MASTER

A Heuristic Approach for the VRPTW using dual information of its LP formulation

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Master Thesis

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Abstract

This thesis deals with the Vehicle Routing Problem with Time Windows (VRPTW), one of the most applicable theoretical problems in current times. With it being an NP-Hard problem, we have to look at heuristics to achieve a suitable solution in an acceptable time frame.

We introduce a duality analysis of a master Linear Programming (MLP) formulation of the VRPTW. With it, we can access information on the customers and routes of the system and which to prioritize. By relaxing the MLP formulation, we show through the dual analysis that there is a competition between customers to be serviced by a certain vehicle. Based on this, we can choose to group customer to a vehicle or introduce a new one, which services customers that are not being served enough in the current solution.

Based on these insights, a heuristic has been developed with three phases: preprocessing, warm-up and saturation. Route centers are selected to represent a vehicle, and from there routes are constructed. We identify three main components of the heuristic: route construction, finding a new route center and customer grouping. By balancing these three components, the heuristic comes to a full integer solution.

Based on a computational study, we show that the heuristic works well in many cases, but improvements still have to be made further. The project will continue on after this thesis to be submitted to a leading journal.
Preface

The following work is the culmination of many months of research, coding, testing and frustrations. Because of these things, I am extremely proud of the final result that you are about to read.

This research topic has been running for some time longer than this master thesis shows, and can be considered as being very involved. From the mathematics behind it to the actual digging through code, it has taken considerable time to get to the point we are at the moment. The theoretical backbone of the heuristic is not only complex, it is also vital in understand why exactly the heuristic is important.

Preliminary work has been done on this topic before, including the first version of the code that was used for this research. Over the last months, both myself and dr. Firat have worked hard to bring it to a working point, where results are put out in reasonable time.

The results of the study have been written in the form of a paper. After submitting this piece to the university, it will be reworked to shape it into a form for submission to a leading journal in the area of logistics and operations management. Because of that, at some points the explanations can be brief. I welcome anyone who wants to know more to dive deeper into the methodology and setup of the heuristic. The mathematics involved are by no means simple, but they are not as difficult as one might think at first glance.

I would like to thank dr. Firat for all the help and guidance he has given during the course of this project. In a time of uncertainty and adjusting to a new form of life, I could always fall back on his experience and know-how. Even when time was very limited, dr. Firat was always able to carve out a slot so we could talk in more detail about the code or the report. For that, my deepest thanks and appreciation.

I also want to thank dr. Medeiros de Carvalho and dr.ir. Hurkens, for their speed in reading the thesis and their extensive questions during the thesis defense.

A quick and essential thanks also goes to the many people on StackOverflow, who have almost always had the problems I had, but were smart enough to ask for answers on the internet.

A final thanks goes out to all my friends and family, whose continuous support has made this project much more enjoyable.
A Heuristic Approach for the VRPTW using dual information of its LP formulation

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Abstract

This paper introduces a duality analysis of a master Linear Programming (MLP) formulation of the Vehicle Routing Problem with Time Windows (VRPTW). The considered MLP model is the slightly modified version of the relaxation of the Dantzig-Wolfe decomposition by expressing a VRPTW solution as a non-negative convex combination of constructed routes. The MLP model is basically the so-called reformulation of the VRPTW used in many Branch-and-Price (BP) algorithms. Our dual analysis shows that a pricing competition occurs in the dual model and the dual values of decision variables can guide us in making certain decisions like customer grouping and introducing a new vehicle to an existing (incomplete) solution. By using our dual interpretation, we propose a heuristic algorithm that greedily constructs a routing plan by iteratively solving the MLP model as a central optimization mechanism. The objects to select in the MLP model are routes that are constructed by using a Dynamic Programming (DP) based method. We keep the total number of routes bounded by a constant number, hence the size of the MLP model is fixed. A complete routing plan, i.e. an integer solution to the MLP model, is obtained by making the aforementioned decisions. We provide further details of the algorithm and show its efficiency by means of a computational study.

Keywords: Integer Linear Programming, Vehicle Routing Problem, Capacity Management
1. Introduction

The Vehicle Routing Problem with Time Windows (VRPTW) is one of the basic benchmark problems in optimization. It is a generalization of the Vehicle Routing Problem (VRP) that was firstly introduced by Dan59. The NP-hardness of the VRPTW is rooted in the Traveling Salesman Problem (TSP).

Many exact solution methods to the VRPTW use a reformulation with a set packing structure and employ a Column Generation (CG) method in a Branch-and-Bound search, for example Desrochers92. Although remarkable progress is obtained in the size of solved instances, exact algorithms suffer from long running times in solving real-life instances. The main issue is that the pricing sub-problem is NP-hard and requires either a long running time or large amounts of memory to solve optimally. Some researchers worked on developing heuristics based on Branch-and-Bound methods, whose termination criterion is either time or solution quality or a mix of both.

The basic idea of our approach is to express the customer visits as decision variables and thus not enforcing the requirement that every customer should be visited by exactly one vehicle. Initially, we have an incomplete VRPTW solution when the master Linear Programming (MLP) model is solved, based on finding one or more "route centers", which are the foundations of paths and represent a vehicle. Then, we greedily assign certain customers to those route centers and reach a complete routing solution. The decision of assigning customers to route centers is based on the evidence obtained from the solutions of the MLP model and its dual. Relaxing the requirement of visiting customers exactly once is not a new idea, for example Kohl97 and Kalle06 worked on exact algorithms based on Lagrangian relaxation in which the relaxed constraints of the VRPTW are the aforementioned ones.

In this work, the proposed heuristic approach makes use of the information given by LP-duality in order to find good-quality solutions to the VRPTW. Our approach has important similarities to exact algorithms. It uses the master LP model with set packing structure that is used by many Branch-and-Price
algorithms. Our algorithm does not backtrack during its course, and it makes
greedy decisions in this sense. As customers are assigned to used vehicles, the
path sets are revised in order to update the information obtained from dual
solutions.

Our contribution. The contribution of this paper is two-fold. Firstly, we
provide a dual interpretation of the MLP formulation of the VRPTW. Our
dual interpretation shows that competition happens among customers in the
dual model, and the values of dual decision variables provide us with some
information about that customer competition. As the second contribution of
this paper, we propose a heuristic approach to solve the VRPTW that makes
use of the information provided by our dual interpretation. Our computational
experimentation shows that our heuristic is promising in finding good quality
solutions for benchmark cases.

The paper is organized as follows. First, we briefly describe and categorize
the VRPTW in Section 2. Related work in the literature is outlined in Section
3. We will take a deeper look at the theoretical backbone in Section 4. Section
5 presents our proposed heuristic algorithm to the VRPTW by first outlining
its important properties in an overview, then expanding on each part. Computa-
tional results are reported in Section 6. Finally, conclusions and possible
research directions are discussed in Section 7.

2. Preliminaries

This section briefly describes the VRPTW, and defines several concepts that
are necessary for a formal description of our heuristic method.

2.1. Problem description

An instance of the VRPTW consists of a set \( N = \{0, 1, \ldots, n\} \) of locations
on a plane, where 0 is the depot and others are customer locations, a set \( V \) of
homogeneous vehicles of capacity \( Q \in \mathbb{Z}_+ \). Every customer \( i \in N \setminus \{0\} \), also
denoted by \( N' \), requires a service of length \( sv_i \in \mathbb{Z}_+ \) time units for a demand of
amount \( q_i \in \mathbb{Q} \). The service at customer \( i \) can only start in time interval \([e_i, l_i]\)
where \( e_i, l_i \in \mathbb{Z}_+ \) are called earliest time (or release date), and latest arrival time (or due date) respectively. Hence, arriving earlier than \( e_i \) requires waiting till \( e_i \), but later than \( l_i \) implies violation of the feasibility. The planning horizon of the problem is defined by the time window of the depot and it is denoted by \([e_0, l_0]\). The distance between customers \( i \) and \( i' \) is denoted by \( d_{i,i'} \), and is equal to the Euclidean distance of the arc \([i, i'] \in N \times N\) on a plane where customer locations are specified as \( x- \) and \( y- \)coordinates. We assume that a unit distance is traveled in a unit time, i.e. the distance of an arc is equal to the travel time on it.

**Problem: Vehicle Routing Problem with Time Windows (VRPTW)**

**Instance and feasibility:**

Set \( N \) of customers with demands and time windows and the depot, set \( V \) of homogenous vehicles with capacities.

