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Beta Working Paper series 396

BETA publicatie	WP 396 (working paper)
ISBN	
ISSN	
NUR	804
Eindhoven	November 2012

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Abstract

This paper considers a combination of vehicle routing and loading dock scheduling. Each route has a start instant at the depot and this instant is subject to capacity constraints for handling the route. This is an example of synchronized routing. Examples of physical constraints are a limited number of loading docks and a limited size of loading crews. During each route, there are also scheduling aspects being taken into account, such as the obedience of compulsory working time directives and meeting strict time windows for delivery. The complexity of this situation is tamed by a decomposition scheme where columns for a master problem (which takes the dock capacity into account) are generated by a routine based on dynamic programming. This column generations framework is assembled as a heuristic: after generating sufficient columns from the point of view of the linear relaxation of the master problem, one single instance of an integer linear program is solved. Strong evidence of the effectiveness of this approach is provided by cases from two large retailers, one based in The Netherlands and the other in the United Kingdom. The latter has the added challenge of an heterogeneous fleet with different dock capacity constraints.

Keywords: synchronized routing, working time directives, scheduling, column generation, dynamic programming.

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1 Introduction

Models for Vehicle Routing Problems (VRP) have become more and more elaborate in the past decades. The focus of these model extensions has been on so-called intra-route constraints. Intra-route constraints effect only single routes, such that they can be evaluated *locally*. Examples are limited vehicle capacities, time windows for serving customers, and precedence relations (e.g., pickup and deliveries). Recent advances in technology for measuring road conditions has increased the attention to VRP models accounting for traffic congestion ([1, 2, 3, 4, 5]). Moreover, renewed laws regarding driving and working hours to increase road safety lead to the inclusion of even more complex intra-route constraints ([6, 7, 8, 9]).

In addition to intra-route constraints, also inter-route constraints emerge in VRP applications. Inter-route constraints are defined *globally*, i.e., they effect multiple routes. Examples are a limited number of long tours (in terms of, e.g., number of stops) and loading/unloading capacities at the depot (in terms of, e.g., number of docks available for loading the vehicles). Hempsch and Irnich [10] propose a generic model for VRPs with inter-route constraints. Moreover, they derive some efficient local search techniques for evaluating neighborhood solutions regarding these inter-route constraints.

Other works regarding inter-route constraints are of Wen et al. [11] and Ebben et al. [12]. Wen et al. [11] consider workload restrictions at a central depot from a cross-docking perspective. The cross-docks require alignment of the deliveries and pickups at the depot. Ebben et al. [12] consider a dynamic vehicle scheduling problem with multiple resource capacity constraints. The application they consider is an automated transport system using Automated Guided Vehicles. The problem is a real-time scheduling problem with full truckloads. The inter-route constraints appear in terms of a restricted number of vehicle parking places, which are used when vehicles have to wait until a dock becomes available for (un)loading the vehicle.

We consider in this paper a problem motivated by practice. A large retailer in the UK faces many trucks that are scheduled to leave the depot early in the morning when provisioning its grocery stores. Ignoring the limited number of docks available for loading these vehicles leads to congestion at the depot, and resulting dispatch delays. To avoid this congestion at the depot, we must balance the workload for loading the vehicles. Therefore, we consider a VRP with inter-route constraints in terms of a limited number of loading docks at the depot. Moreover, we consider vehicle capacities, time windows, and driving hours regulations.

When it comes to avoiding congestion, timing plays a crucial role. Since waiting time at customers is costly, we consider minimizing route duration as one of the objectives ([13, 5]). As a result, different sequences of stops may result in different departure times from the depot and, therefore, different loading periods. So, delay caused by congestion can be avoided by reordering the stops within a route. In addition, the start times of certain routes may be delayed (if time windows along the route allow this) to create room at busy periods at the depot. We exploit this opportunity in our solution approach. Start time optimization is one of the main differences with existing models for depot loading dock constraints, such as the one from Hempsch and Irnich [10].

We propose to solve the VRP with loading dock constraints using column generation. Column generation is a decomposition approach that has proved to be successful in solving rich vehicle routing problems ([14, 15]). Moreover, the decomposition framework allows for a strong separation of inter-route and intra-route constraints.

