivery, i.e., a vehicle can visit a sequence of delivery customers and, afterwards, it can visit a sequence of pickup customers, but the visits to delivery and pickup customers cannot be mixed in the same trip. Waiting at satellites and customers is undesirable and comes at a cost or penalty: indeed, there is often limited parking availability near the customers, and there is no waiting or warehousing activity at satellites, hence a vehicle stationing there has a negative impact on traffic congestion. Thus, *coordination* between the arrivals of vehicles at facilities and customers and the corresponding time windows is a key issue of this problem. In addition, a set of *waiting stations* (such as parking lots) is available where the vehicles can wait before going to a satellite or to a customer at no cost. Note that, although driving at a slower speed could be a way for reaching the customer or the facility at the right time, it would also increase traffic congestion since the vehicle would be on the road for a longer time. Therefore, waiting at waiting stations is the preferred choice in our setting. We underline that MT-PDTWCF is different from the Two-Echelon Vehicle Routing Problem, in which both tiers are taken into account, and synchronization may occur between vehicles of the two tiers. Therefore, in the following, we refer to *coordination* rather than synchronization, between vehicle arrivals and the operating time windows of customers and satellites. The goal is to find minimum (fixed, routing and waiting) cost multi-trip routes for a given fleet of vehicles that serve all pickup and delivery customers, while respecting capacity, time windows and coordination constraints.

The problem under study is similar to the one introduced in Nguyen et al. (2017). There are two main differences between the two problems: the first one is that, in Nguyen et al. (2017), only delivery customers are pre-assigned to a specific satellite, while the choice on the specific satellites serving pickup customers has to be determined; we assume, on the contrary, that the first tier solution determines the satellite associated with each (delivery or pickup) customer; the second difference is that MT-PDTWCF introduces the flexibility of waiting at customers and/or satellites at a given cost, and the possibility of going to a waiting station at any time, including between customer visits. Indeed, in Nguyen et al. (2017), waiting is only possible at waiting stations before moving to a satellite. As mentioned above, the cost associated with the waiting at customers or satellites represents a penalty representing the increased traffic congestion caused by a vehicle stop outside waiting stations. On the contrary, waiting at a waiting station is not penalized since they are appropriate for the vehicle stops, and waiting there does not cause any inconvenience. The additional flexibility of MT-PDTWCF allows considering alternative options of waiting at customers, satellites and waiting stations, that can further reduce traffic congestion, while taking into account the trade-off between waiting and routing costs.

To the best knowledge of the authors, Nguyen et al. (2017) proposed the only solution method directly aimed at this class of problems, which is a tabu search meta-heuristic. No exact method has been proposed for this class of problems yet. Our objective is to contribute to filling this gap. We propose an Integer Linear Programming (ILP) formulation and a Branch-and-Cut-and-Price algorithm for the MT-PDTWCF. The ILP model contains exponentially many variables, associated with trips, that are combined to form complete routes. To compute a lower bound, we developed a bi-directional dynamic programming algorithm (Righini & Salani, 2006; 2008), employed in a column generation procedure. It is designed to cope with the specific features of MT-PDTWCF, namely multi-trip, pickup and delivery customers associated with intermediate facilities, and coordination between vehicle arrivals and the operating time windows of customers and satellites. Especially the latter needs to be carefully addressed, by considering the possibility of stopping at waiting stations or at customers and facilities at

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a given cost, and influences the structure of the algorithm. Effective dominance rules and label filtering procedures are proposed to reduce the number of labels. Starting from the well-known subset-row and rounded capacity inequalities, we defined valid inequalities that are embedded in the Branch-and-Cut-and-Price algorithm and allow deriving significantly stronger lower bounds. Different branching rules are applied to obtain integer optimal solutions. We analyze the behavior and performance of the proposed Branch-and-Cut-and-Price algorithm through a comprehensive set of experimentations.

The paper starts with a brief overview of related literature, in Section 2, followed by the formal description of the problem and the model we introduce in Section 3. Section 4 describes the solution method we propose, which is evaluated by computational experiments reported in Section 5. Finally, we draw our conclusions and present future research directions in Section 6. In an Appendix we report the used notation.

2. Literature review

MT-PDTWCF generalizes several Vehicle Routing Problems (VRP, see, e.g., Lahyani, Khemakhem, & Semet, 2015; Toth & Vigo, 2014; Vidal, Crainic, Gendreau, & Prins, 2013), as it includes pickup and delivery, multi-trips and time windows both at customers and facilities. The most challenging aspect of the MT-PDTWCF, often neglected in previous VRP variants, is the vehicle arrivals and time windows coordination at the intermediate facilities. Related problems include the *Vehicle Routing Problem with Backhauls* (VRPB), the *Vehicle Routing Problem with Cross-Docking* (VRPCD), and the *Multi-trip Vehicle Routing Problem* (MTVRP). In the VRPB (see, e.g., Golden, Baker, Alfaro, & Schaffer, 1985; Irnich, Schneider, & Vigo, 2014), the set of customers is partitioned into two subsets: *line-haul* and *backhaul* customers, where the former ones require the delivery of loads from the depot, while the latter ones have loads to be picked up and sent to the depot. MT-PDTWCF generalizes the VRPB, as the latter determines a single-trip routing with first delivery customers and then pickup ones, and time windows coordination is not taken into account. The VRPCD (see, e.g., Grangier, Gendreau, Lehuédé, & Rousseau, 2017; Maknoon & Laporte, 2017), on the contrary, addresses synchronization of vehicle operations at a cross-dock facility. It consists of picking up goods, consolidating them at an intermediate facility without storage, and then delivering goods to the customers. Synchronization takes place at the intermediate facility. In the MTVRP (see, e.g., Cattaruzza, Absi, & Feillet, 2016; Hernandez, Feillet, Giroudeau, & Naud, 2016) all delivery customers are served before pickup ones, however each vehicle may perform more than one trip. MT-PDTWCF generalizes the latter problem, as each route can visit several satellites (multi-trip feature) and coordination constraints and costs are also taken into account. In addition, the feature of including route duration and waiting costs in the objective function is often studied in the context of Time-Dependent VRPs (see, e.g., Dabia, Ropke, Van Woensel, & De Kok, 2013; Visser & Spliet, 2017).

MT-PDTWCF falls in the category of *collaborative urban transportation*, for which a survey was recently presented in Cleophas, Cottrill, Ehmke, and Tierney (2019): this concept considers the opportunity of collaboration between different stakeholders in freight transportation between distribution centers and the city, with the goal of reducing traffic congestion and pollution by limiting the number of vehicles travelling in urban areas. This category also includes problems that consider the opportunity of transporting freight by combining trips made by pickup and delivery vehicles with the use of public transport lines. The *Pickup and Delivery Problem with Time Windows and Scheduled Lines (PDPTW-SL)*, proposed in Ghilas, Demir, and Van Woensel (2016), considers two transport options: either a pickup and delivery vehicle from the origin to the destination or a combination of a pickup and delivery vehicle and a public transport line. An adaptive large neighborhood search is proposed in Ghilas et al. (2016) to solve this problem. The same problem is also studied in Ghilas, Cordeau, Demir, and Woensel (2018), where a branch-and-price algorithm is developed. Another related problem, in which transfers among pickup and delivery vehicles can be made only at given locations, is the *Pickup and Delivery Problem with Transfers (PDP-T)* studied in Cortés, Matamala, and Contardo (2010), Masson, Lehuédé, and Péton (2013), and generalized in Masson et al. (2017). Recently, in Fontaine, Crainic, Jabali, and Rei (2019), a two-tier multimodal system, which combines different transportation modes, such as traditional road-based carriers and rail vehicles, was studied, and a Benders decomposition method was proposed. Similar to these problems, that consider the synchronization with scheduled lines, MT-PDTWCF needs to respect the time windows of the satellites. In addition, bus stops do not have any storage capacity as it happens for satellites. However, MT-PDTWCF deals with a different context: it does not consider using public transport lines, it allows vehicles to wait at customers and satellites at a given penalty and at waiting stations at no cost, and considers that vehicles can perform multiple trips.

In MT-PDTWCF, we deal with penalties associated with the waiting at satellites and customers when the vehicle arrives before the corresponding time window: in this regard, MT-PDTWCF is related to the VRP with *Soft Time Windows* (VRPSTW), in which customers can be served outside their preferred time windows at a given penalty. In the latter case, a time window represents a preference about the time at which vehicle should visit a customer, and violations to these preferences can be allowed. Among the exact approaches, in Liberatore, Righini, and Salani (2011), a branch-and-price algorithm is proposed, in which the pricing problem is solved by bidirectional dynamic programming. Bettinelli, Ceselli, and Righini (2014) considers the same type of penalization, but in the case of a multi-depot heterogeneous-fleet pickup and delivery problem. A branch-and-price algorithms is proposed in Taş, Gendreau, Dellaert, Van Woensel, and De Kok (2014) to solve VRPSTW and stochastic travel times. We underline that, differently from the VRPSTW, in MT-PDTWCF time windows both at satellites and customers are hard, and, thus, every customer will always be served within his/her time window, and the same holds for the supply points. In addition, MT-PDTWCF features several new characteristics, such as time windows not only at customers but also at satellites, multiple trip for each vehicle, and the option to use waiting stations, which distinguish it from previous works found in the literature.

MT-PDTWCF is also related to scheduling problems in which penalties are associated with violation of release dates. Recently, in Bulhoes, Sadykov, Subramanian, and Uchoa (2018), a general purpose exact algorithm for problems involving setup times and a non-regular objective function, such as a cost function that includes earliness penalties, was proposed. Although we can identify some similarities with MT-PDTWCF, by considering jobs as customers, machines as vehicles that serve customers, setup times as routing costs and the objective of minimizing the weighted job earliness as the aim of minimizing waiting costs, we can also identify many differences: customer demand and vehicle capacity do not have their counterpart in the job scheduling problem, there is no distinction between pickup and delivery customers, a job can begin earlier than its release date while in MT-PDTWCF customers have hard time windows. In addition, specific features of MT-PDTWCF, i.e., multiple trips, satellite time windows and waiting stations, are not considered in Bulhoes et al. (2018).

In the recent literature, we can find several works that are more closely related to MT-PDTWCF. In particular, MT-PDTWCF generalizes the *Time-dependent Multi-zone Multi-trip Vehicle Routing problem with Time Windows* (TMZT-VRPTW), which considers

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synchronization, but only delivery customers. In Crainic et al. (2009), the TMZT-VRPTW and several variants were introduced, and mathematical formulations and a heuristic approach based on decomposition were proposed. The idea is to first solve the Vehicle Routing with Time Windows subproblems representing the delivery to the customers of each satellite; then a minimum cost network flow problem is solved to put together the vehicle trips obtained as solution of the subproblems. An implementation of this method is presented by Crainic, Errico, Rei, and Ricciardi (2015a) and Crainic et al. (2015b). To assess the quality of the solutions, constraints on vehicle capacity and time windows both at satellites and customers are relaxed to derive a lower bound. Nguyen et al. (2013) propose a tabu search meta-heuristic for TMZT-VRPTW, featuring two different neighborhoods, corresponding, respectively, to the assignment of vehicles to satellites and of customers to vehicles. The choice of the neighborhoods is performed in a dynamic way during the search, and diversification is applied to examine unvisited regions of the search space. The reported computational experiments show that the method produces good quality results on instances with up to 3600 customers.

MT-PDTWCF belongs to the problem class studied in Nguyen et al. (2017), where a tabu search heuristic algorithm is proposed. It extends the method by Nguyen et al. (2013) by new neighborhoods to deal with both pickup and delivery customers. The algorithm in Nguyen et al. (2017) was the first method developed for MT-PDTWCF and was tested on instances including up to 72 satellites and 7200 customers. Recently, an extension of the problem, called *Multi-trip Multi-traffic Pickup and Delivery Problem with Time Windows and Synchronization* (MTT-PDTWS) has been studied in Crainic et al. (2016). In MTT-PDTWS, multi-trip delivery and pickup routes are executed to serve three types of customer requests: customer-to-external zone (i.e. pickup customers), external zone-to-customer (i.e. delivery customers) and customer-to-customer (i.e. load to be transported from a pickup customer to a delivery customer). Therefore, MTT-PDTWS extends MT-PDTWCF by considering customer-to-customer requests. In Crainic et al. (2016), the tabu search proposed in Nguyen et al. (2013) is extended to deal with this additional type of service.