A feasible route of a vehicle is a sequence of visited customers such that total demand does not exceed the vehicle capacity, and that every visited customer is serviced within its time window, and depot departure and depot arrival stay within the planning horizon.

A feasible routing solution is a set of feasible routes such that every customer is serviced exactly by one vehicle, and the number of used vehicles does not exceed the number of available vehicles in the depot.

**Question:** Does there exist a routing plan with number of vehicles less than \( k \) and for \( k \) vehicles with a smaller total travel distance less than \( D \)?
2.2. Preprocessing

Given an instance of the VRPTW, we conduct some preprocessing steps. Firstly, we adapt the time windows as follows

\[ e_i = \max\{e_i, e_0 + d_{0,i}\}, l_i = \min\{l_i, l_0 - d_{i,0}\}, \quad i \in N \]  

(1)

Having found adapted time windows, incoming and outgoing arcs around customers are ranked with respect to their adapted lengths. Incoming and outgoing arc lists of customers are non-decreasingly ordered and the indices of arcs in these lists become their ranking. Let \( \text{start}_i \) denote the start time of the service of customer \( i \). It follows that \( e_i \leq \text{start}_i \leq l_i \).

2.2.1. Simple lower bounds on the number of used vehicles

Let \( L_{Veh} \) denote the lower bound on the number of vehicles in all feasible routing solutions for a given VRPTW instance.

Using total demand. Trivially, we can find minimum number of vehicles to serve all customers by the total customer demand as

\[ L_{Veh} \geq L_P = \lceil \sum_{i \in N'} q_i/Q \rceil \]  

(2)

Using incompatible customers. Another way to get a lower bound on the number of vehicles is by using incompatible customers.

(Incompatible customers) Two customers that cannot be served in a route without violating temporal constraints or vehicle capacity are called incompatible.

A customer set in which every pair of customers is incompatible also gives us a lower bound on the number of vehicles in a feasible routing solution. The maximum cardinality of aforementioned customer set can be found by solving the maximum independent set problem in customer network. Unfortunately, this problem is NP-Hard in the strong sense. Therefore, we settle on a heuristic for finding a maximal independent set. In this heuristic, an independent set
of customers is constructed greedily. Having chosen a customer to add to the independent set, all customers in the network that are connected by an arc to the chosen customer are deleted. This continues until no customer is left to choose. The decision of selecting the first customer to start the independent set is be made by checking the number of connected customers in the network. By taking this, we eliminate as many candidates as possible.

The process is visualized in Figure 1. Nodes represent customers, and an arc represents the fact that two customers can exist in one route together. Firstly, in Figure 1a, an initial route center (RC) is found. This customer is the one with the most connections to other customers in the network. Then all its neighbours are eliminated from the set in Figure 1b. This process repeats in Figure 1c and 1d until we arrive in the final solution in Figure 1e.

Let \( IND \) denote the set of maximal independent set found by using the heuristic described above. In this case, \( IND \subset N' \). Then, we define \( L_{veh} \) as follows

\[
L_{veh} = \max\{L_P, |IND|\}
\]

2.3. Constructing the Routes

Route centers. We distinguish some customers as the ones defining routes, meaning that each of such customers have sets of routes passing through them. Eventually, this corresponds to dedicating one vehicle to every route center in our solutions.

(Route Center) The building block of routes and the representation of a vehicle in the solution. Each route must contain exactly one route center.

Let \( RC \subset N' \) denote the set of route centers. In our algorithm \( RC \) is initialized with the customers in the independent set solution, \( IND \). Then, some other customers may be added and we will refer to this extension of \( RC \) as “route center selection”.

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Figure 1: Finding Independent Customers
Routes. A sequence $r = (r_1, r_2, \ldots, r_{l(r)})$ of customers with subset $C_r$ of visited customers, is called a “route”, if $r$ satisfies the following feasibility conditions:

- Every customer $i \in N$ is visited by $r$ at most once, i.e. $|C_r| = l(r)$
- Route $r$ has exactly one route center, i.e. $|C_r \cap RC| = 1$
- Every customer in $r$ is serviced within it time window.
- Total demand does not exceed vehicle capacity, i.e. $\sum_{i=1}^{l(r)} q_{ri} \leq Q$.

3. Related work

There is extensive literature for the VRPTW that contains a wide range of algorithms like priority rule based simple heuristics, (adaptive) large neighborhood search, and exact algorithms. A good summary of the literature of the VRPTW until the 1990s can be found in the review of Des88. In this survey, the authors mention that the literature lacks (at that time) an exact approach to the VRPTW, and few years later Desrochers92 proposed one of the first exact solution methods to the VRPTW. The authors’ method solves a reformulation of the VRPTW with a set packing structure and employs the CG technique in order to do bounding in a Branch-and-Bound search. The corresponding sub-problem amounts to finding the shortest path in a modified network with time windows and capacity constraints, and it is solved by using a Dynamic Programming method. The largest instance size that is solved optimally was 14 customers at that time, and the results of Desrochers92 showed that a high ratio of 25-customer instances are solved optimally within 10 minutes by using the computation power of the 1990s.

Some years later, Fisher97 proposed two optimization algorithms to the VRPTW, namely a Lagrangian Relaxation/Variable splitting approach and a K-tree approach. In the former, two sub-problems (a semi-assignment problem and shortest path problem with time windows and capacity constraints) are solved. The authors report that 100-customer benchmark instances with clustered and randomly located customers solve to optimality with varying solution
times between 10 and 70 minutes. The conclusion is that both optimization algorithms perform best especially on the instances with clustered customers.

Fixing decision variables in a VRPTW formulation is a general trick researchers have used. For example, the authors of Cacchiani14 propose a heuristic approach to the Periodic Vehicle Routing Problem (PVRP). The proposed algorithm solves a master LP model by fixing binary variables to 1 whose solution values are 1, and fixing the value of the variable that has the highest fractional value. After the fixing, the authors find new columns by taking into account the changed dual values of the master LP model. Another example can be found in the work by Desaulniers20. They work in branch-price-and-cut algorithms for the VRPTW, where it is possible to fix a variable to zero according to the dual solution. It deals with a set of arcs, from which one can be eliminated to fix the variables. In their paper, they extend this to two-arc sequences, which are much more difficult to completely eliminate. The proposed technique indirectly removes them from the sequences in the network, leading to good results on benchmark instances.

In another paper, Huang11 introduce binary variables to allow not visiting/outsourcing some customers, and minimize the weighted sum of these variables in the objective function. The authors propose a Lagrangian heuristic to the Vehicle Routing Problems with the Private Fleet and the Common Carrier (VRPPC). Another paper by Schneider14 deals with the VRPTW with recharging stations, where the vehicles have to recharge after a certain distance has been used. They show that a hybrid solution of neighborhood search and tabu search can lead to good solutions.

The relaxation of constraints is not a new concept. As far back as the 1990’s, Kohl97 showed that Lagrangian relaxation can be used on the VRPTW. The key here was finding the Lagrangian multipliers to come to a good solution. Similarly, a paper by Baldacci11 looked at relaxation of the routes themselves, using dual ascent heuristics found in the literature. The new techniques allow for a reduced set partitioning formulation and quickly and efficiently solve many benchmark instances. Recently, Liu19 has shown that for the VRPTW with
load-dependent costs, there is a possibility of relaxing the constraint that every
customer has to be visited by a vehicle. Instead, they introduce 'virtual' vehicles.
Impressive results were yielded.

A paper that deals with the VRPTW is the paper by Bianchessi2019, which
adds as a constraint that multiple vehicles can service one customer. In the
paper, a new method is proposed which is a tailored version of a branch-and-
price-and-cut algorithm. Integer solutions are built in a relaxed model. A sparse
subnetwork is created, in which all time-window-feasible routes are enumerated,
cutting out all infeasible solutions. Experimentation has shown that this ap-
proach can solve some previously unsolved instances.

In the paper of Gunluk06, the multi-depot VRPTW is studied. The au-
authors propose a so-called Fix-Price Heuristic that works in a similar manner of
our heuristic algorithm. In their follow-on fixing procedure, the columns with
solution values not smaller than 0.95 are fixed to 1. Then, all columns are up-
dated in order respect the fixing decisions. Next, the LP model is solved, and
fixing decisions are made as long as variables with convenient solution values
are found. When no variable with desired solution value is found, the threshold
value is decreased to 0.85. The procedure is terminated if no variables having
solution values greater than or equal to the reduced threshold value. Besides
this fixing procedures, the proposed heuristic approach of Gunluk06 has other
components to solve the studied problem efficiently.