We propose a formulation in which the (inter-route) loading dock constraints are modeled explicitly in the master problem, while the (intra-)route constraints are taken care of by the subproblem. Feasibility with respect to the inter-route constraints depends on the scheduled start times of the vehicle routes: only a given maximum of routes may start simultaneously. In fact, each route has a handling period at the depot and the limitation of loading dock capacity holds during this period, but we discretize the planning horizon into time buckets referred to as *sample intervals* and limit the number of routes whose handling periods intersect the same sampling intervals.

Each vehicle route generated by the column generator may be feasible for a large number of start times. To provide the master problem with a limited number of columns, the column generator generates multiple columns for each visit sequence for a predefined set of start times. Only columns with feasible start times are provided to the master problem. When generating different start times for the same visit sequence these differ in steps equal to the size of the sample intervals.

We test our solution approach on a data set from a large retailer in the UK and another large retailer in the Netherlands. In these cases, the number of loading docks at the depot plays a restrictive role. We investigate the impact of the loading dock constraints on the solution cost, as well as the ‘infeasibility’ of solutions in case these constraints are ignored. Moreover, we do a sensitivity analysis on the size of the sample intervals. The smaller the sample intervals, the more options the master problem gets for finding solutions with respect to the loading dock constraints, but against more computation time.

This paper is organized as follows. In Section 2, we give a formal problem description of the VRP with loading dock constraints. In Section 3, we propose our model for the loading dock constraints and in Section 4, we propose our solution approach. In Section 5, we describe the two case studies and present the outcome and in Section 6, we conclude this paper.

2 Problem Description

We consider an extension of the classical VRP with time windows (VRPTW). In the VRPTW, we are given a homogeneous vehicle fleet, located at one depot, and a set of customers, each having a certain demand and a time window. The objective is to find a set of vehicle tours of minimal cost, each starting and ending at the depot, such that the total demand along each tour does not exceed the vehicle's capacity, and service at each customer starts within the given time window. If a vehicle arrives early at a customer, it has to wait. The traditional objective is to minimize the total distance traveled.

Since waiting times at customers are costly, we include these costs in the objective function. Moreover, in practice waiting times are often not accepted if these can be avoided by departing later from the depot, without making the route infeasible. We refer to such waiting time as *avoidable* waiting time. We remove all avoidable waiting time in a route by optimizing the start time of each route. We refer to this procedure as making the route *compact*. The objective is to 1) complete the route as early as possible, and 2) minimize the route duration.

We also consider driving and working hours regulations, which require breaks of sufficient duration after a maximum amount of accumulated driving/working time. Such breaks highly impact the feasibility of the remainder of the route. In this context, working time includes all activities after starting the route, i.e., loading, traveling, waiting, and serving time.

Making a route compact is much more complex when considering driving hours regulations, as illustrated by Kok et al. [9]. Delaying the start of a route may not only reduce its cost, but may also make it feasible. For example, if a delay of the start of the route reduces waiting time, it also reduces working time, such that less breaks may have to be taken in the route.

The depot has a certain number of loading docks. The total number of simultaneous loading activities may never exceed this number. In one of the two case studies in Section 5, the vehicle fleet is heterogeneous. In that case, there are two types of vehicles, each having its own dock type. The restriction on the number of simultaneous loading activities is then defined per vehicle type.

3 Modeling Depot Loading Docks

The restriction on the number of loading docks is an inter-route restriction. Shifting the start time of a route may reduce the number of violations of the restriction on the number of loading docks. However, the intra-route (in this case timing) restrictions of the route under consideration should also be respected, which can be evaluated locally. To separate the evaluation of the inter- and intra-route restrictions, we propose to model the loading times as follows.

First, we discretize the time in appropriate sized sample intervals. These sample intervals represent periods of time a vehicle occupies a loading dock. Next, for each sample interval, we count all loading activities during this period. The total number of loading activities should not exceed the number of available docks. Figure 1 gives an example of this model with 3 vehicles loading at the depot.

Note that we may lose loading capacity with this model, since vehicles that load only during a part of a sample interval are considered to occupy a dock during the whole sample interval. By making the size of the sample intervals appropriately small, we may resolve this loss of loading capacity. In Section 5, we conduct a sensitivity analysis on the size of the sample intervals.

