Picker routing in AGV-assisted order picking systems

Working Paper DPO-2018-01 (version 7, 23.10.2020)

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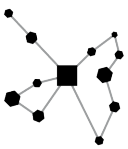
Abstract

To reduce unproductive picker walking in traditional picker-to-parts warehousing systems, automated guided vehicles (AGVs) are used to support human order pickers. In an AGV-assisted order picking system, each human order picker is accompanied by an AGV during the order picking process. AGVs receive the picked items and, once a picking order is complete, autonomously bring the collected items to the shipping area. Meanwhile, a new AGV is requested to meet the picker at the first storage position of the next picking order. Thus, the picker does not have to return to a central depot but continuously picks order after order. This paper addresses both the routing of an AGV-assisted picker through a single-block parallel-aisle warehouse and the sequencing of incoming orders. We present an exact polynomial time routing algorithm for the case of a given order sequence, which is an extension of the algorithm of Ratliff and Rosenthal (1983), and a heuristic for the case in which order sequencing is part of the problem. In addition, we investigate the use of highly effective TSP solvers that can be applied after a transformation of both problem types into a standard TSP. The numerical studies address the performance of these methods and study the impact of AGV usage on picker travel: by using AGVs to avoid returns to the depot and by sequencing in (near-)optimal fashion, picker walking can be reduced by about 20% compared to a traditional setting. Sharing AGVs among the picker workforce enables a pooling effect, so that in larger warehouses only about 1.5 AGVs per picker are required to avoid picker waiting.

Keywords: *warehousing, automated guided vehicles, AGV, order picking, routing*



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1 Introduction

More than 80% of all warehouses in Western Europe still follow the traditional picker-to-parts setup (see Napolitano 2012). In such warehouses, stock keeping units (SKUs) are stored in low-level racks, and human order pickers collect requested items by traveling from shelf to shelf. While, on the positive side, the investment costs for this setup are low, the biggest disadvantage is certainly the large fraction of unproductive picker walking time. The latter is frequently cited to consume 50% and more of the pickers' working hours in a typical picker-to-parts warehouse (Tompkins et al. 2003, de Koster et al. 2007). In recent years, especially triggered by the steadily increasing sales volumes of e-commerce (Statista 2019), many alternative warehousing concepts have been developed to increase the efficiency of order picking. These concepts, which are systematically reviewed by the recent survey papers of Azadeh et al. (2019), Boysen et al. (2019), and Van Gils et al. (2018), reach from adaptations of the traditional picker-to-parts setup, e.g., batching, zoning and sorting as well as mixed-shelves storage, to automated parts-to-picker solutions. The novel concept treated in this paper belongs to the former group: the human order pickers of the traditional picker-to-parts setup are supported by automated guided vehicles (AGVs).

1.1 AGV-assisted order picking

In AGV-assisted order picking, human order pickers are accompanied by AGVs while collecting the items requested by the current picking order at their respective storage positions. The picker puts the collected items into a bin, container, or roll cage (if large-sized SKUs are processed) carried by the AGV. Once a picking order is complete, the AGV autonomously returns to the depot with the collected items, while the picker remains in the storage area. A new AGV is requested to meet the picker at the first storage position of the next picking order. This concept has the following advantages:

- *Reduced walking*: Pickers can continuously pick order after order without intermediate returns to the depot. This increases the pick density per picking tour and reduces the pickers' unproductive walking. It is one of the main intentions of this paper to quantify this positive effect.
- *Easy implementation*: Adding AGVs to an existing picker-to-parts system barely alters the basic fulfillment processes. Consequently, AGV-assisted picking can quickly be implemented without much organizational overhead.
- *Scalability*: By adding additional pickers and AGVs (or by removing them), the concept can quickly be adapted to varying workloads, e.g., when the number of picking orders increases during end-of-season sales. Other concepts based on fixed hardware (e.g., conveyors, automated storage systems or sorters) are not that flexible.

On the negative side, investment costs for the AGVs have to be considered. However, AGVs are a long-established and standardized technology, so that the investments costs are often not overly large, and many warehouses require AGV support anyway, especially if large pick lists, e.g., due to batching, or heavy and bulky items need to be handled. In these cases, updating the existing AGV fleet to capacitate them for AGV-assisted picking generally comes with acceptable additional costs (Boysen et al. 2019). Consequently, most applications of AGV-assisted picking are reported for warehouses handling white goods, home electronic equipment, and carpets (Boysen et al. 2019). However, AGV-assisted picking is not bound to heavy and bulky items; Figure 1 depicts an AGV that handles multiple order bins for small-sized items.

Figure 1: SSI Schäfer's FTS 2Pick^{TM}

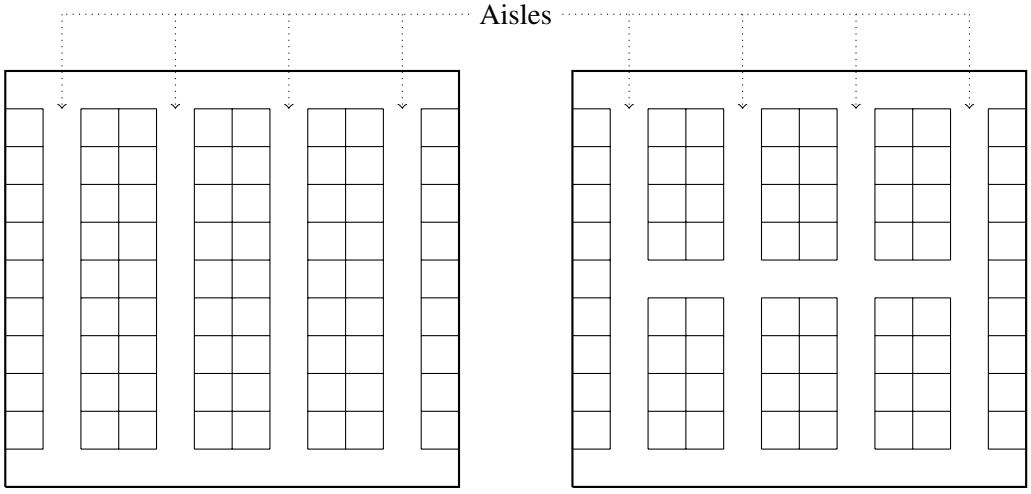
1.2 Decision problems and literature review

AGV-assisted picking is a relatively new concept, and, to the best of our knowledge, this paper is the first to address it. This statement is supported by the recent survey papers of Azadeh et al. (2019) and Boysen et al. (2019), which both mention *Pick Support AGVs* as an important, yet unexplored technology. Therefore, we briefly summarize the main decision problems related to this concept (Boysen et al. 2019):

- *Setup*: The most critical decision when setting up an AGV-assisted picking system is the sizing of the AGV fleet. To save investment costs, the fleet should be as small as possible. However, if the fleet is too small and pickers frequently have to wait for an AGV, the reduced walking does not translate into a better picking performance. Obviously, one picker per AGV is the lower bound for a reasonable fleet size when introducing AGV-assisted order picking. A straightforward heuristic solution is to equip each picker with two AGVs. This allows one AGV to return the previous picking order to the depot and then continue to the first storage position of the subsequent picking order, while the other AGV accompanies the processing of the current order. Except for uncommon warehouse layouts with excessive distances from the depot, two AGVs per picker are thus likely to avoid picker idle time very reliably. In Section 6.4, however, we show that the pooling effect when sharing AGVs among a larger picker workforce allows to considerably reduce the AGV-per-picker ratio.
- *Storage assignment*: To reduce walking distances, traditional storage assignment policies (e.g., class-based storage or full turnover storage (see de Koster et al. 2007)) assign frequently requested SKUs storage space close to the depot. In AGV-assisted picking, however, pickers remain in the storage area, so that locating frequently requested SKUs rather in the center of the warehouse, where they are quickly accessible, seems a valid idea. Exploring this policy and deriving further storage policies for AGV-assisted picking is an interesting field for future research. In our research, we assume a given storage assignment of SKUs.
- *Order batching*: Picking orders need not be identical with customer orders. Especially, if customer orders are small and only contain a few order lines each comprising just a few items, a batching of customer orders to larger picking orders can increase the pick density per tour and thus increase picking performance. Figure 1, for instance, depicts an AGV where six customer orders, each associated with a separate bin to avoid an additional order consolidation after picking, are unified to a single picking order. More details on order batching are, e. g., provided by the survey paper of Henn et al. (2012). In this paper, we presuppose that order batching has been completed and assume given picking orders.
- *Picker routing*: Given a set of picking orders assigned to a picker, the picker routing problem decides

the processing sequence of orders and the picker tour along the storage positions defined by each picking order with the goal of minimizing travel distance or travel time. In traditional picker-to-parts warehouses with a central depot and without AGV support, the order sequence does not impact the walking distance of a picker; the problem decomposes into separate problems for each picking order. The seminal paper of Ratliff and Rosenthal (1983) has shown that the resulting traveling salesman problem (TSP) can be solved in polynomial time in a single-block parallel-aisle warehouse, in which the SKUs are stored in racks along both sides of multiple parallel picking aisles that are enclosed by a storage-free cross aisle at the top and at the bottom (see Figure 2a). This result has been extended to parallel-aisle warehouses with a middle cross aisle (see Figure 2b) by Roodbergen and de Koster (2001). Recently, Pansart et al. (2018) have introduced an exact picker routing algorithm whose runtime increases exponentially only in the number of cross aisles. Goeke and Schneider (2018) present effective modeling approaches for the single-block case, also considering extensions like scattered storage, decoupling of picker and cart, and multiple end depots. De Koster and van der Poort (1998) study an extension in which the picker tour is allowed to start and end at the bottom end of any picking aisle, and start and end point do not have to coincide. Vis and Roodbergen (2009) investigate the routing of straddle carriers in a container terminal. Here, the start point of the tour is assumed to be given whereas the end point can be freely selected. Both start and end point of the tour must be located at the top or bottom end of a picking aisle.

In AGV-assisted order picking, the picker processes order after order without intermediate returns to the depot. Thus, the resulting picker routing problem does not decompose into separate problems, and we have to determine the optimal order sequence and the picker tour to collect all items of the picking orders in the given sequence. This problem corresponds to the clustered TSP (CTSP, Chisman 1975), which is an extension of the TSP in which the cities are partitioned into clusters, and the salesman has to visit the cities of each cluster consecutively. The cities of the CTSP are our picking positions, and the clusters correspond to picking orders. The CTSP is a well-researched standard problem, for which many well-performing solution procedures exist (see, e.g., Jongens and Volgenant 1985, Guttmann-Beck et al. 2000, Bao and Liu 2012, Mestria 2018).



(a) single-block layout (b) two-block layout

Figure 2: Parallel-aisle warehouses with and without intermediate cross aisle.

1.3 Contributions and structure of the paper

This paper investigates the picker routing problem of a single order picker in a single-block parallel-aisle warehouse with AGV support. We are given a set of picking orders, each containing a set of SKUs defining the requested items. Because we assume that each SKU is stored at a given dedicated storage position, a picking order consists of a set of picking positions that have to be visited. A feasible picker tour visits the picking positions of all picking orders and respects the order sequence, i.e., picking positions belonging to the same order have to be visited in direct succession, so that each AGV is loaded with a unique picking order. Among all feasible picker tours, we seek one that minimizes the total travel distance of the picker. For classical picker-to-parts systems (i.e., without picker idle time while waiting for late AGVs), the travel time is an increasing function of the travel distance, so that minimizing the latter is considered as a primary objective in warehouse design and optimization (de Koster et al. 2007). The same is true for an AGV-assisted system with an adequately sized AGV fleet, and therefore we use the same objective function. The resulting optimization problem can be modeled as a CTSP (see Section 2), which—as a generalization of the TSP—is well-known to be strongly NP-hard.