One of the recent works on the VRPTW is conducted by Nagata09. The
authors propose a sophisticated approach for reducing the number of routes,
and it is based on the ejection pool that is combined with a concept reminiscent
of the Guided Local Search. The benchmark instances described by GeHo01
are used in experimentation of the proposed approach. By limiting the solution
time to multiples of 10 minutes (maximum 5 hours), the authors were able to
find new best known solutions for several instance sizes between 400 and 1000
customers. To the best of our knowledge, Nagata09 have currently the best
solutions for the instances of large size in the literature.

There are also more sophisticated methods that have been used for solv-
ing the VRPTW. For example, Xu15 implements a combination of a genetic algorithm and a particle swarm optimization for an extremely complex system to solve the VRPTW. Experimental results show that the algorithm is very efficient and competitive, but also obtains optimal solutions. Kalina15 implemented a method based on agent negotiation, where the problem is decomposed for the different vehicles who are treated as actors. It was an improvement on existing agent-based simulations at the time. An interesting paper is submitted by Ukhan20, in which the authors argue for a system that manages to choose the correct implementation for the VRPTW out of a list of candidates. They show that the speed and quality of results can be dependant on the complexity of the problem, as well as the problem size. Because of that, certain solution methods are more or less suitable. This paper shows that the need for ICT and decisions on the correct method are vital. Having more proper methods to choose from can help a lot.

We refer to surveys by BraGen05a, and BraGen05b for more recent exact heuristic algorithms for the VRPTW, as well as the paper by Costa2019 for a very recent survey on exact branch-and-price algorithms for the generic VRP.

4. Theoretical Background

In this section, we will look more closely at the theoretical framework on which we will base the heuristic. We will take a proper look at the primal-dual method and its implications, showing how we can get information from the dual model. This section will be highly theoretical and mathematical, beginning with a formulation of a linear program to solve the VRPTW. From there, we formulate the dual of this program. These models are nudged to optimality using the complimentary slackness theorem and then restricted, after which an improvement step is detailed. Finally, we will look at how to interpret these values, then at an illustrative example.

Our master LP model allows us to start with a partially feasible solution that serves a subset of customers initially. It contains customer assignment variables
to decide which customers are to be served by available vehicles introduced so far. The objective has as its primary goal “maximizing” the number of selected customers and secondary “minimizing” the total distance traveled in the selected paths. A big coefficient $M$ is used to denote the hierarchy in two aforementioned goals. Note that our master LP finds a routing plan for a given number of vehicles, that is $|RC|$. Next, we give the formulation of our master LP model.

Table 1 explains the parameters and decision variables. The formulation of the master IP model is given in (4)-(7).

<table>
<thead>
<tr>
<th>Table 1: Sets, parameters, and variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sets</strong></td>
</tr>
<tr>
<td>$N'$ set customer locations, $N' = N \setminus {0}$</td>
</tr>
<tr>
<td>$\mathcal{R}$ set of all constructed routes,</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td>$M$ the objective coefficient of primary goal variables</td>
</tr>
<tr>
<td>$c_r$ cost (traveled distance) of route $r \in \mathcal{R}$</td>
</tr>
<tr>
<td>$\delta^i_r$ indicates if route $r \in \mathcal{R}$ visits customer $i \in N'$</td>
</tr>
<tr>
<td><strong>Decision Variables</strong></td>
</tr>
<tr>
<td>$x_r$ selection variable of path $r \in \mathcal{R}$</td>
</tr>
<tr>
<td>$y_i$ selection variable of customer $i \in N'$</td>
</tr>
</tbody>
</table>

\[(SP) \quad \text{Max} \quad M \left( \sum_{i \in N'} y_i \right) - \sum_{r \in \mathcal{R}} c_r x_r \quad (4)\]

subject to:

\[
\sum_{r \in \mathcal{R}} \delta^i_r x_r - y_i = 0, \quad i \in N' \quad (5)
\]

\[
y_i \in \{0, 1\}, \quad i \in N' \quad (6)
\]

\[
x_r \in \{0, 1\}, \quad r \in \mathcal{R} \quad (7)
\]
Constraint (5) couples selections of a customer and the routes visiting that customer. Note that in standard IP reformulations in the literature, for example Desrochers92, all $y_c$ variables are fixed to the value 1 as the right hand side of (5). Next, we relax all binary variables in (6)-(7) and we obtain the master LP model as

\[(P) \quad \text{Max} \quad M \left( \sum_{i \in N'} y_i \right) - \sum_{r \in R} c_r x_r \]  

subject to:

\[
\sum_{r \in R} \delta_i^r x_r - y_i = 0, \quad i \in N' \quad \text{(9)} \]
\[
y_i \leq 1, \quad i \in N' \quad \text{(10)} \]
\[
y_i \geq 0, \quad i \in N' \quad \text{(11)} \]
\[
x_r \geq 0, \quad r \in R \quad \text{(12)} \]

In the following section we use the primal-dual method to analyze how an optimal solution in the dual model is obtained, which will enable us to interpret the values of dual variables in optimal solutions.

4.1. Dual analysis via primal-dual method

In this section, we show how the dual of the master LP model in (8)-(12) is solved optimally by incorporating the primal-dual method. After the explanations, numerical examples will also be given in the end of this section. The primal-dual method was proposed by Dan56, and it has been used to design approximation algorithms for many problems in graph theory. In mathematical programming, it is known that many ideas of the exact algorithms to a number of network design problems are implicit in the primal-dual algorithms. Interested readers are referred to Goemans96 for an extensive analysis of the primal-dual method in network design problems.
To start our analysis, we give the dual of our master LP model by letting 
\( \lambda_i, \gamma_i, \kappa_i \) be the dual variables corresponding to the constraints \((9)-(12)\).

\[
(D) \quad \text{Min} \quad \sum_{i \in N'} \gamma_i
\]

subject to:

\[
(\gamma_i + \kappa_i) - \lambda_i \geq M, \quad i \in N' \tag{14}
\]

\[
\sum_{i \in C_r} \lambda_i \geq -c_r, \quad r \in R \tag{15}
\]

\[
\gamma_i \geq 0, \quad i \in N' \tag{16}
\]

\[
\kappa_i \leq 0, \quad i \in N' \tag{17}
\]

Complementary slackness condition. By the Complementary Slackness (CS) theorem, given primal and dual feasible solutions \((y, x; \lambda, \gamma)\) are optimal if and only if the following equalities are satisfied

\[
x_r \left( \sum_{i \in C_r} \lambda_i + c_r \right) = 0, \quad r \in R \tag{18}
\]

\[
y_i \left( \gamma_i + \kappa_i - \lambda_i - M \right) = 0, \quad i \in N' \tag{19}
\]

\[
(1 - y_i) \gamma_i = 0, \quad i \in N' \tag{20}
\]

\[
(y_i) \kappa_i = 0, \quad i \in N' \tag{21}
\]

For the detailed analysis of the CS conditions and an extensive analysis of the linear optimization, we refer to the the book of BertTsit97. In the primal-dual method, a given dual feasible solution is improved towards the optimal solution by using the “restricted primal” model, which minimizes the violations from the CS conditions. The basic idea is that the satisfaction of CS conditions is greedily increased till full satisfaction is reached. In order give the formal
definition of the restricted primal model, we need to define several sets related to CS conditions as

\[
K = \{ r \in \mathcal{R} | \sum_{i \in \mathcal{C}_r} \lambda_i + c_r = 0 \} \tag{22}
\]

\[
J = \{ i \in N' | \gamma_i + \kappa_i - \lambda_i = M \} \tag{23}
\]

\[
I = \{ i \in N' | \gamma_i = 0 \} \tag{24}
\]

\[
L = \{ i \in N' | \kappa_i = 0 \} \tag{25}
\]

The set \( K \) is said to contain all routes in price balance in the dual solution. Note that only routes in \( K \) can have positive \( x_r \) values by CS condition (18).

Similarly, only customers in \( J \) can have positive selection values. Finally, we define the slack variable \( s_i \) for the customers not in the set \( I \) to quantify the violation from the CS condition. The violation of CS condition (19) due to customers not in set \( J \) is simply the value of \( y_i \).

