# A granular iterated local search for the asymmetric single truck and trailer routing problem with satellite depots at Deutsche Post DHL Group

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**Abstract**

To plan the postal deliveries of our industry partner Deutsche Post DHL Group (DPDHL), the single truck and trailer routing problem with satellite depots (STTRPSD) is solved to optimize mail carriers routes. In this application context, instances feature a high number of customers and satellites, and they are based on real street networks. This motivates the study of the asymmetric STTRPSD (ASTTRPSD). The heuristic solution methods proposed in the literature for the STTRPSD can either solve only the symmetric problem variant, or it is unclear whether they can also be used to solve the ASTTRPSD. We introduce an iterated local search, called ILS-ASTTRPSD, which generates different first-level tours in the perturbation phase, and improves the second-level tours in the local search phase. To speed up the search, granular neighborhoods are used. The computational results on instances from the literature prove the capability of ILS-ASTTRPSD to return high-quality solutions. On DPDHL instances, ILS-ASTTRPSD significantly decreases total travel times of the mail carriers and returns solutions with a different structure compared to the ones provided by DPDHL. Based on these differences, we give recommendations on how DPDHL could design more efficient mail carrier practices. Dedicated computational experiments reveal that considering parking and loading times when solving the ASTTRPSD leads to lower travel times, and that ignoring parking times is more counterproductive than ignoring loading times. Finally, we derive properties of instances for which optimal solutions contain multiple second-level tours rooted at the same parking spot and for which the optimal solutions of the ASTTRPSD correspond to the ones of a pure traveling salesman problem.

**Keywords:** *postal deliveries, asymmetric single truck and trailer routing problem with satellite depots, park and loop, granular iterated local search, large-scale instances*

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# 1 Introduction

Postal routing activities are of major importance for companies like our industry partner Deutsche Post DHL Group (DPDHL). DPDHL has to serve 54 200 districts on six days a week and has to deliver an average of 57 million letters every day. Therefore, decision support to reduce the travel time of the individual mail carriers is a strong lever to reduce total operating costs.

DPDHL's postal delivery tours are executed daily, but they are planned at the tactical level, i.e., they remain unchanged for several months. DPDHL executes the delivery tours using two different means of transportation: a vehicle (car, bike, or carrier) is combined with a mail carrier that walks to carry out the final delivery. This can be modeled as a park and loop problem (PLP, see Bodin and Levy 2000), in which a mail carrier with a vehicle departs from a main depot to serve the demand of a set of households, which are reachable only by walking (without the vehicle). There is a set of given parking spots, where the mail carrier can park the vehicle, get off, and load their bag with letters to serve a group of households. The bag has a limited capacity, but the mail carrier can walk one or multiple subtours, all starting and ending at the same parking spot. We refer to the tour traveled by the mail carrier using a vehicle as *first-level tour* and to the walking subtours as *second-level tours*. The aim of DPDHL is (i) to select a set of parking spots and determine their visiting sequence (first-level tour), and (ii) to choose the household visiting sequence from each selected parking spot (second-level tours) in such a way that each household is visited exactly once. The objective is to minimize the total travel time of all tours of the mail carrier.

The specific PLP that DPDHL has to solve corresponds to the single truck and trailer routing problem with satellite depots (STTRPSD). Because DPDHL executes deliveries on a real street network, the presence of one way streets, crossroads, dead-end streets, turning restrictions, and medial strips between lanes makes travel times neither Euclidean nor symmetric. Consequently, DPDHL has to solve the asymmetric STTRPSD (ASTTRPSD).

The ASTTRPSD can be defined on a directed graph $G = (V, A)$, where $V$ is the vertex set and $A$ is the arc set. The vertex set is partitioned into $V = \{0\} \cup V_D \cup V_C$, where 0 is the depot, $V_D$ is the set of parking spots, and $V_C$ is the set of households. A nonnegative travel time $c_{ij}$ is associated with each arc $(i, j) \in A$. For walking arcs, i.e., $\{(i, j)|(i \in V_C \wedge j \in V_C) \vee (i \in V_C \wedge j \in V_D) \vee (i \in V_D \wedge j \in V_C)\}$, and driving arcs, i.e., $\{(i, j)|(i \in \{0\} \cup V_D \wedge j \in \{0\} \cup V_D)\}$, the travel times satisfy the triangle inequality. However, this is not true in general because driving between two locations $i$ and $j$ may be slower than walking from $i$ to $k$ and from $k$ to $j$. This happens, for example, when two households are located on the opposite sides of a street and crossing the street by walking is possible, but U-turns by vehicles are not allowed. Each household $i \in V_C$ has a nonnegative demand $q_i$. The capacity of the vehicle is denoted by $Q_v$, the capacity of the mail carrier bag by $Q_b$. To guarantee feasibility, we assume that the capacity of the vehicle at least corresponds to the cumulative demand of the households, i.e., $Q_v \geq \sum_{i \in V_C} q_i$. Moreover, we assume that split deliveries are not allowed and that the capacity of the mail carrier bag is at least as large as the maximum household demand, i.e., $Q_b \geq max_{i \in V_C}\{q_i\}$.

A solution $S$ of the STTRPSD consists of (i) a first-level tour $t^1$, i.e., a cycle starting from the depot, visiting a subset of parking spots denoted by $V_D(t^1)$ and returning to the depot, and (ii) a set of second-level tours $T^2$, in which each element of this set starts at a parking spot $k \in V_D(t^1)$ contained in the first-level tour, visits one or more households in $V_C$, and ends at the same parking spot $k$. Multiple second-level tours can be rooted at the same parking spot. The set of households visited in a second-level tour $t^2 \in T^2$ is represented by $V_C(t^2)$.

The travel time of the first-level tour is represented by $c(t^1)$, the travel time of a second-level tour is denoted by $c(t^2)$. A solution is feasible if the cumulative demand of the households visited in every second-level tour does not exceed the bag capacity, i.e., $\sum_{i \in V_C(t^2)} q_i \leq Q_b$ for all $t^2 \in T^2$, and each household is visited exactly once. A feasible solution is optimal if it minimizes the sum of the total travel time of the first and the second-level tours $c(t^1) + \sum_{t^2 \in T^2} c(t^2)$. The time required to park the vehicle at a parking spot $k$ is denoted by $\rho_k$ and can be easily included at the instance level by adding the parking time to the travel time of every arc entering the parking spot $k$ from another parking spot, i.e., to the arcs $\{(i,k) | i \in V_D, i \neq k\}$. If the parking time is assumed to be the same for all parking spots, we simply denote it by $\rho$. Similarly, the time required to load the bag before starting a second-level tour at a parking spot $k$ is denoted by $\ell_k$ and can be included by adding the loading time to the travel time of each arc connecting the parking spot $k$ to a household, i.e., to the arcs $\{(k,i) | i \in V_C\}$. When the loading time is assumed to be independent of the parking spot, we denote it by $\ell$.

Several metaheuristics exist for the symmetric STTRPSD (see Villegas et al. 2010, Accorsi and Vigo 2020, Arnold and Sörensen 2021). However, the heuristic of Accorsi and Vigo (2020) cannot solve the asymmetric problem variant, and, for the methods of Villegas et al. (2010) and Arnold and Sörensen (2021), it is not clear whether they can also solve the ASTTRPSD (for more details, see Section 2). Moreover, apart from their asymmetry, DPDHL instances differ from the artificial instances used in the literature in two additional aspects. First, while the instances in the literature have at most 20 parking spots and 200 households, the DPDHL instances are larger with an average of 724 parking spots and 390 households. Second, all DPDHL instances have more parking spots than households. In each instance, the number of parking spots is approximately double the number of households, representing the possibility, for almost all households, of parking on both sides of the street. An extract of a DPDHL instance is presented in Figure 1. The street network is shown in gray, the households in blue, and the parking spots in magenta.

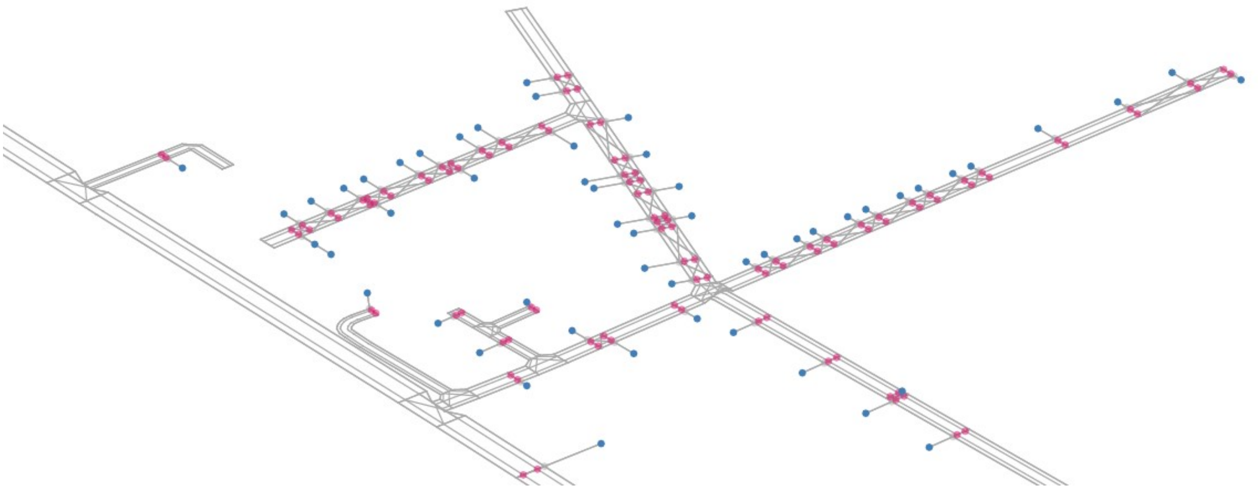


Figure 1: Extract of an exemplary DPDHL instance.

This paper contributes by proposing an iterated local search (ILS) for the ASTTRPSD, called ILS-ASTTRPSD. The structure of the problem allows us to naturally decompose the problem into a first-level tour which is tackled at the perturbation level, and second-level tours which are improved by the local search phase. This decomposition decreases the computational effort otherwise required to apply the perturbation and the local search phase to the first- and second-level tours simultaneously. To speed up the search, our ILS uses granular search (see Toth and Vigo 2003). This principle is based on a sparsification method which is used to restrict the size of the neighborhoods to explore. In our computational experiments, to test the ILS-ASTTRPSD capability of returning high-quality solutions, we first compare ILS-ASTTRPSD solutions to the state-of-the-art heuristic by Reed et al. (2021) for a similar problem. ILS-ASTTRPSD outperforms this method and finds new best-known solutions for a large number of instances. On DPDHL instances, ILS-ASTTRPSD significantly improves the total travel times with respect to the solutions provided by DPDHL. By comparing the structure of ILS-ASTTRPSD and the DPDHL solutions, we draw insights on more efficient mail carrier practices. For completeness, we also use ILS-ASTTRPSD to solve symmetric instances from the literature. The results show that the solution quality is reasonable compared to the specialized methods from the literature.

Moreover, we derive instance conditions under which: (i) multiple second-level tours from the same parking spot may exist in an optimal solution, and (ii) the optimal solution corresponds to the one of a TSP with one dedicated parking spot for each household. Finally, we contribute with managerial insights on the influence of parking and loading times on the solution structure. Results show that considering both parking and loading times leads to shorter travel times and that ignoring parking times returns more costly solutions than ignoring loading times.

The paper is organized as follows. In Section 2, we review the literature on the STTRPSD and related problems. Section 3 describes our ILS-ASTTRPSD, and, Section 4 derives instance properties that characterize special structures of optimal solutions. We present the computational experiments and results in Section 5. Finally, Section 6 concludes the paper.

## 2 Literature review

In this section, we review the literature on the STTRPSD and closely-related problems. The STTRPSD belongs to the class of the truck and trailer routing problems (TTRP), which are discussed in several surveys (Nagy and Salhi 2007, Drexl 2012, Prodhon and Prins 2014, Cuda et al. 2015, Schiffer et al. 2019).

The STTRPSD was first introduced in Villegas et al. (2010). The authors propose a mathematical formulation, a set of symmetric instances, and multiple heuristic methods to solve the problem. The best performing method is a multi-start ILS. However, the authors only report experiments for symmetric instances, and it remains unclear whether their heuristic can also solve asymmetric ones. Belenguer et al. (2016) propose a branch-and-cut algorithm that uses several families of valid inequalities and exact and heuristic separation procedures. Their exact method solves instances with up to 50 households and 10 parking spots to optimality. While the valid inequalities in Belenguer et al. (2016) are specifically tailored to the STTRPSD, Bartolini and Schneider (2020) solve instances of the STTRPSD of the same size via a branch-and-cut algorithm with valid inequalities developed for the capacitated TTRP. Accorsi and Vigo (2020) develop the state-of-the-art metaheuristic for the STTRPSD. Their approach is based on an ILS applied within a multistart framework, and the authors store high-quality first- and second-level tours in a solution pool during the execution of the heuristic. The ILS is composed of a perturbation phase based on a ruin and recreate mechanism and a local search component, namely, a randomized VND with first improvement. Every time the perturbation phase is called, either a subset of parking spots is randomly selected and closed, or random households are removed from every second-level route until their load is less than a specified threshold. The solution is then rebuilt by selecting households according to different criteria and inserting them in the position which minimizes the insertion cost. At the end, a set-partitioning problem is solved with the tours saved in the solution pool. The algorithm of Accorsi and Vigo (2020) has been specifically designed for symmetric instances and cannot be used to solve asymmetric instances. For example, in their algorithm, the authors use, among others, the 2-opt neighborhood operator in intra-route fashion, which causes problems when dealing with asymmetric instances. Arnold and Sörensen (2021) study the STTRPSD as a variant of location-routing problems and propose a progressive filtering heuristic capable of obtaining solutions competitive to those of Villegas et al. (2010). Because Arnold and Sörensen (2021) always use the term "edge" and all experiments are based on symmetric instance sets, it remains unclear whether their heuristic can solve asymmetric instances.