To the best of our knowledge, no exact method has been proposed so far that directly applies to MT-PDTWCF, which has only been faced through heuristic and meta-heuristic algorithms.

3. Problem description and ILP formulation

In this section, we define the Multi-trip Separate Pickup and Delivery Problem with Time Windows at Customers and Facilities (MT-PDTWCF). We consider a single depot g and a fleet of m identical vehicles of capacity Q and fixed cost F based at g. A set of intermediate facilities, called *satellites*, is given, where loads are available for delivery customers and where other loads must be brought from pickup customers in some specific time windows. A set of customers is also given, who can require delivery or pickup of loads, or both, during specific time windows, in the considered planning horizon T. All time windows are considered hard.

We underline that loads can be available at or be brought to the satellites during different time windows of the planning horizon. Similarly, a customer can be a delivery customer or a pickup customer or both during different time windows of the planning horizon. We model this combination of resources and time periods as in Nguyen et al. (2013, 2017) and use the same notation and terminology: we define *supply point* a combination of a satellite and a time window when it is available for delivery or pickup. We define a time window $[t(s) - \eta, t(s)]$, for each supply point $s \in \mathcal{S}$, representing the period in which a vehicle can visit s: η is a small value, thus allowing only a short time window for visiting s. We define $\varphi(s)$, $s \in \mathcal{S}$, as the time needed for all loading and unloading operations of a vehicle at s.

In addition, we define each load as a customer demand, not to be split into multiple visits: specifically, we consider *delivery-customer demands* and *pickup-customer demands*, characterized by the customer, the supply point where the load has to be taken or brought, and the time window. More precisely, we call $\mathcal{C}^D$ and $\mathcal{C}^P$, respectively, the sets of delivery and pickup customer demands. In addition, we define the subsets $\mathcal{C}^D_s \subseteq \mathcal{C}^D$ and $\mathcal{C}^P_s \subseteq \mathcal{C}^P$ as the customer demands that can be serviced by supply point $s \in \mathcal{S}$ (with $\mathcal{C}^D = \cup_{s\in\mathcal{S}}\mathcal{C}^D_s$ and $\mathcal{C}^P = \cup_{s\in\mathcal{S}}\mathcal{C}^P_s$). Sets $\mathcal{C}^P_s$ and $\mathcal{C}^D_s$ constitute, respectively, the *pickup service zone* and the *delivery service zone* of $s \in \mathcal{S}$. For each supply point $s \in \mathcal{S}$, we call $\mathcal{C}^P_s \cup \mathcal{C}^D_s$ the *service zone* of s. For every $s \in \mathcal{S}$, each (delivery or pickup) demand $i \in \mathcal{C}^D_s \cup \mathcal{C}^P_s$ is characterized by $(i, q_i, \delta(i), [e_i, l_i])$, where q_i is the quantity to be delivered or picked up at i, $\delta(i)$ is the needed service time, and $[e_i, l_i]$ is the customer time window.

An important feature of the considered problem is to coordinate the arrivals of vehicles at satellites and customers with the corresponding time windows. A set of *waiting stations* $w \in \mathcal{W}$ is given, where the vehicle can freely wait before going to a supply point or to a customer demand. Vehicles are also allowed to wait, before the start of the time window, at supply points and/or customers at a given cost: we define σ the unit waiting-time cost. The detailed modeling of the operations in the satellite is beyond the scope of this paper. Consequently, we assume (i) there is no limit on the number of vehicles that can be simultaneously present at a supply point $s \in \mathcal{S}$; (ii) all the loading and unloading operations happen at the end of the time window for a duration of $\varphi(s)$ time units; (iii) all vehicles leave at $t(s) + \varphi(s)$ from the supply point. Note that, if the vehicle arrives during the (short) service time window of a supply point s, there is no waiting cost/penalty since we assume that parking is available for the vehicle during such a period.

We represent supply points, waiting stations and customer demands through a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$, with node set $\mathcal{V} = \{g\} \cup \mathcal{S} \cup \mathcal{C}^D \cup \mathcal{C}^P \cup \mathcal{W}$ and arc set $\mathcal{A}$, representing the possible movements between the nodes. Each arc $(i, j) \in \mathcal{A}$ has an associated positive routing coefficient c_{ij} representing the routing cost and time associated with the movement between i and j $(i, j \in \mathcal{V})$.

The *work assignment*, also called *multi-trip route*, of each vehicle is a, possibly empty, sequence of feasible legs (trips), leaving from and going back to the depot, where a *leg* is a sequence of customer services between either two supply points or a supply point and the depot. There can be three types of legs defined as follows:

A. *Starting leg* l: it starts at the external depot g, visits a subset of pickup customers in $\mathcal{C}^P_s$ during their time windows, collecting an amount of loads up to Q, and ends at supply point $s \in \mathcal{S}$ within $[t(s) - \eta, t(s)]$;
B. *Ending leg* l: it starts at supply point $s \in \mathcal{S}$, where it loads an amount of goods up to Q, departs from s at $t(s) + \varphi(s)$ to service, during their time windows, a subset of delivery customers in $\mathcal{C}^D_s$, and ends at the external depot g.
C. *Inter-facility leg* l: it starts at supply point $s \in \mathcal{S}$, where it loads an amount of goods up to Q, and departs from s at $t(s) + \varphi(s)$ to service, during their time windows, a (possibly empty) subset of delivery-customers in $\mathcal{C}^D_s$. Afterwards it visits, during their time windows, a (possibly empty) subset of pickup-customers in $\mathcal{C}^P_{s'}$ to collect an amount of loads up to Q, and finally ends at supply point $s' \in \mathcal{S}$ within $[t(s') - \eta, t(s')]$.

We recall that vehicles may arrive early at a customer i or at a supply point s, and wait, paying a unit waiting-time cost σ. Anywhere along the leg the vehicle is allowed to wait at a waiting station $w \in \mathcal{W}$ without paying any cost.

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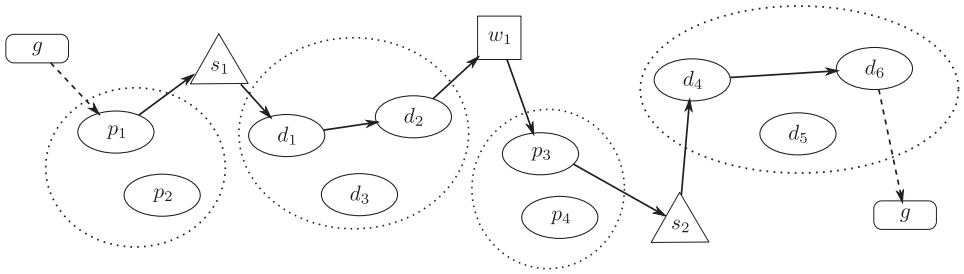

Fig. 1. Example of three-leg work assignment.

Fig. 1 illustrates an example of a three-leg work assignment, where s_1 and s_2 are the supply points, g is the depot, w_1 is a waiting station, $P_{s_1} = \{p_1, p_2\}$ and $D_{s_1} = \{d_1, d_2, d_3\}$ are the sets of pickup and delivery customer demands, respectively, associated with supply point s_1 and $P_{s_2} = \{p_3, p_4\}$, $D_{s_2} = \{d_4, d_5, d_6\}$ are the pickup and delivery customer demands, respectively, associated with supply point s_2. The work assignment consists of a sequence of three legs $\{l_1, l_2, l_3\}$, where $l_1 = \{g, p_1, s_1\}$ is a starting leg, $l_2 = \{s_1, d_1, d_2, w_1, p_3, s_2\}$ is an inter-facility leg and $l_3 = \{s_2, d_4, d_6, g\}$ is an ending leg. As one can see, waiting station w_1 is visited between two customers (d_2 and p_3). However, it is also possible to visit the waiting station before a supply point.

The MT-PDTWCF consists of determining a set of feasible work assignments for the vehicles to serve all customer demands. The objective is to minimize the sum of the fixed costs due to the use of the vehicles, the routing costs for serving the customers and reaching the supply points, and the waiting costs at customers and supply points.

We now define the proposed mathematical formulation. Let $\mathcal{L}$ be the set of all feasible (starting, inter-facility and ending) legs. We denote by $\mathcal{L}^+(s)$ the set of legs starting from $s \in \mathcal{S} \cup \{g\}$, and with $\mathcal{L}^-(s)$ the set of legs ending at $s \in \mathcal{S} \cup \{g\}$. We define a_{il} coefficients as

$$a_{il} = \begin{cases} 1 & \text{if customer demand } i \in \mathcal{C}^P \cup \mathcal{C}^D \text{ is visited by leg } l \in \mathcal{L}; \\ 0 & \text{otherwise;} \end{cases}$$

and define the binary decision variables

$$x_l = \begin{cases} 1 & \text{if leg } l \in \mathcal{L} \text{ belongs to a work assignment} \\ & \textit{(i.e., is selected in the solution)}, \\ 0 & \text{otherwise.} \end{cases}$$

Let π_l be the sum of routing and waiting costs of leg l ($l \in \mathcal{L}$), defined as follows. Let $\mathcal{V}_l = \mathcal{V}_l^C \cup \mathcal{V}_l^S \cup \mathcal{V}_l^W$ be the set of nodes visited by l, with $\mathcal{V}_l^C$ as the set of customer demand nodes, $\mathcal{V}_l^S$ as the set of supply point nodes in l and $\mathcal{V}_l^W$ as the set of waiting stations in l. Let $\mathcal{A}_l$ be the set of arcs belonging to l. Finally, let T_l be the set of arrival time instants θ_i at each node $i \in \mathcal{V}_l^C \cup \mathcal{V}_l^S$ (we do not consider arrival time instants at waiting stations, as no waiting costs need to be considered for those nodes). We define the routing cost of l as $c_l := \sum_{(i,j)\in A_l} c_{ij}$ and its waiting cost as $w_l := \sum_{i \in \mathcal{V}_l^C : \theta_i < e_i} \sigma(e_i - \theta_i) + \sum_{i \in \mathcal{V}_l^S : \theta_s < t(s) - \eta} \sigma(t(s) - \eta - \theta_s)$. Then, $\pi_l := c_l + w_l$.

The MT-PDTWCF can then be formulated as

$$\text{Minimize} \sum_{l \in \mathcal{L}} \pi_l x_l + \sum_{l \in \mathcal{L}^+(g)} F x_l \tag{1a}$$

$$\text{s.t.} \sum_{l \in \mathcal{L}} a_{il} x_l = 1 \qquad \forall i \in \mathcal{C}^P \cup \mathcal{C}^D \tag{1b}$$

$$\sum_{l \in \mathcal{L}^+(g)} x_l \le m \tag{1c}$$

$$\sum_{l \in \mathcal{L}^+(s)} x_l = \sum_{l \in \mathcal{L}^-(s)} x_l \qquad \forall s \in \mathcal{S} \tag{1d}$$

$$x_l \in \{0, 1\} \qquad \forall l \in \mathcal{L}. \tag{1e}$$

The objective function (1a) minimizes the total cost of operating and using the vehicles. Constraints (1b) requires that every customer demand is performed by exactly one leg. Constraint (1c) is the typical limit on the total number of used vehicles, indeed it bounds the number of work assignments to m, which is the number of available vehicles. Constraints (1d) guarantee the flow conservation at each supply point. These constraints allow combining legs into a (multi-trip) work assignment for a vehicle. Note that legs can be combined without any constraints on their timing, since we assume that a leg arrives at a supply point s before $t(s)$ and another leg leaves from the supply point at $t(s) + \phi(s)$ ($s \in \mathcal{S}$). Therefore, legs arriving at/departing from a supply point cannot overlap. In addition, these constraints ensure that each vehicle leaves and goes back to the depot (i.e., it is not possible to only select inter-facility legs). Note that, since we have time windows associated with the supply points and they are short (η is a small value), a work assignment cannot return to the same supply point, thus avoiding the need for subtour elimination constraints. Finally, let us call λ_i, μ and γ_s the dual variables associated with constraints (1b), (1c) and (1d), respectively, with λ_i free ($i \in \mathcal{C}^P \cup \mathcal{C}^D$), $\mu \le 0$ and γ_s free ($s \in \mathcal{S}$).