*Restricted primal model.* For a given a dual feasible solution \((\lambda, \gamma)\) with sets \( K, J, I \); we can formulate a restricted primal problem that minimizes the violation of CS conditions as
(RP)  \[ \text{Min } z_{RP} = \sum_{i \not\in I} s_i + \sum_{r \not\in K} x_r + \sum_{i \not\in (J \cup L)} y_i \]  \hspace{1cm} (26)

subject to:

\[ \sum_{r \in R} \delta_i^r x_r - y_i = 0, \quad i \in N' \]  \hspace{1cm} (27)

\[ y_i \leq 1, \quad i \in I \]  \hspace{1cm} (28)

\[ y_i \geq 0, \quad i \in N' \]  \hspace{1cm} (29)

\[ y_i + s_i = 1, \quad i \not\in I \]  \hspace{1cm} (30)

\[ x_r \geq 0, \quad r \in R \]  \hspace{1cm} (31)

\[ s_i \geq 0, \quad i \not\in I \]  \hspace{1cm} (32)

By constraints (28) and (29), customers in \( I \) can have any \( y \) value, and the violation of CS condition (20) of those not in \( I \) amounts to the value of slack variable \( s \) in constraints (30). From this, we can see there are two possibilities:

Case \( z_{RP}^* = 0 \): Master LP is solved to optimality, i.e. all CS conditions are satisfied.

Case \( z_{RP}^* > 0 \): Dual feasible solution \((\lambda, \gamma, \kappa)\) is improved to another dual feasible solution \((\lambda'', \gamma'', \kappa'')\) with a smaller objective value. To explain how this improvement is achieved, we first need to consider the dual of the \((RP)\) model.
\[(DRP) \quad \text{Max} \quad \sum_{i \in N'} \gamma_i' \quad (33)\]

subject to:

\[\gamma_i' + \kappa_i' - \lambda_i' \leq 1, \quad i \not\in (J \cup L) \quad (34)\]
\[\gamma_i' + \kappa_i' - \lambda_i' \leq 0, \quad i \in (J \cup L) \quad (35)\]
\[\sum_{i \in C_r} \lambda_i' \leq 1, \quad r \not\in K \quad (36)\]
\[\sum_{i \in C_r} \lambda_i' \leq 0, \quad r \in K \quad (37)\]
\[\gamma_i' \leq 1, \quad i \not\in I \quad (38)\]
\[\kappa_i' \geq 0, \quad i \in I \quad (39)\]
\[\gamma_i' \leq 0, \quad i \in I \quad (40)\]

For the sake of simplicity in the notation, decision variables \(\gamma'\) are used in the (DRP) model. They are different from \(\gamma\) dual variables in the dual of the MLP model. In the case of \(z_{RP}^* > 0\), we have \(\sum_{i \in N'} \gamma_i' = z_{RP}^* > 0\) by strong duality. The improved dual solution is found as

\[(\lambda'', \gamma'', \kappa'') = (\lambda, \gamma, \kappa) - \Delta (\lambda', \gamma', \kappa') \quad (41)\]

where \(\Delta > 0\) is called the dual improvement step value. Then we have

\[\sum_{i \in N'} \gamma_i'' = \sum_{i \in N'} \gamma_i - \Delta \sum_{i \in N'} \gamma_i' \leq \sum_{i \in N'} \gamma_i \quad (42)\]

Preserving dual feasibility gives us the maximum value of \(\Delta\). This is done by checking constraints (14)-(16) as

\[\gamma_i'' + \kappa_i'' - \lambda_i'' \geq M \Rightarrow \Delta \leq \min_{i \not\in (J \cup L), \gamma_i', \kappa_i', \lambda_i'} \left\{ \frac{\gamma_i + \kappa_i - \lambda_i - M}{\gamma_i' + \kappa_i' - \lambda_i'} \right\} \quad (43)\]
\[
\sum_{r \in C_r} (\lambda_i - \Delta \lambda'_i) + c_r \geq 0 \Rightarrow \Delta \leq \min_{r \notin K, \sum_i \lambda'_i > 0} \left\{ \frac{\sum_i \lambda_i + c_r}{\sum_i \lambda'_i} \right\}
\]

\[\gamma'_i = \gamma_i - \Delta \gamma'_i \geq 0 \Rightarrow \Delta \leq \min_{i \notin I, \gamma'_i > 0} \left\{ \frac{\gamma_i}{\gamma'_i} \right\}\]

Sets \( J, K, I \) and \( L \) are updated according to solution values. This dual improvement procedure is repeated, by iteratively solving the \((DRP)\) model, till we obtain objective value \( \sum_{i \in N'} \gamma'_i = 0 \) that implies the optimal dual solution is obtained.

4.2. Interpreting dual problem.

In the dual model, \( \gamma \) \((\kappa)\) variables represent positive (negative) budget. If one of \( \gamma \) and \( \kappa \) variables is non-zero, then the other must be zero by CS conditions \((18)-(21)\). Hence, \((\gamma + \kappa)\) is the “budget” of customers in the dual solution. Dual improvement step \( \Delta \) is the “price” paid/collected in a dual improvement iteration. In dual iterations there are some price-collecting customers and some price-paying customers. The decision variable \( \gamma' \) \((\kappa')\) in the \((DRP)\) model tells us if a customer is a price collector (payer). The value of variable \( \gamma'_i \) \((\kappa'_i)\) is the portion of the collected (paid) price for customer \( i \).

A route constrains the total value of the budgets of visited customers. Dual constraints \((15)\) enforce that the total budget of customers visited by route \( r \in R \) can have the smallest value \(-c_r\), and routes with a minimum total budget are said to be in price balance. Once a route reaches price balance, it is added to set \( K \), and the total budget should not change in the next dual iteration (constraint \((37)\)). A route may leave price balance by increasing its total customer budget. In a dual iteration, constraints \((36)\) enforce that routes not in price balance can have at most one dual improvement price drop in total budget. A necessary condition for a route to be selected in the optimal primal solution is to be in price balance. In light of our dual understanding, we have the following observation.
Table 2: Dual pricing rounds of the illustrative example

<table>
<thead>
<tr>
<th>Instance Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N' = {i_1, i_2, i_3, i_4, i_5} ),</td>
</tr>
<tr>
<td>( r_1 = (i_1, i_2, i_3), r_2 = (i_2, i_3), r_3 = (i_2, i_5), r_4 = (i_4, i_5) )</td>
</tr>
<tr>
<td>( c_{r_1} = 75, c_{r_2} = 50, c_{r_3} = 80, c_{r_4} = 60 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dual Pricing Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial dual feasible solution: ( \gamma_{i_k} = 1.5M, \kappa_{i_k} = 0, \lambda_{i_k} = 0.5M, i_k \in N' )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dual iteration</th>
<th>Payers</th>
<th>Collectors</th>
<th>( \Delta )</th>
<th>K</th>
<th>I</th>
<th>( \sum \gamma' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3, 5</td>
<td>2</td>
<td>( M + 50 )</td>
<td>( \emptyset )</td>
<td>( \emptyset )</td>
<td>( 6.5M - 50 )</td>
</tr>
<tr>
<td>2</td>
<td>2, 4</td>
<td>5</td>
<td>( M + 50 )</td>
<td>( {r_2} )</td>
<td>( \emptyset )</td>
<td>( 5.5M - 100 )</td>
</tr>
<tr>
<td>3</td>
<td>3, 5</td>
<td>2</td>
<td>10</td>
<td>( {r_2, r_4} )</td>
<td>( \emptyset )</td>
<td>( 5.5M - 110 )</td>
</tr>
<tr>
<td>4</td>
<td>1, 3, 5</td>
<td>2, 4</td>
<td>0.5M - 60</td>
<td>( {r_2, r_4} )</td>
<td>( {i_3} )</td>
<td>( 5M - 50 )</td>
</tr>
<tr>
<td>5</td>
<td>1, 3</td>
<td>2</td>
<td>85</td>
<td>( {r_1, r_2, r_4} )</td>
<td>( {i_3} )</td>
<td>( 5M - 135 )</td>
</tr>
</tbody>
</table>

Final budgets: \( \gamma_{i_1} = M - 25, \gamma_{i_2} = 2M - 50, \gamma_{i_3} = 0, \gamma_{i_4} = M - 110, \gamma_{i_5} = M + 50 \)

A route center with a high \( \gamma \) value experiences high competition among customers to get serviced by one of its routes in the primal solution. Hence, the route center with smallest \( \gamma \) value in the dual solution is the most convenient for making customer grouping decisions.

In the remainder of this section we give an illustrative example in order to show how dual pricing rounds occur, and present computational results of some initial master LP model due to Solomon benchmark instances.