However, in parallel-aisle warehouses, which are prevalent in practice, only very specially structured distance matrices occur, so that the general CTSP, which assumes arbitrary distance matrices, is needlessly general, and the respective algorithms are unnecessarily complex. For a better distinction, we use the term general CTSP (GCTSP) if we assume arbitrary distance matrices, and the term warehouse CTSP (WCTSP), if we assume the distance matrices arising in parallel-aisle warehouses. We further distinguish CTSPs with given cluster sequence (abbreviated as GCTSP-GCS and WCTSP-GCS, respectively), where the order in which clusters must be visited is given, and CTSPs with open cluster sequence (abbreviated as GCTSP-OCS and WCTSP-OCS, respectively), in which the order in which clusters are visited is a decision. Note that CTSPs with given cluster sequence are important optimization problems in many warehouses. Timely fulfilling customer demands is among the top priorities in most warehouses, so that customer orders are often prioritized according to increasing due dates. Once such a sequence of customer orders exists, picker routing corresponds to solving a CTSP with given cluster sequence.

It is well known that the GCTSP-GCS is already strongly NP-hard (see, e.g., Potvin and Guertin 1998). In this paper, we show that the WCTSP-GCS in a single-block parallel-aisle warehouse—we will refer to this problem as single-block WCTSP-GCS in the following—is polynomially solvable by means of a dynamic programming (DP) approach (Section 3). Indeed, analogous to the TSP in traditional picker-to-parts systems with a central depot, the special parallel-aisle structure of warehouses simplifies the problem. Inside the DP, we have to find optimal tours for picking the items of one cluster for a given start and end point of the tour (that do not have to coincide). Consequently, the algorithm of Ratliff and Rosenthal (1983) cannot be directly used because the authors assume that the start and end point represent the same location, namely the depot. Therefore, we develop a dedicated method for the more general case of arbitrary start and end points, which extends the algorithm of Ratliff and Rosenthal (1983), see Section 4. Note that it is not possible to mimic this algorithm by applying the original algorithm of Ratliff and Rosenthal (1983) to a problem instance with modified distance matrix because by modifying the matrix the special structure required for the application of the algorithm of Ratliff and Rosenthal (1983) is destroyed. Also note that this case is not covered by the algorithms presented in de Koster and van der Poort (1998) or Vis and Roodbergen (2009). In addition, we show how the widespread heuristic routing strategies S-shape and largest-gap (see, e.g., de Koster et al. 2007) can be modified to handle the more general case of given start and end point. Solving the WCTSP-GCS in two-block parallel-aisle warehouses (see Figure 2b) requires an analogous extension of the polynomial time routing procedure of Roodbergen and de Koster (2001), which we leave to future research.

In Section 5, we prove that the single-block WCTSP with open cluster sequence (WCTSP-OCS)—and also the two-block WCTSP-OCS) are strongly NP-hard. We embed the DP for solving the single-block WCTSP-GCS within a greedy heuristic to solve the single-block WCTSP-OCS. Section 6 explores the computational performance of our algorithms using traditional GCTSP solution methods (based on transformations to the standard TSP) as comparison methods. Special emphasis is put on comparing the resulting walking distances with and without AGV support. In this way, warehouse managers can assess the tradeoff between additional investment costs into AGVs and the reduced walking distances. In our problem setting, we presuppose that AGVs are no bottleneck resource. Thus, we assume that an AGV is always available if required, and no picker has to wait for an AGV arriving late. Ensuring this comes at the price of additional AGVs. However, we show that the pooling effect when sharing AGVs among several pickers allows to considerably reduce the fleet size (Section 6.4). Finally, Section 7 concludes the paper.

2 Problem description and notation

This section formally describes the AGV-assisted picker-routing problem assuming general warehouse layouts and introduces the required notation. We present formulations for the GCTSP-OCS (Section 2.1) and the GCTSP-GCS (Section 2.2). Section 2.3 shows how GCTSP instances can be transformed into standard TSP instances, which allows to solve them using highly effective TSP methods.

2.1 General CTSP with open cluster sequence

Given $k = 1, \ldots, l$ picking orders P_k each defining the set of picking positions where the SKUs requested by the respective order are stored. We denote with $m = \sum_{k=1}^{l} |P_k|$ the total number of required picking positions and with P the set of all picking positions to be visited including position 0 representing the start and end point of the picking tour, i.e., $P = \bigcup_{k=1,\ldots,l} P_k \cup \{0\}$. Position 0 can refer to the depot or any other position in the warehouse, e.g., a rest area. To make the presentation of the paper concise, we refer to position 0 as the depot throughout the remainder of the paper. Multiple picking orders may request the same SKU, so that a picking position may have to be visited multiple times. Each of these individual visits has an identity (i.e., a specific order it belongs to) and is therefore contained in P. For any pair of picking positions j and j', we know the walking distance $d_{jj'}$ between them. We seek a tour starting and ending at the depot 0 and visiting all required picking positions in a way that picking positions belonging to an order P_k are picked in direct succession and the length of the tour is minimal.

Table 1: Notation

l	number of picking orders
P	set of all required picking positions (with $P = \{0, 1, \ldots, m\}$ including the depot 0)
P_k	set of picking positions of picking order k
$d_{jj'}$	walking distance between picking positions j and j'
$x_{jj'}$	binary variable: 1, if position j' is visited directly after position j; 0, otherwise
u_j	continuous variable: sequence position of picking position j

Using the notation summarized in Table 1, a mixed-integer program (MIP) for the GCTSP-OCS can be formulated (see, e.g., Mestria 2018):

$$\textbf{GCTSP-OCS:} \quad \text{Minimize} \sum_{j \in P} \sum_{j' \in P} d_{jj'} \cdot x_{jj'} \tag{1}$$

subject to

$$\sum_{j \in P} x_{jj'} = 1 \qquad \forall\, j' \in P \tag{2}$$

$$\sum_{j' \in P} x_{jj'} = 1 \qquad \forall\, j \in P \tag{3}$$

$$\sum_{j \in P_k} \sum_{j' \in P_k} x_{jj'} = |P_k| - 1 \qquad \forall\, k = 1, \ldots, l \tag{4}$$

$$u_{j'} - u_j \geq m \cdot x_{jj'} - m + 1 \qquad \forall\, j, j' \in P \setminus \{0\} \text{ with } j \neq j' \tag{5}$$

$$u_0 = 0 \tag{6}$$

$$1 \leq u_j \leq m \qquad \forall\ j \in P \setminus \{0\} \tag{7}$$

$$x_{jj'} \in \{0, 1\} \qquad \forall\ j, j' \in P \tag{8}$$

Objective function (1) minimizes the total travel distance. Constraints (2) and (3) assign each picking position exactly one predecessor and one successor, respectively. All picking positions belonging to the same order have to be picked in direct succession, which is ensured by (4). The well-known Miller-Tucker-Zemlin constraints defined by (5), (6), and (7) eliminate subtours of the picker (Miller et al. 1960), and finally, (8) defines the binary variables.

2.2 General CTSP with given cluster sequence

For adapting the MIP presented in Section 2.1 to the GCTSP-GCS, constraints (4) are replaced with

$$x_{jj'} \leq \sum_{k=1}^{l-1} a_{jk} \cdot (a_{j'k} + a_{j'k+1}) + a_{jl} \cdot a_{j'l} \qquad \forall\, j, j' \in P \setminus \{0\} \text{ with } j \neq j', \tag{9}$$

where a_{jk} is a binary parameter having value 1 if picking position j is to be visited during processing the k-th picking order (0 otherwise). This leads to $m(m-1)$ additional constraints. To reduce the number of additional constraints to m, the following constraints can be used instead of constraints (9)

$$\alpha_k \leq u_j \leq \omega_k \qquad \forall\, k = 1, \ldots, l;\ j \in P_k, \tag{10}$$

where $\alpha_k = \sum_{k'=1}^{k-1} |P_{k'}| + 1$ ($\omega_k = \sum_{k'=1}^{k} |P_{k'}|$) is the first (last) sequence position that is valid as a picking position of order k. Alternatively, we can simply set all distances $d_{jj'}$ for all $j \in P_l, j' \in P_k$ with $l > k$ or $l + 2 \leq k$ to a prohibitively high value, so that only cluster changes among adjacent clusters are enabled. With these adapted distances the MIP for the GCTSP-OCS can directly be applied without (9) or (10).

Both GCTSPs are challenging optimization problems and suitable algorithms considering the general structure are listed in Section 1.2. The best performing solution methods rely on a transformation of the CTSP into a standard TSP, which is solved by means of high-performance TSP methods. Thus, we also follow this path and explain the instance transformations that are used by the state-of-the-art solution methods in the following section.

2.3 Transformation from GCTSP to TSP

Because the standard TSP is one of the most researched problems in the field of Operations Research, highly effective solution methods exist. In this section, we present transformations from both the GCTSP-OCS and

GCTSP-GCS to the TSP, which enable us to apply TSP methods to solve GCTSP and WCTSP instances (see also Chisman 1975, Helsgaun 2014). In the following, M is a sufficiently large number (greater than the maximum distance in the respective instance). Because we are only interested in solving WCTSP instances, which feature symmetric distances, we assume the distance matrix $d_{jj'}$ of the GCTSP instance to be symmetric. The transformations are designed to produce symmetric TSP instances because the state-of-the-art exact TSP solver used in our numerical experiments is only able to solve symmetric TSP instances.

GCTSP-OCS $\rightarrow$ TSP: We can transform a GCTSP-OCS instance to a TSP instance with $|P|$ vertices and distance matrix $d'_{jj'}$ with $j, j' \in P$ as follows:

$$d'_{jj'} := \begin{cases} d_{jj'}, & \text{if } j \text{ and } j' \text{ are in the same cluster,} \\ d_{jj'} + M, & \text{otherwise.} \end{cases} \tag{11}$$

In the above definition, all edges between vertices from different clusters are penalized with a value of M, so that in an optimal solution all nodes in a cluster are visited consecutively. Recall that the GCTSP includes one cluster for every order P_k and one additional cluster for the depot 0 ($l + 1$ in total). Therefore, the objective value of a solution to the TSP instance is smaller than $(l + 2) \cdot M$ if and only if it is a feasible GCTSP solution. In this case, a value of $(l + 1) \cdot M$ must be subtracted from the objective value of the TSP solution to obtain the objective value of the corresponding GCTSP solution.

GCTSP-GCS $\rightarrow$ TSP: A GCTSP-GCS instance can be transformed into a TSP instance with $|P|$ vertices and distance matrix $d'_{jj'}, j, j' \in P$:

$$d'_{jj'} := \begin{cases} d_{jj'}, & \text{if } j \text{ and } j' \text{ are in the same cluster,} \\ d_{jj'} + M, & \text{if the cluster of } j \text{ directly precedes or follows that of } j' \\ 2 \cdot M, & \text{otherwise} \end{cases} \tag{12}$$

Analog to the previous transformation, objective values smaller than $(l + 2) \cdot M$ indicate that the TSP solution represents a feasible GCTSP-GCS solution and the corresponding GCTSP-GCS objective value is obtained by subtracting $(l + 1) \cdot M$. Because of the symmetry of the distance matrix, any TSP tour can be reversed and the resulting tour has identical objective value. In a GCTSP-GCS solution, a reversed tour also results in a reversed cluster sequence. Thus, this case needs to be handled by checking whether the first visited node in the TSP tour belongs to the first or last cluster of the given cluster sequence.

Recall that both the GCTSP-GCS and GCTSP-OCS allow for arbitrary distance matrices defining the distances among picking positions derived from any distance metric. In the following sections, however, we will show that the special distance matrices in parallel-aisle warehouses can be exploited to derive more efficient algorithms.

3 Solving the single-block warehouse CTSP with given cluster sequence

The GCTSP-GCS is well-known to be strongly NP-hard (Potvin and Guertin 1998). However, in the following, we show that this does not hold for the single-block WCTSP-GCS.