The sample interval model allows for a separation of concerns with respect to the inter- and intra-route constraints. The inter-route constraints are evaluated by counting the number of loading activities for each sample interval. Next, the relevant start times of each route are limited. The earliest relevant start time is the start time of the compact route (recall, a route is compact if the completion time is minimal, and the route duration is minimal given this minimal completion time). The other relevant start times are the start times of the successive sample intervals later than the earliest

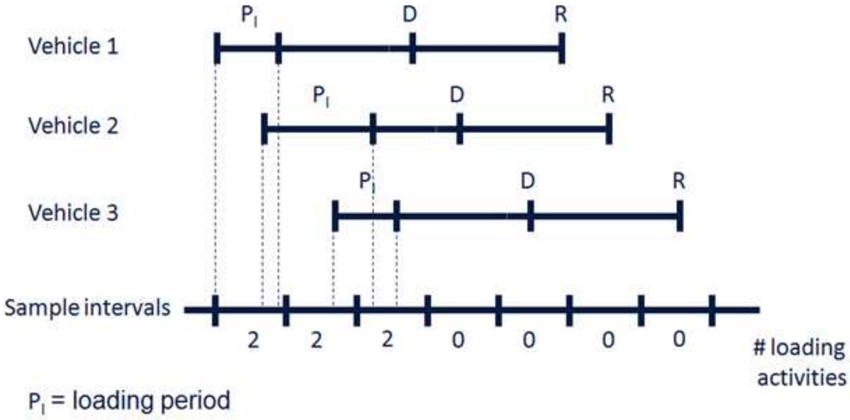

Figure 1: Example of sample interval model

relevant start time, and for which the route is still feasible. The determination of relevant start times, which requires re-evaluation of the intra-route timing constraints, is limited and can be done without explicit knowledge of the inter-route constraints. Figure 2 shows the resulting dock schedule after balancing the workload (assuming that only one loading dock is available) under the relevant start times.

4 Solution Approach

We propose to solve the VRP with loading dock constraints using column generation. The inter-route constraints are evaluated in the master problem, the intra-route constraints in the column generator. Section 4.1 describes the column generator in detail.

For the restricted master problem (RMP), we consider the following generalization of the model presented in Cordeau et al. [16]. We closely follow the notation used there, being Ω_k the set of feasible routes for a vehicle of type $k \in K$ and K the set of different vehicle types. Our model accommodates a heterogeneous fleet.

Unlike the model in [16], we avoid symmetry by aggregating all routes with vehicles of the same type. We can do that since from our model assumptions all routes that only differ by the specific vehicle used have the

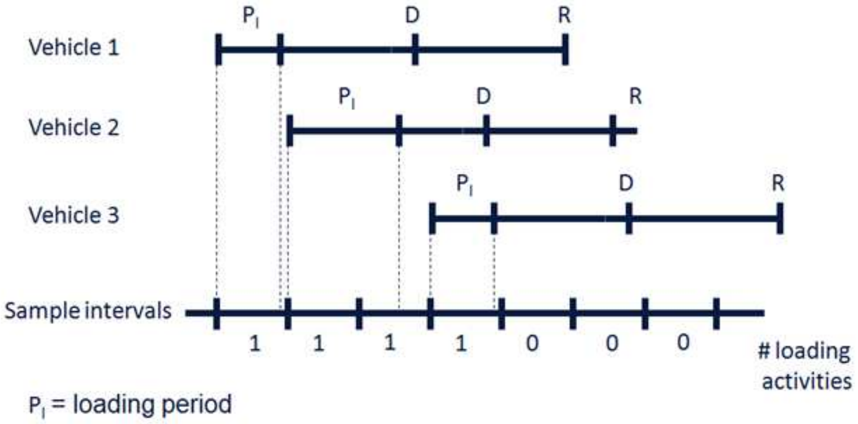

Figure 2: Example of sample interval model after balancing

same cost, provided that these vehicles are of the same type.

For each route $\omega \in \Omega_k$, let c^k_ω be the cost of this route and let θ^k_ω be a binary variable equal to 1 if and only if route ω is selected. Furthermore, let v^k_ω indicate that route ω uses a vehicle of type k, being then equal to 1, and $a_{i\omega}$ indicates if order $i \in N$ is delivered within route ω. Next, $b^k_{t\omega}$ indicates if route ω, which uses a vehicle of type k, is loading at the loading dock during sample interval t. Finally, let n_k be the number of vehicles of type k available and n^k_t the number of docks available for vehicles of type k during t. Here we assume that the docks are specific for a vehicle type, which is a common situation in the UK for loading single and double deck trailers.