4. Solution method

To solve MT-PDTWCF we propose a Branch-and-Cut-and-Price algorithm, based on ILP model (1). As the model contains exponentially many variables, a lower bound on the optimal solution value is obtained by solving its Linear Programming (LP) relaxation by column generation. The pricing problem to derive negative reduced cost legs consists of a *Resource Constrained Elementary Shortest Path Problem* (RCESPP), which is NP-hard (Dror, 1994). To solve it, we propose a bi-directional dynamic programming algorithm (see, e.g., Righini & Salani, 2006; Righini & Salani, 2008), designed to cope with the features of MT-PDTWCF, and combined with effective dominance rules and label filtering to reduce the number of labels. A heuristic pricing algorithm is also developed to speed-up the column generation procedure. Two types of inequalities, that extend powerful well-known inequalities from the literature, are applied to significantly improve the quality of the lower bound. Finally, three branching rules are sequentially applied on fractional solutions to determine an optimal integer solution.

The proposed Branch-and-Cut-and-Price algorithm takes into account the specific features of MT-PDTWCF, namely multi-trip, (pickup and delivery) customer demands belonging to different service zones (as defined in Section 3), and coordination of the arrivals of vehicles at satellites and customers with the corresponding time windows. Since a route is composed by several legs (trips), the dynamic programming algorithm computes single

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legs and then they are combined in the master problem. As we have customer demands divided into service zones, the dynamic programming algorithm considers them separately in label propagation and then combines labels of different zones. For the same reason, the proposed inequalities are defined on specific service zones: this allows dealing with a smaller number of inequalities, that can be easily considered in the dynamic programming algorithm. Finally, the key issue is the coordination of the arrivals of vehicles at satellites and customers with the corresponding time windows and how to deal with the time resource: indeed, a smaller time consumption in a leg is not necessarily an advantage because waiting implies a cost. To tackle this issue, we define a particular label structure, and specific dominance rules and label filtering that allow fathoming labels to speed-up the solution process. All these features are detailed in the next sections.

Section 4.1 describes how we initialize the solution process. Then we present the main components of the algorithm: the lower bound computation with the two types of inequalities in Section 4.2, the pricing algorithm combined with effective dominance rules and label filtering in Section 4.3, the heuristic pricing algorithm in Section 4.4, and the branching rules in Section 4.5.

4.1. Initialization

The first step of the proposed algorithm is to reduce the size of network $\mathcal{G}$ by removing arcs that cannot be used in any optimal solution. In particular, for given $i, j \in \mathcal{C}^P \cup \mathcal{C}^D$, if

$$e_i + \delta(i) + c_{ij} > l_j,$$

then arc (i, j) can be removed from $\mathcal{A}$. We also consider the removal of arcs that connect two customers if the sum of their demands exceeds the capacity of the vehicle. However, such condition never occurs in our test instances. Then we start with a restricted master problem, in which a dummy variable, having very high cost coefficient (10^6 in our computational experiments), is introduced in constraints (1b) to guarantee the feasibility of the model (i.e., that each customer is covered) before starting the column generation of variables x_l.

4.2. Lower bound

To compute a lower bound, we iteratively search for promising legs, i.e., variables with negative reduced cost and add them to the restricted problem. When negative reduced cost variables no longer exist, the linear relaxation of the restricted master problem is equivalent to the LP relaxation of model (1) and gives a valid lower bound for the MT-PDTWCF.

The pricing problem is modeled as a RCESPP, where all the feasibility constraints on the route legs are enforced (see Section 3). We observe that each inter-facility leg is composed of a delivery phase and a pickup phase: therefore, it is possible to compute the two *partial legs* independently and then join them to find a complete leg. Each starting leg or each ending leg can be seen as a special inter-facility leg, where one of the two phases is empty. Therefore, we have a single type of pricing problem to compute all types of legs, i.e., starting, inter-facility or ending legs. Before describing, in Section 4.3, the algorithm used to find negative reduced cost route legs, we explain how a stronger lower bound can be obtained by adding valid inequalities to the linear relaxation of model (1). In particular, we consider subset-row inequalities and rounded capacity inequalities. Both types of inequalities are adapted to deal with MT-PDTWCF by taking into account subsets of customers (in the same or different service zones), and are defined so as to effectively be used within the dynamic programming solution framework. Both types of inequalities turn out to be fundamental in the solution process, as it will be shown in Section 5.

Zone-based subset-row inequalities (ZSR3) We consider the subset-row inequalities introduced by Jepsen, Petersen, Spoorendonk, and Pisinger (2008) for the VRP with Time Windows. In particular, we consider the case in which subsets have cardinality three. Let $\mathcal{C}_3 = \{C \subseteq (\mathcal{C}^P \cup \mathcal{C}^D) : |C| = 3\}$ be the set of all subsets C of customer demands of cardinality 3, and, for $C \in \mathcal{C}_3$, let $\mathcal{L}(C) \subseteq \mathcal{L}$ be the set of legs visiting at least 2 customer demands in C. The following inequalities are valid for model (1):

$$\sum_{l \in \mathcal{L}(C)} x_l \leq 1 \quad \forall C \in \mathcal{C}_3. \tag{2}$$

Given a subset of three customer demands, these inequalities require to select at most one leg among all legs that visit at least two customer demands in the subset. Let us note ρ_C the dual variables associated with inequalities (2), with $\rho_C \leq 0$ $(C \in \mathcal{C}_3)$. Since the number of inequalities in (2) is polynomial in the number of customers, the separation can be easily performed by complete enumeration. In the Branch-and-Cut-and-Price algorithm, we perform the separation when no negative reduced cost variable can be found by the pricing algorithm.

To embed inequalities of the form (2) within the dynamic programming algorithm, instead of considering any subset of three customer demands, we divide them into two groups:

- *Intra-zone subset-row inequalities*, when the three customer demands in C belong to the same (pickup or delivery) service-zone, i.e., the three customer demands are all pickup customer demands or all delivery customer demands of a supply point;
- *Inter-zone subset-row inequalities*, when the three customer demands in C belong to different service-zones, i.e., the three customer demands belong to service zones of different supply points.

Intra-zone and inter-zone inequalities are considered separately during the dynamic programming algorithm. In particular, the dual variables corresponding to the intra-zone inequalities are considered when building a partial leg of a delivery or a pickup service zone, while those of the inter-zone inequalities are considered when joining partial legs into a complete one. We refer to Section 4.3 for further details and introduce here the necessary notation. Given a supply point $s \in \mathcal{S}$, we call $\mathcal{C}_3^{intra,\mathcal{P}}(s) = \{C \subseteq \mathcal{C}_s^P : |C| = 3\}$ the set of subsets of pickup customer demands of cardinality 3 that induce *intra-zone* subset-row inequalities, and $\mathcal{C}_3^{intra,\mathcal{D}}(s) = \{C \subseteq \mathcal{C}_s^D : |C| = 3\}$ the set of subsets of delivery customer demands of cardinality 3 that induce *intra-zone* subset-row inequalities. Given a pair of supply points $s, s' \in \mathcal{S}$, we call $\mathcal{C}_3^{inter}(s, s') = \{C \subseteq (\mathcal{C}_s^D \cup \mathcal{C}_{s'}^P) : |C| = 3, |C \cap \mathcal{C}_s^D| \geq 1, |C \cap \mathcal{C}_{s'}^P| \geq 1\}$ the set of subsets of customer demands of cardinality 3, with at least one customer in the delivery zone of s and another customer in the pickup zone of s', that induce *inter-zone* subset-row inequalities.

Zone-based rounded-capacity inequalities (ZCAP) Rounded capacity inequalities are well known valid inequalities for routing problems (see Naddef & Rinaldi, 2002), which require all subsets of customers to be served by enough vehicles. Instead of considering any subset of customers, we consider a special case of such inequalities in which the set of customers contains either all the pickup customer demands or all the delivery customer demands of a supply point. When we consider all the pickup customer demands associated with a supply point $s \in \mathcal{S}$, the inequalities take the form:

$$\sum_{l \in \mathcal{L}^-(s)} x_l \geq \left\lceil \frac{\sum_{i \in \mathcal{C}_s^P} q_i}{Q} \right\rceil \quad \forall s \in \mathcal{S}. \tag{3}$$

They require that the number of legs visiting pickup customer demands to be served by supply point s is at least the rounded ratio of the sum of the pickup customer demands over the capacity of the vehicle. Similar inequalities can be written for the

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delivery customer demands. Note that we define the rounded capacity inequalities on a delivery service zone or on a pickup service zone: this allows to easily deal with these inequalities within the dynamic programming algorithm (see Section 4.3). In addition, having defined these inequalities on the service zones allows to have a small number of inequalities: thus, they are directly added to the master problem before starting the column generation procedure. We denote $\xi_{\mathcal{P}_s}$ the dual variables associated with inequalities (3), referred to pickup customers, and $\xi_{\mathcal{D}_s}$ the dual variables associated with the same inequalities but referred to delivery customers, with $\xi_{\mathcal{P}_s} \geq 0$ and $\xi_{\mathcal{D}_s} \geq 0$ ($s \in \mathcal{S}$).

4.3. Pricing algorithm

Dynamic programming techniques are very effective in solving RCESPPs, and, in particular, we focus on bi-directional extension of node labels (Righini & Salani, 2006; Righini & Salani, 2008), which is based on forward and backward label propagation. Labels are associated with nodes of $\mathcal{G}$. The proposed dynamic programming algorithm applies bi-directional extension of node labels, which we designed to effectively cope with multi-trip, service zones and coordination features that required ad hoc adaptations of the standard framework. We do not consider the ng-route relaxation, proposed in Baldacci, Mingozzi, and Roberti (2011): indeed, in MT-PDTWCF, the number of customers associated with each supply point is rather small (5 to 10 in the considered instances), and thus the number of neighboring customers in the ng-route relaxation would be very small (3 or 4 customers), giving only negligible improvements. In the following we report the pricing problem, and describe label structure, propagation, join of labels, dominance rules, and label filtering.

Pricing problem. The pricing problem calls for finding a negative reduced cost feasible leg $l \in \mathcal{L}$. We first describe the pricing problem for an inter-facility leg $l \in \mathcal{L}$ with supply points $s, s' \in \mathcal{S}$, and then explain the changes to deal with starting or ending legs. As before, we let $\mathcal{V}_l = \mathcal{V}_l^C \cup \mathcal{V}_l^S \cup \mathcal{V}_l^W$ be the set of nodes visited by l, with $\mathcal{V}_l^C$ as the set of customer demand nodes, $\mathcal{V}_l^S$ as the set of supply point nodes in l and $\mathcal{V}_l^W$ as the set of waiting stations in l, and $\mathcal{A}_l$ be the set of arcs belonging to l. Finally, T_l indicates the set of arrival time instants θ_i at each node $i \in \mathcal{V}_l^C \cup \mathcal{V}_l^S$ (also here, we do not consider arrival time instants at waiting stations, since no waiting costs need to be considered at these nodes). In addition, we define $\mathcal{C}^{*,l}_{intra,\mathcal{D}}(s)$, $\mathcal{C}^{*,l}_{intra,\mathcal{P}}(s)$ and $\mathcal{C}^{*,l}_{inter}(s,s')$ as the sets of all subsets of customer demands of cardinality 3 that induce, respectively, delivery intra-zone, pickup intra-zone and inter-zone subset-row inequalities, such that at least two customer demands are visited by leg l: $\mathcal{C}^{*,l}_{intra,\mathcal{D}}(s) = \{C \in \mathcal{C}_3^{intra,\mathcal{D}}(s) : |V_l \cap C| \geq 2\}$, $\mathcal{C}^{*,l}_{intra,\mathcal{P}}(s) = \{C \in \mathcal{C}_3^{intra,\mathcal{P}}(s) : |V_l \cap C| \geq 2\}$ and $\mathcal{C}^{*,l}_{inter}(s,s') = \{C \in \mathcal{C}_3^{inter}(s,s') : |V_l \cap C| \geq 2\}$. The pricing problem is to find a leg $l \in \mathcal{L}$, satisfying feasibility conditions described in Section 3, such that it has negative reduced cost:

$$\sum_{(i,j)\in\mathcal{A}_l} c_{ij} + \sum_{i\in\mathcal{V}_l^C:\theta_i<e_i} \sigma(e_i-\theta_i) + \sum_{i\in\mathcal{V}_l^S:\theta_s<t(s)-\eta} \sigma(t(s)-\eta-\theta_s) - \sum_{i\in\mathcal{V}_l^C} \lambda_i - \gamma_s + \gamma_{s'} - \sum_{C\in\mathcal{C}^{*,l}_{intra,\mathcal{D}}(s)} \rho_C - \sum_{C\in\mathcal{C}^{*,l}_{intra,\mathcal{P}}(s')} \rho_C - \sum_{C\in\mathcal{C}^{*,l}_{inter}(s,s')} \rho_C - \xi_{\mathcal{D}_s} - \xi_{\mathcal{P}_{s'}} < 0. \quad (4)$$

In the first line we can see the routing and waiting cost of the leg, the second line takes into account the dual variables of constraints (1b) and (1d), while the last line considers the dual variables of the intra-zone and inter-zone subset-row inequalities and of the rounded capacity inequalities. Recall that the latter ones are inserted in the master before starting the column generation procedure, while subset-row inequalities are separated by enumeration.