Theorem 1 *The single-block WCTSP-GCS is solvable in $\mathcal{O}(m^3 + rm^2)$, where r is the number of aisles in the warehouse and m is the total number of required picking positions.*

Proof of Theorem 1. We present a DP procedure, which is able to solve the single-block WCTSP-GCS in polynomial time. Let $k = 1, \ldots, l$ denote the given processing order of the picking orders P_k, and let P_0 and P_{l+1} be two virtual picking orders containing only the depot 0. The DP consists of stages $s = 0, \ldots, l+1$ (with virtual start stage $s = 0$ and end stage $s = l + 1$) representing the picking orders (clusters) P_s. Each stage s contains a number of $|P_s|$ states (s, j') with $j' \in P_s$, which define that picking position j' is the last one visited when completing picking order P_s.

The following Bellman recursion applies:

$$W(s, j') \quad = \quad \min_{j \in P_{s-1}} \Big(W(s-1, j) \; + \; \Omega\big((s-1, j), (s, j')\big) \Big). \tag{13}$$

$W(s, j')$ denotes the objective value of state (s, j'), i.e., the total distance which the picker has traveled after picking orders P_0 through P_s with j' as the last item picked for order P_s. Ω is the partial objective value associated with a transition from state $(s-1, j)$ to (s, j'), i.e., the distance required to pick all items in order P_s when starting at picking position j from order P_{s-1} and ending at position j'.

For the initial objective value, we set $W(0, 0) = 0$. Solving the single-block WCTSP-GCS then corresponds to finding a state of final stage $s = l + 1$ with minimum objective value (total walking distance).

To calculate Ω, we determine a shortest order picking path starting at j, visiting all picking positions $P_s \setminus j'$ and ending in position j' using the routing algorithm presented in Section 4, which extends the algorithm of Ratliff and Rosenthal (1983) and has a runtime complexity of $\mathcal{O}(m + r)$. The DP has no more than m^2 transitions, and each transition requires the computation of a partial objective value by means of the routing algorithm. Thus, the runtime complexity is $\mathcal{O}(m^3 + rm^2)$. □

4 Picking a single order with given start and end point in a single-block parallel-aisle warehouse

This section describes the computation of the partial objective value Ω associated with a transition from stage $s - 1$ to s in the DP method described above. It extends the algorithm of Ratliff and Rosenthal (1983) such that the picking tour does not need to form a closed loop but is a picking path. Input to the algorithm is a designated start point $j \in P_{s-1}$, a designated end point $j' \in P_s$, and a set of vertices P'_s representing the remaining set of picking positions $P_s \setminus j'$ of order s. In the context of the DP, j and j' correspond to the last picking positions of orders $s - 1$ and s, respectively. Like the original algorithm of Ratliff and Rosenthal (1983), our method relies on a single-block parallel-aisle warehouse structure.

The basic property utilized by the algorithm of Ratliff and Rosenthal (1983) is that in optimal solutions aisles can only be passed by the picker in a restricted number of ways, e.g., once through the complete aisle or two loops from the back and front cross aisle. These vertical aisle configurations are to be interconnected horizontally via the cross aisles, for which also only a limited number of possible traversals exists. Given these potential vertical and horizontal configurations, where only some of the former are compatible with the latter, a dynamic programming scheme then connects fitting configurations to states in a step-wise manner until all relevant aisles of the warehouse are visited. In this section, we elaborate on how these basic ingredients have to be adapted in order to integrate a given start and end point.

In Section 4.1, we introduce a representation of the warehouse and of picking paths using undirected multi-graphs. Section 4.2 describes the construction of a minimum-length undirected picking path using this representation. In this way, we provide the means to compute the partial objective value Ω, which we illustrate at an example in Section 4.3. Section 4.4 presents an efficient method for obtaining a directed picking path from its undirected representation. The definitions and theorems in Sections 4.1–4.4 are intentionally kept as close as possible to those of the original paper of Ratliff and Rosenthal (1983). This includes a similar terminology to simplify the discussion for readers that are familiar with the original algorithm. Proofs for all theorems can be found in the online appendix A. Finally, Section 4.5 shows how the S-shape and largest gap heuristic can be modified to handle given start and end points of the picking path.

4.1 Graph representation and preliminaries

In this section, we show how the graph definition of Ratliff and Rosenthal (1983) has to be extended to include a given start and end point. With given j, j', P'_s and r, we define a warehouse graph $G = (V, E)$, whose vertices V represent j and j', every element in P'_s and the front and rear locations e_i and e'_i in every aisle $i = 1, \ldots, r$. Set E consists of an unlimited number of parallel edges between every pair of vertices corresponding to adjacent locations in the warehouse. Associated with every edge is the distance or time it takes to travel between the locations corresponding to the incident vertices, which will be referred to as the length of an edge in the following. Parallel edges always have the same length. Figure 3 shows an example warehouse graph with $r = 5$ and $|P'_s| = 9$. Vertices representing the picking positions in P'_s are denoted by v_p, $p = 1, \ldots, |P'_s|$.

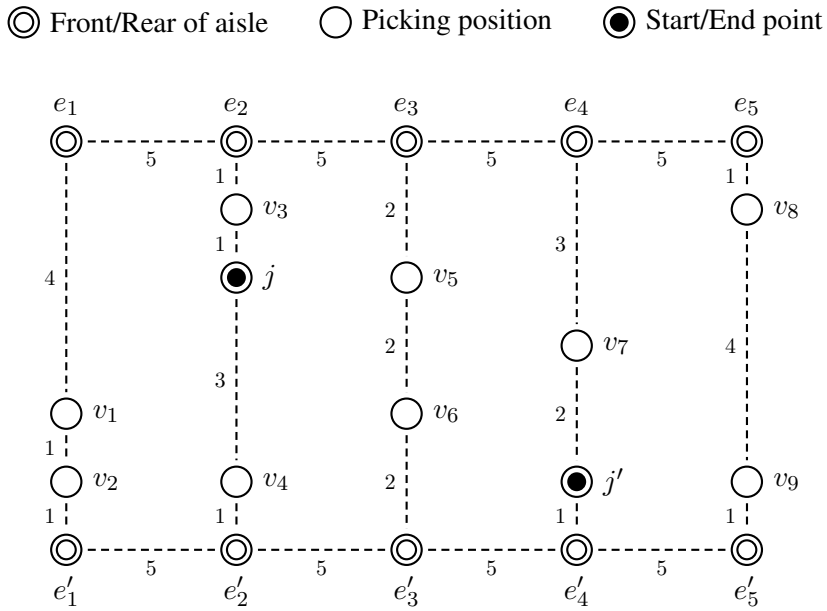


Figure 3: Example warehouse graph with $r = 5$ and $|P'_s| = 9$. Dashed lines represent an unlimited number of parallel edges.

In general, a subgraph of G is a graph whose set of vertices is a subset of those in G, and which has fewer or the same number of edges between any pair of vertices as G has between them. The length of a subgraph is defined as the total length of all its edges.

Definition 1 (Path Subgraph) *A path subgraph (PS) T is a subgraph of G, from which a directed picking path can be constructed such that every arc of the picking path corresponds to exactly one edge in T.*

To differentiate between a picking path and a path subgraph according to Definition 1, recall that a picking

path represents a path starting at position j, visiting all articles $v_p \in P'_s$ and finishing at position j', hence it is represented by a directed graph.

A PS can be interpreted as an intermediate representation of a picking path where all arcs have been replaced by edges. Note that a PS represents at least two picking paths because there are at least two ways of assigning a direction to an undirected path and because the PS might contain cycles, which can be oriented in two different ways. Because the single-block WCTSPs are symmetric, a PS has the same length as all directed picking paths which can be derived from it. Theorem 2 states the formal properties of a PS. It is the adaption of Theorem 1 from Ratliff and Rosenthal (1983) picking paths with non-identical start and end point.

Theorem 2 (Path Subgraph Properties) *A subgraph $T \subset G$ is a path subgraph if and only if*

1. *vertices P'_s have nonzero even degree in T.*
2. *vertices j and j' have nonzero odd degree in T.*
3. *vertices e_i and e'_i have even or zero degree in T for all $i = 1, \ldots, r$.*
4. *excluding vertices with zero degree, T is connected.*

The meaning of Theorem 2 can be easily understood when interpreting the notion of the degree of a vertex as the number of times that the picker passes the picking position represented by the vertex. The number of connected components in a PPS is the number of non-intersecting picking paths, i.e., a connected component represents the picking path of a single picker, and consequently, a valid PS can only contain one connected component.

Similar to the algorithm of Ratliff and Rosenthal (1983), the minimum-length PS is constructed incrementally by iterating over all aisles from 1 to r. To this end, L_i^- denotes a subgraph of G including e_i and e'_i and everything (i.e., edges and vertices) to the left of these vertices, whereas L_i^+ includes L_i^- and everything on aisle i. An illustration of L_3^- and L_3^+ for the example warehouse graph above can be found in Figure 4. Similarly, we define R_i^- as a subgraph of G including e_i and e'_i and everything to the right of these vertices, and R_i^+ as a subgraph of G containing R_i^- and everything on aisle i. In order to keep notation simple, the use of L_i in a statement means that it holds when L_i is substituted by either L_i^- or L_i^+. The use of L_i and R_i together in a statement means that the statement holds when either $L_i = L_i^-$ and $R_i = R_i^+$ or $L_i = L_i^+$ and $R_i = R_i^-$.

Definition 2 (Partial Path Subgraph) *Using the previous definitions, we define a subgraph $T \subset L_i$ to be an L_i partial PS (L_i PPS) if there exists a subgraph $T^c \subset R_i$ such that $T \cup T^c$ forms a valid PS. The subgraph T^c is called a completion of T.*

Theorem 3 (Partial Path Subgraph Properties, see Theorem 2 of (Ratliff and Rosenthal 1983)) *A subgraph $T \subset L_i$ is an L_i PPS if and only if*

1. *every vertex in $T \setminus \{j, j'\}$ has even or zero degree,*
2. *the degrees of vertices $P'_s \cap L_i$ are nonzero and even in T,*
3. *vertices $L_i \cap \{j, j'\}$ have odd degrees in T,*
4. *excluding vertices with zero degree, T is either empty, has a single connected component containing at least one of e_i and e'_i or two connected components of which one contains e_i and the other one contains e'_i.*

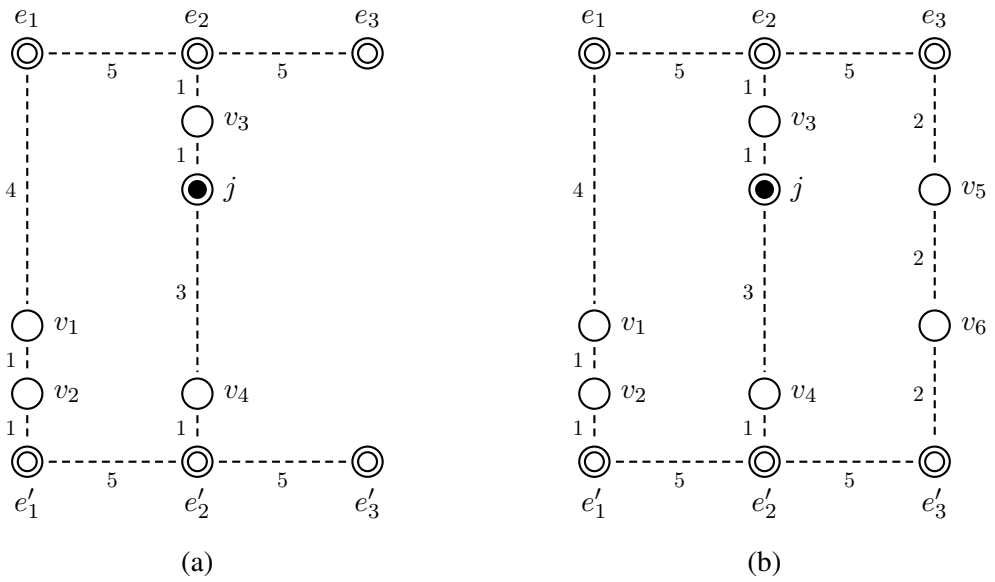


Figure 4: Subgraphs L_3^- (a) and L_3^+ (b) of the example warehouse graph. Dashed lines again represent an unlimited number of parallel edges.