4.3. A illustrative example

Let us consider a simple problem instance that is given in Table 2. Clearly the only feasible, hence optimal, solution to the corresponding master LP model is \( x^*_r_{i_1} = x^*_r_{i_4} = 1 \), and \( x^*_r_{i_2} = x^*_r_{i_3} = 0 \) with objective value \( 5M - 135 \). Table 2 also shows the dual pricing solution after five dual iterations. Initially all customers have a budget of amount \( \gamma = 1.5M \) which results in the dual objective value \( 7.5M \).

In the first iteration, customers \( i_5 \) and \( i_3 \) compete for being serviced in a route of route center \( i_2 \). In the second iteration, route center \( i_4 \) involves a competition with route center \( i_2 \) to service customer \( i_5 \) in its route. The
**Data:** VRPTW Instance (Section 2.1), route sets $\mathcal{R}_c, rc \in RC$

**Result:** Optimal dual solution with pricing rounds

Initial dual feasible solution: $\gamma^0_c = (1 + \theta)M, \lambda^0_c = \theta M, \kappa^0_c = 0$ ;

Set: index $i = 0$, initialize dual improvement step $\Delta = \theta$;

while $\Delta > 0$ do

  Construct/update $\text{DRP}_i$ model as in (33)-(40) with sets $K_i, J_i, I_i, L_i$ ;
  Solve $\text{DRP}_i$ model;
  if Objective value of $\text{DRP}_i$ is zero then
  break ;
  Determine largest value of $\Delta$ by (43) and (45):
  Update $\gamma^{i+1}_c, \lambda^{i+1}_c, \kappa^{i+1}_c$ as in (41) or customers in $\text{DRP}_i$ solution;
  Find sets $K_{i+1}, J_{i+1}, I_{i+1}, L_{i+1}$ ;
  $i$++;

Output optimal dual solution $(\gamma^*, \lambda^*, \kappa^*)$;

**Algorithm 1:** Finding the optimal solution to a VRPTW problem

---

**4.4. Solomon benchmark instances.**

Having shown how the dual improvements occur, an iterative algorithm to solve the dual of the MLP model is implemented. As Algorithm 1 shows, we start with a dual feasible solution in which every customer has an initial budget slightly exceeding the coefficient $M$. As long as the optimal objective value of the $(DRP)$ model is significantly greater than zero and the dual improvement step is positive, the current dual feasible solution is improved. In every dual iteration, sets $K, J, I$ and $L$ are updated. The implementation is coded in Java and the $(DRP)$ model is solved by using CPLEX 12.6.1. The optimal dual solutions found after dual improvement/pricing rounds are verified by the dual solution of the MLP model that has also been found using CPLEX 12.6.1. Numerical results and the number of dual rounds for corresponding instances are given in Table 3. We do not report the solution times, since our main concern here is
Table 3: Computational results of primal-dual method

| Ins. | |RC| | $z_D^*$ | #Rounds |
|------|---------|------|---------|---------|
| C101 | 10      | 99171.06 | 58      |
| C102 | 8       | 87245.36 | 131     |
| C103 | 7       | 77336.33 | 68      |
| C104 | 4       | 48652.58 | 27      |
| C105 | 5       | 55488.42 | 29      |
| C106 | 4       | 45130.29 | 31      |
| C107 | 1       | 11853.27 | 69      |
| C108 | 1       | 11853.27 | 60      |
| C109 | 1       | 11867.77 | 39      |
| R101 | 17      | 91559.96 | 328     |
| R102 | 16      | 92059.64 | 222     |
| R103 | 13      | 90859.44 | 278     |
| R104 | 7       | 74808.94 | 164     |
| R105 | 7       | 61133.50 | 76      |
| R106 | 6       | 60989.03 | 65      |
| R107 | 5       | 57724.92 | 87      |
| R108 | 5       | 59987.25 | 70      |
| R109 | 4       | 43079.24 | 21      |
| R110 | 3       | 35690.76 | 20      |
| R111 | 5       | 57181.50 | 61      |

* Initial set of route centers

to show the equality of the solutions values found by directly solving the MLP model and by solving its dual with pricing rounds.

5. Methodology

In this section we explain a heuristic algorithm to solve the VRPTW. Note that this heuristic is a special way of using the dual understanding of master LP models as seen in Section 4. The heuristic algorithm utilizes the dual understanding that was the topic of the previous section. The algorithm has three phases; Pre-processing, a warm-up phase, and a saturated phase. Before going
into details, we shall provide a schematic overview of the heuristic in Section 5.1. After that, we will dive into the details of route construction in Section 5.2, how the information from the dual is retrieved in Section 5.3, how to find a new route center in Section 5.4, and finally the process of grouping a customer with a route center in Section 5.5.

5.1. An overview of the approach

As can be seen in Figure 2, there are three phases in the heuristic. In the beginning, there is the preprocessing phase. The heuristic algorithm starts with initializing the set of route centers which is done by finding a maximal independent set of (incompatible) customers, as was detailed in Section 2.2. After that, the route centers are initialized in the code. This phase is relatively short and we will not take a deeper look into it.

The second phase is the Warm-Up phase. Routes are constructed using the found route centers as will be detailed in Section 5.2. Immediately after that, the master LP is solved and checked using Gurobi 9.1. The primal and dual solutions of the MLP are ready to proceed further and provide information for the rest of the heuristic. This is the first iteration of the LP, as detailed in Section 5.3.

If we already have a proper solution, we can simply end. If this is not the case, we have to at least get $|RC| \leq L_{veh}$ as was found in Section 2.2. We go to find a new route center, as is detailed in Section 5.4, which also includes a new iteration of the linear program to verify which candidate to pick. Afterwards, the heuristic loops back to create full routes for the new route center and solve the LP again. We call this phase 'Warm-Up' because we want to get to the situation where $|RC| = L_{veh}$.

After that comes the 'Saturated' phase, which is called such because we have reached the lower bound on vehicles. Therefore, the system has to use more sophisticated decision making. There is a large loop in this phase, where route construction is followed by either finding a new route center, customer grouping, or both.
Figure 2: Overview of Heuristic Approach
If the system has found an integer solution with coverage 1.0, we can safely end. If not, we check whether the coverage is below a certain threshold $\beta$. In our implementation, we use 0.875 for $\beta$. Preliminary testing results of the heuristic algorithm showed that the results do not change significantly for $\beta$ values from 0.5 to 0.90. If the coverage is high enough, we go into customer grouping as described in Section 5.5. If not, we need to find another route center.

There is a possibility that customer grouping causes the coverage to go down or make it stagnate. If this is the case, we need a new route center as well. The dual solution of the master LP model is used in both finding new route centers and in customer grouping.

**Complexity and Time.** As seen in the section above, there are four points at which we can do an LP iteration: after the route construction in the Warm-Up and Saturated phases, and during the finding of a new route center in these two phases as well. It can be seen that the number of LP iterations, and thus the time required, heavily depends on the size of $IND$. If this is large and close to $L_{Veh}$, less route centers have to be found and so less LP iterations need to be done. Complex problems will require more iterations to solve. For example, looking forward to Section 6, c101 only needs one LP iteration to solve. The quicker we can get out of the Warm-Up phase, the quicker we will be done with the program.

Since there are a lot of variables, they are compiled in Table 4 for easy lookup.

5.2. Route construction.

In the following section, we will look more closely at how exactly the routes are constructed for the linear program. As was detailed in Section 5, these routes one half of the objective value. At any time, we are trying to minimize the total length of all selected routes. To do that, we try to make the routes as well as possible.
<table>
<thead>
<tr>
<th>Sets</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N'$</td>
<td>Set of customer locations, $N' = N \setminus {0}$</td>
</tr>
<tr>
<td>$R$</td>
<td>Set of all routes</td>
</tr>
<tr>
<td>$R_{rc,i}$</td>
<td>Set of routes going through route center $rc$, of length $i$</td>
</tr>
<tr>
<td>$K_{rc}$</td>
<td>Set of price-balanced paths going through route center $rc$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Customer $c \in N'$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$sv_c$</td>
<td>Service time</td>
</tr>
<tr>
<td>$q_c$</td>
<td>Demand</td>
</tr>
<tr>
<td>$e_c$</td>
<td>Earliest arrival time</td>
</tr>
<tr>
<td>$l_c$</td>
<td>Latest arrival time</td>
</tr>
<tr>
<td>$start_c$</td>
<td>Start time</td>
</tr>
<tr>
<td>$c_{comp}$</td>
<td>Number of competitors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Route $r \in R$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l(r)$</td>
<td>Length</td>
</tr>
<tr>
<td>$C_r$</td>
<td>Set of customers</td>
</tr>
<tr>
<td>$r_i$</td>
<td>Customer at position for $i \in 1, \ldots, l(r)$</td>
</tr>
<tr>
<td>$r_{qual}$</td>
<td>Quality</td>
</tr>
<tr>
<td>$r_gb$</td>
<td>Beginning of grouped part</td>
</tr>
<tr>
<td>$r_ge$</td>
<td>Ending of grouped part</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Route center $rc$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$rc_{cp}$</td>
<td>Length of central path</td>
</tr>
<tr>
<td>$rc_{gr}$</td>
<td>Number of grouped customers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Misc.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>Capacity of a vehicle/route</td>
</tr>
<tr>
<td>$d_{i,j}$</td>
<td>Euclidian distance between customers $i$ and $j$</td>
</tr>
<tr>
<td>$L$</td>
<td>Size of route set</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Coverage threshold</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Lag</td>
</tr>
</tbody>
</table>