If we consider a starting leg, we need to add $F - \mu$ to the reduced cost, as the fixed cost of the vehicle and the dual variable of constraint (1c) need to be taken into account. In addition, for a starting leg from g to s', we do not have the terms including dual variables referred to s, while, for an ending leg from s to g, we do not have the terms including dual variables referred to s'.

To solve this problem, we developed a dynamic programming algorithm. We consider each delivery and pickup service zone of a supply point $s \in \mathcal{S}$. Labels are propagated forward from each supply point s to its delivery customers $i \in \mathcal{C}_s^D$ (delivery service zone) and backward to its pickup customers $j \in \mathcal{C}_s^P$ (pickup service zone). In particular, forward labels represent paths from s to i and backward labels represent paths from j to s. Each label includes information on its resource consumption (e.g., time, vehicle capacity), visited customers and reduced cost. Each label is iteratively considered and the corresponding path is extended to adjacent nodes. Note that, in the extension, we need to consider both the direct arc between two nodes and the possibility to stop at a waiting station in between.

Forward and backward labels belonging to zones of different supply points are joined in pairs to form complete legs. Before giving details on the label structure, we explain the main novelties of the dynamic programming algorithm.

As mentioned above, multi-trip, service zones and coordination features need to be carefully handled in the bi-directional extension of node labels. Since we have multi-trips and (delivery and pickup) customer demands associated with specific supply points, it is important to consider delivery and pickup service zone separately in the label extension and combine them through the joining of labels. This also allows to effectively deal with the dual values of the subset-row and rounded-capacity inequalities. Moreover, we need to consider the opportunity of visiting waiting stations when extending labels of a delivery or a pickup service zone, and when joining labels of different supply points. Another issue consists of the way to cope with coordination and time consumption. Due to the coordination constraints and to the additional flexibility of waiting at supply points or customers that we allow, a smaller time consumption is not necessarily an advantage when evaluating states of the dynamic programming: indeed, it might imply larger waiting costs when propagating to other nodes. On the other hand, a larger time consumption is clearly a limitation, as in classical routing problems with time windows, since it might inhibit to visit some nodes. Thus, there might be an infinite number of non-dominated states associated with the same path, having the same cost, but different time consumptions, obtained by delaying the departure time from a waiting station (or from the depot). To cope with this issue, we group them into a single label by introducing an additional resource ϕ representing the *forward shift* of the label, i.e., the amount of delay that can be introduced without violating the time window constraints of the visited customers. A similar concept has been proposed in Dabia et al. (2013) for the Time Dependent VRP.

Label structure. A label is a tuple $L = (i, \tau, \phi, RC, \chi, \Psi)$, where $i \in \mathcal{S} \cup \mathcal{C}^P \cup \mathcal{C}^D$ is the last customer or supply point reached, τ is the time consumption (i.e., the service starting time at i), ϕ is the forward shift, RC is the reduced cost, χ is the vehicle load, and Ψ is the set of visited customers.

Supply-point labels are initialized as follows:

- Forward label of supply point $s \in \mathcal{S}$ is $(i = s, \tau = t(s), \phi = 0, RC = -\gamma_s, \chi = 0, \Psi = \emptyset)$;
- Backward label of supply point $s \in \mathcal{S}$ is $(i = s, \tau = t(s), \phi = \eta, RC = \gamma_s, \chi = 0, \Psi = \emptyset)$;

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- Forward label of g is $(i = g, \tau = 0, \phi = +\infty, RC = F - \mu, \chi = 0, \Psi = \emptyset)$;
- Backward label of g is $(i = g, \tau = \infty, \phi = +\infty, RC = 0, \chi = 0, \Psi = \emptyset)$.

Both forward and backward labels of supply point $s \in \mathcal{S}$ have time consumption $\tau = t(s)$, since $t(s)$ is the time at which the vehicle starts the (loading/unloading) service at s. The reduced cost of the forward labels of supply point $s \in \mathcal{S}$ is initialized as $-\gamma_s$, since the leg departs from s towards the delivery customers, while one of the backward labels is initialized to γ_s, since the leg arrives at s after servicing the pickup customers. Notice that, since there are no time constraints on the departure and arrival times at the main depot, the labels associated with g have infinite forward shift. In addition, we associate with the forward label of g the fixed cost F of the vehicle minus the dual variable μ of constraint (1c).

Label propagation. We describe in detail the extension rules for forward labels, i.e., from a delivery customer label to another delivery customer label or from a supply point label to a delivery customer label. In both cases, beside this direct label extension, we consider the possibility of extending a label with a stop at a waiting station between the two customers or between the supply point and the customer. Similar rules are applied in the backward search. We refer the reader to the Appendix for more details.

When a label $L = (i, \tau, \phi, RC, \chi, \Psi)$, associated with node $i \in \mathcal{C}_s^D$, is extended to node $j \in \mathcal{C}_s^D$, the new label $L' = (j, \tau', \phi', RC', \chi', \Psi')$ is computed according to the following rules:

$$\tau' = \max\{\tau + \delta(i) + c_{ij}, e_j\} \tag{5a}$$

$$\phi' = \max\{0, \min\{\phi - \nu, l_j - \tau'\}\} \tag{5b}$$

$$RC' = RC + c_{ij} - \lambda_j + \sigma\omega \tag{5c}$$

$$\chi' = \chi + q_j \tag{5d}$$

$$\Psi' = \Psi \cup \{j\}, \tag{5e}$$

where $\nu = \max\{e_j - (\tau + \delta(i) + c_{ij}), 0\}$ is the waiting time and $\omega = \max\{\nu - \phi, 0\}$ is the waiting time reduced by ϕ, since ϕ can (partially or fully) absorb it. In label L', the time consumption τ is increased by the service time duration $\delta(i)$ at node i plus the routing time c_{ij} from i to j. If this value is smaller than e_j, then the vehicle will wait at node j, and the time consumption is set equal to e_j. The forward shift ϕ' (that must be greater or equal to zero) is set as the minimum between the previous forward shift ϕ decreased by waiting time ν and $l_j - \tau'$. Indeed, ϕ' is the remaining amount of delay, after visiting customer j, that can be introduced without violation of the time window constraints of the customers in Ψ'. The reduced cost is updated by adding the routing and waiting costs, and subtracting the dual variable λ_j of the visited customer j. Finally, the vehicle load is increased by the customer demand q_j, and j is added to the visited customers.

We show in Fig. 2 an example of forward label propagation: top, we can see the time window $[e_i, l_i]$ of label L and, bottom, the time window $[e_j, l_j]$ of label L'. In L, we have a time consumption τ and a forward shift ϕ. The arrow from τ indicates the arrival time at node j, i.e., $\tau + \delta(i) + c_{ij}$. As we can see, the vehicle arrives earlier than e_j and therefore must wait for time ν. However, the forward shift ϕ can be used to reduce the waiting time at j. Thus, the reduced cost RC' takes into account the waiting cost $\sigma\omega$. In this example, the new time consumption τ' is set to e_j, and the new forward shift ϕ' becomes zero.

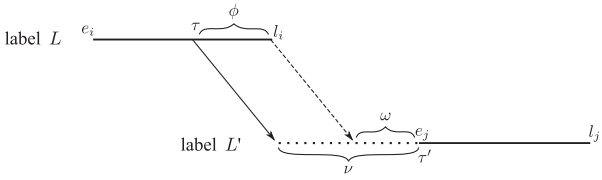

Fig. 2. Example of forward label propagation.

When a label $L = (i, \tau, \phi, RC, \chi, \Psi)$, associated with node $i \in \mathcal{S}$ is extended to node $j \in \mathcal{C}_s^D$, the same computation is performed except for the time consumption that is set to $\tau' = \max\{\tau + \varphi(i) + c_{ij}, e_j\}$.

As described earlier, vehicles can stop at waiting stations instead of going directly from one customer to another. If a label of customer i is extended to customer j through the waiting station w, the new label is computed as:

$$\tau' = \max\{\tau + \delta(i) + c_{iw} + c_{wj}, e_j\} \tag{6a}$$

$$\phi' = l_j - \tau' \tag{6b}$$

$$RC' = RC + c_{iw} + c_{wj} - \lambda_j \tag{6c}$$

$$\chi' = \chi + q_j \tag{6d}$$

$$\Psi' = \Psi \cup \{j\}. \tag{6e}$$

Note that, we need the routing cost $c_{iw} + c_{wj}$ for going from node i to the waiting station w and then to node j. In this case, the vehicle never waits at customer j (since it can wait at the waiting station at no cost), thus $\phi' = l_j - \tau'$. Given a pair of customers i and j, the most convenient waiting station where to stop is $\bar{w} \in \text{argmin}_{w \in \mathcal{W}}\{c_{iw} + c_{wj}\}$. This value $c_{iw} + c_{wj}$ does not depend on the dual variables. Hence, we precompute $\bar{w}$ for each pair of customers.

When a label $L = (i, \tau, \phi, RC, \chi, \Psi)$, associated with node $i \in \mathcal{S}$ is extended to node $j \in \mathcal{C}_s^D$ through the waiting station w, the same computation is performed except for the time consumption that is set to $\tau' = \max\{\tau + \varphi(i) + c_{iw} + c_{wj}, e_j\}$.

The label L' is feasible if

$$j \notin \Psi$$
$$\tau' \leq l_j$$
$$\chi' \leq Q.$$

At the end of the search phase, the legs associated with the feasible labels L' are analyzed to detect if the dual variables of the intra-zone subset-row inequalities have to be subtracted from their reduced costs: in particular, let $\mathcal{C}^*_{intra,\mathcal{D}}(s) = \left\{C \in \mathcal{C}_3^{intra,\mathcal{D}}(s) : \left|\Psi' \cap C\right| \geq 2\right\}$, i.e., $\mathcal{C}^*_{intra,\mathcal{D}}(s)$ is the set of all subsets of delivery customer demands of cardinality 3 that induce intra-zone subset-row inequalities, such that at least two delivery customer demands are visited by the partial leg corresponding to label L'. The reduced cost RC' is updated as $RC' - \sum_{C \in \mathcal{C}^*_{intra,\mathcal{D}}(s)} \rho_C$.

Join of forward and backward labels. In order to obtain complete (starting, ending or inter-facility) route legs, forward and backward labels of delivery and pickup service zones of different supply points are joined in pairs. In other words, the join operation is used to join a label of a delivery service zone of a supply point s with a label of a pickup service zone of a supply point s'. Let us consider the join between a label

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$L_{fw} = (i, \tau_{fw}, \phi_{fw}, RC_{fw}, \chi_{fw}, \Psi_{fw})$ of delivery customer $i \in \mathcal{C}_s^D$ and label $L_{bw} = (j, \tau_{bw}, \phi_{bw}, RC_{bw}, \chi_{bw}, \Psi_{bw})$ of pickup customer $j \in \mathcal{C}_{s'}^P$. The two labels L_{fw} and L_{bw} are compatible if

$$\tau_{fw} + \delta(i) + c_{ij} \leq \tau_{bw}.$$

Indeed, it is necessary that the service starting time τ_{fw} at i, plus the service time $\delta(i)$ and the routing cost c_{ij} from i to j, be smaller or equal to the service starting time τ_{bw} at j. Since the two labels are linked to different service zones, the two labels have visited disjoint sets of customers. Also, the vehicle load resources are always compatible: the forward label performs delivery operations, while the backward label performs pickup operations. Thus at the join point the vehicle is empty.