Definition 3 (Equivalent Partial Path Subgraphs) *With given $T^1 \subset L_i$ and any $T^c \subset R_i$ such that $T^1 \cup T^c$ forms a valid PS, another $T^2 \subset L_i$ is said to be equivalent to T^1, if $T^2 \cup T^c$ also forms a valid PS.*

Graphically speaking, if two PS contain two equivalent L_i PPS, then these PPS can be exchanged between the two PS without invalidating either of them.

Theorem 4 (Equivalence Conditions, see Theorem 3 of Ratliff and Rosenthal (1983)) *Two PPSs T^1 and T^2 of L_i are equivalent if*

1. *both e_i and e'_i have the same degree parity (even, odd, or zero) in T^1 and T^2,*
2. *excluding vertices with zero degree, both T^1 and T^2 have the same number of connected components.*

Every L_i PPS belongs to exactly one equivalence class, which is characterized by the degree parities of e_i and e'_i and the number of connected components. Hence, we denote the equivalence class as a triple (degree of e_i, degree of e'_i, number of connected components), without the braces and commas. For instance, UE1 indicates that the degree of e_i is odd (U for *uneven*, because O for odd could be confused with 0 for zero) and the degree of e'_i is even (E), and there is only one component (1).

Theorem 5 (Possible Equivalence Classes, see Corollary 3.1 of Ratliff and Rosenthal (1983)) *Every possible L_i PPS belongs to one of a set C of 14 equivalence classes*

$$C = \{000,\ 001,\ E01,\ 0E1,\ EE1,\ UU1,\ EE2,\ UU2,\ U01,\ 0U1,\ UE1,\ EU1,\ UE2,\ EU2\}. \quad (14)$$

4.2 Minimum length path subgraph construction

This section defines the vertical and horizontal configurations in which aisles and cross aisles, respectively, can be traversed in optimal solutions and how these configurations are connected in a dynamic program. We know that there is a finite set of equivalence classes, and that every L_i PPS belongs to exactly one of them. We now show how to construct a minimum-length L_i PPS for each equivalence class, starting at $i = 1$ going through $i = 2, \ldots, r$. The shortest L_r^+ PPS from the set of equivalence classes $\{001,\ E01,\ 0E1,\ EE1\}$ will

be the desired minimum-length PS because according to Theorem 2, a valid order picking path graph must be connected and must possess even or zero degree in e_r and e'_r. We begin with the following observation:

Lemma 1 (Maximum Vertex Degrees) *A minimum length PS contains no more than two edges between any pair of vertices.*

Corollary 1 (Possible Edge Configurations) *Following from Lemma 1, there exist 18 possible edge configurations for traversing any aisle, which will be referred to as vertical edge configurations. Further, there exist 9 edge configurations for crossing between adjacent aisles, which will be referred to as horizontal edge configurations.*

The 18 possible vertical edge configurations are shown in Figure 5. Expanding an L_i^- PPS with a vertical edge configurations from Figure 5 will result in an L_i^+ PPS. Configurations 1–5 apply in case aisle i neither includes j nor j'. Configuration 6 applies, if aisle i does not contain any picking positions from $P_k \cup \{j, j'\}$. If aisle i contains either j or j', configurations 7–12 are used for expansion, changing the mode in the resulting L_i PPS from even to odd or vice versa. Configurations 13–17 are applicable if aisle i contains both j and j'. For configuration 4, 11, 12, 13, 16a, and 16b, the longest distance between any two adjacent vertices from $P'_s \cup \{j, j'\}$ is not traversed. For configuration 2, 3, 7, 8, 14, and 15, the longest distance between e_i or e'_i and its adjacent vertex from $P'_s \cup \{j, j'\}$ is not traversed. Configurations 16a and 16b are differentiated for clarity because both j and j' are either contained in the upper or in the lower component of the configuration, but adding either of them to an L_i^- PPS results in an L_i^+ PPS of the same equivalence class for both 16a and 16b. The one of shorter length will be referred to as configuration 16. Finally, configuration 18 represents the trivial case, where all vertices P'_s, j and j' are located in the same aisle.

Table 2 shows the equivalence classes for L_i^+ that result from adding a vertical edge configuration from Figure 5 to an L_i^- PPS of a given equivalence class. The leftmost column states the equivalence class of the L_i^- PPS. A dash (–) indicates infeasible expansions because in those cases either no valid completion exists, or the resulting PS cannot be optimal. An example expansion of an L_3^- PPS with vertical edge configuration 1 is shown in Figure 6.

Figure 7 shows the 9 possible horizontal edge configurations. Adding one of them to an L_{i-1}^+ PPS will result in an L_i^- PPS. As a special case, configuration 5 only applies if there are no picking positions to the right of aisle $i-1$.

Table 3 states the equivalence class of an L_i^- PPS resulting from adding a horizontal edge configuration from Figure 7 to an L_{i-1}^+ PPS of a given equivalence class. For instance, an L_i^- PPS of equivalence class 0E1 results from adding edge configuration 3 from Figure 7 to an L_{i-1}^+ PPS of equivalence class 0E1 or EE1.

To find the minimum-length PS, the algorithm starts in aisle 1, with an empty L_1^- PPS belonging to equivalence class 000. For the current aisle i, all L_i^- (L_i^+) PPSs are expanded with all applicable edge configurations from Figure 5 (7), leading to a set of L_i^+ (L_{i+1}^-) PPSs. From this set, we only keep the shortest L_i PPS for each equivalence class. Then, the algorithms continues with the next aisle $i+1$. As stated above, for the last aisle r, the shortest L_r^+ PPS belonging to the set of equivalence classes $\{001,\ \text{E01},\ \text{0E1},\ \text{EE1}\}$ is the desired minimum-length PS.

To determine the runtime complexity, we first observe that the algorithm iterates over r aisles. Second, in order to expand the L_i PPSs for every aisle i, the algorithm constructs the (fixed number of) edge configurations. Here, the construction of vertical configurations 4, 11, 12, 13 and 16 require the iteration over all picking positions located within aisle i. Thus, the algorithm iterates over no more than $\mathcal{O}(|P_k|)$ picking positions in total. Because $|P_k| \leq m$, this results in a runtime complexity of $\mathcal{O}(m+r)$ for determining the minimum-length PS.

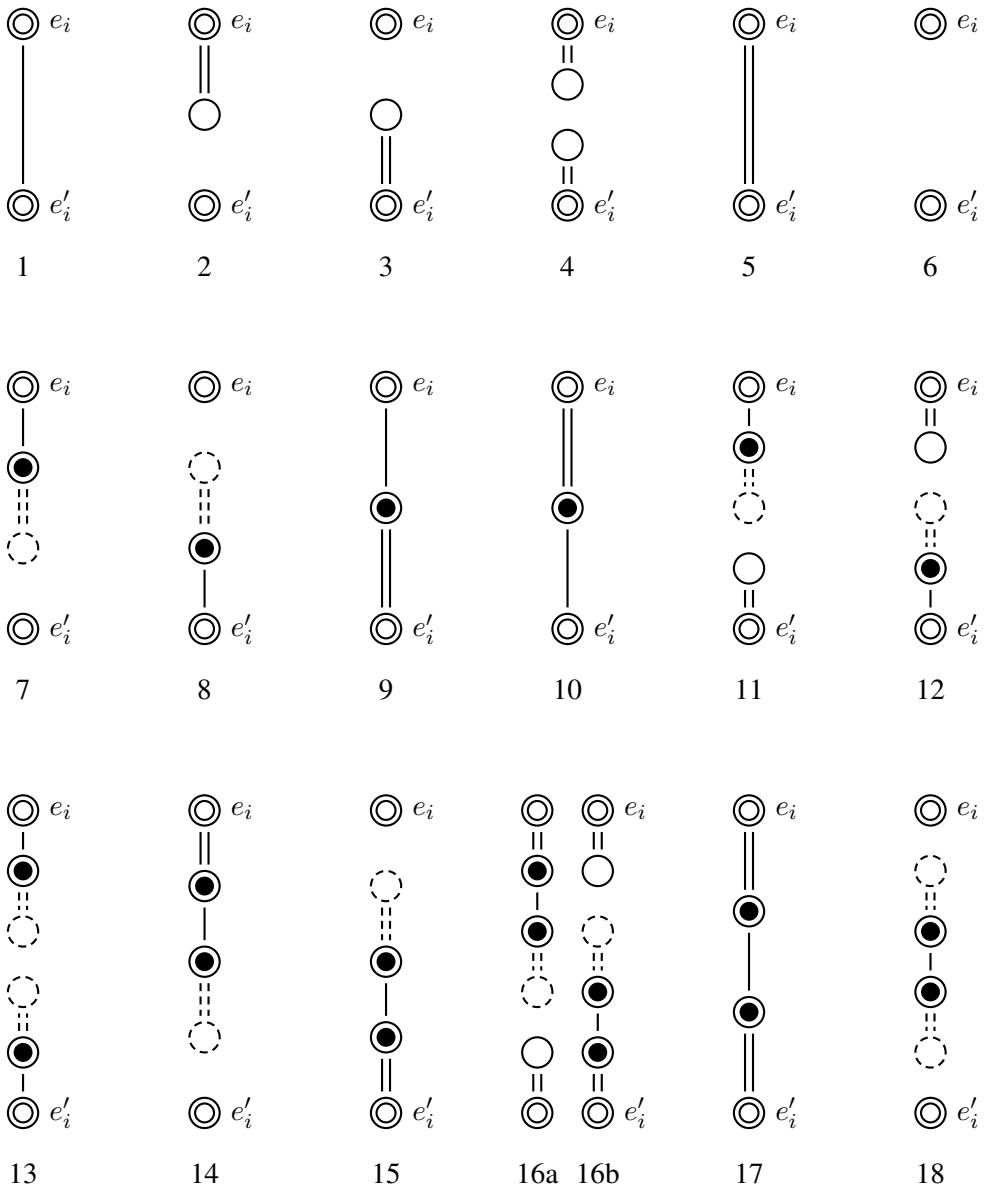


Figure 5: Possible vertical edge configurations for traversing any aisle i. Dashed parts are optional.

Table 2: Transition matrix for vertical edge configurations.