$$\min \sum_{k \in K} \sum_{\omega \in \Omega_k} c^k_\omega \theta^k_\omega \tag{1}$$

$$\text{st:} \sum_{k \in K} \sum_{\omega \in \Omega_k} a_{i\omega} \theta^k_\omega = 1 \qquad \forall i \in N \tag{2}$$

$$\sum_{\omega \in \Omega_k} v^k_\omega \theta^k_\omega \leq n_k \qquad \forall k \in K \tag{3}$$

$$\sum_{\omega \in \Omega_k} b^k_{t\omega} \theta^k_\omega \leq n^k_t \qquad \forall t \in T, k \in K \tag{4}$$

$$\theta^k_\omega \in \{0, 1\} \qquad \forall k \in K, \omega \in \Omega_k \tag{5}$$

We aim at minimizing total costs in (1) while (2) forces each order to be delivered from a route. The number of available vehicles of each type is limited by (3) while (4) ensures enough dock capacity per sample interval and per vehicle type.

We remark that constraints (2) are equalities, i.e. defining a partition model; since the specificities of our problem prevent obtaining good solutions by removing possibly doubly covered rows which are allowed in a cover model. One of the reasons is the deprecation of waiting times in routes, which often arise when eliminating one order from a route.

Our approach is as follows:

- Start with a set of dummy columns that ensures feasibility of (2) by delivering one order per route. These will have prohibitively high costs and consume neither real vehicles in (3) nor docks in (4), i.e. v_{ω}^{k} and $b_{t\omega}^{k}$ are all equal to 0.
- For each set of columns, we consider a restricted Master Problem defined only on them.
- Solve the Linear Relaxation of the restricted Master Problem to obtain the shadow prices of all constraints.
- Request new columns with negative reduced costs from the generator.
- Repeat until no new columns are added or no improvement in the objective function is registered for a prespecified number of iterations.
- Optionally eliminate columns which seem less promising.
- Solve the integer version of the last obtained restricted master problem

4.1 Column Generator

To generate the columns, we use the Dynamic Programming (DP) based on the famous DP algorithm for the Traveling Salesman Problem (TSP) of Held and Karp [17]. This algorithm for the TSP can be described as follows. The TSP considers the problem of visiting a set $V = \{0, 1, ..., n-1\}$ of n cities exactly once, starting and ending at city 0, and minimizing the total travel distance. The travel distance between each pair of cities $i, j \in V$ is given by c_{ij}. A state $(S, j), j \in S, S \subseteq V \backslash 0$ in the DP algorithm represents a path with minimal travel distance, starting at city 0, visiting all cities in S exactly once, and ending in city j. The cost $C(S,j)$ of a state is given by the length of this path. In the first stage, the costs of the states are determined by $C(\{j\},j) = c_{0j}, \forall j \in V\backslash 0$. Next, in each successive stage the costs of the states are calculated with the recurrence relation $C(S,j) = \min_{i \in S\backslash j}\{C(S\backslash j, i) + c_{ij}\}$. Finally, the length of the optimal TSP tour is given by $\min_{j \in V\backslash 0}\{C(V\backslash 0, j) + c_{j0}\}$.

All intra-route constraints in the problem definition — such as vehicle capacity, time windows, driving hours regulations — can be incorporated in this framework as described by Gromicho et al. [18]. Also the costs for the TSP can be easily altered to represent the reduced costs for the new column. The shadow prices of the sample intervals are hereby ignored, as the start time is determined after the DP algorithm. For each vehicle type, a TSP is solved using the bounding described in [18] to get reasonable computation times. The number of solutions expanded in each stage of the DP algorithm (H) as well as the number of expansion per solution (E) are bounded.

During the DP algorithm, the best b feasible (possible intermediate) solutions are kept as possible columns. For each of these b best routes, we create multiple columns for the RMP by considering several different start times. First, for each route the latest start time is determined for which the completion time of the route is minimal; this is the first start time considered. This is done as starting earlier would introduce avoidable waiting times during the route. After this, the start time is repeatedly shifted to the start loading at the dock at the start times of the following sample intervals. This shift is performed at most $s-1$ times to limit the number of columns generated in case the time windows are not restrictive. This results in at most $b \times s$ generated routes which are returned as columns to the RMP. Note, all but one of these routes start at the start of a sample interval to minimize the number of sample intervals that intersect the loading at the loading dock. The only exception for each route is the first start time considered (the start time of the compact route).