Let s and s' be the starting supply points of L_{fw} and L_{bw}, respectively, and let $\xi_{\mathcal{D}_s}$ and $\xi_{\mathcal{P}_{s'}}$ be the dual variables of the rounded capacity inequalities associated with the delivery service zone of s and with the pickup service zone of s', respectively. Also, let $\mathcal{C}^*_{inter}(s, s') = \left\{C \in \mathcal{C}_3^{inter}(s, s') : \left|(\Psi_{fw} \cup \Psi_{bw}) \cap C\right| \geq 2\right\}$, i.e., $\mathcal{C}^*_{inter}(s, s')$ is the set of all subsets of customer demands of cardinality 3 that induce inter-zone subset-row inequalities, such that at least two customer demands are visited by the leg, between s and s', that will result from the join of labels L_{fw} and L_{bw}.

The reduced cost of the route leg resulting from the join of L_{fw} and L_{bw} is

$$RC_{fw} - \xi_{\mathcal{D}_s} + c_{ij} + \sigma\omega - \xi_{\mathcal{P}_{s'}} + RC_{bw} - \sum_{C \in \mathcal{C}^*_{inter}(s,s')} \rho_C,$$

where ω denotes the necessary waiting time between i and j that cannot be absorbed by the forward shift of both labels. It is defined as

$$\omega = \max\{0, \tau_{bw} - (\tau_{fw} + c_{ij} + \delta(i)) - (\phi_{bw} + \phi_{fw})\}.$$

Indeed, the waiting time at node j is given by the difference between the service starting time τ_{bw} at j, minus the sum of the ending time of service $\tau_{fw} + \delta(i)$ at i, plus the routing time c_{ij} between the two nodes, reduced by the sum of the forward shifts $\phi_{fw} + \phi_{bw}$.

As previously, it is necessary also for the join to consider the possibility to stop at a waiting station $w \in \mathcal{W}$. In this case, the feasibility condition for the join is

$$\tau_{fw} + \delta(i) + c_{iw} + c_{wj} \leq \tau_{bw}$$

and the resulting reduced cost is

$$RC_{fw} - \xi_{\mathcal{D}_s} + c_{iw} + c_{wj} - \xi_{\mathcal{P}_{s'}} + RC_{bw} - \sum_{C \in \mathcal{C}^*_{inter}(s,s')} \rho_C.$$

Notice that, to obtain a complete starting leg, the join operation is applied between a backward label of a supply point $s \in \mathcal{S}$ and the label of g, while to obtain a complete ending leg the join operation is applied between the label of g and a forward label of a supply point $s \in \mathcal{S}$. After joining, we discard all the labels with $RC \geq 0$.

Dominance rules. Effective dominance rules, capable of fathoming a large number of labels, are a fundamental ingredient in a labeling algorithm for the RCESPP. As mentioned above, it is not easy to detect whether a larger time consumption is an advantage or a disadvantage when comparing labels. Hence, in principle, only labels with the same time consumption can be directly compared. This limitation significantly reduces the number of labels that can be fathomed. We use the two following dominance rules that combine the information on time consumption, cost and forward shift to compare labels with different time consumption. With Dominance Rule 1, we try to dominate a label L'' with a label L' by allowing to wait at the customer (if necessary), and thus paying the corresponding waiting cost. With Dominance Rule 2, we try to dominate a label L'' with a label L' by allowing to wait at a waiting station w. Recall that waiting at a waiting station is possible at any time and there is no restriction on the number of waiting stations visited. These two dominance rules are applied in sequence (one after the other) and guarantee that only dominated labels are removed. Note that the two dominance rules are independent of each other. More precisely, if at least one of the two rules can be applied, label L'' is dominated by label L' and can be removed.

Proposition 1 (Dominance Rule 1). *A forward label $L' = (i, \tau', \phi', RC', \chi', \Psi')$, with $i \in \mathcal{C}_s^D$, dominates a forward label $L'' = (j, \tau'', \phi'', RC'', \chi'', \Psi'')$ if*

$$\begin{cases} i = j \\ \tau' \leq \tau'' \\ RC' + \sigma \max\{0, \tau'' + \phi'' - (\tau' + \phi')\} \leq RC'' \\ \chi' \leq \chi'' \\ \Psi' \subseteq \Psi''. \end{cases} \tag{7}$$

The term $\sigma \max\{0, \tau'' + \phi'' - (\tau' + \phi')\}$ is the cost incurred by label L' to wait until time $\tau'' + \phi''$, the latest feasible service starting time for label L''. In other words, it is not enough to have $RC' \leq RC''$, since L'' might have more possibilities to delay without violating the time window constraints of the visited customers. Therefore, we consider the time needed in L' to reach the latest feasible service starting time of L'', and evaluate the corresponding waiting cost. If RC' increased by this cost is still smaller or equal to RC'', then L'' is dominated.

Proposition 2 (Dominance Rule 2). *A forward label $L' = (i, \tau', \phi', RC', \chi', \Psi')$, with $i \in \mathcal{C}_s^D$, dominates a forward label $L'' = (j, \tau'', \phi'', RC'', \chi'', \Psi'')$ if*

$$\begin{cases} i = j \\ \tau' + \max_{h \in \mathcal{C}_s^D} \{\min_{w \in \mathcal{W}} \{c_{iw} + c_{wh} - c_{ih}\}\} \leq \tau'' \\ RC' + \max_{h \in \mathcal{C}_s^D} \{\min_{w \in \mathcal{W}} \{c_{iw} + c_{wh} - c_{ih}\}\} \leq RC'' \\ \chi' \leq \chi'' \\ \Psi' \subseteq \Psi''. \end{cases} \tag{8}$$

Here, $\max_{h \in \mathcal{C}_s^D} \{\min_{w \in \mathcal{W}} \{c_{iw} + c_{wh} - c_{ih}\}\}$ is the maximum routing time (and cost) over all possible next customers $h \in \mathcal{C}_s^D$, which can be reached by visiting a waiting station before h. Dominance Rule 2 is used to dominate labels by considering the possibility of visiting a waiting station from the current node i before visiting the next node h. Instead of directly going from node i to node h (at cost c_{ih}), we consider the possibility of going from node i to the best waiting station for pair i, h (at cost $c_{iw} + c_{wh}$). If the time consumption τ' increased by the maximum additional routing time towards/from the waiting station is still smaller or equal to τ'' and the reduced cost RC' increased by the maximum additional routing cost is still smaller or equal to RC'', then L'' is dominated. The waiting station is chosen such that it is the most convenient for customers i and h, and the additional routing time (and cost) to reach customer h through the waiting station is chosen as the maximum one among all possible customers (since L' dominates L'' only if the *worst* situation is considered). Note that it is always possible to go to a waiting station later than immediately after customer i, but, since waiting stations have no limit on the number of visits, we can dominate label L'' as described above without checking what happens afterwards.

Similar dominance rules can be defined for backward labels. Dominance rules are applied during the label propagation, i.e., we check if a label is dominated by other labels before extending it.

Filtering final labels. Once the label propagation phase is terminated, and before applying the join operation, it is possible to filter the final labels using more effective dominance rules, which require weaker conditions to be satisfied. In particular, it is possible to drop conditions on the load of the vehicle and on the

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set of visited customer demands. By removing these conditions, we are able to dominate additional labels. Recall that join is applied to combine a label of a delivery service zone and a label of a pickup service zone. Therefore, joining occurs with an empty vehicle and it is not necessary to check the vehicle load for final labels. In addition, forward and backward propagations operate on disjoint sets of customer demands and, thus, joining a forward label and a backward label never causes visiting a customer demand more than once. This allows removing the condition on the visited customer set. However, since inter-zone inequalities are used, they must be taken into account in this phase. Indeed, these inequalities contribute to increase the reduced cost. In particular, we add to the labels an additional resource α_C for each inequality $C \in \cup_{s' \in \mathcal{S}, s' \neq s} \mathcal{C}_3^{inter}(s, s')$, where $s \in \mathcal{S}$ is the supply point of the considered label. The value of α_C represents the number of customer demands of the considered label that are involved in inequality C. We apply the following rule for the filtering of final labels: A forward final label $L' = (i, \tau', \phi', RC', \chi', \Psi')$, with $i \in \mathcal{C}_s^D$, dominates a forward final label $L'' = (j, \tau'', \phi'', RC'', \chi'', \Psi'')$ if

$$\begin{cases} i = j \\ \tau' \leq \tau'' \\ RC' + \sigma \max\{0, \tau'' + \phi'' - (\tau' + \phi')\} \leq RC'' \\ \alpha'_C \leq \alpha''_C \quad \forall C \in \cup_{s' \in \mathcal{S}, s' \neq s} \mathcal{C}_3^{inter}(s, s'). \end{cases} \tag{9}$$

In other words, it is not necessary to check that $\Psi' \subseteq \Psi''$, but only that $\alpha'_C \leq \alpha''_C$, $\forall C \in \cup_{s' \in \mathcal{S}, s' \neq s} \mathcal{C}_3^{inter}(s, s')$. Indeed, if the number α'_C of customer demands involved in an inter-zone inequality C for label L' is smaller or equal to the number α''_C of customer demands involved in the same inequality for label L'', the contribution of the dual variable ρ_C is either the same in both labels or it is larger for L''. Thus, since $\rho_C \leq 0$, this ensures dominance of L' over L'', provided that the other conditions above are satisfied.

4.4. Heuristic pricing algorithm

In order to speed-up the column generation procedure, we developed a heuristic pricing algorithm (HP). It is similar to the exact pricing algorithm described in Section 4.3, but uses relaxed dominance rules to fathom a larger number of non-promising labels. More precisely, the check on the set of visited customers $\Psi' \subseteq \Psi''$ is removed from both rules (7) and (8). HP is used to quickly find negative reduced cost legs. We noticed, during preliminary experiments, that the failure rate of HP in finding negative reduced cost columns increases when subset-row inequalities are added to the master problem. Hence, we use HP in the initial iterations of column generation and stop calling it as subset-row inequalities are generated. Clearly, the exact pricing algorithm is applied to derive a valid lower bound, when HP is not able to find a negative reduced cost column.

4.5. Branching rules

We consider three branching rules to be applied alternatively when a fractional solution is found. The first one limits the total number of vehicles, the second one imposes bounds on the number of vehicles visiting a supply point, and the third branching rule fixes or forbids an arc.

Let $\nu = \sum_{l \in \mathcal{L}^+(g)} x_l$ be the number of vehicles used in the optimal solution of the linear relaxation master problem. When ν is fractional, we impose in one branch to use at most $\lfloor \nu \rfloor$ and at least $\lceil \nu \rceil$ vehicles in the other. This branching decision can be enforced by introducing a constraint of the form

$$\sum_{l \in \mathcal{L}^+(g)} x_l \leq \lfloor \nu \rfloor$$

or

$$\sum_{l \in \mathcal{L}^+(g)} x_l \geq \lceil \nu \rceil$$

in the master problem and it does not affect the structure of the pricing problem. Indeed, we have an additional constraint whose dual variable can be taken into account, in a similar way as variable μ, in the initialization of the forward and backward labels of the depot g.

When an integer number of vehicles is used, we search for a supply point $\bar{s} \in \mathcal{S}$ visited by a fractional number of vehicles. Let $\nu_s = \sum_{l \in \mathcal{L}^+(s)} x_l$ be the number of vehicles visiting supply point $s \in \mathcal{S}$ in the optimal solution of the linear master problem; we perform a binary branching similar to the previous case, by adding to the master problem one of the following constraints in each child subproblem:

$$\sum_{l \in \mathcal{L}^+(\bar{s})} x_l \leq \lfloor \nu_{\bar{s}} \rfloor$$

or

$$\sum_{l \in \mathcal{L}^+(\bar{s})} x_l \leq \lceil \nu_{\bar{s}} \rceil.$$

When there are multiple supply points with fractional vehicle flow, the one with the fractional part closest to 0.5 is selected, as it often yields a stronger effect on the fractional solution when branching. The structure of the pricing problem is not destroyed in this case as well.