Eq. cl.	**Vertical edge configuration**													
	1	2, 14	3, 15	4, 16	5, 17	6	7	8	9	10	11	12	13	18
000	UU1	E01	0E1	EE2	EE1	000	U01	0U1	UE1	EU1	UE2	EU2	UU2	001
001	–	–	–	–	–	001	–	–	–	–	–	–	–	–
E01	UU1	E01	EE2	EE2	EE1	E01	U01	EU2	UE1	EU1	UE2	EU2	UU2	–
0E1	UU1	EE2	0E1	EE2	EE1	0E1	UE2	0U1	UE1	EU1	UE2	EU2	UU2	–
EE1	UU1	EE1	EE1	EE1	EE1	EE1	UE1	EU1	UE1	EU1	UE1	EU1	UU1	–
UU1	EE1	UU1	UU1	UU1	UU1	UU1	EU1	UE1	EU1	UE1	EU1	UE1	EE1	–
EE2	UU1	EE2	EE2	EE2	EE1	EE2	UE2	EU2	UE1	EU1	UE2	EU2	UU2	–
UU2	EE1	UU2	UU2	UU2	UU1	UU2	EU2	UE2	EU1	UE1	EU2	UE2	EE2	–
U01	EU1	U01	UE2	UE2	UE1	U01	E01	UU2	EE1	UU1	EE2	UU2	EU2	–
0U1	UE1	EU2	0U1	EU2	EU1	0U1	UU2	0E1	UU1	EE1	UU2	EE2	UE2	–
UE1	EU1	UE1	UE1	UE1	UE1	UE1	EE1	UU1	EE1	UU1	EE1	UU1	EU1	–
EU1	UE1	EU1	EU1	EU1	EU1	EU1	UU1	EE1	UU1	EE1	UU1	EE1	UE1	–
UE2	EU1	UE2	UE2	UE2	UE1	UE2	EE2	UU2	EE1	UU1	EE2	UU2	EU2	–
EU2	UE1	EU2	EU2	EU2	EU1	EU2	UU2	EE2	UU1	EE1	UU2	EE2	UE2	–

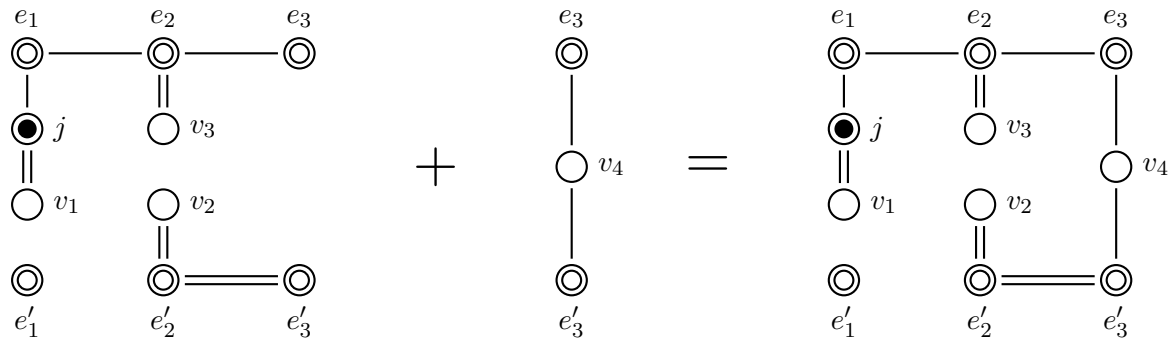


Figure 6: Adding vertical edge configuration 1 to an L_3^- PPS of type UE2 results in an L_3^+ PPS of type EU1.

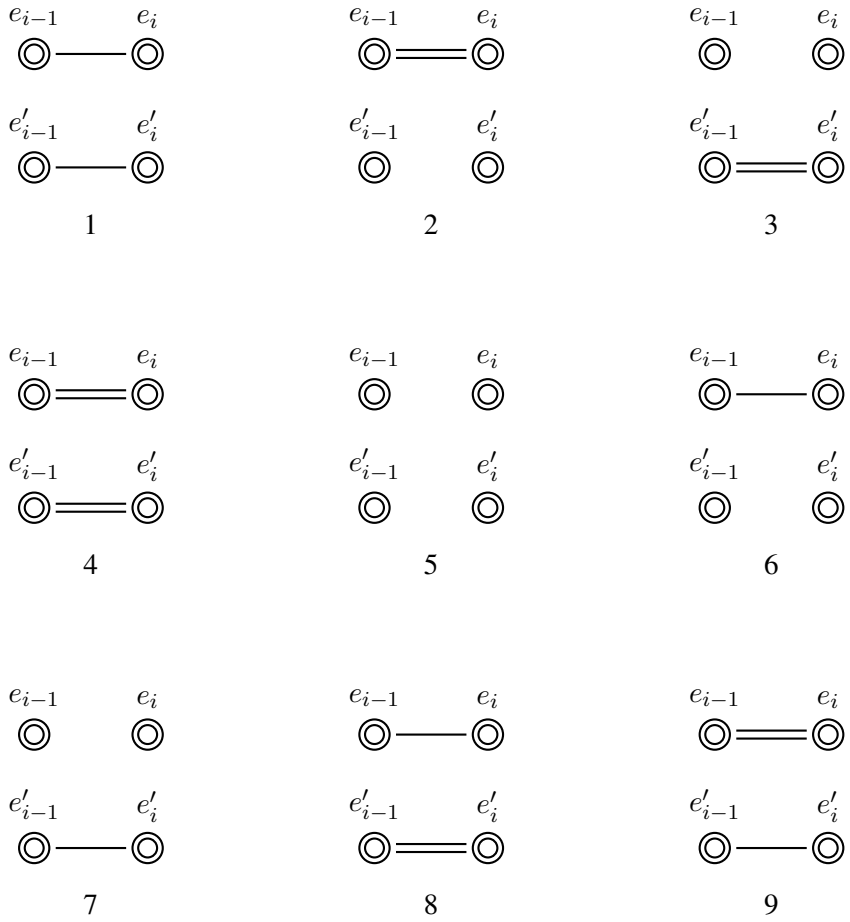


Figure 7: Possible horizontal edge configurations for crossing from aisle $i-1$ to aisle i.

Table 3: Transition matrix for horizontal edge configurations.

Eq. cl.	Horizontal edge configuration								
	1	2	3	4	5	6	7	8	9
000	–	–	–	–	000	–	–	–	–
001	–	–	–	–	001	–	–	–	–
E01	–	E01	–	–	001	–	–	–	–
0E1	–	–	0E1	–	001	–	–	–	–
EE1	–	E01	0E1	EE1	001	–	–	–	–
UU1	UU1	–	–	–	–	–	–	–	–
EE2	–	–	–	EE2	–	–	–	–	–
UU2	UU2	–	–	–	–	–	–	–	–
U01	–	–	–	–	–	U01	–	–	–
0U1	–	–	–	–	–	–	0U1	–	–
UE1	–	–	–	–	–	U01	–	UE1	–
EU1	–	–	–	–	–	–	0U1	–	EU1
UE2	–	–	–	–	–	–	–	UE2	–
EU2	–	–	–	–	–	–	–	–	EU2

4.3 Numerical example

To illustrate the procedure described above, we determine the minimum-length PS for the example given in Figure 3. First, we calculate the shortest L_1^+ PPSs by adding all applicable vertical edge configurations from Figure 5 to the initially empty L_1^- PPS of equivalence class 000. Because aisle 1 contains neither j nor j', vertical edge configurations 1–5 are used, and all resulting L_1^+ PPSs are of even mode. Vertical edge configuration 6 is not applicable because aisle 1 is not empty. From Table 2, we see that adding vertical edge configuration 1 to a PPS of equivalence class 000 leads to a PPS of equivalence class UU1, whereas adding vertical edge configuration 2 to a PPS of equivalence class 000 leads to a PPS of equivalence class E01. The resulting equivalence classes for edge configurations 3, 4 and 5 are 0E1, EE2 and EE1 respectively. Secondly, we add horizontal edge configurations from Figure 7 to the L_1^+ PPSs to obtain the shortest L_2^- PPSs. From Table 3, we see that for the equivalence classes obtained in the previous step, only horizontal edge configurations 1–5 are applicable. The PPS of equivalence class EE1 can be expanded with more than one horizontal edge configuration. Also, we obtain more than one PPS for equivalence classes E01 and 0E1, in which case we keep the shortest one for each equivalence class. The shortest L_i^+ and L_i^- PPSs for the following aisles can be calculated in the same fashion by using the transition matrices in Tables 2 and 3, respectively. Because j is located in aisle 2, the algorithm transitions into odd mode by constructing the L_2^+ PPSs using vertical edge configurations 7–12. The algorithm transitions back into even mode by constructing the L_4^+ PPSs because vertex j' is located in aisle 4.

Table 4 shows a cost and transition matrix for the example in which each row corresponds to an L_i PPS equivalence class. The entries of the cost matrix are triplets of the form (costs, equivalence class of predecessor, edge configuration). The shortest L_5^+ PPS among equivalence classes 001, E01, 0E1, EE1 is the minimum-length PS, which in the given example is of equivalence class EE1 and has length 57. Tracing back through the matrix using the denoted predecessors, the shortest tour is obtained by the sequence of edge configurations $V_1 = 3$, $H_2 = 3$, $V_2 = 8$, $H_3 = 7$, $V_3 = 1$, $H_4 = 6$, $V_4 = 8$, $H_5 = 1$, $V_5 = 1$, where V_i and H_i denote the vertical and horizontal edge configuration in aisle i, respectively. The edge configurations of the minimum-length PS depicted in Figure 8 are given by the underlined entries in the cost matrix.

Table 4: Cost matrix for the example in Figure 3.

Eq. cl.	**Aisle 1**	**Aisle 2**		**Aisle 3**		**Aisle 4**		**Aisle 5**	
	L_1^+	L_2^-	L_2^+	L_3^-	L_3+	L_4^-	L_4+	L_5^-	L_5+
000	–	–	–	–	–	–	–	–	–
001	–	–	–	–	–	–	–	–	–
E01	10, 000, 2	20, E01, 2	–	–	–	–	41, U01, 7	51, E01, 2	61, E01, 2
0E1	4, 000, 3	14, 0E1, 3	–	–	–	–	43, 0U1, 8	53, 0E1, 3	63, 0E1, 3
EE1	12, 000, 5	32, EE1, 4	–	–	–	–	43, U01, 9	63, EE1, 4	57, UU2, 1
UU1	6, 000, 1	16, UU1, 1	–	–	–	–	45, 0U1, 9	55, UU1, 1	57, E01, 1
EE2	4, 000, 4	24, EE2, 4	–	–	–	–	41, U01, 11	61, EE2, 4	55, E01, 4
UU2	–	–	–	–	–	–	41, U01, 8	51, UU2, 1	55, UU2, 4
U01	–	–	28, E01, 7	27, UE1, 6	35, U01, 2	36, UE1, 6	–	–	–
0U1	–	–	20, 0E1, 8	25, 0U1, 7	33, 0U1, 3	38, 0U1, 7	–	–	–
UE1	–	–	22, UU1, 8	37, UE1, 8	31, 0U1, 1	46, UE1, 8	–	–	–
EU1	–	–	20, UU1, 11	35, EU1, 9	33, U01, 1	48, EU1, 9	–	–	–
UE2	–	–	18, 0E1, 11	33, UE2, 8	35, U01, 3	50, UE2, 8	–	–	–
EU2	–	–	20, 0E1, 12	35, EU2, 9	33, 0U1, 2	48, EU2, 9	–	–	–

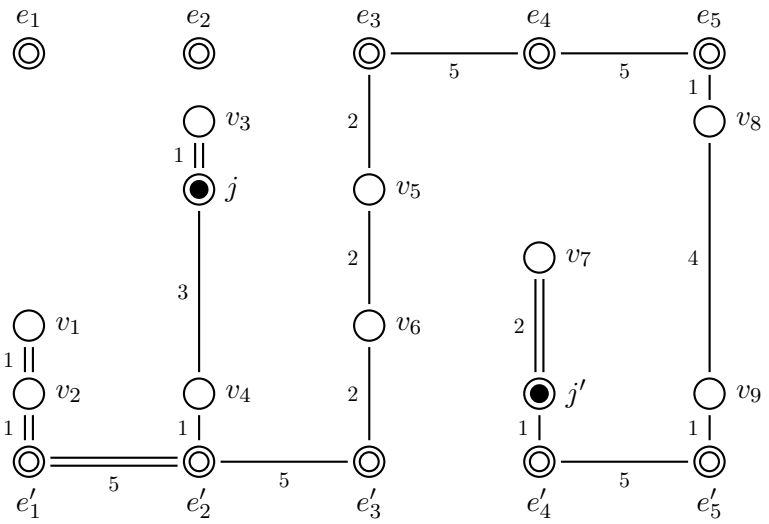


Figure 8: Minimum-length PS for the example in Figure 3.