A problem similar to the STTRPSD is the capacitated delivery problem with parking (CDPP) introduced by Reed et al. (2021). The authors explicitly model the time required for a delivery man to search for a parking spot and identify the conditions under which considering the parking time changes the solution structure. Their problem is different from ours in the following aspects. First, they assume that the parking and household locations coincide. Consequently, whenever the parking search time is set to zero, the optimal solution corresponds to that of a TSP, in which every household is served from the parking spot at the same location. In the ASTTRPSD, when no parking times are considered, the optimal solution may differ from the TSP solution because driving on a street network is not always faster than walking, and a household may have more than one associated parking spot. Second, in their paper, the loading time depends on the number of packages to be delivered. Because the sum of all households' demand must be satisfied, the loading time is a constant that can be excluded from the optimization. In the ASTTRPSD, because the mail carrier can directly take the letters in blocks, the loading time is not dependent on the number of letters but fixed per second-level tour. Consequently, the loading time must be included in the optimization because it may influence the number of second-level tours in the solution. Reed et al. (2021) propose a heuristic to address their problem. The computational results show gaps to the optimal solution of at most 5.5% for instances with up to 100 households.

The STTRPSD is also related to PLPs. The practice of combining walking and driving is introduced by Levy and Bodin (1989) in a location arc routing problem for postal deliveries and formalized as "park-and-loop" problem by Bodin and Levy (2000). For model formulations of the PLPs proposed by Bodin and Levy (2000), we refer to Bode (2013). Additional variants of PLPs are the multi-modal PLP for postal deliveries (Gussmagg-Pfliegl et al. 2011), the doubly open park-and-loop routing problem (Cabrera et al. 2022), and the park-and-loop routing problem with parking selection (Le Colleter et al. 2022).

The two-echelon structure of the STTRPSD also relates it to the two-echelon driving and walking distribution problem for last-mile delivery studied in Martinez-Sykora et al. (2020). The authors propose a mathematical formulation of the problem, derive valid inequalities, and solve instances with up to 30 vertices via branch-and-cut. However, different from our problem, the authors do not allow multiple second-level tours starting from the same parking spot.

# 3 Granular iterated local search

In this section, we introduce the ILS-ASTTRPSD algorithm. The pseudocode is given in Figure 2.

After obtaining a starting solution using the two-phase construction heuristic explained in Section 3.1, the ILS described in Section 3.2 is executed. In each ILS iteration, a local search phase based on a VND with first improvement (Section 3.2.1) is applied. Whenever a better solution than the incumbent best is found, the best found solution is updated. The VND terminates when the total travel time of the solution stops improving. Next, the perturbation phase is applied to the best found solution (Section 3.2.2) to generate a new solution having different opened parking spots and second-level tours adapted for this new configuration. The ILS terminates after $\eta$ iterations without improvement.

**Algorithm 1:** Pseudocode of ILS-ASTTRPSD algorithm

```
S ← constructionHeuristic()
S* ← S
while termination criterion not satisfied do
    while improvementVND do
        S ← VND(S)
        if c(S) < c(S*) then
            S* ← S
            c(S*) ← S
        end
    end
    S ← perturbation(S*)
end
```

Figure 2: Pseudocode of ILS-ASTTRPSD algorithm.

## 3.1 Construction heuristic

Our construction heuristic consists of two phases: an iterated clustering algorithm (Section 3.1.1) used to obtain a starting solution and an improvement phase (Section 3.1.2) used to optimize the selection of opened parking spots.

### 3.1.1 Iterated clustering algorithm

The iterated clustering algorithm is inspired by the clustering algorithm proposed by Fischetti et al. (1997). In their paper, the authors use this algorithm to generate instances of the group TSP from the instances of the classical TSP contained in the TSPLIB library (Reinelt 1991). While Fischetti et al. (1997) apply the algorithm to create clusters using vertices from the same vertex set, we use the set of parking spots to select the cluster centroids and the set of households to form clusters. The algorithm takes as input a parameter $K$ that specifies the number of clusters (i.e., open parking spots) to form. Then, it selects $K$ centers (i.e., parking spots) by considering the $K$ vertices located as far as possible from each other. Finally, it assigns each vertex (i.e., household) to its nearest center. The advantage of this algorithm is that it produces well-distributed opened parking spots in the street network. However, it requires to specify a value for $K$ as input, and the optimal value of $K$ is unknown.

To overcome this problem, we propose an iterated version of this clustering algorithm that is summarized in Figure 3. We initialize the number of parking spots to open to the lower bound value of the number of required second-level tours to satisfy the total household demand. Then, we execute the clustering algorithm of Fischetti et al. (1997) for increasing values of $K$ (in steps of one). Once the parking spots to open and the assignment of households to parking spots have been determined, we solve a TSP on the opened parking spots to build the first-level tour $t^1$. For each parking spot, we build a temporary second-level tour, in which the assigned households appear according to the lexicographic order. Next, we check, for each parking spot, if the sum of the demands of the households assigned to that parking spot exceeds the bag capacity of the mail carrier. If this situation occurs, we start moving one household at a time starting from the first visited one to a new second-level tour rooted at the same parking spot until all second-level tours rooted at that parking spot become feasible. Then, we solve a TSP for every second-level tour in $T^2$. The algorithm terminates after a given number of iterations without improvement.

**Algorithm 2:** Pseudocode of the iterated clustering algorithm

```
initialize S = ∅, c(S) = +∞, γ = 0, K = ⌈∑_{i∈V_C} q_i/Q_b⌉
while γ < γ_max do
    clusteringAlgorithm(K)
    S′ ← solveTSP(t^1)
    S′ ← solveTSP(t^2) ∀t^2 ∈ T^2
    K += 1
    if c(S′) < c(S) then
        γ = 0
        S ← S′, c(S) ← c(S′)
    else
        γ += 1
    end
end
```

Figure 3: Pseudocode of the iterated clustering algorithm.

### 3.1.2 Construction heuristic improvement phase

In the improvement phase, we optimize the choice of the opened parking spots by keeping the households visited in each second-level tour $V_C(t^2)$, $t^2 \in T^2$ unchanged and the visiting sequence of the second-level tours fixed.

First, we build the weighted layered graph shown in Figure 4. We start by appending a vertex representing the depot 0 at the beginning and at the end of the graph. Each layer of the graph corresponds to a second-level tour $t^2 \in T^2$. Because the visiting sequence of the second-level tours is kept fixed, the layers can be arranged in sequence. The nodes within one layer represent the parking spots associated with the households in that particular second-level tour, i.e., $V_C(t^2)$. For simplicity, the figure shows the situation in which only one parking spot is associated with each household, but each household can potentially have more than one associated parking spot. Each arc connects a parking spot of one layer to a parking spot of the successive one. For the sake of representation, the figure does not show the weights on the arcs which represent the travel time between pairs of connected parking spots. By solving a shortest path problem on such a weighted layered graph, we identify the optimal selection of parking spots to open.

If this procedure results in a different choice of the opened parking spots with respect to the one of the solution $S$ returned by the iterated clustering algorithm, the second-level tours that were rooted in a parking spot that was previously open need to be adjusted. In each of those second-level tours, the first visited household becomes the closest one to the new opened parking spot. The visiting sequence of the remaining households is determined according to the order in which they appeared after the new first visited household in the previous version of the second-level tour. At the end of this improvement phase, the number of opened parking spots may have changed, e.g., if two second-level tours are now rooted in the same parking spot, or if two second-level tours which were rooted in the same parking spot are now rooted in two different parking spots.

## 3.2 Iterated local search

Our ILS implements the classical ILS framework originally proposed by Lourenço et al. (2003). Each iteration of ILS is composed of two phases: (i) a VND phase with the goal of improving the travel time of the second-level tours (Section 3.2.1), and (ii) a perturbation phase with the goal of generating a new configuration of opened parking spots (Section 3.2.2).

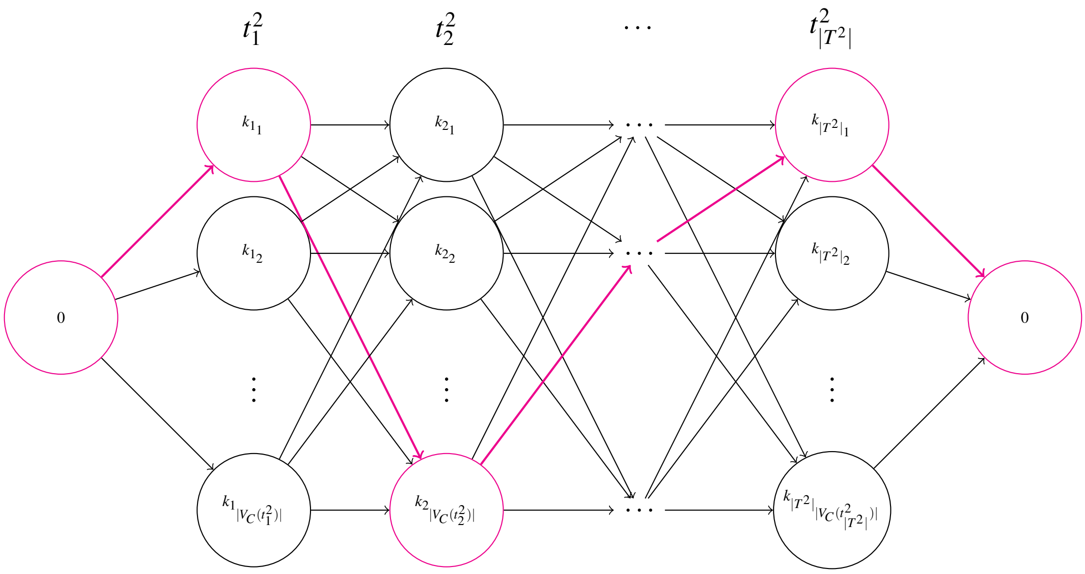



Figure 4: Structure of the auxiliary weighted layered graph and shortest path problem solution in magenta.

### 3.2.1 Variable neighborhood descent

VND iteratively evaluates neighboring solutions that are obtained by applying to a solution $S$ a move uniquely defined by a so-called generator arc $(i, j)$ and a neighborhood operator $o \in O$. After the move is applied, the arc $(i, j)$ is contained in the resulting solution. Because the pivoting rule of our VND is first improvement, the order according to which the neighborhood operators and the generator arcs are traversed influences the search trajectory. For this reason, the elements in the sets of the neighborhood operators $O$ and of the households $V_C$ (which are used as the origin vertices of the generator arcs) are randomly shuffled at the beginning of each ILS iteration, before calling the VND, resulting in the lists $\tilde{O}$ and $\tilde{V}_C$. This increases the likelihood that different search trajectories are explored and different solutions are obtained in case the same configuration of opened parking spots is considered more than once.

Figure 5 shows the pseudocode of the VND. The VND traverses the list $\tilde{O}$ of neighborhood operators described in Section 3.2.1.1. For each operator, the generator arc list is traversed. Specifically, each arc is obtained by pairing a vertex $i$ from the list $\tilde{V}_C$ of households with a vertex $j$ from the list of the closest households and parking spots to household $i$. This latter list is denoted by $L_i$ and obtained as described in Section 3.2.1.2. Given a neighborhood operator and a generator arc, a move is applied to a solution $S$ and a new solution $S^{'}$ is obtained. If the total travel time of the new solution $S^{'}$ is lower than the total travel time of $S$, then the new solution $S^{'}$ becomes the new incumbent in the VND, and the search restarts from the first operator.

**3.2.1.1 Neighborhood operators** The neighborhood operators contained in set $O$ are defined using the generator arc principle introduced in Section 3.2.1. They are depicted in Figure 6 and are:

- 2-opt* is used in inter-route and intra-parking spot fashion, i.e., it is not evaluated for second-level tours rooted at different parking spots.
- split creates a new second-level tour containing a single household, and it is defined in both intra- and inter-parking spot fashion.

**Algorithm 3:** Pseudocode of VND(S)

```
Input: S
improvementVND = false
for o ∈ Õ do
    for i ∈ Ṽ_C do
        for j ∈ L_i do
            S' ← move(o, i, j, S)
            if C(S') < C(S) then
                improvementVND = true
                S ← S'
                C(S) ← C(S')
                return S
            end
        end
        if improvementVND = true then
            return S
        end
    end
    if improvementVND = true then
        return S
    end
end
return S
```

Figure 5: Pseudocode of VND(S).

- exchange swaps one household between second-level tours or within a second-level tour, and it is defined in both intra- and inter-parking spot fashion.
- relocate-1 moves one household between second-level tours or within a second-level tour, and it is defined in both intra- and inter-parking spot fashion.
- relocate-b, where the "b" stands for "backwards", relocates all predecessors of a household (parking spot excluded) before another one, and it is defined in both intra- and inter-parking spot fashion.

The relocate-1 and split operators reduce the number of opened parking spots by one if the following three conditions apply simultaneously: (i) the second-level tour of household $i$ is composed of only $i$, (ii) the parking spot of $i$ is used only for the second-level tour of $i$, and (iii) the second-level tour of $j$ is rooted at a different parking spot (for relocate-1) and $j$ is different from the parking spot of $i$ (for split). Similarly, the relocate-b operator reduces the number of opened parking spots by one if (i) $i$ is the last visited household of a second-level tour, (ii) the parking spot of $i$ is used only for the second-level tour of $i$, and (iii) the second-level tour of $j$ is rooted at a different parking spot. For this reason, to compute the impact that each move has on the total travel time of a solution, we also consider the saving in the first-level tour travel time if these conditions hold for the above mentioned operators.