When no supply point has fractional vehicle flow, we branch on the arc selection. We compute the flow on the arcs corresponding to the optimal fractional solution of the master problem, and select the arc (i, j) whose flow is the closest to 0.75. Arcs with integer flow are not considered. Arc (i, j) is forbidden in one branch. The arc is then removed from $\mathcal{G}$ and, in the dynamic programming procedure, labels of node i will not be extended to node j. In this way, the pricing algorithm will not produce any route leg containing (i, j). All the variables already present in the master problem associated with route legs visiting i and j in sequence (even if stopping at a waiting station in between) are discarded as well. We impose to use arc (i, j) in the second branch. This is enforced by removing from $\mathcal{G}$ the arcs (i, j') for $j \neq j'$ and by removing from the master problem all the variables associated with route legs vising vertex i followed by a vertex different from j. Since this branching rule has generally a weaker impact on fractional solutions, it is only used when the two previous rules cannot be applied.

5. Experimental analysis

The aim of our experiments is to analyze the performance of the proposed Branch-and-Cut-and-Price algorithm. In particular, we first evaluate the impact of the proposed zone-based subset-row and zone-based rounded capacity inequalities on the computation of the lower bound at the root node (Section 5.2). Then, we report the results obtained by the Branch-and-Cut-and-Price algorithm (Section 5.3). Finally, in Section 5.4, we consider other problem settings of MT-PDTWCF.

The algorithm described in Section 4 has been implemented in C++ using SCIP 4.0.1, linked to CPLEX 12.6.1, as a Branch-and-Cut-and-Price framework. All parameters are set at their default values, except from preprocessing and automatic cut generation that are not used. All experiments are executed on an Intel i7-3820, 3.6 gigahertz workstation by using a single core.

5.1. Test instances

We generated seven sets of 10 problem instances, using the same parameters proposed in Crainic et al. (2015b) and

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Table 1
Datasets description.

Dataset	$\|\mathcal{S}\|$	#ws	#cust/zone	#cust dem	#pc	#dc
D1	5	5	5	50	25	25
D2	5	5	7	70	35	35
D3	5	5	9	90	45	45
D4	5	5	6	60	30	30
D5	10	5	6	120	60	60
D6	15	5	6	180	90	90
E1	10	5	10	200	100	100

Nguyen et al. (2017). The first three sets, called D1-D3, have the same number of supply points and different number of customers per service zone. The following three sets, called D4-D6, instead, have the same number of customers per service zone, but a different number of supply points. Finally, the last set, called E1, has 10 supply points and an average of 10 pickup and 10 delivery demands for each service zone. We decided to identify the last set with a different letter, because the larger number of customers per service zone makes them considerably more difficult than the previous six sets.

We consider a square of size 200 where customers, supply points, and waiting stations are uniformly distributed. The opening time of the supply points is randomly generated in the interval [0,14400]. The parameters η and φ, representing, respectively, the length of the time window of each supply point and the time needed for all loading and unloading operations of a vehicle at a supply point, are set to 100 and 30 respectively. The number of vehicles m is set to 50. The travel times are computed as the Euclidean distances between customers and supply points.

Customers are assigned to supply points based on their proximity. More precisely a customer is assigned to its first, second, third and fourth nearest supply point with probability 0.5, 0.25, 0.15, and 0.1, respectively. The ready time of a delivery customer is computed as the sum of the opening time of the corresponding supply point, the loading time at the supply point, the routing time between the supply point and the customer, and a random value in the interval [0,300]. The time window duration is uniformly selected in the [150,450] range. Similarly, the due date of a pickup customer is generated by subtracting the service time at the customer, the routing time from the customer to the supply point, and a random value in the interval [0,300] from the opening time of the supply point. The service time of all customers is set to 20. The demand of each customer is randomly generated in the interval [5,25] and the vehicle capacity is set to 100. The main depot is set at the middle point of the square. A fixed cost $F = 500$ is accounted for each vehicle used. Waiting at customer and supply points is allowed with a penalty $\sigma = 0.5$. All parameters used for generating these instances are the same as in Crainic et al. (2015b) and Nguyen et al. (2017), except from the waiting cost σ that has been introduced to adapt the instances to MT-PDTWCF.

The description of the datasets is summarized in Table 1. In particular, we report the name of the dataset, the number $\mathcal{S}$ of supply points, the number of waiting stations (#ws), the number of (delivery or pickup) customer demands per zone (#cust/zone), the total number of delivery and pickup customer demands (#cust dem), the number of pickup customer demands (#pc) and the number of delivery customer demands (#dc).

The time limit was set to one hour in all tests with D1-D6 and to two hours in all tests with E1.

5.2. Lower bound

We have considered four configurations: the linear relaxation of model (1) without any additional cut (no cuts in Table 2), with zone-based subset-row inequalities (ZSR3), with zone-based rounded-capacity inequalities (ZCAP), and with both. The results are summarized in Table 2. The average percentage gap with respect to the optimal solution values and the average computing time, expressed in seconds, are reported for each configuration and each class of instances. In addition, we display the number of zone-based subset-row inequalities that are generated in configurations ZSR3 and ZSR3+ZCAP. We report in the last row the average values of gaps and computing times over all classes of instances.

Without valid inequalities, the linear relaxation of model (1) gives a rather weak bound (the average gap is 8.67% on all instances). Zone-based subset-row inequalities are able to considerably improve the lower bound, reducing the average gap to 1.17%, but the computing times increase, especially on class D3 and E1 (recall that we allow two hours of time limit for E1 instances, and one hour for D instances). The zone-based rounded-capacity inequalities are also effective in reducing the duality gap, even if not as much as ZSR3, and the computing time often decreases. We recall that such inequalities are added to the master problem since the beginning and they seem to significantly help a fast convergence of the column generation procedure. We achieve the strongest bound (the average gap is about 0.5%) within reasonable computing times (292 seconds on average) using both types of inequalities (2) and (3). As it can be seen from Table 2, the proposed valid inequalities are crucial to allow solving the problem to optimality. Indeed, the average gap reduces from 8.67% to 0.52%, thus significantly limiting the number of branch-and-bound nodes that need to be explored, as it will be shown in Section 5.3. We also observe that the number of zone-based subset-row inequalities generated in configuration ZSR3 is larger than the corresponding number in configuration ZSR3+ZCAP (almost double on average). Therefore, zone-based rounded-capacity inequalities help reducing the number of dynamically added cuts, and, hence, the computing time.

As frequently happens with exact algorithms, the variance of the gap values reported in Table 2 can be large. However, we observed a drastic reduction of the variance when the valid inequalities are present. Hence, the configuration with both ZSR3 and ZCAP is the one we used in the Branch-and-Cut-and-Price algorithm.

5.3. Branch-and-Cut-and-Price

Table 3 reports the results obtained on the seven classes of instances by the Branch-and-Cut-and-Price algorithm described in Section 4. We report for each class of instances, the average gap and computing time at the root node, the average gap when the time limit is reached, the average number of explored nodes for the solved instances, the average computing time for the solved instances, the average computing time (timep) for solving the pricing problems for the solved instances, and the number of instances solved to optimality by the proposed Branch-and-Cut-and-Price algorithm (BCP).

All the instances of sets D1 to D6 could be solved to optimality within the time limit of 1 hour, exploring a small number of nodes: 44 instances out of 60 are closed at the root node, and a maximum of 9 nodes are explored. This feature often appears in the exact solution of difficult combinatorial problems as the VRP, where either the root node gap is very small (e.g., below 1%) or the problem can hardly be solved to optimality. In our case, the use of the proposed valid inequalities is very important and allows solving to optimality many instances.

All instances of set E1 were solved to optimality within the time limit of two hours. In particular, all instances but E1-10 were solved to optimality within one hour time limit with an average computing time of 1663 seconds, while E1-10 required 4511 seconds. The average computing time is about one order of magnitude

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Table 2
Lower bound evaluation: results obtained by solving the linear relaxation without using any cut, with zone-based subset-row inequalities (ZSR3), with zone-based rounded-capacity inequalities (ZCAP), and with both types of inequalities.

Class	No cuts		ZSR3			ZCAP		ZSR3+ZCAP		
	Gap%	Time (second)	Gap	Time (second)	#cuts	Gap%	Time (second)	Gap%	Time (second)	#cuts
D1	6.83	0.17	1.40	0.89	16.6	1.99	0.16	0.00	0.60	10.6
D2	11.62	0.91	0.68	16.91	136.4	2.59	0.58	0.39	2.98	45.4
D3	8.65	7.37	1.04	238.82	199.6	5.24	5.03	1.03	150.47	150.6
D4	10.59	0.39	1.44	5.06	55.1	1.30	0.32	0.52	0.55	9.9
D5	8.28	2.42	1.24	12.44	98.9	2.23	1.57	0.84	2.70	19.7
D6	7.87	7.96	0.86	28.87	148.8	2.20	5.57	0.63	9.76	39.5
E1	6.83	158.61	1.51	3042.55	355.0	4.15	122.14	0.26	1878.38	254.1
Avg. all	8.67	25.40	1.17	477.93	144.34	2.81	19.34	0.52	292.21	75.69

Table 3
Results of the Branch-and-Cut-and-Price algorithm on MT-PDTWCF.

Class	Lower bound		BCP				
	Gap%	Time (second)	Gap%	#nodes	Time (second)	Timep (second)	#solved
D1	0.00	0.60	0.00	1.0	0.61	0.37	10
D2	0.39	2.98	0.00	1.4	3.05	2.08	10
D3	1.03	150.47	0.00	2.4	167.61	144.82	10
D4	0.52	0.55	0.00	1.4	0.58	0.30	10
D5	0.84	2.70	0.00	2.4	2.98	1.32	10
D6	0.63	9.76	0.00	2.0	10.21	3.96	10
E1	0.26	1878.38	0.00	1.6	1947.57	1848.50	10

larger than the longest computing time of the D instances. The algorithm seems to be more sensitive to the size of the service zones than to the number of supply points. This is not surprising. The coordination constraints force to use more strict dominance rules in the dynamic programming procedure. In fact, having consumed a shorter amount of time is not necessarily an advantage. Thus, less labels can be fathomed out and the dynamic programming procedure becomes more time consuming with respect to classical VRP problems.

We observe that most of the computing time is spent in solving the pricing problems, as often happens when applying column generation based methods to the VRP and its variants. In addition, we mention that, although we allow the generation of zone-based subset-row inequalities during the exploration of the decision tree, only a very small number (at most 10) of cuts is generated after the root node.

5.4. Other problem settings

5.4.1. No-wait policy

In the MT-PDTWCF a penalty σ is incurred for each time unit of waiting at customers or supply points. We investigated also the case in which waiting is completely forbidden, i.e., $\sigma = \infty$, since it is a realistic setting for congested city centers. We still allow waiting at waiting stations. In this setting, Dominance Rule 1 (7) is less effective since it always fails if $\tau' + \phi' < \tau'' + \phi''$. To improve the performance of the labeling algorithm, it is convenient to block a label extension if

$$\tau' + \phi' + \delta(i) + c_{ij} < e_j.$$

This means that we avoid propagating a label from node i to node j if it implies waiting at the customer j. Of course it is still possible to extend the label from i to j through a waiting station.

The results obtained on the seven classes of instances are summarized in Table 4. The table has the same structure of the previous one. The Branch-and-Cut-and-Price algorithm is again able to solve all the 60 instances in classes D1 to D6. Seven instances in class E1 could be solved within the time limit of two hours. However, for three E1 instances the algorithm was still processing the root node after two hours of computing time: in this case, the quality of the heuristic solution obtained by SCIP was very poor. Indeed, we can observe that the number of nodes to determine the optimal solution is usually rather small, and many instances can directly be solved to optimality at the root node. When the root node computation is completed, finding a good quality heuristic solution turns out to be easier for the SCIP solver. However, the solution process of the root node requires long computing times for the E1 instances and this leads to larger gaps. E1 instances are more difficult mainly due to the larger number of customers in each service zone: this difficulty is more evident in this setting due to the weakness of dominance rule (7), as explained above.

Table 4
Results of the Branch-and-Cut-and-Price algorithm with no-wait policy.