4.4 Picking path construction

To obtain the directed order picking path of the order picker from a given PS, a procedure similar to the one presented in Ratliff and Rosenthal (1983) can be used.

Theorem 6 (Picking Path Construction Procedure) *Given a valid PS, a picking path can be constructed by the following procedure:*

1. *Start at vertex j.*
2. *If there is a pair of unused parallel edges incident to the current vertex, use one of them to go to the next vertex, then continue with step 2.*
3. *If there are any unused single edges (i.e., not one of a pair of parallel edges), use one of them to go to the next vertex, then continue with step 2.*
4. *If there is a pair of parallel edges with one edge used and one edge still unused, use the unused edge to go to the next vertex, then continue with step 2.*
5. *Stop. Now the currently visited vertex is j', and the order picking path is complete.*

4.5 Heuristic routing strategies for picking a single order with given start and end point

In practice, warehouse managers often do not use an optimal routing policy because optimal solutions may have a complicated shape and may cause confusion for the pickers (de Koster et al. 2007). To address this issue, we modify the well-known S-shape and largest gap heuristics (see Hall 1993) to replace the optimal routing policy presented above. These routing heuristics are originally designed for a setting in which the picker returns to the depot after each completed order. They are briefly described in the following:

- The S-shape heuristic traverses an aisles either entirely (if picks are required in there) or not at all (if no pick is required). This leads to S-shaped tours where pickers access the front and back cross aisle in an alternating manner.

- The largest gap heuristic divides the warehouse into two areas where the largest distance between two neighboring picking positions within the same aisle partitions picks either into the front and back part. Picks in the front part are accessed from the front cross aisle and picks in the back part are accessed from the back cross aisle.

We adapt both heuristics to our setting in which the picker starts from a given starting position j, collects all items of order P_k, and ends at position j'. The original heuristics are modified such that (i) they remain simple enough to be executed by the pickers with only minimum guidance, and (ii) they yield the same results as the original heuristics if start and end point are located at the depot.

The first step in both modified heuristics is to determine the first picking position v_f to be visited after the starting position as follows:

- Construct a set B of candidate positions for v_f: Let A_l (A_r) denote the leftmost (rightmost) aisle that contains items included in P_k. If A_l (A_r) contains two or more picking positions, the frontmost and rearmost positions in A_l (A_r) are added to B. If A_l (A_r) contains only one picking position, add this position to B. Note that $1 \leq |B| \leq 4$.
- Determine the subset $B' \subseteq B$ of positions that are closer to j than to j'. If B' is not empty, v_f is the position in B' that is closest to j. Otherwise, v_f is the position in B that is closest to j.

With given v_f, the modified heuristics work as follows: first go from j to v_f on the shortest path and pick all items that are passed on the way. If all items in P_k have been picked, go directly to j'. If no additional items have to be picked in the aisle containing v_f, continue traversing the aisle and stop at the entry. If additional items have to be picked in the aisle, traverse the aisle in the direction of these items and continue until the last item is picked. In case P_k is completed, go directly to j'. Otherwise continue to the entry of the aisle. The picker is now located at the entry of an aisle which is either to the left or right of all remaining aisles that contain items to be picked. We interpret this position as the position of the depot in the original S-shape or largest gap heuristic, and all remaining items are now picked in the same way as in the original heuristic. In contrast to the original heuristics, the picker directly goes to j' after the last item is picked.

5 Solving the single-block warehouse CTSP with open cluster sequence

In this section, we first show that the single-block as well as multi-block WCTSP-OCS are NP-hard in the strong sense. Note that such a proof is required due to the special distance matrices occurring in parallel-aisle warehouses. Furthermore, we determine a lower bound on the objective value of the single-block WCTSP-OCS (Section 5.1). In Section 5.2, we present a greedy heuristic for the single-block WCTSP-OCS, which aims at short runtimes while keeping a decent solution quality. As the numerical experiments will show, the other end of the spectrum, i.e., a heuristic with very good solution quality but longer runtimes is already available by using the transformation described in Section 2.3 together with a state-of-the-art heuristic TSP solver.

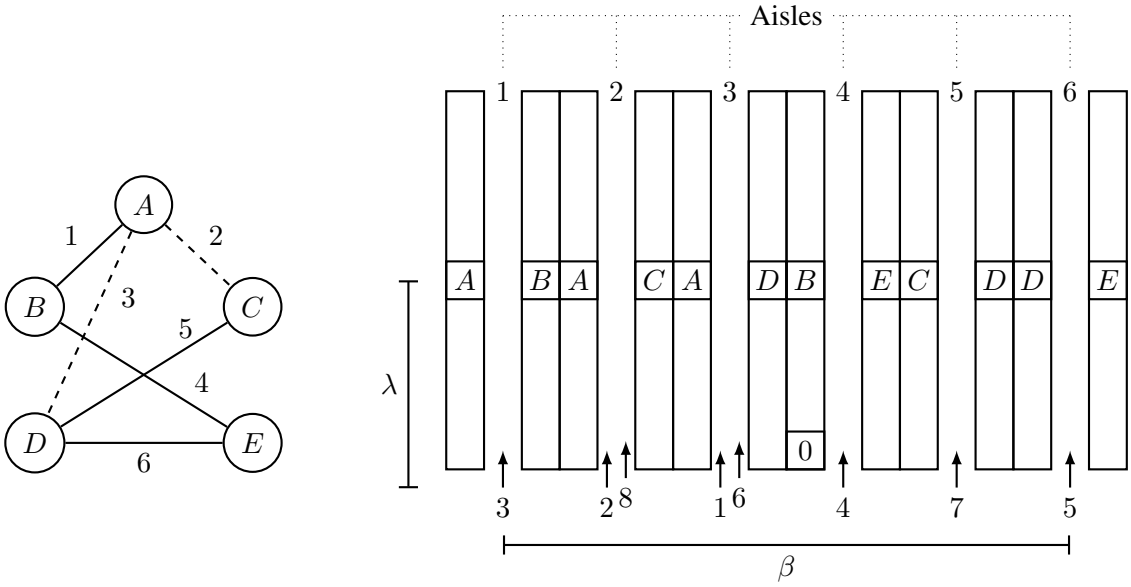
5.1 Complexity and lower bound

Theorem 7 *The single-block as well as multi-block WCTSP-OCS are NP-hard in the strong sense.*

We prove this theorem by a reduction from the Hamiltonian Path problem (HPP), which is well-known to be strongly NP-hard (Garey and Johnson 1979). It can be stated as follows: Given an undirected graph

$G = (V, E)$, the HPP determines whether or not a path through the graph exists that visits all vertices $v \in V$ exactly once.

Proof of Theorem 7. Consider an instance I of HPP given by graph $G = (V, E)$. We construct an instance I' of the WCTSP-OCS in polynomial time as follows. We introduce $l = |V|$ picking orders and $r = |E|$ aisles according to the layout depicted in Figure 2a. We, thus, have a picking order for each node. Furthermore, we have a distinct aisle for each edge in G. Each aisle corresponding to an edge (v, v') contains one picking location for the picking order corresponding to v and one picking location for the picking order corresponding to v', both of which are located in the middle of the aisle. Thus, in total we have $m = 2r$ picking positions. Note that if and only if there is an edge connecting nodes v and v', the orders corresponding to these nodes have an aisle to be visited in common. The distance from the entry of an aisle to its middle is λ (see Figure 9b). The distance between the leftmost and the rightmost aisle is $\beta < \frac{\lambda}{2l}$. The start position of the picker is at the beginning of a facultative rack (indicated by position 0 in Figure 9b).



(a) HPP instance I (b) Corresponding WCTSP instance I'

Figure 9: Transformation of an HPP instance (a) into a WCTSP instance (b).

We will now show that I is a yes-instance if and only if there is a feasible solution to I' with a total travel distance of less than $2\lambda \cdot (m - l + 1)$.

Existence of a Hamiltonian path with vertices $v_0, v_1, \ldots, v_l$ in I implies a solution to I' with less than $2\lambda \cdot (m - l + 1)$ total travel distance, which can be constructed in the following way: We start at position 0 and pick every item in v_0 such that we end in the middle of the aisle corresponding to edge (v_0, v_1). For every v_k with $0 < k < l$, we start in the middle of the aisle corresponding to edge (v_{k-1}, v_k) and pick all items of the order corresponding to vertex v_k such that we end in the middle of the aisle corresponding to (v_k, v_{k+1}). Finally, we start in the middle of the aisle corresponding to (v_k, v_{k+1}), pick all items of the order corresponding to vertex v_l and return to position 0.

Visiting an aisle and walking from the entry of an aisle to the picking position located in the middle and back takes a distance of 2λ. In the worst case, any picking position is visited individually, so that we have m aisle visits. The Hamiltonian path, however, allows us to save $l - 1$ aisle visits because the first item of a successive order can directly be picked without additional walking. For any order, the horizontal travel in

front of the aisles can always be executed within a walking distance of at most twice the warehouse width $\beta < \frac{\lambda}{2l}$. Thus, the total horizontal travel cannot exceed λ, and the total distance of our constructed solution to I' does not exceed $2\lambda \cdot (m - l + 1)$.

If there is a solution S to I' with total walking distance of less than $2\lambda \cdot (m-l+1)$, the first picking position visited for each picking order (except for the very first order) must be in the same aisle as the last position of the preceding order. Hence, each order must have at least one aisle in common with its preceding order in S, and, thus, there must be an edge between the nodes corresponding to these picking orders. Hence, the sequence of nodes (picking orders) corresponding to S represents a Hamiltonian path. In Figure 9b, the numbers at the bottom indicate the aisle visiting sequence of a solution that fulfills this requirement: first, the picker visits aisle 3, collecting the first item of order A. Then, the picker moves to aisle 2 and collects the second item of order A. Next, to aisle 1, collecting the last item of order A and the first item of order B, before moving to aisle 4 to collect the second item of order B and the first item of order E. The picker proceeds accordingly and visits aisles 6, 3, 5, and 2. The order processing sequence is (A, B, E, D, C), which directly corresponds to the sequence of nodes in the Hamiltonian path in Figure 9a. □

Strictly speaking, this proof is only for the single-block parallel-aisle warehouse layout depicted in Figure 2a. However, if we imagine the aisles defined above only as the first block up to the middle aisle (with no additional picking positions beyond), then the same transformation also holds for the multi-block WCTSP-OCS (Figure 2b).

Lemma 2 (Lower Bound) *A lower bound for the single-block WCTSP-OCS is given by*

$$\text{LB} \quad = \quad \sum_{k=1}^{l} \left(\text{SP}(P_k) \; + \; \min_{j \in P_k,\, j' \in P \setminus P_k} d_{jj'} \right) \; + \; \min_{j \in P \setminus 0} d_{0j}, \tag{15}$$

where $\text{SP}(P_k)$ *is the length of the shortest Hamiltonian path through all positions in* P_k.

Proof of Lemma 2. Because all positions in a cluster must be visited successively, each cluster will at least require the length of the shortest Hamiltonian path through all its positions, which is expressed by the first term within the sum in (15). The second term within the sum originates from the fact that every cluster must be left exactly once. The last term accounts for having to leave the depot position. □

Note that for the single-block WCTSP-OCS, the value of $\text{SP}(P_k)$ can be computed efficiently by means of the routing algorithm from Section 4, where start and end points j and j' are chosen from P_k such that $\text{SP}(P_k)$ is minimum.

5.2 Greedy best insertion heuristic

In this section, we present a greedy algorithm, called best insertion (BI), for the single-block WCTSP-OCS. The method starts from an order sequence only containing the two instances of the depot P_0, P_{l+1}. Then, all possible combinations of remaining orders and potential insertion positions are evaluated by means of the described DP, and the best combination is chosen. This process is repeated until all orders have been inserted. There are no more than l^2 combinations of orders and insertion positions, and the procedure performs l insertions in total. Thus, the runtime complexity of BI is $\mathcal{O}(l^3 \cdot (m^3 + rm^2))$.