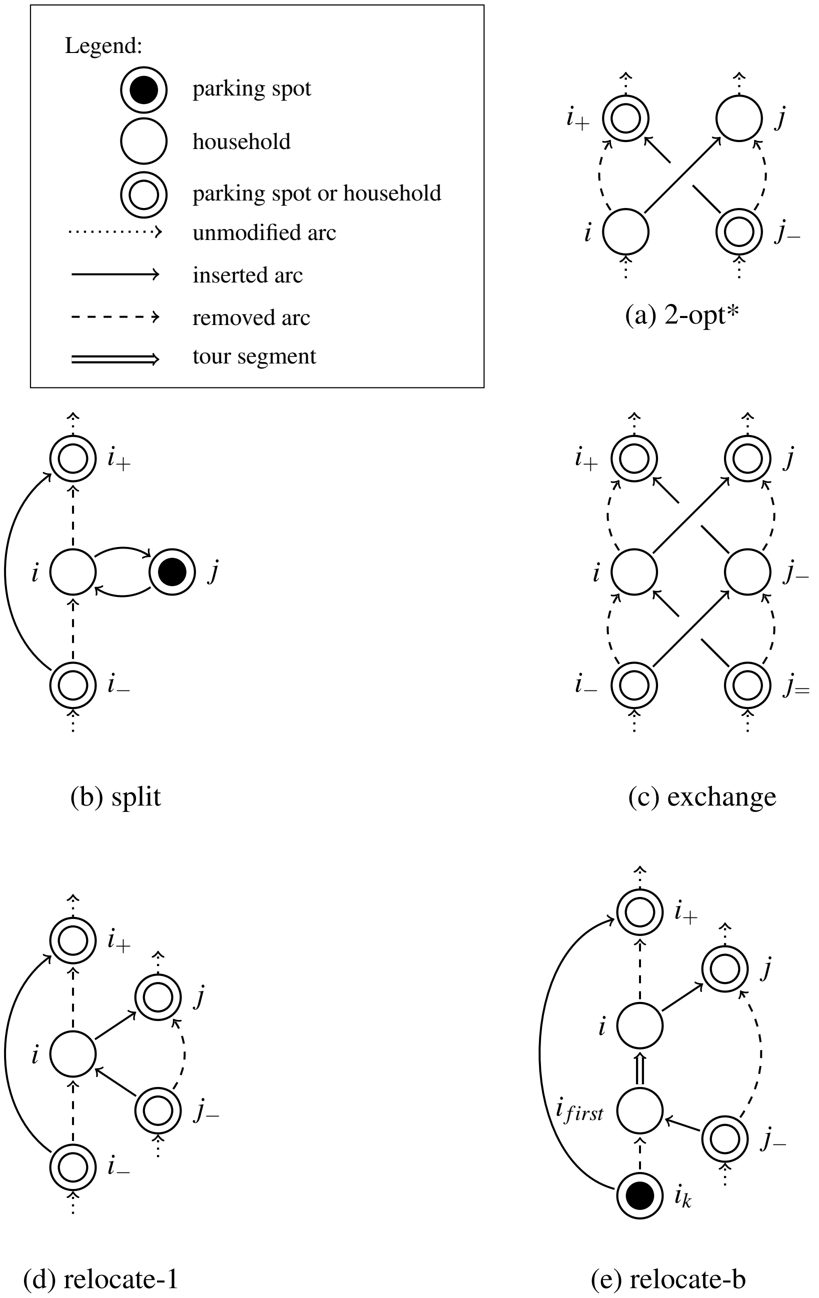



Figure 6: Neighborhood operators of ILS-ASTTRPSD. The generator arc is denoted by $(i, j)$. The predecessor and successor of $i$ are denoted $i_-$ and $i_+$, respectively. The first visited household in a second-level tour is denoted by $i_{first}$.

**3.2.1.2 Composition of $L_i$** To speed up the search, we consider only a small portion of the total number of arcs in $A$ to be used as generator arcs. This technique has been proposed by Toth and Vigo (2003) and has later been applied in multiple works (see, e.g., Prins et al. 2007, Escobar et al. 2014, Goeke 2019).

In ILS-ASTTRPSD, each generator arc is obtained by pairing a vertex $i$ from the list $\tilde{V}_C$ of households with a vertex $j$ from the list $L_i$. List $L_i$ contains the $\lceil \kappa_c V_C \rceil$ closest households and the $\lceil \kappa_k V_D \rceil$ closest opened parking spots to the household vertex $i$, with $0 < \kappa_c < 1$ and $0 < \kappa_k < 1$, respectively. Sparsifying on a per-household basis is vital considering that in DPDHL instances the households are positioned along street segments. This ensures that a given number of arcs incident to isolated households is always considered. In $L_i$, the vertices appear sorted according to increasing values of travel time to $i$. We have also tested the impact of considering a different sorting of the vertices, i.e., first the $\lceil \kappa_c V_C \rceil$ closest households vertices, and then the $\lceil \kappa_k V_D \rceil$ closest parking spot vertices, both sorted according to increasing values of travel times. However, preliminary results have shown a similar solution quality but a slight increase in runtimes.

### 3.2.2 Perturbation

The goal of the perturbation phase is to generate, in each iteration of our ILS, a different configuration of opened parking spots. To this end, in each iteration of ILS, we randomly choose one of the following perturbation moves:

- open a closed parking spot
- close an opened parking spot.

Depending on the chosen perturbation move, a transformation heuristic is applied to transform the current solution into a solution with the new parking spot configuration:

- **Transformation heuristic when a closed parking spot is opened**: When a closed parking spot is opened, we adjust the second-level tours by first creating a new second-level tour for each household for which this new parking spot is closer than the currently assigned one. Then, we check if there are opened parking spots with no assigned households, and we close them. If the new opened parking spot is still open, i.e., it has at least one assigned household, we insert it in the first-level tour using a best insertion heuristic.
- **Transformation heuristic when an opened parking spot is closed**: When an opened parking spot is closed, we first solve a TSP on the first-level tour because simply removing the closed parking spot could result in suboptimal solutions. Then, we remove all second-level tours rooted at that parking spot. Finally, we create a new second-level tour that serves each unconnected household from its closest opened parking spot.

## 4 Conditions for particular optimal solution structures

In this section, we state properties of instances that lead to a particular optimal solution structure. We believe that these properties are useful for the following reasons. First, they allow to gain insights on the structure of optimal solutions by just analyzing the values of the parameters in the instances, i.e., without the need for solving them. Second, by recognizing that specific properties of instances are fulfilled, tailored solution methods could be implemented. Third, these properties will allow us to verify if the structure of the heuristic solutions obtained by ILS-ASTTRPSD is in line with the structure of optimal solutions.

The first property refers to the presence of multiple second-level tours from the same parking spot. Specifically, there can be multiple second-level tours rooted at the same parking spot only if (i) the cumulative demand of the visited households from the same parking spot exceeds the bag capacity, and (ii) it is more convenient to serve those households from that parking spot than from a different one. This first property can be formalized as follows.

**Property 4.1** (Presence of multiple second-level tours from the same parking spot) *In an optimal solution of the ASTTRPSD, multiple second-level tours from the same parking spot may exist only if there exists at least one pair of parking spot vertices $s_1, s_2$, with $s_1 \neq s_2$, a household vertex $h_1$, and a subset of household vertices $H$, with $|H| \geq 1$, such that the following two conditions are both verified:*

*C*1. $q_{h_1} + \sum_{i \in H} q_i > Q_b$

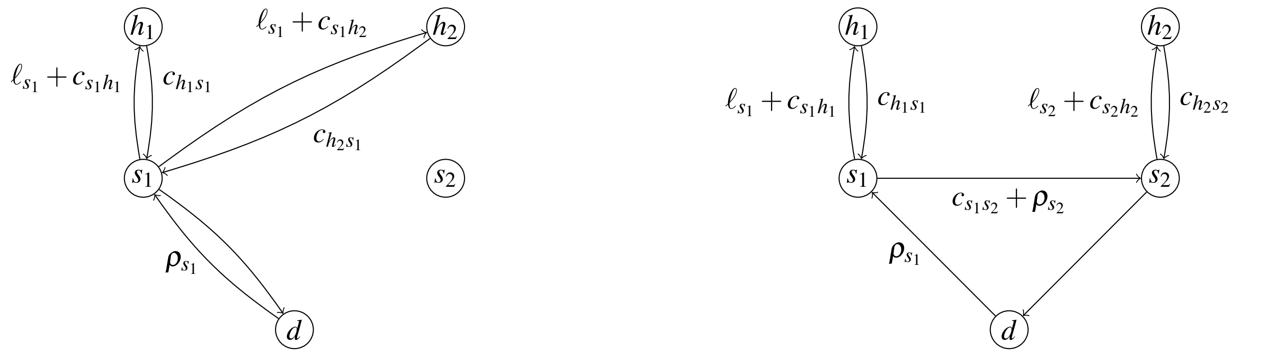
*and*

*C*2. $\rho_{s_1} + \ell_{s_1} + c_{s_1 h_1} + c_{h_1 s_1} + \ell_{s_1} + c_{s_1 H_0} + c_{H_{|H|} s_1} \leq \rho_{s_1} + \ell_{s_1} + c_{s_1 h_1} + c_{h_1 s_1} + c_{s_1 s_2} + \rho_{s_2} + \ell_{s_2} + c_{s_2 H_0} + c_{H_{|H|} s_2}$,

*that can be reduced to:*

$\ell_{s_1} + c_{s_1 H_0} + c_{H_{|H|} s_1} \leq c_{s_1 s_2} + \rho_{s_2} + \ell_{s_2} + c_{s_2 H_0} + c_{H_{|H|} s_2}$.

While condition $C1$ is straightforward, Figure 7 shows an example of condition $C2$ for two parking spots $s_1$ and $s_2$, a household $h_1$, and, without loss of generality, a subset of household vertices $H = \{h_2\}$. Figure 7(a) represents the left-hand side of condition $C2$ in which multiple second-level tours are rooted at the same parking spot, while Figure 7(b) shows the right-hand side of condition $C2$ in which each household is served from a different parking spot.




(a) Left-hand side of condition C2. (b) Right-hand side of condition C2.

Figure 7: Example of left-hand and right-hand side of condition C2.

We note that, if the cumulative demand of the visited households from the same parking spot does not exceed the bag capacity, there cannot be multiple second-level tours rooted at that parking spot because of the triangle inequality holding for the walking network.

The second property states the condition under which an optimal solution of the ASTTRPSD corresponds to the one of a TSP in which one parking spot is opened for each household. This situation occurs only if serving a household in a second-level tour already visiting another household is never convenient. This property can be formalized as follows.

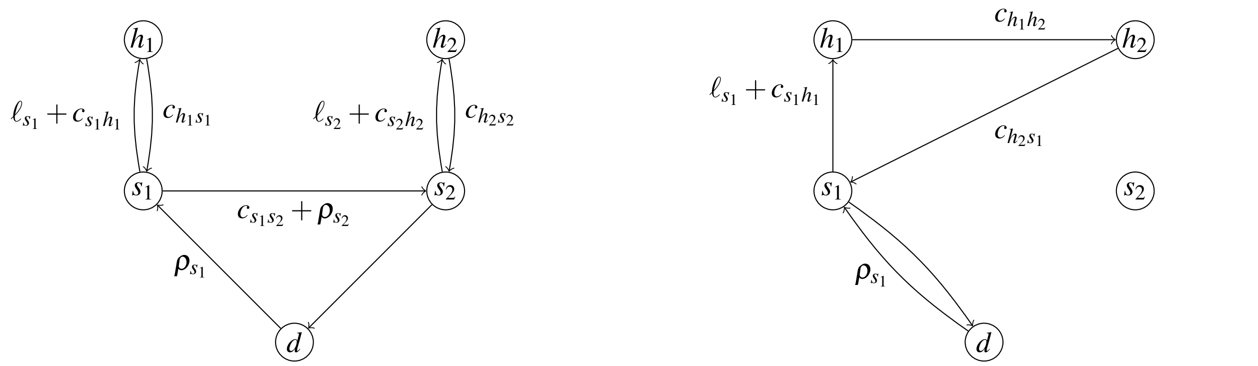
**Property 4.2** (The solution of the ASTTRPSD corresponds to a TSP solution) *The optimal solution of the ASTTRPSD corresponds to the one of a TSP in which one parking spot for each household is opened and each household is visited from that parking spot, only if for every pair of parking spot vertices $s_1, s_2$, with $s_1 \neq s_2$,* *and of household vertices $h_1$, $h_2$, the following condition is verified:*

$$\rho_{s_1} + \ell_{s_1} + c_{s_1h_1} + c_{h_1s_1} + c_{s_1s_2} + \rho_{s_2} + \ell_{s_2} + c_{s_2h_2} + c_{h_2s_2} < \rho_{s_1} + \ell_{s_1} + c_{s_1h_1} + c_{h_1h_2} + c_{h_2s_1}$$

*that can be reduced to:*

$$c_{h_1s_1} + c_{s_1s_2} + \rho_{s_2} + \ell_{s_2} + c_{s_2h_2} + c_{h_2s_2} < c_{h_1h_2} + c_{h_2s_1}.$$

Figure 8 shows an example of the condition for two parking spots $s_1$ and $s_2$ and two households $h_1$ and $h_2$. Figure 8(a) represents the left-hand side of the condition in which each household is served from a dedicated parking spot, while Figure 8(b) shows the right-hand side of the condition in which multiple households are served in the same second-level tour.




(a) Left-hand side of condition stated in Property 4.2. (b) Right-hand side of condition stated in Property 4.2.

Figure 8: Example of left-hand and right-hand side of the condition stated in Property 4.2.

The solution of such a TSP in which one parking spot for each household is opened and each household is visited from that parking spot is always a feasible solution for the ASTTRPSD. Hence, it provides an upper bound for the optimal objective function value of the ASTTRPSD solution.

# 5 Computational experiments

The goal of the computational experiments is twofold. First, we evaluate the performance of ILS-ASTTRPSD. Second, we evaluate the impact of considering parking and loading times on the solution structure.

Section 5.1 describes the instance sets used in our experiments. Section 5.2 explains the computational environment and how the parameters for ILS-ASTTRPSD have been set. Finally, Section 5.3 presents the ILS-ASTTRPSD performance assessment (Section 5.3.1) and evaluates the impact of considering parking and loading times (Section 5.3.2).

## 5.1 Description of the instances

Our computational experiments are mainly based on the DPDHL instances described in Section 5.1.2. However, because for DPDHL instances optimal solutions are not available, we also test the performance of ILS-ASTTRPSD on the instances of Reed et al. (2021), see Section 5.1.1. Finally, to test the ILS-ASTTRPSD capability of returning good solutions also for symmetric instances, we execute ILS-ASTTRPSD on the well-known STTRPSD instances available in the literature. For a detailed description of these instances, we refer to Villegas et al. (2010).

### 5.1.1 Reed et al. (2021) instances

The instances for the CDPP proposed by Reed et al. (2021) are available at https://doi.org/10.25820/data.006124. The authors consider three counties, i.e., Cook, Adams, and Cumberland to represent urban, suburban, and rural household geographies, respectively. The authors assume that the driver can park at each household location. To get instances of the ASTTRPSD, we duplicate the household locations to obtain the locations of the parking spots. All travel times are expressed in minutes and taken from real-world data, and the instances are asymmetric. For each county, a different parking time is considered to reflect the time required to find a parking spot. Specifically, $\rho = 9$ for Cook county, $\rho = 5$ for Adams county, and $\rho = 1$ for Cumberland county. The loading time is set to $\ell = 2.1$, and it is charged for each served household. For each combination of county and capacity $Q_b$ varying from one to six, ten instances with $|V_C| = 50$ households and five instances with $|V_C| = 100$ households are considered.