Table 4: Reference Table for customers, routes and sets
Our route construction method has certain similarities to the one proposed by Kok10. In their proposed DP heuristic, the number of states at every iteration is bounded, and the expansion of states is limited by a constant number. However, in their case, they are looking at a situation with driving hour regulations. In our heuristic, we put a bound on both the total number of states (routes), as well as the number of routes at every iteration of the route construction. We will take into account the time windows of customers, as per the VRPTW.

To do that, we propose a greedy method of route construction. Starting from the building block of only having the route center, step by step we extend the routes by adding one customer at a time. Because we are using a greedy method, we end up with good routes of a smaller length as well. This means that while the linear program is being solved, it also has a chance to take these good shorter routes into account. That adds a layer of flexibility to the method, which wouldn’t be there if we only considered longer routes.

In the ILP reformulation we used within our algorithm, the routes are grouped for every route center in $RC$. Let $R_{rc}$ denote the routes set of route center $rc$. The routes in $R_{rc}$ are constructed greedily such that $R_{rc} = \bigcup_i R_{rc,i}$ where $i$ denotes the length of routes in subset $R_{rc,i}$. It is important to mention that the subsets are fixed size, i.e. $|R_{rc,i}| = L$ where $L$ a predetermined size depending on the dedicated memory.

Central Paths, Grouped Paths and Full Paths. There are two phases in route construction, based on the customer grouping. In the first phase, the central paths are extended to grouped paths, by doing extensions with only the grouped customers. More information on the grouping can be found in Section 5.5.

(Central Path) A sequence of customers in a route that contains only a specific number of “fixed” customers is called a central path of that route.

The central paths are chosen from the paths that were created during route construction. The paths that are chosen all come from the grouped paths:
(Grouped Path) A sequence of customers in a route that contains all “fixed” customers is called a grouped path of that route.

Grouped paths are created during the route construction phase, and consist only of grouped customers. Central paths are chosen during the customer grouping, and are the foundation of the route construction, reducing the number of possibilities and thus allocating more memory to the creation of new paths. Grouped paths are then extended into full paths. It can be the case that a grouped path is already a full path. If this is the case, all possible customers have been grouped.

The length of a central path of a route center is denoted by \( r_{cp} \). The number of grouped customers of a route center is denoted by \( r_{gr} \). Initially, \( r_{cp} = 1 \) and \( r_{gr} = 0 \). In the second phase, the grouped paths are extended to full paths, which also include customers that are not grouped with the route center. So, for a route center \( rc \in RC \), \( R_{rc,i} \) where \( r_{cp} \leq i \leq r_{gr} \) only uses grouped customers. For \( i > r_{gr} \), all customers are considered for extensions.

Next, we will take a look at exactly how the extensions work in the heuristic. Extensions are done in both directions, so forward and backward, in that order.

**Forward Extensions.** The procedure for finding forward extensions can be found in Algorithm 2. For \( R_{rc,i} \), we firstly take the routes of \( R_{rc,i-1} \) and extend them based on the pseudocode. Line 4 checks if the customer is already in the route. Line 5 checks that the earliest time we can make it to the customer is at most the latest arrival time of this customer, i.e. we do not violate time windows. Line 6 checks the capacity of the vehicle is not exceeded. Lines 7 and 8 deal with making it back to the depot and having enough time to start from the depot, respectively.
Data: route center $rc$, length $l$, Route set $R_{rc,l-1}$, Customers $N'$

Result: Route set $R_{rc,l}$

1. Create empty route set $R_{rc,l}$;

2. forall $r \in R_{rc,l-1}$ do

3. forall $c \in N'$ do

4. if $c \in C_r$ or $c = rc$ then Continue;

5. if $e_{rl(r)} + sv_{rl(r)} + d_{rl(r)},c > l_c$ then Continue;

6. if $\sum_{i=1}^{l_r(r)} q_r_i > Q$ then Continue;

7. if $e_{rl(r)} + sv_{rl(r)} + d_{rl(r),c} + sv_c + d_{c,0} > l_0$ then Continue;

8. if $\min(l_c - d_{rl(r)},c - sv_c - \sum_{i=1}^{l_r(r)} d_{r_i,r_{i+1}},l_{rl(r)}) - d_{0,r_1} \leq e_0$ then Continue;

9. Extension is considered feasible;

10. Determine quality value $r_{qual}$;

11. if $|R_{rc,l}| < L$ then

12. Insert $r$ into $R_{rc,l}$;

13. else if $r_{qual} > lowest quality found in R_{rc,l}$ then

14. Insert $r$ into $R_{rc,l}$, kick out route with lowest quality;

15. else Continue;

16. Output $R_{rc,l}$;

Algorithm 2: Extending routes forward

All feasible extensions are given a quality value, as is seen on line 10. This quality value of route $r$ with route center $rc$ is measured in two parts:

- $\sum_{i=1}^{l_r-1} d_{r_i,r_{i+1}}$. The total traveled distance of the extension. This is looked at normalized against other found extensions. We want to minimize this, to be as efficient as possible.

- $\frac{l_0 - (e_{rl(r)} + sv_{rl(r)} + d_{rl(r)},c + sv_c)}{l_0 - (l_c + sv_c)}$. The time spent in the route, referenced against the time that is left to get to the depot from the route center. In other words, how efficiently you are using your time.

The quality can also be considered as a detour cost, or how efficient it is to visit that specific customer.

As mentioned in Section 2.3 we only allow $L$ routes of length $i$ for a certain route center. To determine if a route is selected, we look at the quality as detailed above. If $|R_{rc,l}| < L$ so far, we add the new route to $R_{rc,l}$. If $|R_{rc,l}| = L$, we check where to insert the new route based on the quality it has. If it has a
lower quality than the last route in \( R_{rc,i} \), we do not put it in the route set. If it is inserted, we kick out the route with the lowest quality. This is represented in Algorithm 2 by lines 11-15.

**Backward Extensions.** For backward extensions, we consider a very similar setup as for the forward extensions, so we will not go into it in detail. It is depicted in Algorithm 3 and works very similar.

The quality of a backwards extension is made similarly to that of a forward extension. For backwards extensions, we consider the same set \( R_{rc,l} \) as for the forward extensions. The set will thus end up as a good mixture between these two methods.

It can be the case that we create an extension that is already existing in \( R_{rc,l} \). If this happens, we filter out the newly created one and just continue with the heuristic. This filtering is done by checking whether two routes are the same based on the arrival, ending, and sum of IDs of all customers in the route.

**Data:** route center \( rc \), length \( l \), Route set \( R_{rc,l-1} \), Customers \( N' \)

**Result:** Route set \( R_{rc,l} \)

1. Get route set \( R_{rc,l} \), which is filled with forward routes.
2. forall \( r \in R_{rc,l-1} \) do
   3. forall \( c \in N' \) do
      4. if \( c \in C_r \) or \( c = rc \) then Continue;
      5. if \( l_{r_1} - d_{c,r_1} \leq e_c + sv_c \) then Continue;
      6. if \( \sum_{i=1}^{l(r)} q_r + q_c > Q \) then Continue;
      7. if \( \min(l_{r_1} - d_{c,r_1} - sv_c,l_c) - d_{0,c} \leq l_0 \) then Continue;
      8. Extension is considered feasible;
      9. Determine quality value \( r_{qual} \);
     10. if \(|R_{rc,l}| < L \) then
         11. Insert \( r \) into \( R_{rc,l} \);
     12. else if \( r_{qual} > \) lowest quality found in \( R_{rc,l} \) then
         13. Insert \( r \) into \( R_{rc,l} \), kick out route with lowest quality;
     14. else Continue;
15. Output \( R_{rc,l} \);

**Algorithm 3:** Extending routes backward
**Insertions.** Insertions are different from extensions in the way they approach previous routes and how to check for them. Here, we will describe why these insertions are necessary and how they function.