4.2 Extensions

As mentioned in Section 4, our model already accommodates for a heterogeneous vehicle fleet. However, each type of vehicles may have its own set of loading docks assigned to it. If some docks can accommodate multiple vehicle types, a new subproblem is added to the problem: assigning the routes to a dock. When a route is assigned to a dock, it should not switch to another dock for another sample interval, because this takes time and is disapproved in practice.

To accommodate for this subproblem, the docks should be divided in different dock types D where every dock of a specific type should be able to handle the exact same set of (types of) vehicles. We change the model by choosing explicitly a feasible dock type for each route, adding multiple columns for the same route if the vehicle type can be accommodated by multiple dock types.

To incorporate this in the RMP, we add the dock type $d \in D$ to the notation of θ and Ω ($\omega \in \Omega_{dk}$ and θ_{ω}^{dk}). Furthermore, the superscript k on $b_{t\omega}^{k}$ and n_t^k is changed to d ($b_{t\omega}^{d}$, n_t^d), to reflect the dock type that is used by route ω. For each route generated by the generator for vehicle type k, multiple columns are added to the RMP for each dock $d \in D$ that can load vehicles of type k.

5 Case Study

We test our solution approach on two case studies. Case 1 contains a dataset from a large retailer in the UK; Case 2 contains a dataset from a large retailer in the Netherlands. We implemented the column generation approach in C++, and embedded it in the vehicle routing software ORTEC Transport and Distribution (OTD). This software already contains an implementation of the DP algorithm used as column generator. This implementation can handle a vary wide range of realistic constraints. We extended the DP algorithm with the possibility of using *reduced cost* as the objective, and with providing multiple columns at once. The latter was done by providing the best b solutions found for the subproblem. We ran our tests on a PC with 3.00 GHZ Duo CPU and 3,25 GB of RAM.

We run three tests with the case studies. First, we investigate the impact of the loading dock constraints. We do this by solving each case two times, where we relax the loading dock constraints the second time. Second, we investigate the impact of the size of the sample intervals. Third, we investigate the impact of adding flexibility by introducing some *avoidable* waiting time (recall that *avoidable* waiting time is waiting time that can be avoided by departing later from the depot, without making the route infeasible). In the case of the UK retailer, time windows are very strict (often even limited to one minute). Therefore, delaying the start of a trip beyond the earliest relevant start is often infeasible. We investigate the impact of adding some flexibility by allowing to introduce a limited amount of 'avoidable' waiting time.

5.1 Description of the test set

5.1.1 Case 1

Two vehicle types are distinguished: single deck trailers and double deck trailers. Both trailer types have their own dedicated loading docks: 10 for single deck trailers and 2 for double deck trailers. Therefore, the master problem contains two loading dock constraints. The loading time for each vehicle is fixed at 30 minutes.

Each trailer type results in a separate subproblem (single deck trailers and double deck trailers have different characteristics, such as capacities, but within each type the characteristics are the same). Besides a difference in capacity, single deck and double deck trailers also differ in costs: 0.30 per kilometer and 30 per hour for the single deck trailers, 0.50 per kilometer and 50 per hour for the double deck trailers.

The case contains 313 orders. There are 150 vehicles available: 120 single deck trailers and 30 double deck trailers. Time windows are often very strict, limited to 1 minute (these time windows actually represent appointments for a delivery *time*, instead of a delivery *time window*). Since we only consider compact routes (waiting time in a route that can be avoided by delaying the start of the route is not allowed), this often leads to only one feasible start time for a given visit sequence.

In addition to time windows, vehicle capacities, and loading dock constraints, the problem also contains restrictions with respect to drivers' hours regulations. Since the case considers day planning, the relevant rules are limited: a break of at least 45 minutes should be taken after at most 4.5 hours of driving or at most 6 hours of working. For scheduling the breaks and making the routes compact, the labeling algorithm of Goel ([19]) has been embedded in the column generator. For performance reasons, only the 'cheapest' label is maintained at each state of the DP algorithm.

5.1.2 Case 2

Case 2 contains only one vehicle type. There are 329 orders and 200 vehicles are available to serve them. The costs of these vehicles is 0.33 per kilometer, 35 per hour, and 100 fixed cost per used vehicle. There are 10 loading docks available and the loading time is variable, depending on the amount to be loaded. The drivers' hours regulations are the same as in Case 1.