### 5.1.2 DPDHL instances

The set of real-world, non-Euclidean, asymmetric instances from DPDHL consists of 35 instances based on a German city. The instances contain a number of households $|V_C|$ between 245 and 465 (average 390), and a number of parking spots $|V_D|$ between 412 and 882 (average 724). For most of the households, there are two associated parking spots, representing a possible parking spot on each side of the street. The bag capacity $Q_b$ is set to 25, and the demand of each household $q_i$ is within the interval $[0, 25]$. Considering households with a demand of zero is meaningful because they represent currently uninhabited houses that could change their status before the problem is solved again. If this happens, second-level tours in our solution might get infeasible because of capacity violation. However, recalling that DPDHL is interested in solving the problem at a tactical level, our solution still provides a good indication of how to serve currently uninhabited houses.

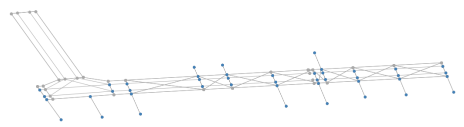
For each instance, two networks are given: (i) a walking network defined on a graph $G_w = (V_w, A_w)$ consisting of walking nodes $V_w$ and walking arcs $A_w$, and (ii) a driving network defined on a graph $G_d = (V_d, A_d)$ consisting of driving nodes $V_d$ and driving arcs $A_d$. Figure 9 shows an example of the two networks. For each

(a) Walking network $G_w$. (b) Driving network $G_d$.

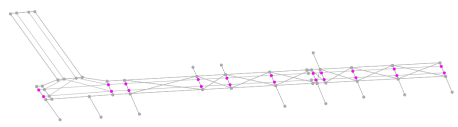
Figure 9: Example of walking and driving network.

household, there are two vertices in $V_w$: one representing the house itself and one representing the so-called "walking portal" corresponding to the point on the sidewalk, where the mail carrier enters the driveway of the house. The parking spots associated with the households are included both in $V_w$ and $V_d$ because they are reachable by driving and by walking. Figure 10 shows an example of these vertices in $V_w$ and $V_d$. To compute the travel time $c_{ij}$ between vertices $i$ and $j$, we solve a shortest path problem using Dijkstra's algorithm on:

- graph $G_d$, if $i$ and $j$ are both parking spots,
- graph $G_w$, if $i$ is a parking spot and $j$ is a household,



(a) Vertices representing the parking spots, walking portals, and houses in $V_w$.



(b) Vertices representing the parking spots in $V_d$.

Figure 10: Example of vertices in $V_w$ and $V_d$.

- graph $G_w$, if $i$ is a household and $j$ is a parking spot,
- graph $G_w$, if $i$ and $j$ are both households.

Because the travel time from the walking portal to the associated household always occurs for the mail carrier, it is a constant and, hence, it is not part of the optimization. Therefore, to compute $\{c_{ij}|(i \in V_C \wedge j \in V_C) \vee (i \in V_C \wedge j \in V_D) \vee (i \in V_D \wedge j \in V_C)\}$, we only consider the travel time from and up to the walking portal.

Finally, because at DPDHL parking and loading times are not separately known, DPDHL instances are characterized by a penalty $P$ of 22 seconds every time a second-level tour is performed. This penalty represents the parking and the loading time for the block of letters to be delivered in a second-level tour. Graph $G$ is modified by adding $P = 22$ to the arc travel times $\{c_{ij}|i \in V_D \wedge j \in V_C\}$, i.e., to the travel time of every walking arc connecting a parking spot to a household. If multiple second-level tours are rooted at the same parking spot, the total time required for parking is overestimated because it is added multiple times although parking occurs only once. However, because DPDHL has considered this graph structure to get their solutions, we use the same structure in the computational experiments of Section 5.3.1 to allow for a fair comparison.

## 5.2 Computational environment and parameter tuning

ILS-ASTTRPSD was implemented in C++ and compiled using clang version 12.0.0. The experiments were performed on an Intel(R) Xeon(R) computer with a CPU E5-2430 v2 processor, at 2.50GHz with 64 GB RAM under CentOS GNU/Linux 7. Every time a TSP is solved exactly, we use Gurobi solver version 9.5.0.

The values of the parameters for ILS-ASTTRPSD are summarized in Table 1. Because our algorithm contains randomized elements, we performed ten runs of ILS-ASTTRPSD for each instance. The values for the termination criterion of ILS-ASTTRPSD and for the sparsification intensity values have been determined after performing parameter tuning experiments considering the following values: $\eta = [500, 1000, 1500, 2000, 2500]$ and $\kappa_c = \kappa_k = 0.01$, or $\kappa_c = \kappa_k = 0.015$. The best configuration in terms of solution quality and runtime trade-off has been chosen (see Table 1).

Nevertheless, preliminary experiments have also shown that ILS-ASTTRPSD runtimes may get long when the number of parking spots is greater than or equal to 100 and the following relationship is fulfilled:

$$\frac{1}{(\rho/\bar{c}_{V_D})|V_D|} \geq 0.04,$$

where $\rho$ is the parking time, $\bar{c}_{V_D}$ is the average inter-parking spot distance, and $|V_D|$ is the number of parking spots that is used as an adjustment factor. This relationship is satisfied for big instances representing rural settings with very small parking times compared to the inter-parking spot distance. For these instances, we have observed that by setting the number of iterations without improvement to values larger than 50, the solution quality improves only marginally at the expense of very long runtimes. For this reason, in such settings, the number of iterations without improvement $\eta$ is set to 50.

| Component | Parameter values |
|---|---|
| termination criterion iterated clustering algorithm | $\gamma_{max} = 10$ |
| termination criterion ILS-ASTTRPSD | $\eta = 2000$ |
| sparsification intensity households | $\kappa_c = 0.015$ |
| sparsification intensity parking spots | $\kappa_k = 0.015$ |

Table 1: ILS-ASTTRPSD parameter values.

### 5.3 Results

In this section, we test the performance of ILS-ASTTRPSD (Section 5.3.1) and evaluate the impact of considering parking and loading times when solving the ASTTRPSD (Section 5.3.2).

#### 5.3.1 ILS-ASTTRPSD performance assessment

To assess the performance of ILS-ASTTRPSD, we compare our solutions to the ones of Reed et al. (2021) and to the ones obtained by the DPDHL data analytics department for the DPDHL instances. For completeness, Appendix A compares the results of ILS-ASTTRPSD to the ones of the state-of-the-art heuristics on symmetric STTRPSD instances.

**5.3.1.1 Comparison on Reed et al. (2021) instances** We run ILS-ASTTRPSD on all instances of Reed et al. (2021) and compare to the solutions returned by both their heuristic and the commercial solver Gurobi 9.0.0, which is able to solve some of the instances to optimality.

Table 2 reports the results of this comparison. The first three columns identify the instance based on the county, the number of households $|V_C|$, and the bag capacity $Q_b$. The fourth column reports the average value of the best known solutions (BKS) over ten instances (if $|V_C| = 50$) or over five instances (if $|V_C| = 100$). The BKSs are taken from Reed et al. (2021). If the optimal solutions returned by Gurobi are available, these are used in the computation of the best known solutions (BKSs). Otherwise, the heuristic solutions found by Reed et al. (2021) are used. Combinations of county, number of households, and bag capacity for which all instances have been solved to optimality are highlighted in bold. Concerning the runtimes of Gurobi to solve instances to optimality, Reed et al. (2021) only mention a few examples. When $|V_C| = 50$ and $Q_b = 3$, the average runtime is 21240, 15840, and 11160 seconds for Cook, Adams, and Cumberland counties, respectively. When $|V_C| = 100$ and $Q_b = 2$, the average runtime is 1440 seconds for Cook county, 11160 seconds for Adams county, and 30600 seconds for Cumberland county. The fifth column reports the average gap to the BKS ($\Delta_{BKS}(\%)$) of the heuristic of Reed et al. (2021). The final columns report the average gap to the BKS reached by ILS-ASTTRPSD in the best ($\Delta^b_{BKS}(\%)$) and average ($\Delta^a_{BKS}(\%)$) run, respectively, and the average runtime in seconds ($t(s)$). Underlined values improve on the BKS. A comparison of ILS-ASTTRPSD to the heuristic of Reed et al. (2021) based on the runtimes is not possible due to the lack of information regarding the characteristics of the machine of the University of Iowa's Argon high performance computing cluster used in Reed et al. (2021). Reed et al. (2021) state that the average runtime of their heuristic is at most 42 seconds by running parallelized experiments using the Gurobi solver and limiting the thread count to 32.

The results show that, in the best run, ILS-ASTTRPSD always finds solutions of better quality than the ones provided by the heuristic of Reed et al. (2021). Specifically, on instances for which optimal solutions are available, ILS-ASTTRPSD returns smaller optimality gaps, and on instances for which only the heuristic solution of Reed et al. (2021) is available, ILS-ASTTRPSD finds new best-known solutions. The same results are obtained in the average run of ILS-ASTTRPSD, except for the instances referring to Cook county with $|V_C| = 50$ and $|V_C| = 100$, and $Q_b = 2$. Comparing the gaps of the best run of ILS-ASTTRPSD to optimal solutions across counties, the best performance is obtained with rural household geographies (Cumberland county), followed by suburban (Adams county), and urban (Cook county) ones. Instead, the comparison of the gaps to the BKSs of the best and average runs of ILS-ASTTRPSD across counties shows that the highest improvements are obtained for the suburban county, followed by the urban, and rural ones.

Looking at the last column of Table 2, ILS-ASTTRPSD shows reasonable runtimes. While the runtimes of ILS-ASTTRPSD are roughly equivalent for instances with suburban and urban geographies (Adams and Cook), the ones for the Cumberland county are longer. We note that these instances correspond to big rural instances for which $\eta$ has been set to 50 (see Section 5.2). These longer runtimes are due to very small parking times compared to inter-parking spot distances that cause the opening of a lot of parking spots. This requires, for ILS-ASTTRPSD, to solve a TSP on the first-level tour every time that a perturbation move closing an opened parking spot is applied. These results are in line with the observation of Reed et al. (2021), where some of the Cumberland county instances with 100 households could not be solved to optimality even for small bag capacities.

**5.3.1.2 Comparison on DPDHL instances** We compare the results obtained with ILS-ASTTRPSD to the ones provided by the DPDHL analytics department on DPDHL instances. We remark that the DPDHL solutions have not been obtained by manual planning but by using a local search heuristic. Their local search algorithm takes as input the solution that is currently implemented in practice and applies operators to merge and split second-level tours. A post-processing phase that uses the 2-opt and 3-opt heuristic is finally executed.

Table 3 presents the comparison of the DPDHL solutions to the solutions obtained by ILS-ASTTRPSD. The first columns in the table contain for each instance: the instance name, the number of households ($|V_C|$), the number of parking spots ($|V_D|$), the cumulative demand ($\sum_{i \in V_C} q_i$), and the average inter-household distance ($\overline{c_{ij}}$). The sixth column contains the objective function values of the DPDHL solution. Because the runtimes of the DPDHL algorithm are not available, we do not include this information in the table. The last columns of the table contain for each instance: the gap to the DPDHL solution of the ILS-ASTTRPSD best run ($\Delta^b(\%)$), of the ILS-ASTTRPSD average run ($\Delta^a(\%)$), and the runtime of the ILS-ASTTRPSD average run ($\bar{t}(s)$). On all instances, ILS-ASTTRPSD improves the solution of DPDHL in the best run. The same applies for the average run, except for two instances on which we perform slightly worse, and for one instance on which we achieve the same solution quality. Even if an average improvement by 1.95% may seem limited, we remark that this is only for one postal district. Considering that DPDHL has to serve thousands of districts, a small percentage improvement entails considerable cost savings.

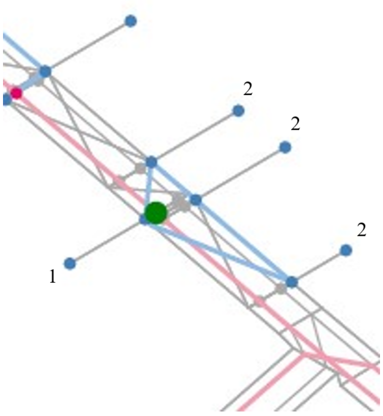
Because postal delivery tours are planned at the tactical level, runtime is not crucial for DPDHL. Still, the average runtime of ILS-ASTTRPSD corresponds to approximately 20 minutes, meaning that improvements

| Instance | | | *BKS* | Reed et al. (2021) | ILS-ASTTRPSD | | |
|---|---|---|---|---|---|---|---|
| County | $\|V_C\|$ | $Q_b$ | | $\Delta_{BKS}(\%)$ | $\Delta^b_{BKS}(\%)$ | $\Delta^a_{BKS}(\%)$ | $t(s)$ |
| adams | 50 | 1 | **296.9** | 4.0 | 0.5 | 1.3 | 61.4 |
| adams | 50 | 2 | **286.7** | 2.2 | 0.3 | 0.6 | 37.1 |
| adams | 50 | 3 | **281.8** | 3.1 | 0.1 | 0.5 | 31.4 |
| adams | 50 | 4 | **280.2** | 3.6 | 0.0 | 0.2 | 30.3 |
| adams | 50 | 5 | 290.2 | 0.0 | -3.9 | -3.5 | 25.0 |
| adams | 50 | 6 | 290.2 | 0.0 | -4.4 | -4.1 | 22.9 |
| adams | 100 | 1 | **538.0** | 4.9 | 1.1 | 1.9 | 517.3 |
| adams | 100 | 2 | **515.2** | 2.6 | 0.7 | 1.3 | 228.7 |
| adams | 100 | 3 | 523.2 | 0.0 | -3.2 | -2.6 | 128.8 |
| adams | 100 | 4 | 521.7 | 0.0 | -4.7 | -4.4 | 108.4 |
| adams | 100 | 5 | 521.7 | 0.0 | -5.9 | -5.5 | 81.0 |
| adams | 100 | 6 | 521.3 | 0.0 | -6.6 | -6.2 | 77.4 |
| Avg. adams | | | 405.6 | 1.7 | -2.2 | -1.7 | 112.5 |
| cook | 50 | 1 | **328.3** | 5.5 | 1.7 | 3.5 | 18.2 |
| cook | 50 | 2 | **292.4** | 1.3 | 1.0 | 2.8 | 11.2 |
| cook | 50 | 3 | **272.5** | 3.4 | 0.9 | 2.1 | 9.9 |
| cook | 50 | 4 | **261.8** | 5.5 | 0.6 | 1.6 | 20.5 |
| cook | 50 | 5 | 273.9 | 0.0 | -7.2 | -6.0 | 26.1 |
| cook | 50 | 6 | 272.4 | 0.0 | -9.1 | -8.3 | 29.5 |
| cook | 100 | 1 | **621.0** | 4.9 | 1.6 | 2.9 | 254.0 |
| cook | 100 | 2 | **547.9** | 0.5 | 1.5 | 2.7 | 54.8 |
| cook | 100 | 3 | 526.1 | 0.0 | -1.6 | -0.7 | 41.4 |
| cook | 100 | 4 | 513.3 | 0.0 | -3.5 | -2.8 | 63.8 |
| cook | 100 | 5 | 507.9 | 0.0 | -5.5 | -4.7 | 72.4 |
| cook | 100 | 6 | 505.2 | 0.0 | -7.0 | -6.3 | 89.6 |
| Avg. cook | | | 410.2 | 1.8 | -2.2 | -1.1 | 57.6 |
| cumberland | 50 | 1 | **192.9** | 1.6 | 0.1 | 0.2 | 275.1 |
| cumberland | 50 | 2 | **192.6** | 1.5 | 0.1 | 0.1 | 253.3 |
| cumberland | 50 | 3 | **192.6** | 1.5 | 0.1 | 0.1 | 246.1 |
| cumberland | 50 | 4 | **192.6** | 1.5 | 0.1 | 0.1 | 239.2 |
| cumberland | 50 | 5 | 195.5 | 0.0 | -1.5 | -1.5 | 234.5 |
| cumberland | 50 | 6 | 195.5 | 0.0 | -1.5 | -1.5 | 238.0 |
| cumberland | 100 | 1 | 360.6 | 1.2 | 0.2 | 0.5 | 7942.5 |
| cumberland | 100 | 2 | 360.1 | 1.1 | -0.0 | 0.1 | 760.1 |
| cumberland | 100 | 3 | 364.0 | 0.0 | -1.1 | -1.0 | 562.8 |
| cumberland | 100 | 4 | 364.0 | 0.0 | -1.2 | -1.1 | 509.6 |
| cumberland | 100 | 5 | 364.0 | 0.0 | -1.2 | -1.1 | 567.1 |
| cumberland | 100 | 6 | 364.0 | 0.0 | -1.2 | -1.1 | 506.6 |
| Avg. cumberland | | | 278.2 | 0.7 | -0.6 | -0.5 | 1027.9 |
| Avg. | | | | 1.4 | -1.7 | -1.1 | 399.3 |