Insertions are closely linked to the customer grouping as described in Section 5.5. In previous iterations of the heuristic, it was observed that the customer grouping is not flawless. Specifically, what seemed to happen was that some customers in important routes would be "skipped" for customer grouping. This caused the heuristic to not come to a complete integer solution. One way to ensure feasible solutions would be found, is by using insertions into existing routes.

Before doing the insertions themselves, we have to take a look at which customers we are actually going to consider. To do this, there is a simple heuristic to find candidates. If we are looking to create insertions of length \( l \), we look into the route set \( R_{rc,l-1} \). We iterate over all customers \( c \in N' \) and then routes \( r \in R_{rc,l-1} \). For every position in between two customers \( r_i, r_{i+1} \), we then check if there exists an arc between \( r_i \) and \( c \) and an arc between \( c \) and \( r_{i+1} \). This would mean there is actually space to insert this customer.

Then, we check if the added distance of inserting this customer would not be too much, compared to the rest of the route. If this is the case, we add the customer to the set \( \text{Insertioncustomers} \). It can be seen that if a customer is in \( \text{Insertioncustomers} \), it can be inserted in at least one path \( r \) of length \( l - 1 \).

Finding the insertions themselves works very similarly. For every customer \( c \in \text{Insertioncustomers} \), we look at every route \( r \) in \( R_{rc,l-1} \), and we check every position \( i = 1, 2, \ldots, l(r) \). We consider an insertion in between customers \( r_i \) and \( r_{i+1} \) feasible if:

- There exists an arc from customer \( r_i \) to \( c \).
- There exists an arc from \( c \) to customer \( r_{i+1} \).
- There is enough time after \( r_i \) to insert a customer.
- \( \sum_{i=1}^{l(r)} q_{r_i} + q_c \leq Q \). The added capacity can still fit in the vehicle.
• $c \notin C_r$. The customer is not already in the route.

• $c$ is not already grouped with a route center.

• $e_{r_i} + s v_{r_i} + d_{r_i,c} < l_c$. The arrival at customer $c$ does not exceed its time window.

• Coming back to the path at $r_{i+1}$ is possible within the timeframe.

• The quality is satisfied.

If an insertion is feasible, it is added to $R_{rc,i}$.

Already, it can be seen that insertions would take a long time if we allow them at every length $l$. Therefore, after testing, it was deemed necessary only in one situation: the route construction iteration after all grouped customers have been used.

**Route Set.** The route set $R_{rc,2}$ is fully enumerated in order to be able to get dual solutions with as much as information possible. As mentioned before, route sets $R_{rc,i}$ for $i \geq 3$ may be huge in size in general. Hence we require that $|R'_{rc,i}| \leq L$ for $i \geq 3$ where $L$ is a constant number, based on the memory that has been used in the route construction so far. For route centers with a short expected route length, this means more memory is allocated to each possible length. So $R'_{rc}$ becomes a fixed-size route set of the route center $rc$ which results in a fixed-size MLP model containing the selection variables of routes in sets $R'_{rc,i}$, for all $i \geq 1$, and $rc \in RC$.

5.3. **Solving the Master LP**

In this section, a brief overview is given on what happens after the routes have been constructed. We will not go into detail on the exact workings of the program, but will mention the information that will be used by the customer grouping and new route center finding.
Information. Before the LP has been solved, we retrieve two pieces of information. Firstly, we set the $\gamma$ values of all customers to the ones found by Gurobi. Subsequently, the $y_i$ values are recorded as well for later use. Secondly, the price-balanced paths are determined.

(Price-balanced path) A path with a reduced cost of 0. Only price-balanced paths can be selected by the LP.

As seen in Section 4 we call the set of all price-balanced paths $K$.

Solving the LP. The master LP is solved after route construction has finished. In this way, the system can immediately use the most recent information available.

The LP iteration first has to be set up by the system. We make use of Gurobi v9.1. The primal is created and initialized, after which the customers and their constraints are added to it. From there, Gurobi solved the LP iteration with the primary goal of maximizing the coverage, and the secondary goal of minimizing the route length as discussed in Section 4.

5.4. Route Center Selection

In this section, we go over the procedure for selecting a new route center. As seen in Figure 2 this happens in two phases of the program. First we look at finding the candidates, then at the actual selection. Note that during the selection, we have another LP iteration to find the best suitable new route center.

Finding Candidates. The procedure of selecting a new route center begins with determining route center candidates.

(Route Center Candidate) A customer $c \notin RC$ that has evidence of being a good route center, based on dual values.

For each existing route center, a network is created, similarly to the one used in customer grouping in Section 5.5. This network only counts the number of
appearances of each customer $c$ in the price-balanced routes of the route center. So, for customer $c$, that would be $\sum_{r \in K_c} \delta^c_r$.

From there, the number of competitors is determined for each $c$.

(Competitor) A customer $c' \in N', c' \neq c, c' \notin RC$ which never appears in $K_c$. The number of competitors of $c$ is denoted by $c_{comp}$.

$c_{comp}$ is found by going through all routes $r \in K_c$, and checking which customers appear. The interpretation is that, the more competitors there are, the fewer different customers $c$ sees. If a customer does not appear in many different routes of a route center, it means it is more likely to not belong to that route center.

Let $CAND$ denote the set of route center candidates. The customer list is sorted on the competitive value, calculated as:

$$competitiveValue = \frac{c_{comp}}{\max_{c' \in N', c' \neq c, c' \notin RC} c'_{comp}}$$

(46)

If there is room in $CAND$ and $c$ is not close to any $c' \in CAND$, $c$ is added to $CAND$.

Selecting a new Route Center. After the candidates have been selected and put into $CAND$, we start route construction once more. This time, we include every $cand \in CAND$ as a candidate route center in the LP, with each $cand$ being given a fraction of the memory for a normal route center. Routes are created for these $cand$ based on the methodology found in Section 5.2.

Based on this, we have found a new possible solution. We have to bound the number of candidates that can be selected in the MLP model. To do that, we add a constraint:

$$\sum_{r \in R_c, c \in CAND} x_r \leq 1$$

(47)

Per iteration of finding a new route center, we set the limit of selection to 1. This is so that we don’t add unnecessary route centers. The candidate that is chosen is the one with the highest primal selection value. Ties are broken by
Further ties are broken by the $\gamma^*$ values of customers. It can be seen that this is considered as another iteration of the linear program.

Once a new route center has been found, the constructed routes of all route centers and candidates are removed. The candidates are removed from $CAND$. Afterwards, the route sets $R_{rc}$ for every route center is constructed once more and the LP is solved.

5.5. Customer grouping

In this section, we will look at the customer grouping procedure. As seen in Figure 2, this happens during the Saturated phase of the program.

In Section 3, we mention several studies using variable fixing. The main advantage of variable fixing is to reduce the problem size and focus the heuristic’s efforts on finding the solution. In this work, we exploit the structure of the dual model as explained in Section 4. The main idea of customer grouping is to assign a customer to a route center, such that all routes of the route center have to include that customer. By doing that, the number of possible routes gets restricted and the number of variables for each route centers is reduced. The decision on which customer to group is based on the information from the dual.

The main motivation for doing customer grouping is that, by reducing the number of variables, we are able to reduce the problem size and be more focused on the solution. We use the information from the dual, and introduce the concept of grouping scores. After that, we look at how exactly the central paths are being set up for use in route construction.

**Grouping Scores.** To confidently make a grouping decision, we need evidence that grouping a certain customer will actually help us in finding the optimal solution. This evidence comes in the form of the grouping scores:

(Grouping Score) A quantified value of the confidence of assigning a customer to a route center, based on the dual information.

In this section, we will explain how exactly these scores are calculated and what impacts these scores have on grouping decisions.
First, we must find a base on which to build the grouping scores. To do that, we introduce the concept of a network for a route center \( rc \). In Section 4 we introduced the set \( K \), which contains all price-balanced paths. Let \( K_c \) be the set of price-balanced paths that go through customer \( c \in N' \), and \( K_{rc} \) be the price-balanced paths that include route center \( rc \in RC \). Then, we find the network as:

\[
\text{(Network) Representation of } K_{rc}, \text{ where scores and tallies of all customer in } N' \text{ are being recorded.}
\]

For the customer grouping, we consider a special kind of this network, called a weighted dual network. In a weighted dual network, we specifically go through the routes to find the dual scores. The heuristic goes through all \( r \in K_{rc} \) one by one.