Class	Lower bound		BCP			
	Gap%	Time (second)	Gap%	#nodes	Time (second)	#solved
D1	0.00	0.61	0.00	1.0	0.62	10
D2	0.36	2.67	0.00	1.4	2.75	10
D3	0.83	207.40	0.00	2.2	233.88	10
D4	0.55	0.48	0.00	1.6	0.51	10
D5	0.92	2.21	0.00	3.4	2.95	10
D6	0.58	8.90	0.00	114.9	33.69	10
E1	19.35	4683.41	19.08	2.7	3865.63	7

Table 5
Results of the Branch-and-Cut-and-Price algorithm on the configuration in Nguyen et al. (2017).

Class	Lower bound		BCP			
	Gap%	Time (second)	Gap%	#nodes	Time (second)	#solved
D1	0.38	0.12	0.00	3.80	0.14	10
D2	0.86	11.56	0.00	393.30	76.31	10
D3	1.12	2046.65	0.9	2.71	1622.75	7
D4	0.38	0.37	0.00	2.0	0.42	10
D5	0.51	3.43	0.00	413.70	26.80	10
D6	0.72	6.53	0.00	534.30	42.46	10

5.4.2. Configuration of Nguyen et al. (2017)

We have experimented the behavior of the Branch-and-Cut-and-Price algorithm with a third problem setting, where the stop

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Table 6
Solution characteristics for the three problem settings.

Class	#v	#l	#l/v	#Mc/l	Fixed cost	Routing cost	Waiting cost
Standard setting							
D1	2.2	7.6	3.5	11	1100.0	1535.9	79.6
D2	3.0	12.4	4.3	13	1500.0	1942.6	59.9
D3	3.1	13.2	4.5	14	1550.0	2205.6	81.2
D4	2.6	10.0	4.0	13	1300.0	1788.5	33.3
D5	3.2	17.9	6.1	12	1600.0	3146.2	98.8
D6	4.5	27.3	6.2	12	2250.0	4212.4	200.4
E1	5.3	25.6	5.1	15	2650.0	4011.4	219.3
No wait setting							
D1	2.2	7.7	3.6	10	1100.0	1685.1	0.0
D2	3.0	12.4	4.3	14	1500.0	2069.7	0.0
D3	3.1	13.1	4.5	14	1550.0	2351.7	0.0
D4	2.6	10.0	4.0	13	1300.0	1846.7	0.0
D5	3.2	17.9	6.1	12	1600.0	3332.7	0.0
D6	4.5	27.4	6.2	12	2250.0	4576.0	0.0
E1	5.3	25.7	5.1	15	2642.9	4450.1	0.0
Configuration of Nguyen et al. (2017)							
D1	3.8	9.5	2.6	10	1900.0	1482.4	548.0
D2	6.4	16.2	2.6	13	3200.0	1842.2	536.9
D3	6.1	16.7	2.8	13	3071.4	2140.4	887.5
D4	4.3	11.6	2.8	12	2150.0	1730.0	568.0
D5	6.4	22.2	3.6	12	3200.0	3061.8	1475.0
D6	7.2	33.4	5.0	12	3600.0	4336.7	1853.3

at waiting stations is possible only immediately before going to a supply point. Waiting at customer and supply points is allowed with a penalty ($\sigma = 0.5$). This setting corresponds to the one used in Nguyen et al. (2017). In this setting, we insert a cutoff given by the upper bound computed by the tabu search proposed in Nguyen et al. (2017). The obtained results are reported for D instances in Table 5. We can see that all but three instances in class D3 are solved to optimality. This class is the most difficult for BCP in this setting, since it has the largest number of customers in each service zone. We do not report the results for the E1 instances, since the algorithm did not succeed in computing the lower bound for most of the E1 instances within two hours of computing time. Restricting the possibility of going to a waiting station only right before a supply point creates more opportunities to trade waiting costs with routing costs in the dynamic programming, thus making the dominance rule less effective.

5.5. Solution analysis

We analyze the characteristics of the optimal solutions obtained for the three problem settings. In particular, we report in Table 6, for each of the three problem settings considering only the instances solved to optimality, the average number #v of used vehicles, the average number #l of performed legs, the average number #l/v of legs per vehicle, the maximum number #Mc/l of customers per leg, the average fixed cost, routing cost and waiting cost.

We can see that the average numbers of used vehicles and legs are similar in the standard and in the no wait settings. However, larger routing costs clearly arise in the latter setting, since waiting at customers and supply point is forbidden, and the vehicle needs to travel to a waiting station. We also observe that, for all classes, the total routing and waiting cost in the standard setting is smaller (about 3% on average) than the routing cost in the no wait setting. Therefore, the flexibility of waiting at customers and supply points at a given cost can help reducing the total cost and the number of vehicles.

When it is allowed to go to a waiting station only right before a supply point (i.e., the setting used in Nguyen et al. (2017)), the number of used vehicles and fixed costs significantly increase (about 40% on average). In addition, the number of legs also increases, and each vehicle performs a smaller number of legs. This is not desirable, as it can also increase the traffic congestion. In addition, even the total routing and waiting cost is larger in this setting than in the standard setting (more than 20% on average).

6. Conclusion and future work

We studied the Multi-trip Separate Pickup and Delivery Problem with Time Windows at Customers and Facilities, arising in two-tiered city logistics systems, which includes several practical features such as multi-trip, pickup and delivery customers, and coordination of vehicle arrivals and time windows at customers and facilities. The problem was introduced by Nguyen et al. (2017), where a tabu search algorithm was proposed. We extended the problem with the possibility of waiting at waiting stations at any stage, as well as waiting at customers and facilities at a given cost. We proposed an Integer Linear Programming model with exponentially many variables, and a Branch-and-Cut-and-Price algorithm, the first exact method for this class of problems. In this algorithm, column generation is applied to derive a lower bound on the optimal solution value, the pricing problem, which consists of an Elementary Shortest Path Problem with Resource Constraints, being solved by a bi-directional dynamic programming algorithm, tailored for the problem at study. Valid inequalities, extended from the subset-row and rounded capacity inequalities, are embedded in the Branch-and-Cut-and-Price. To speed-up the solution process, we propose effective dominance rules, label filtering, and a heuristic dynamic programming algorithm.

We tested a set of instances including up to 200 customers by considering three problem settings that differ for the possibility of waiting at customers and supply points. The obtained results show that, for the general setting in which waiting is allowed at customers and supply points at a given cost, the proposed Branch-and-Cut-and-Price algorithm is able to solve to optimality all instances with up to 180 customers within one hour of time limit, and all instances with up to 200 customers in two hours of time limit. As explained in the computational results, not only the total number of customers affects the performance of the proposed algorithm, but especially the number of customers per service zone, which is 10 for the instances with 200 customers. When waiting is not allowed at customers and supply points, all instances with up to 180 customers are solved to optimality within one hour of time

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limit, while three instances with 200 customers remain unsolved. The setting in which waiting at customers and supply points is allowed at a given cost, but it is possible to use a waiting station only right before a supply point, turns out to be the most difficult one: three instances with 90 customers and 9 customers per service zone remain unsolved, even though with a small average optimality gap.

The analysis of the characteristics of the obtained solutions suggests that waiting at customers and supply points is a real-world feature that can be easily handled by the proposed algorithm. With respect to the no wait policy, smaller routing costs arise when waiting is allowed. In addition, going to a waiting station only right before a supply point is more restrictive and can cause larger global costs. Therefore, the introduced flexibility of waiting at customers and supply points at a given cost, and going to a waiting station at any time, can help reducing costs and traffic congestion. Future research will be dedicated to study further extensions of the two-tiered city logistics systems, by including additional real-world features and taking into account stochastic elements, such as uncertainty in the customer demand and in the routing time.

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Appendix A. Notation

g	the main depot
m	number of vehicles
Q	vehicle capacity
F	vehicle fixed cost
T	planning horizon
$\mathcal{S}$	set of supply points
$[t(s)-\eta, t(s)]$	time window of supply point $s \in \mathcal{S}$
$\varphi(s)$	time for loading/unloading operations at $s \in \mathcal{S}$
$\mathcal{C}^D$	set of delivery-customer demands
$\mathcal{C}^P$	set of pickup-customer demands
$\mathcal{C}^D_s$	subset of delivery-customer demands served by $s \in S$ (delivery service zone of s)
$\mathcal{C}^P_s$	subset of pickup-customer demands served by $s \in S$ (pickup service zone of s)
q_i	delivery or pickup quantity at customer demand $i \in \mathcal{C}^D \cup \mathcal{C}^P$
$\delta(i)$	service time at customer demand $i \in \mathcal{C}^D \cup \mathcal{C}^P$
$[e_i, l_i]$	time window of customer $i \in \mathcal{C}^D \cup \mathcal{C}^P$
$\mathcal{W}$	set of waiting stations
σ	unit waiting-time cost
$\mathcal{G}=(\mathcal{V},\mathcal{A})$	directed graph
c_{ij}	routing cost and time of arc $(i,j) \in \mathcal{A}$
$\mathcal{L}$	set of feasible starting, ending and inter-facility route legs
$\mathcal{L}^+(s)$	set of route legs starting from $s \in \mathcal{S} \cup \{g\}$
$\mathcal{L}^-(s)$	set of route legs ending at $s \in \mathcal{S} \cup \{g\}$
$\mathcal{L}^+(g)$	set of route legs starting from g

(continued on next page)

a_{il}	binary coefficient assuming value 1 if customer demand $i \in \mathcal{C}^D \cup \mathcal{C}^P$ is visited by leg $l \in \mathcal{L}$
x_l	binary variable assuming value 1 if leg $l \in \mathcal{L}$ belongs to a work assignment
$\mathcal{V}_l$	set of nodes visited by leg $l \in \mathcal{L}$
$\mathcal{V}^C_l$	set of customer demand nodes visited by leg $l \in \mathcal{L}$
$\mathcal{V}^S_l$	set of supply point nodes visited by leg $l \in \mathcal{L}$
$\mathcal{V}^W_l$	set of waiting station nodes visited by leg $l \in \mathcal{L}$
$\mathcal{A}_l$	set of arcs belonging to leg $l \in \mathcal{L}$
T_l	set of arrival time instants at each node $i \in \mathcal{V}_l$, $l \in \mathcal{L}$
θ_i	arrival time instant at node $i \in \mathcal{V}^C_l \cup \mathcal{V}^S_l$
c_l	routing cost of leg $l \in \mathcal{L}$
w_l	waiting cost of leg $l \in \mathcal{L}$
π_l	routing and waiting cost of leg $l \in \mathcal{L}$
λ_i	dual variables associated with covering constraints, $i \in \mathcal{C}^D \cup \mathcal{C}^P$
μ	dual variable associated with the fleet size constraint
γ_s	dual variables associated with flow conservation constraints, $s \in \mathcal{S}$
$\mathcal{C}_3$	set of all subsets of customer demands of cardinality 3
$\mathcal{L}(C)$	set of legs visiting at least two customer demands in $C \in \mathcal{C}_3$
ρ_C	dual variables associated with zone-based subset-row inequalities, $C \in \mathcal{C}_3$
$\mathcal{C}_3^{intra,\mathcal{P}}(s)$	set of subsets of pickup customer demands of cardinality 3 that induce intra-zone inequalities, $s \in \mathcal{S}$
$\mathcal{C}_3^{intra,\mathcal{D}}(s)$	set of subsets of delivery customer demands of cardinality 3 that induce intra-zone inequalities, $s \in \mathcal{S}$
$\mathcal{C}_3^{inter}(s,s')$	set of subsets of customer demands of cardinality 3 that induce inter-zone inequalities, $s, s' \in \mathcal{S}$
$\xi_{\mathcal{P}_s}$	dual variables associated with rounded capacity inequalities on a pickup service zone
$\xi_{\mathcal{D}_s}$	dual variables associated with rounded capacity inequalities on a delivery service zone
τ	time consumption associated with a label
ϕ	forward shift associated with a label
RC	reduced cost associated with a label
χ	vehicle load associated with a label
Ψ	set of visited customers associated with a label

Appendix B. Backward propagation

We here present the extension rules for backward labels, i.e., from a pickup customer label to another pickup customer label or from a supply point label to a pickup customer label. In both cases, beside this direct label extension, we consider the possibility of extending a label with a stop at a waiting station between the two customers or between the supply point and the customer. We recall that, in the forward propagation described in Section 4.3, the forward shift represents the amount of delay that can be introduced without violating the (end of the) time window constraints of the visited customers. On the contrary, in the backward propagation, it corresponds to the amount of anticipation that can be introduced without violating the (beginning of the) time window constraints of the visited customers. Therefore, we call it backward shift.