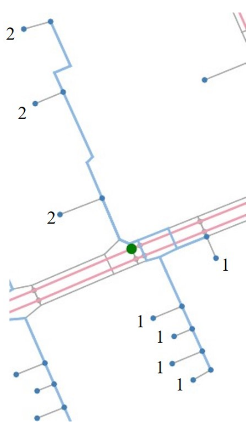
Table 2: Comparison of the average results of Reed et al. (2021)'s heuristic with ILS-ASTTRPSD. Each row of the table reports the average results over 10 instances if $V_C = 50$, and over 5 instances if $V_C = 100$. Optimality has been proven for the solutions in boldface by Reed et al. (2021). Results that improve on the previous BKS are underlined.

are found quickly. We observe that the runtimes are not strictly related to the instance dimension. For example, instances 25 and 35 have approximately the same number of households and parking spots, but their average runtimes differ significantly. This might be due to a particular search trajectory of ILS-ASTTRPSD or to the geography of a particular instance. For example, instance 35 has a higher average inter-household distance compared to instance 25. The same can be observed when comparing instances 13, 16, 19, and 26. While these instances have similar dimension, instance 16 with the highest average inter-household distance is the one with the highest runtime. This result is in line with our observation for Reed et al. (2021) instances in Section 5.3.1.1, where instances of rural geographies, i.e., with larger inter-household distances, are the most difficult to solve.

To understand why ILS-ASTTRPSD returns better-quality solutions than the algorithm of DPDHL, we compare the structure of the solutions of ILS-ASTTRPSD and DPDHL. Table 4 presents this comparison with respect to: the first-level tour travel time $c(t^1)$, the travel time of the second-level tours $\sum_{t^2 \in T^2} c(t^2)$, the number of opened parking spots $|V_D(t^1)|$, the number of second-level tours $|T^2|$, and the average number of households served in each second-level tour $\overline{|V_C(t^2)|}$. By looking at the last row of the table reporting the average values, we observe that ILS-ASTTRPSD solutions are characterized by shorter travel times for first- and second-level tours. Considering that in ILS-ASTTRPSD solutions, a lower number of parking spots are opened and that more households are served within each second-level tour, this suggests that ILS-ASTTRPSD performs a better selection of parking spots to open and provides better-quality second-level tours. Moreover, in the DPDHL solutions, the number of opened parking spots exactly corresponds to the number of second-level tours across all instances. This means that, in the DPDHL results, there are no second-level tours rooted at the same parking spot. In the ILS-ASTTRPSD solutions, for some instances, the number of second-level tours is higher than the number of opened parking spots, indicating that starting multiple second-level tours from the same parking spot might be beneficial to decrease travel times. By analyzing these instances, we observed that this is useful if, for example, one single household is located very close to others and exhibits a very high demand, or if there are two dead-end streets crossing at a main street where the parking spot is located (see Figures 11(a) and 11(b)). The vertex highlighted in green represents the parking spot at which two second-level tours are rooted, the vertices in blue are the households, the first-level tour is represented in magenta, and the second-level tours in blue. The numbers next to each household represent the second-level tour that they belong to.




(a) Instance 10.




(b) Instance 6.

Figure 11: Examples of multiple second-level tours from the same parking spot for two instances.

| | | | | | DPDHL | ILS-ASTTRPSD | | |
|---|---|---|---|---|---|---|---|---|
| Instance | $\|V_C\|$ | $\|V_D\|$ | $\sum_{i \in V_C} q_i$ | $\overline{c_{ij}}$ | | $\Delta^b(\%)$ | $\Delta^a(\%)$ | $\bar{t}(s)$ |
| 1 | 382 | 746 | 646 | 417.16 | 11047.67 | -1.18 | -0.85 | 1264.51 |
| 2 | 465 | 852 | 713 | 556.17 | 11307.95 | -2.74 | -2.31 | 1784.86 |
| 3 | 424 | 778 | 703 | 399.71 | 10130.74 | -0.92 | -0.41 | 1438.54 |
| 4 | 433 | 742 | 711 | 333.05 | 8916.46 | -4.44 | -4.02 | 1447.48 |
| 5 | 403 | 698 | 826 | 464.93 | 9874.41 | -3.31 | -2.49 | 1460.92 |
| 6 | 378 | 585 | 887 | 527.94 | 9618.68 | -4.33 | -3.77 | 1130.51 |
| 7 | 361 | 643 | 884 | 340.49 | 8366.41 | -1.94 | -1.50 | 1243.83 |
| 8 | 452 | 872 | 791 | 497.59 | 10207.59 | -1.78 | -1.10 | 2157.41 |
| 9 | 250 | 412 | 483 | 614.93 | 7560.05 | -2.74 | -2.17 | 525.97 |
| 10 | 298 | 481 | 1092 | 293.17 | 8967.08 | -1.93 | -1.51 | 692.75 |
| 11 | 389 | 758 | 756 | 504.81 | 9900.64 | -2.81 | -2.17 | 1126.18 |
| 12 | 374 | 729 | 628 | 456.74 | 10774.5 | -2.83 | -2.36 | 1222.89 |
| 13 | 418 | 762 | 770 | 433.92 | 9539.38 | -1.46 | -0.88 | 1324.16 |
| 14 | 360 | 697 | 653 | 522.93 | 9910.45 | -3.17 | -2.19 | 975.74 |
| 15 | 441 | 854 | 700 | 537.55 | 11657.85 | -1.85 | -0.87 | 1584.94 |
| 16 | 416 | 793 | 621 | 834.63 | 12542.86 | -0.90 | -0.51 | 1448.51 |
| 17 | 427 | 812 | 634 | 375.59 | 9376.12 | -1.06 | -0.60 | 1570.28 |
| 18 | 452 | 882 | 725 | 600.57 | 11042.54 | -1.36 | -0.69 | 1787.35 |
| 19 | 414 | 767 | 654 | 409.54 | 13517.72 | -1.40 | -0.82 | 1368.85 |
| 20 | 378 | 720 | 696 | 444.09 | 10302.26 | -2.43 | -1.66 | 1078.21 |
| 21 | 458 | 772 | 627 | 475.02 | 11549.82 | -1.46 | -0.89 | 1393.34 |
| 22 | 447 | 770 | 673 | 327.47 | 11160.20 | -3.39 | -2.79 | 1397.45 |
| 23 | 430 | 815 | 641 | 353.29 | 11280.73 | -2.04 | -0.93 | 1414.08 |
| 24 | 334 | 639 | 606 | 647.47 | 11211.68 | -0.75 | 0.11 | 1350.33 |
| 25 | 342 | 640 | 601 | 375.88 | 9792.03 | -1.22 | -0.17 | 774.70 |
| 26 | 419 | 814 | 740 | 400.45 | 11573.60 | -2.44 | -1.77 | 1351.10 |
| 27 | 368 | 700 | 568 | 930.46 | 11439.95 | -1.04 | -0.77 | 1007.06 |
| 28 | 395 | 762 | 571 | 385.66 | 12231.05 | -1.14 | -0.55 | 1567.54 |
| 29 | 384 | 746 | 745 | 321.71 | 10173.03 | -0.43 | -0.00 | 1337.85 |
| 30 | 369 | 722 | 676 | 543.72 | 10765.11 | -2.50 | -1.35 | 762.33 |
| 31 | 410 | 728 | 736 | 413.50 | 9758.15 | -1.95 | -1.53 | 1168.34 |
| 32 | 429 | 837 | 788 | 696.90 | 11345.84 | -1.76 | -1.38 | 2006.24 |
| 33 | 245 | 477 | 453 | 1629.02 | 12999.68 | -2.11 | -1.98 | 1460.67 |
| 34 | 353 | 695 | 735 | 359.09 | 10254.06 | -0.45 | 0.17 | 786.97 |
| 35 | 341 | 644 | 498 | 510.62 | 9974.97 | -1.08 | -0.59 | 1199.02 |
| Avg. | 389.69 | 724.11 | 692.31 | 512.45 | | -1.95 | -1.35 | 1303.19 |

Table 3: Comparison of the DPDHL solutions to the solutions of the best and average run of ILS-ASTTRPSD on DPDHL instances.

Our results suggest that by adopting ILS-ASTTRPSD solutions:

- Mail carriers drive and walk less.
- Mail carriers park less. Allen et al. (2018) noticed that drivers prefer walking instead of continually moving the vehicle for very small distances and trying to find parking spots.
- Performing multiple second-level tours from the same parking spot may be beneficial especially in the presence of households having high demand or in the presence of a particular road network structure.

| | $c(t^1)$ | | $\sum_{t^2 \in T^2} c(t^2)$ | | $\lvert V_D(t^1)\rvert$ | | $\lvert T^2\rvert$ | | $\overline{\lvert V_C(t^2)\rvert}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| Instance | DPDHL | ILS-ASTTRPSD | DPDHL | ILS-ASTTRPSD | DPDHL | ILS-ASTTRPSD | DPDHL | ILS-ASTTRPSD | DPDHL | ILS-ASTTRPSD |
| 1 | 2902.35 | 2722.11 | 8145.32 | 8195.37 | 58 | 55 | 58 | 55 | 6.59 | 6.95 |
| 2 | 3797.08 | 3598.03 | 7510.87 | 7399.67 | 55 | 52 | 55 | 52 | 8.45 | 8.94 |
| 3 | 2405.94 | 2274.41 | 7724.80 | 7763.23 | 51 | 48 | 51 | 48 | 8.31 | 8.83 |
| 4 | 2357.01 | 2313.49 | 6559.45 | 6207.38 | 50 | 46 | 50 | 46 | 8.66 | 9.41 |
| 5 | 2466.07 | 2193.87 | 7408.34 | 7353.59 | 58 | 55 | 58 | 57 | 6.95 | 7.07 |
| 6 | 2196.52 | 2156.09 | 7422.15 | 7046.51 | 65 | 61 | 65 | 63 | 5.82 | 6.00 |
| 7 | 1866.04 | 1635.10 | 6500.37 | 6568.96 | 67 | 59 | 67 | 59 | 5.39 | 6.12 |
| 8 | 1968.59 | 1918.29 | 8238.99 | 8107.29 | 63 | 66 | 63 | 67 | 7.17 | 6.75 |
| 9 | 2390.87 | 2309.35 | 5169.18 | 5043.64 | 51 | 46 | 51 | 46 | 4.90 | 5.43 |
| 10 | 2059.21 | 2090.90 | 6907.87 | 6703.39 | 76 | 73 | 76 | 75 | 3.92 | 3.97 |
| 11 | 2311.93 | 2194.77 | 7588.71 | 7427.85 | 56 | 54 | 56 | 54 | 6.95 | 7.20 |
| 12 | 3462.30 | 3329.56 | 7312.20 | 7140.46 | 55 | 60 | 55 | 61 | 6.80 | 6.13 |
| 13 | 2588.76 | 2464.53 | 6950.62 | 6935.72 | 58 | 54 | 58 | 54 | 7.21 | 7.74 |
| 14 | 3145.48 | 2967.53 | 6764.98 | 6628.38 | 50 | 49 | 50 | 49 | 7.20 | 7.35 |
| 15 | 3258.84 | 2958.45 | 8399.01 | 8483.83 | 56 | 51 | 56 | 51 | 7.88 | 8.65 |
| 16 | 4168.42 | 4154.70 | 8374.43 | 8274.80 | 49 | 52 | 49 | 52 | 8.49 | 8.00 |
| 17 | 2808.81 | 2667.19 | 6567.31 | 6609.27 | 37 | 33 | 37 | 34 | 11.54 | 12.56 |
| 18 | 3104.88 | 3098.29 | 7937.66 | 7794.34 | 44 | 44 | 44 | 44 | 10.27 | 10.27 |
| 19 | 5589.42 | 5513.26 | 7928.30 | 7814.77 | 54 | 50 | 54 | 52 | 7.67 | 7.96 |
| 20 | 3309.68 | 3143.57 | 6992.58 | 6908.79 | 57 | 50 | 57 | 50 | 6.63 | 7.56 |
| 21 | 3702.90 | 3509.14 | 7846.92 | 7872.37 | 48 | 38 | 48 | 39 | 9.54 | 11.74 |
| 22 | 3002.92 | 2841.29 | 8157.28 | 7940.38 | 45 | 42 | 45 | 42 | 9.93 | 10.64 |
| 23 | 3043.75 | 2862.57 | 8236.98 | 8187.91 | 51 | 49 | 51 | 49 | 8.43 | 8.78 |
| 24 | 3947.10 | 3894.33 | 7264.58 | 7233.02 | 67 | 68 | 67 | 68 | 4.99 | 4.91 |
| 25 | 3369.26 | 3330.91 | 6422.77 | 6341.60 | 40 | 39 | 40 | 39 | 8.55 | 8.77 |
| 26 | 3773.79 | 3537.61 | 7799.80 | 7753.07 | 49 | 49 | 49 | 50 | 8.55 | 8.38 |
| 27 | 4493.87 | 4408.21 | 6946.08 | 6913.10 | 50 | 50 | 50 | 50 | 7.36 | 7.36 |
| 28 | 4103.63 | 3963.43 | 8127.42 | 8128.11 | 55 | 44 | 55 | 45 | 7.18 | 8.78 |
| 29 | 3768.42 | 3618.65 | 6404.61 | 6510.23 | 46 | 40 | 46 | 42 | 8.35 | 9.14 |
| 30 | 4097.62 | 3966.66 | 6667.49 | 6528.79 | 47 | 43 | 47 | 43 | 7.85 | 8.58 |
| 31 | 2018.49 | 2053.61 | 7739.66 | 7514.26 | 57 | 59 | 57 | 59 | 7.19 | 6.95 |
| 32 | 3543.11 | 3331.90 | 7802.72 | 7814.57 | 76 | 68 | 76 | 69 | 5.64 | 6.22 |
| 33 | 6019.41 | 5705.95 | 6980.27 | 7019.42 | 105 | 103 | 105 | 103 | 2.33 | 2.38 |
| 34 | 3452.49 | 3162.04 | 6801.58 | 7045.64 | 65 | 54 | 65 | 54 | 5.43 | 6.54 |
| 35 | 3682.26 | 3860.12 | 6292.71 | 6007.28 | 64 | 65 | 64 | 65 | 5.33 | 5.25 |
| Avg. | 3262.21 | 3135.71 | 7311.26 | 7234.77 | 56.43 | 53.40 | 56.43 | 53.89 | 7.24 | 7.64 |

Table 4: Comparison of statistics of the DPDHL solutions to the solutions of the best run of ILS-ASTTRPSD for DPDHL instances.