One of the aspects of the grouping score has to do with the relative closeness to the grouped section of a route. The grouped section is the subsection of the route that contains only grouped customers. This grouped section has a beginning index \( r_{gb} \) and an end index \( r_{ge} \). It holds that \( r_1 \leq r_{gb} \leq r_{ge} \leq r_l \).

We call the closeness to the grouped section of a route of customer \( i \): \( r_{ci} \). The scores are determined as:

- For \( r_i < r_{gb} \), \( r_{ci} = r_{gb}/(r_{gb} - r_i) \). Here, \( r_{gb} \) is the length of the tail on the front.
- For \( r_{gb} \leq r_i \leq r_{ge} \), \( r_{ci} = 0 \).
- For \( r_{ge} > r_i \), \( r_{ci} = (l - r_{ge})/(1 + r_i - r_{ge}) \). Here, \( (l - r_{ge}) \) is the length of the tail at the end of the route.

As can be seen, the closer the customer is to the grouped section of a route, the smaller the score. Therefore, while the heuristic algorithm calculates scores for all customer-route center pairings, the customers visited right before and after route centers have the highest probability of having these good scores.

After the network is created, every customer \( c \) has three items recorded:
Based on the network, scores can be calculated for the route center. One score is determined for every customer that has been seen by the route center at least once. There are three components to the score:

1. The stability of the route center, which is the $\gamma$ value relative to all other route centers’ $\gamma$. What this component measures is how 'confident' the LP is in assigning customers to this route center overall.
2. The primal values of the customer, as determined by the networking strategy above in $\sum_{r \in K_{rc}} x_r$. If a visit is strongly selected in the primal solution, that provides evidence to the claim that grouping is a good idea.
3. The dual competition of the customer, which is the relative closeness $\sum_{r \in K_{rc}} r_{cil}$ as described above. This is rooted in the dual values.

Each of these components has a weight associated with them as well. All of these weights are also determined by the total coverage achieved so far. For example, the stability of the route center is important if the coverage is very low, since we will have to find new route centers soon. Similarly, the primal values are more important when the coverage is high, since there will be a lot of competition. Note that only a customer with good scores in all three of these components is considered to have a strong grouping score.

After this process is repeated for every route center, all the customer-route center pairings are sorted based on their score. Those customers with a score higher than the threshold $\alpha$ will be grouped. In our implementation, $\alpha = 0.7$. Every grouped customer is then assigned to its route center.

Central Route Setting. From this point on, we consider the setting of central paths. As discussed in Section 5.2, central paths are the building blocks of...
routes, from which the rest follows. One could ask why we need central paths in the first place. After all, if you start with creating routes using only grouped customers, the variables are sufficiently bounded. While that is true, the reason we want central routes is twofold.

Firstly, customer grouping works best when we have a lot of customers grouped with one route center. However, what happens then is that the route construction does not gain much from having the grouped customer. There would be many possible routes of a short length. Making paths using 3 grouped customers is quick; making them using 30 could take a long time.

Secondly, if we manage to set central paths of a longer length, this frees up memory for the rest of the route construction. Recall that $L$ is the number of paths that can exist for routes of length $l$. $L$ is based on the allocated memory for the route center, divided in such a way to let routes flourish. If we are able to set the central paths, our building block, to become longer, the memory that has been freed up and can be used for the rest of the route set. Therefore, setting the central path lets us explore more possibilities, while not increasing the total size of the route set.

Now that we know why, let us look at how exactly we determine the central paths for a route center. After customer grouping has been finished, we go over all route centers $rc \in RC$ in the system. As we saw before, the number of grouped customers for a route center is $rc_{gr}$. If new customers have been grouped with this route center, we need to consider if we want to set new central paths as well.

After experimentation, the result of this is the concept of lag. Lag is the amount of difference between the length of the central path and the total number of grouped customers for this route center. In other words, $rc_{gr} - rc_{cp} = \epsilon$, where $\epsilon$ is the lag between the two. The advantage of using this notion of lag is that we restrict the number of possible routes of a shorter length, but allow more flexibility in routes of a longer length.

We check whether we have exceeded $\epsilon$ after customer grouping. If this is not the case, we can simply return to the route construction. If $\epsilon$ is indeed
exceeded, we go to select the new route centers. We first determine how much longer the central paths will be. This is equal to \( r_c - \epsilon = l \). We take the paths of this length \( l \) and of them, set the top \( k \) as central. In our implementation, \( k = 5 \). The paths are retrieved from the previous iteration of route construction. Once we find the new central paths, we can start the next iteration of route construction using these as the building block. These central paths are added to the LP as well, even if they are not price-balanced.

6. Computational results

We implemented the proposed heuristic algorithm in Java coding environment. During the course of the algorithm, all MLP models are solved by using Gurobi 9.1. The results that are presented in this section are obtained by using a personal computer with Intel i5 3.1 GHz Processor, and 16GB capacity of RAM.

100-customer instances of Sol87 are used in our experimentation as benchmark instances. Table 5 gives preprocessing values of the instances. For example, C101 has initially the number of route centers equal to the lower bound on the number of vehicles. In instances C107-C109 and C204-C208 there is only one route center in the beginning. The high number of MLP iterations for these instances are due to runs of the model to find new route centers.

Table 6 shows the results found by our implementation. In a group of instances, the columns show the names of instances, solution properties of our heuristic; first number of vehicles and second traveled distance, and the percentage gap between the best known solution in travel distances. Finally, we list number of MLP solving iterations for the instances in the last column of an instance.

The results of the C10X instances show that, while they can take a bit of time, all except one solve to optimality. For C20X, one instance clearly stands out. C204 optimally only has three vehicles, and so the optimality gap here is considered to be very large. For the other instances, the biggest gap found was
### Table 5: Maximal Independent Sets, lower bound of number of vehicles

| Instance | $|IND|$ | $L_{veh}$ | Instance | $|IND|$ | $L_{veh}$ |
|----------|--------|--------|----------|--------|--------|
| C101     | 10     | 10     | C201     | 2      | 3      |
| C102     | 8      | 10     | C202     | 2      | 3      |
| C103     | 7      | 10     | C203     | 2      | 3      |
| C104     | 4      | 10     | C204     | 1      | 3      |
| C105     | 5      | 10     | C205     | 1      | 3      |
| C106     | 4      | 10     | C206     | 1      | 3      |
| C107     | 1      | 10     | C207     | 1      | 3      |
| C108     | 1      | 10     | C208     | 1      | 3      |
| C109     | 1      | 10     |          |        |        |

3.7% for C203 and 4.7% for C205, and all others are at 1.0% or below. For C202, C203 and C204, the running times are quite large. Many iterations of customer grouping had to be performed in these instances before getting to a solution with complete coverage. They get faster over time as central paths get longer and more variables are fixed.

### 7. Conclusions and further research

This paper has two main contributions. Firstly, it provides a dual analysis of a master LP formulation of the VRPTW by using the primal-dual method. Secondly, a heuristic algorithm of the VRPTW is proposed by using the understanding from the dual analysis. In the dual analysis it is observed that the dual solution is the final state of a pricing competition among customers to appears in primal route of route centers.

The most popular route center has a high dual decision variable, which means that the primal solution of that route center is not reliable to make customer grouping decisions. On the other hand, the existence of desperate customers in the dual solution, i.e. customers with highly negative dual variables, provides
The proposed heuristic algorithm uses a master LP model of the VRPTW as a central optimization mechanism. It finds a complete routing solution by making customer grouping decisions by checking the evidence by not only using the primal selection values, but also the dual solution properties of the master LP model. To the best of our knowledge, this work is the first one incorporating the properties of the dual solution in solving routing problems. We believe that several issues in the proposed heuristic algorithm can be improved, leading to better results. Firstly the speed needs to be looked at, for example by limiting the number of times route construction is done. Limiting the number of LP iterations could work in our favor as well, though we should be careful with this since it could influence the grouping decisions being made.

The master LP model under consideration of this paper can be used for several extensions of the VRPTW that involve real-life aspects like time-dependent travel times, stochastic travel times, and driving time regulations. These aspects of the problem will then be considered in the route construction routine of the
heuristic.

Finally, our dual analysis can be used to analyze other Operations Research problems that can be formulated as a master LP model. Then the dual interpretation will be useful in understanding the underlying processes resulting in the dual solution. This may give an opportunity to develop similar heuristic approaches for these problems.

8. Bibliography

References