5.2 Impact of loading dock constraints

We first investigate the impact of the loading dock constraints in both cases. We set the size of the sample intervals to 30 minutes. If we relax the loading dock constraints, the maximum number of simultaneous loading activities in the solution for Case 1 is 22 single deck trailers. This is more than double the amount of available loading docks for these trailers. In Case 2, the maximum number of simultaneous loading activities is 14. In other words, ignoring the loading dock constraints may lead to heavy congestion at the depot.

When we include the loading dock constraints, the solution cost for Case 1 increases by 16%. This is to be expected due to the large congestion issue to be solved by balancing the workload at the depot. Moreover, the very strict time windows in Case 1 does not allow to solve the workload balancing problem by delaying the start times of the vehicle routes; reordering the stops is really necessary. For Case 2, the impact of the loading dock constraints is much less. The solution cost even decreases by 1% when including the loading dock constraints (this can be explained by the heuristic solution method). Since the congestion problems at the depot are much less than in Case 1 and the time windows are wider, there are many more options to solve the workload balancing problem

5.3 Sensitivity analysis: impact size of sample intervals

We investigate the impact of the size of the sample intervals on computation time and solution quality by reducing it to 15 and 5 minutes. Table 1 shows that the size of the sample intervals has the biggest impact on the results of Case 2. The solution cost reduces by 7% when reducing the size of the sample intervals from 30 to 15 minutes, against 23% more computation time. A sample interval duration of 5 minutes is best for Case 1. For Case 2, a 15 minutes sample interval duration gives the best trade off between solution quality and computation time.

Sample interval duration (min.)	Case 1 Cost	Case 1 CPU	Case 2 Cost	Case 2 CPU
5	97%	103%	93%	139%
15	100%	100%	93%	123%
30	100%	100%	100%	100%

Table 1: Relative change in solution cost and computation time with respect to 30 minute sample interval duration

5.4 Sensitivity analysis: impact allowing avoidable waiting time

By allowing to advance the start of the loading time, we get more room for scheduling the loading activities at the depot. However, this introduces avoidable waiting time at the customers, which is disrespected in practical applications. To investigate the impact of allowing some avoidable waiting time, we solve the two cases again for several values of allowed waiting time. Table 2 shows that, in general, solution cost decreases with increasing allowed avoidable waiting time.

Max allowed avoidable waiting time (min.)	Case 1 Cost	Case 2 Cost
0	100%	100%
15	95%	99%
30	95%	98%

Table 2: Relative change in solution cost with respect to 0 minute avoidable waiting time

6 Conclusions

We considered a rich VRP in which inter-route constraints in the form of a limited number of loading docks play a restrictive role. Our model makes some simplifying assumptions, such as grouping the start times into equal intervals. We proposed a heuristic solution method based on column generation, where we solve the final master problem for the columns generated for the relaxed master problem. As column generator, we used a truncated dynamic programming heuristic. We compared our approach with the naive approach that just neglects dock capacity, and did a sensitivity analysis on the duration of the sample intervals. Moreover, we investigated the impact of allowing extra waiting time at the depot to solve the workload balancing problem.

We believe that the applicability of this framework is very strong due to the effect of complexity taming provided by column generation: most of the complexity goes into the generator and this is relieved from the task of assembling multiple routes, since it generates individual routes that were assembled by the master problem. For the generator, we could successfully use the rich dynamic programming framework of Gromicho et al. [18].

References

[1] S. Ichoua, M. Gendreau, and J.Y. Potvin. Vehicle dispatching with time-dependent travel times. *European journal of operational research*, 144(2):379–396, 2003.

[2] B. Fleischmann, M. Gietz, and S. Gnutzmann. Time-varying travel times in vehicle routing. *Transportation science*, 38(2):160–173, 2004.

[3] T. Van Woensel, L. Kerbache, H. Peremans, and N. Vandaele. Vehicle routing with dynamic travel times: A queueing approach. *European Journal of Operational Research*, 186(3):990–1007, 2008.

[4] A.L. Kok. *Congestion Avoidance and Break Scheduling within Vehicle Routing*. PhD thesis, University of Twente, School of Management and Governance, 2010.