- Because of the lower number of opened parking spots, mail carriers serve more households in each second-level tour. However, this does not imply longer walking times.

### 5.3.2 Impact of ignoring parking and loading times

When parking does not require difficult maneuvers or when loading does not imply any other operation than grabbing a bag, parking and loading times are negligible. However, if these operations are not immediate, ignoring the time required for parking and loading may result in a solution of bad quality and in increased total travel times.

As mentioned in Section 1, by adding additional times to the travel times of specific arcs of $G$, we can obtain different problem settings. To assess the impact of ignoring parking and loading times, we execute ILS-ASTTRPSD on DPDHL instances considering the following graphs:

1. Graph 1 ($G_1$) represents an ASTTRPSD only with travel times. In this problem setting, the parking and loading times are neglected.
2. Graph 2 ($G_2$) represents an ASTTRPSD with parking times, but loading times are neglected. If the vehicle stops at a parking spot, a parking time $\rho$ of 11 seconds is added. Graph $G$ is modified by adding $\rho = 11$ to every $c_{ij}, i \in V_D, j \in V_D, i \neq j$, i.e., to the travel time of every driving arc entering a parking spot. Neglecting loading times represents, for example, problem settings in which the mail carrier's bag already contains the letters of all households.

3. Graph 3 ($G_3$) represents an ASTTRPSD with loading times, but parking times are neglected. Every time the mail carrier has to load the bag with letters to start a new second-level tour, a loading time $\ell$ of 11 seconds is added. Graph $G$ is modified by adding $\ell = 11$ to every $c_{ij}, i \in V_D, j \in V_C$, i.e., to the travel time of every walking arc connecting a parking spot to a household. Neglecting parking times represents problem settings in which parking operations are straightforward.

4. Graph 4 ($G_4$) represents an ASTTRPSD with travel, parking, and loading times. If the vehicle stops at a parking spot, a parking time $\rho$ of 11 seconds is charged, and every time the mail carrier has to load the bag with letters to start a new second-level tour, a loading time $\ell$ of 11 seconds is charged. Graph $G$ is modified by adding $\rho = 11$ to every $c_{ij}, i \in V_D, j \in V_D, i \neq j$, i.e., to the travel time of every driving arc entering a parking spot, and $\ell = 11$ to every $c_{ij}, i \in V_D, j \in V_C$, i.e., to the travel time of every walking arc connecting a parking spot to a household.

In the above graphs, when considered, the time values for parking and loading are both set equal to 11 to fairly compare settings in which parking or loading are ignored. The solutions obtained by running ILS-ASTTRPSD on instances based on graphs $G_1$, $G_2$, and $G_3$ represent good solutions for the cases in which parking and loading times, loading times, and parking times are ignored, respectively. For a fair comparison of the objective function values, we use the solutions of the best run of ILS-ASTTRPSD obtained for the instances based on graphs $G_1$, $G_2$, and $G_3$, and evaluate the solutions based on the travel times of graph $G_4$, i.e., the one including both parking and loading times. This allows us to measure the impact of ignoring parking and/or loading times. Table 5 summarizes the average objective function values over the 35 DPDHL instances decomposed into first ($c(t^1)^{G_4}$) and second-level tours ($c(T^2)^{G_4}$) travel times. The last column contains the average gap to the total objective function value of graph $G_4$. For the first-level tour, we report driving time, parking time, total time, and the average gap to the first-level tour travel time of graph $G_4$. For the second-level tours, we report walking time, loading times, total time, and the average gap to the second-level tours travel times of graph $G_4$. The results of the last column of the table suggest that the highest increase in travel times occurs when both parking and loading times are neglected (graph $G_1$), followed by the case in which parking times (graph $G_3$), and loading times (graph $G_2$) are ignored. The higher increase in travel times in graph $G_3$ compared to graph $G_2$ may be even more remarkable in real-world settings in which parking usually requires more time than loading. Ignoring parking and/or loading times (graphs $G_1$, $G_2$, and $G_3$) always results in longer driving times and shorter walking times compared to instances in which they are considered (graph $G_4$). The absence of parking and/or loading times leads to the opening of a higher number of parking spots and second-level tours, so that the time for parking, for driving between parking spots, and for loading increases, while the walking times decrease.

| | $c(t^1)^{G_4}$ | | | | $c(T^2)^{G_4}$ | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Graph | Driving | Parking | Total | $\overline{\Delta}_{c(t^1)^{G_4}}(\%)$ | Walking | Loading | Total | $\overline{\Delta}_{c(T^2)^{G_4}}(\%)$ | $\overline{\Delta}_{c^{G_4}}(\%)$ |
| $G_1$ | 3541.80 | 1859.33 | 5401.12 | 47.99 | 4669.00 | 1862.19 | 6531.19 | -2.40 | 15.39 |
| $G_2$ | 3218.65 | 841.06 | 4059.71 | 11.23 | 5544.87 | 863.61 | 6408.48 | -4.23 | 1.23 |
| $G_3$ | 3231.57 | 863.39 | 4094.96 | 12.20 | 5527.68 | 867.46 | 6395.14 | -4.43 | 1.44 |
| $G_4$ | 3088.70 | 561.00 | 3649.70 | - | 6102.91 | 588.39 | 6691.30 | - | - |

Table 5: Comparison of average objective function values (over 35 instances) obtained by taking the solutions of ILS-ASTTRPSD for the instances of graphs $G_1$, $G_2$, $G_3$, and $G_4$, and by evaluating them based on the travel times of $G_4$.

To understand the reason of the travel time differences of Table 5, we compare the structure of the solutions based on some metrics. The average results of these metrics over all instances for each graph are summarized in Table 6, while the detailed results are reported in Appendix B. The travel times reported in this table are computed according to the travel times of the graph each line refers to. When parking times are set to zero (graphs $G_1$ and $G_3$), the number of opened parking spots $|V_D(t^1)|$ and of second-level tours $|T^2|$ is higher than in the settings where parking times are considered (graphs $G_2$ and $G_4$). A consequence of the lower number of opened parking spots in graphs $G_2$ and $G_4$ is the larger number of second-level tours originating from the same parking spot compared to their number in graphs $G_1$ and $G_3$. The average number of households served in each second-level tours increases as the number of opened parking spots decrease. In general, as more time components are added to the instances, the solution structure gets more consolidated, i.e., fewer parking spots are opened, fewer second-level tours are used, and more households are served within each second-level tour.

| | $c(t^1)$ | | $c(T^2)$ | | $\lvert V_D(t^1)\rvert$ | $\lvert T^2\rvert$ | $\overline{\lvert V_C(t^2)\rvert}$ |
|---|---|---|---|---|---|---|---|
| Graph | Driving | Parking | Walking | Loading | | | |
| $G_1$ | 3541.80 | - | 4669.44 | - | 169.03 | 169.29 | 2.36 |
| $G_2$ | 3218.65 | 841.06 | 5544.87 | - | 76.46 | 78.51 | 5.22 |
| $G_3$ | 3231.57 | - | 5527.68 | 867.46 | 78.49 | 78.86 | 5.16 |
| $G_4$ | 3088.70 | 561.00 | 6102.91 | 588.39 | 51.00 | 53.49 | 7.73 |

Table 6: Comparison of objective function values and metrics of the solutions of ILS-ASTTRPSD for the instances of graphs $G_1$, $G_2$, $G_3$, and $G_4$. The values for each graph type are reported as averages over 35 instances.

The results in Table 6 are also in line with the properties stated in Section 4. By comparing the number of opened parking spots reported in columns $|V_D(t^1)|$ of Table 6, we observe that for graph $G_1$, the number of opened parking spots is closer to the solution of a TSP, in which each household is served by a dedicated parking spot. Conversely, with graphs $G_2$, $G_3$, and $G_4$, less parking spots are opened. This is a consequence of Property 4.2. To understand why, for each graph type, we make explicit the condition stated in Property 4.2 that corresponds to the following:

$$\begin{aligned}
&\textit{Graph } G_1: \quad c_{h_1s_1}+c_{s_1s_2}+c_{s_2h_2}+c_{h_2s_2}<c_{h_1h_2}+c_{h_2s_1}.\\
&\textit{Graph } G_2: \quad c_{h_1s_1}+c_{s_1s_2}+\rho_{s_2}+c_{s_2h_2}+c_{h_2s_2}<c_{h_1h_2}+c_{h_2s_1}.\\
&\textit{Graph } G_3: \quad c_{h_1s_1}+c_{s_1s_2}+\ell_{s_2}+c_{s_2h_2}+c_{h_2s_2}<c_{h_1h_2}+c_{h_2s_1}.\\
&\textit{Graph } G_4: \quad c_{h_1s_1}+c_{s_1s_2}+\rho_{s_2}+\ell_{s_2}+c_{s_2h_2}+c_{h_2s_2}<c_{h_1h_2}+c_{h_2s_1}.
\end{aligned}$$

Across all graphs, this condition contains some common terms. However, for graph $G_1$, this condition is more likely to be fulfilled than for the other graphs because the left-hand side includes fewer terms than the ones in the other graphs. For graphs $G_2$, $G_3$, and $G_4$, the conditions are more difficult to be satisfied due to the presence of the parking time and/or of the loading time.

Finally, by comparing columns $|V_D(t^1)|$ with $|T^2|$ of Table 6, we observe that with graphs $G_1$ and $G_3$, the number of opened parking spots is almost equal to the one of the second-level tours. Conversely, with graphs $G_2$ and $G_4$, more second-level tours originate from the same parking spot. This is a consequence of Property 4.1. To understand why, for each graph type, we make explicit the conditions stated in Property 4.1.

Because $C1$ is the same for all graphs, we focus only on $C2$, that corresponds to the following:

$$\begin{aligned}
&Graph\ G_1, C2: \quad c_{s_1H_0} + c_{H_{|H|}s_1} \leq c_{s_1s_2} + c_{s_2H_0} + c_{H_{|H|}s_2}.\\
&Graph\ G_2, C2: \quad c_{s_1H_0} + c_{H_{|H|}s_1} \leq c_{s_1s_2} + \rho_{s_2} + c_{s_2H_0} + c_{H_{|H|}s_2}.\\
&Graph\ G_3, C2: \quad \ell_{s_1} + c_{s_1H_0} + c_{H_{|H|}s_1} \leq c_{s_1s_2} + \ell_{s_2} + c_{s_2H_0} + c_{H_{|H|}s_2}.\\
&Graph\ G_4, C2: \quad \ell_{s_1} + c_{s_1H_0} + c_{H_{|H|}s_1} \leq c_{s_1s_2} + \rho_{s_2} + \ell_{s_2} + c_{s_2H_0} + c_{H_{|H|}s_2}.
\end{aligned}$$

Across all graphs, condition $C2$ contains some common terms. However, for graph $G_1$, condition $C2$ is more difficult to fulfill than for the other graphs because the right-hand side includes fewer terms than the ones in the other graphs. This means that the solution has less second-level tours rooted at the same parking spot. The same applies to graph $G_3$ due to the presence of the loading times on both sides of the inequality (which, for our instances, are the same for all parking spots). For graphs $G_2$ and $G_4$, condition $C2$ is more likely to be satisfied due to the presence of the parking time only on the right-hand side of the inequality. Hence, these solutions contain more second-level tours rooted at the same parking spot.

The fact that our heuristic solutions present structures that are in line with those of optimal solutions is an additional indicator of the quality of our solutions.

# 6 Conclusion

Motivated by the challenging task of solving large-scale ASTTRPSD instances for postal deliveries, we propose a new metaheuristic, called ILS-ASTTRPSD. For the asymmetric instances from the literature, ILS-ASTTRPSD provides high-quality solutions in short runtimes. For DPDHL instances, ILS-ASTTRPSD is always able to reduce total travel times compared to the solutions provided by DPDHL. This result is due to a different solution structure in which mail carriers spend less time for driving and walking and stop at fewer parking spots. This also contributes to reduce the stress originating from parking activities. Our solutions also exhibit multiple second-level tours rooted at the same parking spot, which is convenient under particular conditions related to the road network structure and to single households with high demands. In our solutions, mail carriers serve more households in each second-level tour without causing longer walking times. Through additional computational experiments, we evaluate the impact of not considering parking and loading times. While ignoring both these time components results in higher travel times, the drawbacks of ignoring loading times are more limited than those of ignoring parking times. Finally, the results of our computational experiments are in line with the two properties necessary for multiple second-level tours being rooted at the same parking spot, and for the ASTTRPSD solution to correspond to a TSP solution.