When a label $L=(i,\tau,\phi,RC,\chi,\Psi)$, associated with node $i \in \mathcal{C}^P_s$, is extended to node $j \in \mathcal{C}^P_s$, the new label $L'=(j,\tau',\phi',RC',\chi',\Psi')$ is computed according to the following rules:

$$\tau' = \min\{\tau - \delta(j) - c_{ji}, l_j\} \tag{10a}$$

$$\phi' = \max\{0, \min\{\phi - \nu, \tau' - e_j\}\} \tag{10b}$$

$$RC' = RC + c_{ji} - \lambda_j + \sigma\omega \tag{10c}$$

$$\chi' = \chi + q_j \tag{10d}$$

$$\Psi' = \Psi \cup \{j\}, \tag{10e}$$

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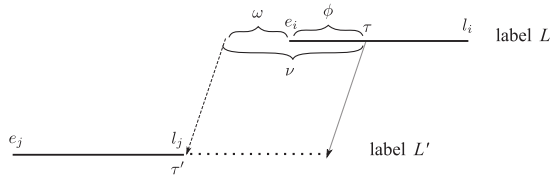

Fig. 3. Example of backward label propagation.

where $\nu = \max\{\tau - \delta(j) - c_{ji} - l_j, 0\}$ is the waiting time and $\omega = \max\{\nu - \phi, 0\}$ is the waiting time reduced by ϕ, since ϕ can (partially or fully) absorb it. In label L', the time consumption τ is decreased by the sum of the service time duration $\delta(j)$ at node j and the routing time c_{ji} from j to i. If this value is larger than l_j, then the vehicle will wait at node i, and the time consumption is set equal to l_j. The backward shift ϕ' (that must be greater or equal to zero) is set as the minimum between the previous backward shift ϕ decreased by waiting time ν and $\tau' - e_j$. Indeed, ϕ' is the remaining amount of anticipation, after visiting customer j, that can be introduced without violation of the time window constraints of the customers in Ψ'.

We show in Fig. 3 an example of backward label propagation: top, we can see the time window $[e_i, l_i]$ of label L and, bottom, the time window $[e_j, l_j]$ of label L'. In L, we have a time consumption τ and a backward shift ϕ. The arrow from τ indicates the arrival time at node j, i.e., $\tau - \delta(j) - c_{ji}$. As we can see, the vehicle would arrive later than l_j and therefore must wait at customer i for time ν. However, the backward shift ϕ can be used to reduce the waiting time at i. Thus, the reduced cost RC' takes into account the waiting cost $\sigma\omega$. In this example, the new time consumption τ' is set to l_j, and the new backward shift ϕ' becomes zero.

When a label $L = (i, \tau, \phi, RC, \chi, \Psi)$, associated with node $i \in \mathcal{S}$ is extended to node $j \in \mathcal{C}_s^P$, the same computation as above is performed: indeed the loading/unloading time does not need to be considered when we propagate in the backward direction from a supply point to a customer.

As in the forward propagation, we consider that vehicles can stop at waiting stations instead of going directly from one customer to another. If a label of customer i is extended to customer j through the waiting station w, the new label is computed as:

$$\tau' = \min\{\tau - \delta(j) - c_{jw} - c_{wi}, l_j\} \tag{11a}$$

$$\phi' = \tau' - e_j \tag{11b}$$

$$RC' = RC + c_{jw} + c_{wi} - \lambda_j \tag{11c}$$

$$\chi' = \chi + q_j \tag{11d}$$

$$\Psi' = \Psi \cup \{j\}. \tag{11e}$$

As in the forward propagation, we consider the routing cost which is now $c_{jw} + c_{wi}$ for going from node j to the waiting station w and then to node i. In addition, the vehicle never waits at customer i (since it can wait at the waiting station at no cost), thus $\phi' = \tau' - e_j$.

When a label $L = (i, \tau, \phi, RC, \chi, \Psi)$, associated with node $i \in \mathcal{S}$ is extended to node $j \in \mathcal{C}_s^P$ through the waiting station w, the same computation as above is performed.

References

Baldacci, R., Mingozzi, A., & Roberti, R. (2011). New route relaxation and pricing strategies for the vehicle routing problem. *Operations research, 59*(5), 1269–1283.

Bettinelli, A., Ceselli, A., & Righini, G. (2014). A branch-and-price algorithm for the multi-depot heterogeneous-fleet pickup and delivery problem with soft time windows. *Mathematical Programming Computation, 6*(2), 171–197.

Bulhoes, T., Sadykov, R., Subramanian, A., & Uchoa, E. (2018). On the exact solution of a large class of parallel machine scheduling problems. *Technical Report*. Universidade Federal Fluminense. Cadernos do LOGIS 2018-3

Cattaruzza, D., Absi, N., & Feillet, D. (2016). The multi-trip vehicle routing problem with time windows and release dates. *Transportation Science, 50*(2), 676–693.

Cattaruzza, D., Absi, N., Feillet, D., & González-Feliu, J. (2017). Vehicle routing problems for city logistics. *EURO Journal on Transportation and Logistics, 6*(1), 51–79.

Cleophas, C., Cottrill, C., Ehmke, J. F., & Tierney, K. (2019). Collaborative urban transportation: Recent advances in theory and practice. *European Journal of Operational Research, 273*(3), 801–816.

Cortés, C. E., Matamala, M., & Contardo, C. (2010). The pickup and delivery problem with transfers: Formulation and a branch-and-cut solution method. *European Journal of Operational Research, 200*(3), 711–724.

Crainic, T. G. (2008). City logistics. In *State-of-the-art decision-making tools in the information-intensive age* (pp. 181–212). INFORMS.

Crainic, T. G., Errico, F., Rei, W., & Ricciardi, N. (2012). Integrating c2e and c2c traffic into city logistics planning. *Procedia-social and Behavioral Sciences, 39*, 47–60.

Crainic, T. G., Errico, F., Rei, W., & Ricciardi, N. (2015a). Modeling demand uncertainty in two-tier city logistics tactical planning. *Transportation Science, 50*(2), 559–578.

Crainic, T. G., Gajpal, Y., & Gendreau, M. (2015b). Multi-zone multi-trip vehicle routing problem with time windows. *INFOR: Information Systems and Operational Research, 53*(2), 49–67.

Crainic, T. G., Nguyen, P. K., & Toulouse, M. (2016). Synchronized multi-trip multi--traffic pickup & delivery in city logistics. *Transportation Research Procedia, 12*, 26–39.

Crainic, T. G., Ricciardi, N., & Storchi, G. (2009). Models for evaluating and planning city logistics systems. *Transportation science, 43*(4), 432–454.

Crainic, T. G., & Sgalambro, A. (2014). Service network design models for two-tier city logistics. *Optimization Letters, 8*(4), 1375–1387.

Dabia, S., Ropke, S., Van Woensel, T., & De Kok, T. (2013). Branch and price for the time-dependent vehicle routing problem with time windows. *Transportation Science, 47*(3), 380–396.

Dror, M. (1994). Note on the complexity of the shortest path models for column generation in vrptw. *Operations Research, 42*(5), 977–978.

Fontaine, P., Crainic, T. G., Jabali, O., & Rei, W. (2016). The impact of combining inbound and outbound demand in city logistics systems. In *41st ieee annual computer software and applications conference (compsac): 2* (pp. 766–770). IEEE.

Fontaine, P., Crainic, T. G., Jabali, O., & Rei, W. (2019). Scheduled service network design with resource management for two-tier multimodal city logistics. *Publication Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport*. Montréal, QC, Canada: Université de Montréal.

Ghilas, V., Cordeau, J.-F., Demir, E., & Woensel, T. V. (2018). Branch-and-price for the pickup and delivery problem with time windows and scheduled lines. *Transportation Science, 52*(5), 1191–1210.

Ghilas, V., Demir, E., & Van Woensel, T. (2016). An adaptive large neighborhood search heuristic for the pickup and delivery problem with time windows and scheduled lines. *Computers & Operations Research, 72*, 12–30.

Golden, B., Baker, E., Alfaro, J., & Schaffer, J. (1985). The vehicle routing problem with backhauling: Two approaches. In *Proceedings of the twenty-first annual meeting of the SE TIMS*. Myrtle Beach, SC, USA

Grangier, P., Gendreau, M., Lehuédé, F., & Rousseau, L.-M. (2016). An adaptive large neighborhood search for the two-echelon multiple-trip vehicle routing problem with satellite synchronization. *European Journal of Operational Research, 254*(1), 80–91.

Grangier, P., Gendreau, M., Lehuédé, F., & Rousseau, L.-M. (2017). A matheuristic based on large neighborhood search for the vehicle routing problem with cross–docking. *Computers & Operations Research, 84*, 116–126.

Guastaroba, G., Speranza, M. G., & Vigo, D. (2016). Intermediate facilities in freight transportation planning: a survey. *Transportation Science, 50*(3), 763–789.

Hernandez, F., Feillet, D., Giroudeau, R., & Naud, O. (2016). Branch-and-price algorithms for the solution of the multi-trip vehicle routing problem with time windows. *European Journal of Operational Research, 249*(2), 551–559.

Irnich, S., Schneider, M., & Vigo, D. (2014). Chapter 9: Four variants of the vehicle routing problem. In *Vehicle routing: Problems, methods, and applications, second edition* (pp. 241–271). SIAM, Philadephia.

Jepsen, M., Petersen, B., Spoorendonk, S., & Pisinger, D. (2008). Subset-row inequalities applied to the vehicle routing problem with time windows. *Operations Research, 56*, 497–511.

Lahyani, R., Khemakhem, M., & Semet, F. (2015). Rich vehicle routing problems: From a taxonomy to a definition. *European Journal of Operational Research, 241*(1), 1–14.

Liberatore, F., Righini, G., & Salani, M. (2011). A column generation algorithm for the vehicle routing problem with soft time windows. *4OR, 9*(1), 49–82.

Maknoon, Y., & Laporte, G. (2017). Vehicle routing with cross-dock selection. *Computers & Operations Research, 77*, 254–266.

Masson, R., Lehuédé, F., & Péton, O. (2013). An adaptive large neighborhood search for the pickup and delivery problem with transfers. *Transportation Science, 47*(3), 344–355.

Masson, R., Trentini, A., Lehuédé, F., Malhéné, N., Péton, O., & Tlahig, H. (2017). Optimization of a city logistics transportation system with mixed passengers and goods. *EURO Journal on Transportation and Logistics, 6*(1), 81–109.

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Naddef, D., & Rinaldi, G. (2002). Branch-and-cut algorithms for the capacitated vrp. In *The vehicle routing problem* (pp. 53–84). SIAM Monographs on Discrete Mathematics and Applications. SIAM, Philadelphia.

Nguyen, P. K., Crainic, T. G., & Toulouse, M. (2013). A tabu search for time-dependent multi-zone multi-trip vehicle routing problem with time windows. *European Journal of Operational Research, 231*(1), 43–56.

Nguyen, P. K., Crainic, T. G., & Toulouse, M. (2017). Multi-trip pickup and delivery problem with time windows and synchronization. *Annals of Operations Research, 253*(2), 899–934.

Righini, G., & Salani, M. (2006). Symmetry helps: Bounded bi-directional dynamic programming for the elementary shortest path problem with resource constraints. *Discrete Optimization, 3*(3), 255–273.

Righini, G., & Salani, M. (2008). New dynamic programming algorithms for the resource constrained elementary shortest path problem. *Networks, 51*(3), 155–170.

Taş, D., Gendreau, M., Dellaert, N., Van Woensel, T., & De Kok, A. (2014). Vehicle routing with soft time windows and stochastic travel times: A column generation and branch-and-price solution approach. *European Journal of Operational Research, 236*(3), 789–799.

Toth, P., & Vigo, D. (2014). *Vehicle routing: Problems, methods, and applications*. Philadelphia, PA: SIAM. MOS-SIAM series on optimization

Vidal, T., Crainic, T. G., Gendreau, M., & Prins, C. (2013). Heuristics for multi-attribute vehicle routing problems: A survey and synthesis. *European Journal of Operational Research, 231*(1), 1–21.

Visser, T., & Spliet, R. (2017). Efficient move evaluations for time-dependent vehicle routing problems. *Technical Report*. Erasmus University Rotterdam, The Netherlands.

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