[5] A.L. Kok, E.W. Hans, and J.M.J. Schutten. Vehicle routing under time-dependent travel times: The impact of congestion avoidance. *Computers & Operations Research*, 39(5):910 – 918, 2012. ISSN 0305-0548. doi: 10.1016/j.cor.2011.05.027. URL `http://www.sciencedirect.com/science/article/pii/S0305054811001614`.

[6] A. Goel. Vehicle scheduling and routing with drivers' working hours. *Transportation Science*, 43(1):17–26, 2009.

[7] A. L. Kok, C. M. Meyer, H. Kopfer, and J. M. J. Schutten. A dynamic programming heuristic for the vehicle routing problem with time windows and european community social legislation. *Transportation Science*, 44(4):442–454, 2010.

[8] Eric Prescott-Gagnon, Guy Desaulniers, Michael Drexl, and Louis-Martin Rousseau. European driver rules in vehicle routing with time windows. *Transportation Science*, 44:455–473, November 2010. ISSN 1526-5447. doi: http://dx.doi.org/10.1287/trsc.1100.0328. URL `http://dx.doi.org/10.1287/trsc.1100.0328`.

[9] A. L. Kok, E. W. Hans, J. M. J. Schutten, and W. H. M. Zijm. A dynamic programming heuristic for vehicle routing with time-dependent travel times and required breaks. *Flexible Services and Manufacturing Journal*, 22:83–108, 2010.

[10] Christoph Hempsch and Stefan Irnich. Vehicle routing problems with inter-tour resource constraints. In Bruce Golden, S. Raghavan, Edward Wasil, Ramesh Sharda, and Stefan Vo, editors, *The Vehicle Routing Problem: Latest Advances and New Challenges*, volume 43 of *Operations Research/Computer Science Interfaces Series*, pages 421–444. Springer US, 2008. ISBN 978-0-387-77778-8. URL `http://dx.doi.org/10.1007/978-0-387-77778-8\_19`. 10.1007/978-0-387-77778-8_19.

[11] M. Wen, J. Larsen, J. Clausen, J.-F. Cordeau, and G. Laporte. Vehicle routing with cross-docking. *Journal of the Operational Research Society*, 60(12):1708–1718, 2008.

[12] M.J.R. Ebben, M.C. van der Heijden, and A. van Harten. Dynamic transport scheduling under multiple resource constraints. *European Journal of Operational Research*, 167(2):320 – 335, 2005. ISSN 0377-2217. doi: 10.1016/j.ejor.2004.03.020. URL `http://www.sciencedirect.com/science/article/pii/S0377221704002802`.

[13] M.W.P. Savelsbergh. The vehicle routing problem with time windows: minimizing route duration. *ORSA journal on computing*, 4(2):146–154, 1992.

[14] H. Xu, Z.L. Chen, S. Rajagopal, and S. Arunapuram. Solving a practical pickup and delivery problem. *Transportation science*, 37(3):347–364, 2003.

[15] Alberto Ceselli, Giovanni Righini, and Matteo Salani. A column generation algorithm for a rich vehicle-routing problem. *Transportation Science*, 43(1):56–69, 2009.

[16] Jean-François Cordeau, Gilbert Laporte, Martin W.P. Savelsbergh, and Daniele Vigo. Chapter 6 vehicle routing. In Cynthia Barnhart and Gilbert Laporte, editors, *Transportation*, volume 14 of *Handbooks in Operations Research and Management Science*, pages 367 – 428. Elsevier, 2007. doi: 10.1016/S0927-0507(06)14006-2. URL `http://www.sciencedirect.com/science/article/pii/S0927050706140062`.

[17] M. Held and R.M. Karp. A dynamic programming approach to sequencing problems. *Journal of the Society for Industrial and Applied Mathematics*, 10(1):196, 1962.

[18] J. Gromicho, J.J. van Hoorn, A.L. Kok, and J.M.J. Schutten. Restricted dynamic programming: A flexible framework for solving realistic VRPs. *Computers & Operations Research*, 39(5):902 – 909, 2012. ISSN 0305-0548. doi: 10.1016/j.cor.2011.07.002. URL `http://www.sciencedirect.com/science/article/pii/S030505481100195X`.

[19] Asvin Goel. The minimum duration truck driver scheduling problem. *EURO Journal of Transportation and Logistics*, pages 1–22, 2012. ISSN 2192-4376. URL `http://dx.doi.org/10.1007/s13676-012-0014-9`. 10.1007/s13676-012-0014-9.

*Todo list

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