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# Appendix

## A Comparison on symmetric STTRPSD instances

In this section, we report the results obtained by ILS-ASTTRPSD on symmetric STTRPSD instances from the literature. Due to the different structure of the literature instances, we decreased the sparsification intensity for households and parking spots to $\kappa_c = 0.10$ and $\kappa_k = 0.10$, and increased the number of iterations without improvement $\eta$ to 3000. Moreover, every three iterations of ILS-ASTTRPSD without improvement, we perturb the best found solution in the last three iterations. Table 7 shows the comparison of our results to the state-of-the-art approaches in the literature, i.e.: the hybrid metaheuristic of Accorsi and Vigo (2020) (AVXS), the multi-start iterated local search of Villegas et al. (2010) (MS-ILS), and the progressive filtering heuristic of Arnold and Sörensen (2021) (PF). Because the algorithm of Accorsi and Vigo (2020) is available online, we report the runtimes of AVXS executed on our machine. To allow for a fair runtime comparison with MS-ILS and PF, we used the CPU single-thread rating defined by PassMark Software (2022). The website assigns a score of 1483 to our CPU, and a score of 574 and 2233 to the CPU used by Villegas et al. (2010) and Arnold and Sörensen (2021), respectively. Thus, we convert the runtimes of Villegas et al. (2010) by dividing them by 2.58 and by multiplying the runtimes of Arnold and Sörensen (2021) by 1.51. We are aware that a completely precise comparison of runtimes is not possible due to the different programming languages and other factors. However, we follow the procedure adopted by the literature, and we compare with respect to the CPU.

The results show that ILS-ASTTRPSD returns good-quality solutions with a best and an average gap to the BKS significantly below 1%. Our algorithm is competitive to the MS-ILS of Villegas et al. (2010) and to the PF of Arnold and Sörensen (2021) especially for the large-sized instances. For some of these instances, ILS-ASTTRPSD reaches solutions of a better quality in the best and/or in the average run. The average runtimes of ILS-ASTTRPSD are larger than the ones of the other state-of-the-art heuristics. However, because DPDHL only plans postal delivery tours at the tactical level, the runtimes are still acceptable.

| | | AVXS | | | MS-ILS | | | PF | | ILS-ASTTRPSD | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Instance | *BKS* | $\Delta^b(\%)$ | $\Delta^a(\%)$ | $\bar{t}(s)$ | $\Delta^b(\%)$ | $\Delta^a(\%)$ | $\bar{t}(s)$ | $\Delta(\%)$ | $t(s)$ | $\Delta^b(\%)$ | $\Delta^a(\%)$ | $\bar{t}(s)$ |
| STTRP-25-5-1-c | 405.46 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 4.42 | 0.00 | 60.40 | 0.00 | 0.00 | 11.28 |
| STTRP-25-5-1-rd | 584.03 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 4.88 | 0.00 | 258.21 | 0.00 | 0.00 | 10.18 |
| STTRP-25-5-2-c | 374.79 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 4.42 | 0.00 | 253.68 | 0.00 | 0.00 | 34.81 |
| STTRP-25-5-2-rd | 508.48 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 3.95 | 0.00 | 277.84 | 0.00 | 0.00 | 32.03 |
| STTRP-25-10-1-c | 386.45 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 5.12 | 0.00 | 134.39 | 0.00 | 0.00 | 12.0 |
| STTRP-25-10-1-rd | 573.96 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 5.35 | 0.00 | 66.44 | 0.00 | 0.00 | 11.25 |
| STTRP-25-10-2-c | 380.86 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 4.88 | 0.00 | 140.43 | 0.00 | 0.12 | 22.93 |
| STTRP-25-10-2-rd | 506.37 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 4.88 | 0.02 | 99.66 | 0.00 | 0.01 | 19.66 |
| STTRP-50-5-1-c | 583.07 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 27.44 | 0.00 | 78.52 | 0.00 | 0.00 | 50.65 |
| STTRP-50-5-1-rd | 870.51 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 23.72 | 0.00 | 75.50 | 0.00 | 0.00 | 53.73 |
| STTRP-50-5-2-c | 516.98 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 22.09 | 0.00 | 327.67 | 0.00 | 0.09 | 196.14 |
| STTRP-50-5-2-rd | 766.03 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 22.79 | 0.00 | 146.47 | 0.00 | 1.16 | 105.65 |
| STTRP-50-10-1-c | 387.83 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 31.86 | 0.32 | 89.09 | 0.34 | 0.47 | 36.04 |
| STTRP-50-10-1-rd | 811.28 | 0.00 | 0.00 | 1.90 | 0.00 | 0.00 | 27.91 | 0.00 | 83.05 | 0.00 | 0.06 | 29.98 |
| STTRP-50-10-2-c | 367.01 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 29.07 | 0.00 | 161.57 | 0.00 | 0.00 | 110.40 |
| STTRP-50-10-2-rd | 731.53 | 0.00 | 0.00 | 2.20 | 0.00 | 0.00 | 24.42 | 0.00 | 172.14 | 1.61 | 1.82 | 141.31 |
| STTRP-100-10-1-c | 614.02 | 0.00 | 0.00 | 9.50 | 0.00 | 0.06 | 134.88 | 0.00 | 107.21 | 0.00 | 0.16 | 175.58 |
| STTRP-100-10-1-rd | 1271.78 | 0.00 | 0.00 | 11.90 | 0.65 | 0.87 | 115.35 | 0.00 | 129.86 | 0.95 | 1.55 | 212.44 |
| STTRP-100-10-2-c | 547.44 | 0.00 | 0.00 | 6.00 | 0.00 | 0.02 | 150.93 | 0.00 | 209.89 | 0.00 | 0.05 | 202.58 |
| STTRP-100-10-2-rd | 1097.28 | 0.00 | 0.00 | 9.00 | 0.00 | 0.06 | 100.93 | 0.00 | 203.85 | 0.00 | 0.60 | 404.61 |
| STTRP-100-20-1-c | 642.61 | 0.00 | 0.00 | 11.20 | 0.00 | 0.00 | 112.09 | 0.36 | 123.82 | 0.00 | 0.13 | 254.75 |
| STTRP-100-20-1-rd | 1143.10 | 0.00 | 0.00 | 9.70 | 0.00 | 0.31 | 116.74 | 0.39 | 143.45 | 0.16 | 0.36 | 104.56 |
| STTRP-100-20-2-c | 581.56 | 0.00 | 0.00 | 7.80 | 0.00 | 0.11 | 139.53 | 2.26 | 205.36 | 0.00 | 0.63 | 398.84 |
| STTRP-100-20-2-rd | 1060.75 | 0.01 | 0.24 | 15.00 | 0.00 | 0.20 | 114.19 | 0.60 | 218.95 | 0.28 | 1.08 | 270.06 |
| STTRP-200-10-1-c | 819.96 | 0.00 | 0.00 | 49.30 | 0.31 | 1.03 | 447.44 | 0.20 | 226.50 | 0.53 | 0.79 | 1249.40 |
| STTRP-200-10-1-rd | 1755.41 | 0.00 | 0.00 | 66.20 | 0.45 | 1.59 | 399.77 | 0.21 | 285.39 | 0.84 | 2.05 | 1301.08 |
| STTRP-200-10-2-c | 710.70 | 0.00 | 0.06 | 44.80 | 0.51 | 1.31 | 452.79 | 0.22 | 295.96 | 1.17 | 1.59 | 1248.26 |
| STTRP-200-10-2-rd | 1445.94 | 0.00 | 0.00 | 40.70 | 0.00 | 0.84 | 360.00 | 0.00 | 681.01 | 1.78 | 2.33 | 1462.46 |
| STTRP-200-20-1-c | 907.17 | 0.00 | 0.00 | 51.30 | 0.25 | 0.70 | 532.79 | 2.05 | 382.03 | 0.08 | 0.41 | 740.40 |
| STTRP-200-20-1-rd | 1610.62 | 0.00 | 0.00 | 53.70 | 0.22 | 1.30 | 496.98 | 2.58 | 311.06 | 0.72 | 1.57 | 1028.85 |
| STTRP-200-20-2-c | 814.42 | 0.00 | 0.01 | 38.30 | 0.77 | 0.95 | 567.67 | 0.18 | 608.53 | 0.04 | 0.72 | 1710.74 |
| STTRP-200-20-2-rd | 1413.32 | 0.00 | 0.00 | 54.10 | 0.00 | 0.81 | 468.37 | 1.45 | 552.66 | 0.74 | 0.98 | 1390.63 |
| Avg | | 0.00 | 0.01 | 15.52 | 0.10 | 0.32 | 154.93 | 0.34 | 222.21 | 0.29 | 0.58 | 407.29 |

Table 7: Comparison of the solutions of the heuristics from the literature to the ones of ILS-ASTTRPSD for symmetric instances.

## B Detailed results for the impact of ignoring parking and loading times

### B.1 Detailed results for graph $G_1$

| Instance | $\lvert V_C \rvert$ | $\lvert V_D \rvert$ | $\sum_{i \in V_C} q_i$ | $\overline{c_{ij}}$ | $c(t^1)$ | $\sum_{t^2 \in T^2} c(t^2)$ | $\lvert V_D(t^1) \rvert$ | $\lvert T^2 \rvert$ | $\overline{\lvert V_C(t^2) \rvert}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 382 | 746 | 646 | 417.16 | 3186.72 | 5471.77 | 174 | 174 | 2.20 |
| 2 | 465 | 852 | 713 | 556.17 | 3972.45 | 5156.11 | 150 | 150 | 3.10 |
| 3 | 424 | 778 | 703 | 399.71 | 2983.57 | 4839.58 | 178 | 178 | 2.38 |
| 4 | 433 | 742 | 711 | 333.05 | 2456.27 | 4381.36 | 136 | 136 | 3.18 |
| 5 | 403 | 698 | 826 | 464.93 | 2863.95 | 4414.85 | 197 | 198 | 2.04 |
| 6 | 378 | 585 | 887 | 527.94 | 2471.13 | 4410.89 | 173 | 175 | 2.16 |
| 7 | 361 | 643 | 884 | 340.49 | 1868.59 | 4294.22 | 139 | 139 | 2.60 |
| 8 | 452 | 872 | 791 | 497.59 | 2369.00 | 5215.32 | 197 | 197 | 2.29 |
| 9 | 250 | 412 | 483 | 614.93 | 2496.43 | 3370.08 | 98 | 98 | 2.55 |
| 10 | 298 | 481 | 1092 | 293.17 | 2401.62 | 3892.34 | 156 | 158 | 1.89 |
| 11 | 389 | 758 | 756 | 504.81 | 2476.11 | 4872.41 | 185 | 185 | 2.10 |
| 12 | 374 | 729 | 628 | 456.74 | 3566.43 | 4610.93 | 174 | 174 | 2.15 |
| 13 | 418 | 762 | 770 | 433.92 | 2684.91 | 4602.22 | 160 | 160 | 2.61 |
| 14 | 360 | 697 | 653 | 522.93 | 3371.13 | 3969.06 | 181 | 181 | 1.99 |
| 15 | 441 | 854 | 700 | 537.55 | 3510.49 | 5360.06 | 218 | 218 | 2.02 |
| 16 | 416 | 793 | 621 | 834.63 | 4460.93 | 5492.73 | 200 | 200 | 2.08 |
| 17 | 427 | 812 | 634 | 375.59 | 2961.07 | 4734.62 | 163 | 163 | 2.62 |
| 18 | 452 | 882 | 725 | 600.57 | 3453.10 | 5198.55 | 204 | 204 | 2.22 |
| 19 | 414 | 767 | 654 | 409.54 | 5738.47 | 5410.20 | 162 | 163 | 2.54 |
| 20 | 378 | 720 | 696 | 444.09 | 3600.95 | 4102.34 | 198 | 198 | 1.91 |
| 21 | 458 | 772 | 627 | 475.02 | 3979.46 | 5484.10 | 140 | 140 | 3.27 |
| 22 | 447 | 770 | 673 | 327.47 | 2988.59 | 6197.99 | 118 | 118 | 3.79 |
| 23 | 430 | 815 | 641 | 353.29 | 3534.22 | 5412.74 | 185 | 185 | 2.32 |
| 24 | 334 | 639 | 606 | 647.47 | 4367.17 | 4251.95 | 189 | 189 | 1.77 |
| 25 | 342 | 640 | 601 | 375.88 | 3723.74 | 4033.70 | 148 | 149 | 2.30 |
| 26 | 419 | 814 | 740 | 400.45 | 4010.82 | 4798.18 | 223 | 223 | 1.88 |
| 27 | 368 | 700 | 568 | 930.46 | 4965.45 | 4199.24 | 190 | 190 | 1.94 |
| 28 | 395 | 762 | 571 | 385.66 | 4845.79 | 4997.82 | 193 | 193 | 2.05 |
| 29 | 384 | 746 | 745 | 321.71 | 3941.85 | 4540.14 | 132 | 132 | 2.91 |
| 30 | 369 | 722 | 676 | 543.72 | 4261.53 | 4386.76 | 155 | 155 | 2.38 |
| 31 | 410 | 728 | 736 | 413.50 | 2329.96 | 5035.29 | 179 | 179 | 2.29 |
| 32 | 429 | 837 | 788 | 696.90 | 3900.44 | 4879.95 | 170 | 171 | 2.51 |
| 33 | 245 | 477 | 453 | 1629.02 | 6321.45 | 3433.80 | 172 | 172 | 1.42 |
| 34 | 353 | 695 | 735 | 359.09 | 3762.65 | 4456.70 | 153 | 153 | 2.31 |
| 35 | 341 | 644 | 498 | 510.62 | 4136.67 | 3522.25 | 126 | 127 | 2.69 |
| Avg. | 389.69 | 724.11 | 692.31 | 512.45 | 3541.80 | 4669.44 | 169.03 | 169.29 | 2.36 |

Table 8: Statistics of the best run of ILS-ASTTRPSD for DPDHL instances with graph $G_1$.