6 Computational experiments

This section describes the numerical studies to assess the performance of the proposed algorithms and to evaluate the benefits of using AGVs to assist order pickers. Section 6.1 introduces the benchmark instances, Section 6.2 provides the parameter settings of the algorithms, and Section 6.3 discusses the results and gives some managerial insights. Finally, in Section 6.4, we study the number of AGVs that is required to support a given number of pickers without causing waiting times.

6.1 Test instances

The instances used in our experiments are based on the instances of Henn and Wäscher (2012). Although the authors introduced these instances for the order batching problem with picker capacity, they can be interpreted as single-block WCTSP instances without requiring any modification (see Section 6.3 for details). We distinguish three benchmark sets, each containing 400 instances:

Original: These are the original instances of Henn and Wäscher (2012) without any modifications. The instances assume a parallel-aisle single-block warehouse as depicted in Figure 2a. The warehouse contains $r = 10$ picking aisles, each with 45 picking positions on both sides. The length of a picking position is 1 length unit (LU). Whenever the picker is leaving an aisle at the top or bottom, she must move 1 LU in vertical direction to reach the cross aisle. The distance between neighboring aisles is 5 LU. The depot is located below the leftmost picking aisle, more precisely 0.5 LU below vertex e'_1 in Figure 3.

The instance set (as well as the other two sets described below) can be further subdivided into two groups, each containing 40 instances for different numbers of picking orders $l \in \{20, 40, 60, 80, 100\}$, resulting in a total of 200 instances per group. In the first group, the frequency for any SKU to appear in an order is uniformly distributed over all SKUs within the warehouse, and, thus, this group is called uniformly distributed demands (UDD). In the second group, called class-based demands (CBD), 10% of the SKUs, all of which are located in aisle 1, make up 52% of the required picking positions; the next 30% SKUs, located in aisles 2-4, make up 36%, and the last 60% of SKUs, located in the remaining six aisles, make up 12% of picking positions. In both groups, the number of picking positions to be visited in each order is uniformly distributed in the interval $[5, 25]$.

Central Depot: This instance set differs from the original one with regard to the location of the depot in the warehouse and the arrangement of the picking aisles: in each instance, the position of the depot is moved from the bottom left to the bottom of the 5$^{\text{th}}$ picking aisle, more precisely 0.5 LU below vertex e'_5 in Figure 3. In addition, the picking aisles are rearranged according to the following mapping:

Aisle in original instance:	1	2	3	4	5	6	7	8	9	10
Aisle in modified instance:	5	6	4	7	3	8	2	9	1	10

This mapping also ensures that the article distribution in the modified instances is reasonable for CBD.

Large Orders: This instance set differs from the original one with regards to the number of picking positions per order, which is on average doubled in these instances. To generate a new instance of set Large Orders, we use a pair of instances from set Original: For every set of 40 instances with a given demand distribution type and number of orders l, we combine instances number 1 and 2 from set Original to generate instance 1 of set Large Orders, instances 2 and 3 of set Original to generate instance 2 of

set Large Orders, and so on. Instance number 40 of set Large Orders is generated from instances 40 and 1 of set Original. The instance of set Large Orders is obtained by merging the picking positions of the individual orders in the two instances from set Original, i.e., the two orders with number k in the instances from set Original form order number k of the newly generated instance. In the resulting instances, the number of picking positions per order lies in the interval $[10, 50]$.

The described instance sets are provided as online supplement.

6.2 Solution methods and computational environment

All dedicated WCTSP solution methods presented in this paper are coded in C++. Besides their performance, our numerical studies investigate how well WCTSP instances can by solved by state-of-the-art TSP methods from the literature.

The first such method that we include in our studies is the exact TSP solver Concorde (CC). It is only able to solve symmetric TSP instances, and WCTSP instances first need to be transformed using the rules from Section 2.3. For CC, source code and precompiled binaries are available at `http://www.math.uwaterloo.ca/tsp/concorde.html`. In all our experiments, the precompiled binary of CC is used with default settings and a time limit of 2 hours per run. If the time limit is reached before an optimal solution is found, CC returns an upper bound.

The second method is the Lin-Kernighan-Helsgaun heuristic for the GCTSP presented in Helsgaun (2014) and called CLKH. CLKH itself is based on the transformation of GCTSP instances into TSP instances according to Section 2.3, which are solved using the original LKH heuristic for the TSP with a special parameter setting to account for the particular structure of GCTSP instances. Thus, both methods investigated in our studies actually rely on a transformation of WCTSP instances into TSP instances. The source code of CLKH is available at `http://akira.ruc.dk/~keld/research/CLKH/`. We compiled the source code using GCC 9.1 with full optimizations enabled (-O3).

All experiments were conducted on a computing cluster featuring Intel Xeon E5-2430v2 CPUs with a maximum clock speed of 3.0 GHz and 64 Gb RAM per computing node. On each CPU, only one core was used in order to report meaningful runtimes.

6.3 Impact of AGV assistance on picker routing efficiency

This section describes the experiments to assess (i) the performance of the algorithms proposed in this paper, and (ii) the benefits of using AGVs to assist order pickers. In these experiments, we interpret the benchmark instances from Section 6.1 in different ways:

- Traditional picker routing problem without AGV support: Each order has to be picked independently, and the picker returns to the depot after each completed order. In this case, the sequence in which the orders are processed is irrelevant. We use the solution cost obtained with this variant to assess the potential performance gains obtained through AGV usage.
- Single-block WCTSP-GCS: The order picker is assisted by an AGV, and the picker directly continues picking the next order after each completed one without returning to the depot. The orders are picked in the exact order in which they appear in the instance description. This variant is used to evaluate (i) the performance of our DP algorithm, CC, and CLKH, and (ii) the potential performance gains of freely choosing the order picking sequence in the problem with open order sequence.

- Single-block WCTSP-OCS: The order picker is again assisted by an AGV, but the processing sequence of the orders is now part of the decision and not fixed. This variant is used to study the performance of the algorithms CC, CLKH, and BI.

Performance of the solution methods Table 5 provides an aggregate view of the computational results on the benchmark sets from Section 6.1. The instances in each set are grouped according to their demand distribution, i.e., uniformly distributed demands (UDD) vs. class based demands (CBD), and the number of orders $l \in \{20, 40, 60, 80, 100\}$. For each of the solution methods, column $\bar{\Delta}(\%)$ shows the average percentage improvement in travel distance of the results obtained on the considered problem variant (single-block WCTSP-GCS or single-block WCTSP-OCS) compared to the results of the traditional picker routing problem. Note that for CC on the WCTSP-GCS, $\bar{\Delta}(\%)$ is not reported because CC finds the same optimal solutions as DP on all instances. Column $\bar{t}$ reports average runtimes in seconds. For the single-block WCTSP-OCS, column #opt reports the number of instances solved to optimality by CC. Finally, column LB reports the lower bound described in Section 5.1 (also as average percentage improvement with regards to the results of the traditional picker routing problem). The detailed results on each instance are reported in the online appendix B, and the corresponding solutions are provided as online supplement.

Concerning the WCTSP-GCS, our DP is able to solve all individual instances of the three benchmark sets to optimality within fractions of a second. The runtime of DP is neither affected by the demand distribution (UDD and CBD) nor the location of the depot. A slight increase of the runtime can be noted for a larger number of orders, and a notable increase for a larger number of picking positions per order (shown by the results on set Large Orders). However, even on the largest instances with $l = 100$ orders in set Large Orders, the average runtime of DP is below 150 milliseconds, which qualifies the algorithm for real-time applications. CC is also able to find optimal solutions for all WCTSP-GCS instances, however, the runtimes are roughly two orders of magnitude higher than those of DP. The influence of the different problem characteristics on the behavior of CC is very similar to that of DP. CLKH nearly matches the solution quality of DP and CC: it is able to find optimal solutions for 1048 of the 1200 instances (see Tables 8–37 in the online appendix), and the deviations on the remaining instances are very small. However, although the algorithm is heuristic, the average runtimes lie clearly above those of CC for all instance sets. Summarizing, our dedicated DP method significantly outperforms the two comparison methods.

On the WCTSP-OCS instances, CC is able to find and prove the optimal solution for 1175 out of the 1200 instances within the time limit. The objective values of CC on the remaining 25 instances lie on average 0.0007% below those of CLKH and 0.34% above the LB (see Tables 8–37 in the online appendix), indicating a very good solution quality also on these instances. The runtimes tend to increase with a larger number of orders and strongly increase with a larger number of picking positions per order. CLKH is able to match 872 of the 1175 optimal solutions and achieves roughly the same overall average quality within clearly shorter runtimes. The influence of a larger number of orders and a larger number of picking positions are visible but less pronounced than for CC. BI is able to find solutions that deviate by no more than 1.6% from those of CLKH on any of the considered instance groups (combination of instance set and demand distribution) but are found within runtimes that are nearly two orders of magnitude shorter. Finally, we note that the proposed (relatively straightforward) LB is of good quality, on average it does not deviate by more than 1% from the best solution found by CC for any of the considered instance groups. Summarizing, if enough computing time is available, WCTSP-OCS instances of the considered size can be solved to (near-)optimality using CC. If less time is available or even larger instances with regards to the number of orders or the number of picking positions per order are considered, high-quality solutions within runtimes still adequate for a short-

Table 5: Results on the WCTSP instance sets grouped by demand distribution and number of orders.