### B.2 Detailed results for graph $G_2$

| Instance | $\|V_C\|$ | $\|V_D\|$ | $\sum_{i \in V_C} q_i$ | $\overline{c_{ij}}$ | $c(t^1)$ | $\sum_{t^2 \in T^2} c(t^2)$ | $\|V_D(t^1)\|$ | $\|T^2\|$ | $\overline{\|V_C(t^2)\|}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 382 | 746 | 646 | 417.16 | 3954.19 | 6114.57 | 87 | 88 | 4.34 |
| 2 | 465 | 852 | 713 | 556.17 | 4452.55 | 5881.19 | 69 | 72 | 6.46 |
| 3 | 424 | 778 | 703 | 399.71 | 3135.63 | 6161.82 | 65 | 68 | 6.24 |
| 4 | 433 | 742 | 711 | 333.05 | 2973.50 | 4925.16 | 62 | 62 | 6.98 |
| 5 | 403 | 698 | 826 | 464.93 | 3184.15 | 5594.19 | 74 | 76 | 5.30 |
| 6 | 378 | 585 | 887 | 527.94 | 3028.39 | 5299.49 | 79 | 86 | 4.40 |
| 7 | 361 | 643 | 884 | 340.49 | 2573.98 | 4777.37 | 80 | 83 | 4.35 |
| 8 | 452 | 872 | 791 | 497.59 | 3084.00 | 6023.88 | 99 | 101 | 4.48 |
| 9 | 250 | 412 | 483 | 614.93 | 3192.46 | 3540.12 | 66 | 66 | 3.79 |
| 10 | 298 | 481 | 1092 | 293.17 | 3076.58 | 4638.54 | 88 | 100 | 2.98 |
| 11 | 389 | 758 | 756 | 504.81 | 3021.81 | 5824.76 | 79 | 82 | 4.74 |
| 12 | 374 | 729 | 628 | 456.74 | 4318.65 | 5358.94 | 86 | 88 | 4.25 |
| 13 | 418 | 762 | 770 | 433.92 | 3321.60 | 5330.96 | 75 | 77 | 5.43 |
| 14 | 360 | 697 | 653 | 522.93 | 4006.95 | 4904.38 | 80 | 82 | 4.39 |
| 15 | 441 | 854 | 700 | 537.55 | 4175.47 | 6496.90 | 93 | 93 | 4.74 |
| 16 | 416 | 793 | 621 | 834.63 | 5160.32 | 6486.38 | 79 | 81 | 5.14 |
| 17 | 427 | 812 | 634 | 375.59 | 3184.06 | 5573.94 | 44 | 45 | 9.49 |
| 18 | 452 | 882 | 725 | 600.57 | 4095.58 | 6157.79 | 74 | 74 | 6.11 |
| 19 | 414 | 767 | 654 | 409.54 | 6380.72 | 6128.33 | 81 | 82 | 5.05 |
| 20 | 378 | 720 | 696 | 444.09 | 4041.28 | 5304.00 | 75 | 77 | 4.91 |
| 21 | 458 | 772 | 627 | 475.02 | 4489.09 | 6181.17 | 79 | 82 | 5.59 |
| 22 | 447 | 770 | 673 | 327.47 | 3311.86 | 6887.50 | 48 | 50 | 8.94 |
| 23 | 430 | 815 | 641 | 353.29 | 3456.05 | 6863.50 | 66 | 66 | 6.52 |
| 24 | 334 | 639 | 606 | 647.47 | 5359.55 | 4790.01 | 105 | 106 | 3.15 |
| 25 | 342 | 640 | 601 | 375.88 | 4157.09 | 4963.29 | 62 | 65 | 5.26 |
| 26 | 419 | 814 | 740 | 400.45 | 4517.72 | 6031.93 | 87 | 88 | 4.76 |
| 27 | 368 | 700 | 568 | 930.46 | 5171.84 | 5472.63 | 67 | 68 | 5.41 |
| 28 | 395 | 762 | 571 | 385.66 | 4671.00 | 6803.53 | 62 | 64 | 6.17 |
| 29 | 384 | 746 | 745 | 321.71 | 4314.25 | 5224.66 | 54 | 56 | 6.86 |
| 30 | 369 | 722 | 676 | 543.72 | 4624.25 | 5331.46 | 57 | 60 | 6.15 |
| 31 | 410 | 728 | 736 | 413.50 | 2899.62 | 5853.49 | 77 | 79 | 5.19 |
| 32 | 429 | 837 | 788 | 696.90 | 4299.04 | 5924.93 | 78 | 80 | 5.36 |
| 33 | 245 | 477 | 453 | 1629.02 | 7211.50 | 4232.91 | 124 | 124 | 1.98 |
| 34 | 353 | 695 | 735 | 359.09 | 4294.94 | 4956.69 | 83 | 85 | 4.15 |
| 35 | 341 | 644 | 498 | 510.62 | 4950.03 | 4029.86 | 92 | 92 | 3.71 |
| Avg. | 389.69 | 724.11 | 692.31 | 512.45 | 4059.71 | 5544.87 | 76.46 | 78.51 | 5.22 |

Table 9: Statistics of the best run of ILS-ASTTRPSD for DPDHL instances with graph $G_2$.

### B.3 Detailed results for graph $G_3$

| Instance | $\|V_C\|$ | $\|V_D\|$ | $\sum_{i\in V_C} q_i$ | $\overline{c_{ij}}$ | $c(t^1)$ | $\sum_{t^2\in T^2} c(t^2)$ | $\|V_D(t^1)\|$ | $\|T^2\|$ | $\overline{\|V_C(t^2)\|}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 382 | 746 | 646 | 417.16 | 3039.75 | 7076.93 | 84 | 84 | 4.55 |
| 2 | 465 | 852 | 713 | 556.17 | 3616.64 | 6692.90 | 71 | 72 | 6.46 |
| 3 | 424 | 778 | 703 | 399.71 | 2513.42 | 6769.97 | 76 | 76 | 5.58 |
| 4 | 433 | 742 | 711 | 333.05 | 2290.97 | 5593.20 | 63 | 63 | 6.87 |
| 5 | 403 | 698 | 826 | 464.93 | 2263.03 | 6517.12 | 72 | 72 | 5.60 |
| 6 | 378 | 585 | 887 | 527.94 | 2239.93 | 6112.51 | 88 | 90 | 4.20 |
| 7 | 361 | 643 | 884 | 340.49 | 1667.22 | 5719.82 | 82 | 82 | 4.40 |
| 8 | 452 | 872 | 791 | 497.59 | 1946.48 | 7147.32 | 98 | 99 | 4.57 |
| 9 | 250 | 412 | 483 | 614.93 | 2466.46 | 4275.05 | 64 | 64 | 3.91 |
| 10 | 298 | 481 | 1092 | 293.17 | 2223.41 | 5566.27 | 103 | 104 | 2.87 |
| 11 | 389 | 758 | 756 | 504.81 | 2202.24 | 6651.75 | 85 | 85 | 4.58 |
| 12 | 374 | 729 | 628 | 456.74 | 3316.72 | 6363.21 | 86 | 86 | 4.35 |
| 13 | 418 | 762 | 770 | 433.92 | 2580.43 | 6130.92 | 82 | 82 | 5.10 |
| 14 | 360 | 697 | 653 | 522.93 | 3045.48 | 5883.47 | 76 | 76 | 4.74 |
| 15 | 441 | 854 | 700 | 537.55 | 3075.68 | 7659.97 | 82 | 82 | 5.38 |
| 16 | 416 | 793 | 621 | 834.63 | 4264.82 | 7428.49 | 77 | 77 | 5.40 |
| 17 | 427 | 812 | 634 | 375.59 | 2719.15 | 6092.18 | 43 | 43 | 9.93 |
| 18 | 452 | 882 | 725 | 600.57 | 3281.58 | 6978.94 | 79 | 79 | 5.72 |
| 19 | 414 | 767 | 654 | 409.54 | 5646.67 | 6916.10 | 87 | 88 | 4.70 |
| 20 | 378 | 720 | 696 | 444.09 | 3174.08 | 6171.94 | 74 | 74 | 5.11 |
| 21 | 458 | 772 | 627 | 475.02 | 3603.80 | 7156.08 | 74 | 76 | 6.03 |
| 22 | 447 | 770 | 673 | 327.47 | 2877.46 | 7375.79 | 58 | 58 | 7.71 |
| 23 | 430 | 815 | 641 | 353.29 | 2908.14 | 7360.18 | 75 | 76 | 5.66 |
| 24 | 334 | 639 | 606 | 647.47 | 4111.37 | 6046.87 | 103 | 103 | 3.24 |
| 25 | 342 | 640 | 601 | 375.88 | 3483.39 | 5637.83 | 61 | 62 | 5.52 |
| 26 | 419 | 814 | 740 | 400.45 | 3635.39 | 6911.00 | 93 | 93 | 4.51 |
| 27 | 368 | 700 | 568 | 930.46 | 4464.12 | 6187.95 | 71 | 71 | 5.18 |
| 28 | 395 | 762 | 571 | 385.66 | 4083.96 | 7365.45 | 74 | 74 | 5.34 |
| 29 | 384 | 746 | 745 | 321.71 | 3798.01 | 5758.49 | 61 | 62 | 6.19 |
| 30 | 369 | 722 | 676 | 543.72 | 4031.77 | 5920.57 | 60 | 60 | 6.15 |
| 31 | 410 | 728 | 736 | 413.50 | 2058.83 | 6717.91 | 79 | 79 | 5.19 |
| 32 | 429 | 837 | 788 | 696.90 | 3488.66 | 6759.55 | 81 | 83 | 5.17 |
| 33 | 245 | 477 | 453 | 1629.02 | 5909.94 | 5558.96 | 126 | 126 | 1.94 |
| 34 | 353 | 695 | 735 | 359.09 | 3291.54 | 6093.44 | 72 | 72 | 4.90 |
| 35 | 341 | 644 | 498 | 510.62 | 3784.39 | 5231.62 | 87 | 87 | 3.92 |
| Avg. | 389.69 | 724.11 | 692.31 | 512.45 | 3231.57 | 6395.14 | 78.49 | 78.86 | 5.16 |

Table 10: Statistics of the best run of ILS-ASTTRPSD for DPDHL instances with graph $G_3$.

### B.4 Detailed results for graph $G_4$

| Instance | $\|V_C\|$ | $\|V_D\|$ | $\sum_{i \in V_C} q_i$ | $\overline{c_{ij}}$ | $c(t^1)$ | $\sum_{t^2 \in T^2} c(t^2)$ | $\|V_D(t^1)\|$ | $\|T^2\|$ | $\overline{\|V_C(t^2)\|}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 382 | 746 | 646 | 417.16 | 3295.01 | 7606.96 | 54 | 55 | 6.95 |
| 2 | 465 | 852 | 713 | 556.17 | 4130.20 | 6862.38 | 51 | 54 | 8.61 |
| 3 | 424 | 778 | 703 | 399.71 | 2758.07 | 7227.29 | 46 | 49 | 8.65 |
| 4 | 433 | 742 | 711 | 333.05 | 2793.95 | 5736.55 | 44 | 45 | 9.62 |
| 5 | 403 | 698 | 826 | 464.93 | 2557.62 | 6920.93 | 50 | 57 | 7.07 |
| 6 | 378 | 585 | 887 | 527.94 | 2794.63 | 6368.91 | 59 | 65 | 5.82 |
| 7 | 361 | 643 | 884 | 340.49 | 2294.81 | 5890.15 | 57 | 60 | 6.02 |
| 8 | 452 | 872 | 791 | 497.59 | 2531.29 | 7480.28 | 61 | 64 | 7.06 |
| 9 | 250 | 412 | 483 | 614.93 | 2828.57 | 4499.06 | 47 | 49 | 5.10 |
| 10 | 298 | 481 | 1092 | 293.17 | 2733.36 | 6004.36 | 65 | 75 | 3.97 |
| 11 | 389 | 758 | 756 | 504.81 | 2654.32 | 6951.82 | 52 | 54 | 7.20 |
| 12 | 374 | 729 | 628 | 456.74 | 3928.47 | 6523.39 | 56 | 58 | 6.45 |
| 13 | 418 | 762 | 770 | 433.92 | 3026.20 | 6363.56 | 53 | 54 | 7.74 |
| 14 | 360 | 697 | 653 | 522.93 | 3452.48 | 6110.31 | 48 | 51 | 7.06 |
| 15 | 441 | 854 | 700 | 537.55 | 3421.94 | 8018.91 | 46 | 47 | 9.38 |
| 16 | 416 | 793 | 621 | 834.63 | 4780.26 | 7602.97 | 51 | 53 | 7.85 |
| 17 | 427 | 812 | 634 | 375.59 | 2967.57 | 6250.93 | 33 | 34 | 12.56 |
| 18 | 452 | 882 | 725 | 600.57 | 3469.33 | 7393.77 | 39 | 42 | 10.76 |
| 19 | 414 | 767 | 654 | 409.54 | 6001.20 | 7294.00 | 47 | 50 | 8.28 |
| 20 | 378 | 720 | 696 | 444.09 | 3684.95 | 6334.85 | 48 | 51 | 7.41 |
| 21 | 458 | 772 | 627 | 475.02 | 3809.20 | 7541.52 | 35 | 38 | 12.05 |
| 22 | 447 | 770 | 673 | 327.47 | 3157.37 | 7487.01 | 40 | 41 | 10.90 |
| 23 | 430 | 815 | 641 | 353.29 | 3244.84 | 7750.61 | 44 | 45 | 9.56 |
| 24 | 334 | 639 | 606 | 647.47 | 4670.41 | 6435.32 | 70 | 70 | 4.77 |
| 25 | 342 | 640 | 601 | 375.88 | 3640.29 | 6051.64 | 32 | 36 | 9.50 |
| 26 | 419 | 814 | 740 | 400.45 | 4042.97 | 7234.58 | 47 | 49 | 8.55 |
| 27 | 368 | 700 | 568 | 930.46 | 4974.99 | 6358.32 | 47 | 48 | 7.67 |
| 28 | 395 | 762 | 571 | 385.66 | 4240.42 | 7832.63 | 41 | 42 | 9.40 |
| 29 | 384 | 746 | 745 | 321.71 | 4091.35 | 5987.94 | 40 | 44 | 8.73 |
| 30 | 369 | 722 | 676 | 543.72 | 4520.78 | 6025.44 | 45 | 45 | 8.20 |
| 31 | 410 | 728 | 736 | 413.50 | 2480.40 | 7026.45 | 58 | 59 | 6.95 |
| 32 | 429 | 837 | 788 | 696.90 | 3908.49 | 7180.35 | 63 | 69 | 6.22 |
| 33 | 245 | 477 | 453 | 1629.02 | 6772.28 | 5881.35 | 103 | 103 | 2.38 |
| 34 | 353 | 695 | 735 | 359.09 | 3702.97 | 6474.28 | 51 | 53 | 6.66 |
| 35 | 341 | 644 | 498 | 510.62 | 4378.48 | 5486.61 | 62 | 63 | 5.41 |
| Avg. | 389.69 | 724.11 | 692.31 | 512.45 | 3649.70 | 6691.30 | 51.00 | 53.49 | 7.73 |

Table 11: Statistics of the best run of ILS-ASTTRPSD for DPDHL instances with graph $G_4$.