Instance Group	WCTSP-GCS					WCTSP-OCS							
	DP		CC	CLKH		CC			CLKH		BI		LB
	$\bar{\Delta}(\%)$	$\bar{t}$	$\bar{t}$	$\bar{\Delta}(\%)$	$\bar{t}$	#opt	$\bar{\Delta}(\%)$	$\bar{t}$	$\bar{\Delta}(\%)$	$\bar{t}$	$\bar{\Delta}(\%)$	$\bar{t}$	$\bar{\Delta}(\%)$
Original, UDD													
$l = 20$	-15.83	0.01	1.99	-15.83	25.10	40	-19.20	5.63	-19.20	27.77	-18.27	0.08	-20.47
$l = 40$	-15.93	0.01	5.15	-15.93	44.12	40	-19.51	14.12	-19.51	49.15	-18.58	0.32	-20.25
$l = 60$	-16.21	0.02	7.85	-16.21	55.80	40	-19.83	36.56	-19.83	78.07	-18.81	0.71	-20.38
$l = 80$	-16.23	0.03	11.41	-16.23	69.38	40	-19.90	243.21	-19.90	101.84	-18.89	1.32	-20.33
$l = 100$	-16.31	0.03	15.22	-16.31	81.30	40	-20.04	144.43	-20.04	121.18	-19.04	2.14	-20.40
Avg.	-16.10	0.02	8.32	-16.10	55.14	200	-19.70	88.79	-19.69	75.60	-18.72	0.91	-20.36
Original, CBD													
$l = 20$	-17.68	0.01	1.73	-17.68	18.38	40	-21.96	4.24	-21.96	16.25	-20.74	0.06	-23.44
$l = 40$	-17.56	0.01	4.00	-17.55	29.64	40	-22.02	12.73	-22.02	26.55	-20.76	0.24	-22.88
$l = 60$	-17.68	0.02	7.26	-17.68	42.34	40	-22.48	48.89	-22.48	37.62	-21.21	0.53	-23.11
$l = 80$	-17.67	0.03	9.82	-17.67	52.96	40	-22.51	129.01	-22.51	48.63	-21.26	1.02	-22.98
$l = 100$	-17.87	0.03	13.65	-17.87	66.11	40	-22.71	361.04	-22.71	59.22	-21.48	1.72	-23.11
Avg.	-17.69	0.02	7.29	-17.69	41.89	200	-22.34	111.18	-22.34	37.65	-21.09	0.72	-23.11
Centered depot, UDD													
$l = 20$	-14.13	0.01	2.00	-14.13	24.97	40	-17.48	5.39	-17.48	27.69	-16.57	0.08	-18.98
$l = 40$	-14.51	0.01	4.56	-14.51	38.69	40	-18.07	14.73	-18.06	53.90	-17.06	0.32	-18.93
$l = 60$	-14.63	0.02	8.56	-14.63	56.02	40	-18.35	37.96	-18.34	73.14	-17.33	0.71	-18.93
$l = 80$	-14.64	0.03	11.83	-14.64	71.17	40	-18.44	148.94	-18.44	95.98	-17.43	1.32	-18.90
$l = 100$	-14.71	0.03	15.70	-14.71	81.88	39	-18.56	440.16	-18.56	118.23	-17.54	2.14	-18.94
Avg.	-14.52	0.02	8.53	-14.52	54.55	199	-18.18	129.44	-18.18	73.79	-17.19	0.91	-18.94
Centered depot, CBD													
$l = 20$	-17.82	0.01	2.07	-17.82	15.90	40	-23.11	6.84	-23.11	22.39	-21.62	0.06	-25.13
$l = 40$	-17.91	0.01	4.83	-17.91	26.20	40	-23.61	20.04	-23.61	44.38	-21.98	0.23	-24.68
$l = 60$	-18.08	0.02	8.01	-18.07	44.28	40	-24.20	73.06	-24.19	61.48	-22.55	0.52	-24.94
$l = 80$	-18.15	0.02	11.10	-18.15	47.15	39	-24.32	336.97	-24.31	78.05	-22.66	1.01	-24.88
$l = 100$	-18.29	0.03	15.70	-18.29	61.90	39	-24.41	400.98	-24.41	90.66	-22.80	1.69	-24.88
Avg.	-18.05	0.02	8.34	-18.05	39.08	198	-23.93	167.58	-23.92	59.39	-22.32	0.70	-24.90
Large orders, UDD													
$l = 20$	-12.25	0.03	6.56	-12.25	61.42	40	-14.10	39.35	-14.09	73.72	-13.50	0.31	-14.84
$l = 40$	-12.38	0.06	26.11	-12.37	101.54	40	-14.44	172.04	-14.43	139.81	-13.79	1.10	-14.87
$l = 60$	-12.51	0.09	46.44	-12.50	151.17	39	-14.57	575.65	-14.56	199.12	-13.92	2.53	-14.87
$l = 80$	-12.54	0.12	86.73	-12.53	199.57	38	-14.63	776.29	-14.62	284.44	-13.99	5.10	-14.88
$l = 100$	-12.62	0.14	154.10	-12.61	245.17	32	-14.72	2120.38	-14.70	346.72	-14.07	8.69	-14.91
Avg.	-12.46	0.09	63.99	-12.45	151.78	189	-14.49	736.74	-14.48	208.76	-13.85	3.54	-14.87
Large orders, CBD													
$l = 20$	-13.90	0.03	5.11	-13.89	60.54	40	-16.18	17.05	-16.18	57.75	-15.52	0.21	-17.05
$l = 40$	-13.86	0.05	12.72	-13.86	87.04	40	-16.27	64.00	-16.27	100.07	-15.53	0.81	-16.78
$l = 60$	-14.00	0.08	24.48	-14.00	127.39	38	-16.58	658.33	-16.58	145.75	-15.86	1.90	-16.93
$l = 80$	-14.04	0.11	42.79	-14.03	166.82	35	-16.56	1426.71	-16.55	193.77	-15.86	3.89	-16.84
$l = 100$	-14.02	0.13	69.90	-14.02	192.39	36	-16.63	1919.56	-16.62	247.84	-15.91	6.96	-16.86
Avg.	-13.96	0.08	31.00	-13.96	126.84	189	-16.45	817.13	-16.44	149.04	-15.74	2.75	-16.89

term planning horizon can be obtained by CLKH, and fast solutions for real-time scenarios with decent quality by BI.

Observations on the benefits of using AGVs and the influence of problem parameters Based on the optimal solutions found by DP and CC, we make two general observations that are valid independent of the problem type considered (single-block WCTSP-GCS or WCTSP-OCS) and the type of instances (Original, Central Depot, Large Orders): First, the reduction in travel distance is slightly stronger for larger instances, i.e., instances with a higher number of orders. Second, the reduction in travel distance is higher on the CBD instances compared to the UDD case. In general, the total traveled distance to collect all orders on CBD instances is notably smaller than on UDD instances (see Tables 8–37 in the online appendix). However, the savings achievable through AGV support on the few unfavorable picking orders containing picking positions far from the depot have a larger impact.

Considering the results on the WCTSP-GCS, we note that the reported gains compared to the traditional approach without AGV support are obtained solely by the utilization of AGVs without any further managerial effort (the order processing sequence is given by the instance description and not modified). These gains lie between roughly 14.5% and 18% for instance sets Original and Central Depot and between approximately 12% and 14% for instance set Large Orders. The decrease in gains for set Large Orders stem from the fact that orders with more picking positions require longer travel times, which reduces the relevance of the depot returns and therefore the savings potential of AGV support. For instance set Central Depot, the gains are a slightly smaller than for set Original (with the left-side depot) for demand distribution UDD and slightly larger for CBD.

The results for the WCTSP-OCS show that a (near-)optimal decision on the order processing sequence is able to further increase the gains compared to the traditional approach without AGV support. For the instances of sets Original and Central Depot, the increase of the gains lies between roughly 3.6% and 5.9%; it is slightly higher for demand distribution CBD, and the depot location does not have a major influence. On the instances of set Large Orders, the additional gains are smaller with roughly 2% for UDD and 2.5% for CBD.

Performance of the picker routing heuristics Table 6 reports the results obtained when using the modified S-shape and largest gap heuristics presented in Section 4.5 to route the pickers, i.e., we compute the partial objective values within our DP using these heuristics. We only discuss the results for instance set Original because the main findings do not change when the location of the depot is modified or the number of picking positions are increased (the respective results can be found in Table 38 in the online appendix B). As before, solution quality is measured as relative gap to the optimal solution of the traditional picker routing problem. Columns WCTSP-GCS show the performance of the DP using the modified S-shape and largest gap heuristic to solve the single-block WCTSP-GCS. As comparison values, column Exact→WCTSP-GCS reports the results of the DP when determining the partial objective in optimal fashion, i.e., we repeat the values reported in column DP in Table 5. As additional comparison values, we report the results of the S-shape and largest gap heuristic for the traditional picker routing problem, i.e., in a scenario without AGV support, in columns Traditional. All runtimes are below 100 milliseconds and are therefore not reported.

Table 6 shows that AGV-assisted order picking with heuristic routing strategies is clearly beneficial compared to traditional order picking based on the same heuristics. For both heuristics, utilizing AGVs yields a substantial improvement in route length compared to traditional picker routing by means of the respective heuristic: for S-shape, the average improvement is ∼24% on UDD instances (∼35% on CBD), for largest gap ∼8% on UDD (∼20% on CBD). While both heuristics forgo potential cost savings compared to op-

timally solving the WCTSP-GCS, the S-shape heuristics turns out to be clearly inferior to the largest gap approach. This can be explained by the fact that the number of picking positions per order is relatively small compared to the number of picking aisles, and a traversal strategy is inappropriate if the number of picks per aisle is small (see Hall 1993). However, the most important insight of this study is that routing AGV-assisted pickers heuristically can barely reach the performance of optimally routing pickers without AGV support. Only the largest gap heuristic can improve on the latter scenario by a marginal 1.26% in the CBD instances. Thus, the price of more intuitive heuristic picker tours is huge, and optimal solutions obtained by DP seem a clearly superior choice.

Table 6: Comparison of results on set Original when applying the modified S-shape and largest gap heuristics.

Instance	**Exact**	**S-Shape**		**Largest Gap**	
Group	WCTSP-GCS	WCTSP-GCS	Traditional	WCTSP-GCS	Traditional
UDD					
$l = 20$	-15.83	9.06	32.73	2.89	10.32
$l = 40$	-15.93	8.60	32.54	2.30	10.23
$l = 60$	-16.21	8.08	32.47	2.41	10.39
$l = 80$	-16.23	7.93	32.21	2.14	10.05
$l = 100$	-16.31	7.99	32.55	2.17	10.38
Avg.	-16.10	8.33	32.50	2.38	10.27
CBD					
$l = 20$	-17.68	5.33	39.82	-0.59	19.26
$l = 40$	-17.56	5.17	40.03	-1.20	19.07
$l = 60$	-17.68	4.35	39.69	-1.43	19.32
$l = 80$	-17.67	4.47	39.58	-1.46	19.22
$l = 100$	-17.87	4.49	39.96	-1.63	19.18
Avg.	-17.69	4.76	39.82	-1.26	19.21

Summary of managerial insights From the practitioner's perspective, the computational results of this section translate into three main findings:

- Assisting human order pickers with AGVs promises a reduction of picker travel of about 20%. Given the large fraction of unproductive picker travel of around 50% of the pickers' working hours (Tompkins et al. 2003, de Koster et al. 2007), this indicates considerable potential savings. Naturally, it depends on the labor costs in the respective region whether these potential savings in personnel costs can outweigh the additional investment costs into AGVs.
- Compared to a picker routing based on given order sequences, integrating sequence planning into the optimization task only leads to an additional reduction of picker travel of 2–6%. When deciding the processing sequence of orders, typically, an efficient order picking is only one important aspect. Moreover, the due dates of the orders promised to customers need to be considered, see Sharp et al. (1991) for more details. Our results suggest that by applying our efficient solution procedure for given order sequences, considerable reductions of picker travel can be realized for any order sequence. Thus, selecting order sequences just by their urgency and handing them over to picker routing based on given order sequences seems a simple, yet effective planning approach that leads to a good compromise in the tradeoff between urgency and efficiency.
- Finally, routing the AGV-picker-tandems heuristically with the S-shape or largest gap heuristic seems not a good idea. Compared to optimal solutions considerable performance gains are missed, so that an

investment into AGV-assisted picking should be accompanied by the additional invest into a pick-by-voice or handheld scanner solution, which allows to route the pickers (and their accompanying AGVs) according to optimal solutions.

These three findings base on the assumption that the AGV fleet is properly dimensioned and pickers never have to wait for late AGVs. In the following section, we explore the fleet sizes required to fulfill this assumption.

6.4 Experiments on the AGV fleet size

To investigate the AGV fleet size that is necessary to realize an order picking system without picker waiting, we set up the following experiment. We assume that different numbers of pickers are simultaneously picking orders in the warehouse. The demand type is either UDD or CBD, and we assign to each picker an exclusive instance from the respective Original instance set with $l = 100$. For example, in the case of UDD, picker 1 is assigned instance 100-UDD-1, picker 2 is assigned instance 100-UDD-2, and so on. The instances are treated as instances of the single-block WCTSP-GCS and are solved using our DP.

We determine the AGV fleet size required to realize the solution returned by the DP for a single instance, i.e., a single picker, using the following procedure: Let i_k and j_k denote the first and last item which the picker collects for order P_k. Let t_k (t'_k) be the moment in time in which the picker visits i_k (j_k) on an optimal picking tour determined according to Section 4.4. Assuming that no picker waiting must occur, the AGV that accompanies the picker during the picking of order P_k must start its trip at the depot at time $t_k - \frac{d_{0i_k}}{\sigma}$ such that it arrives simultaneously with the picker at position i_k, where σ is the factor by which the AGV can travel faster than the picker. The AGV will return to the depot at time $t'_k + \frac{d_{j_k 0}}{\sigma}$. Using this information, we can determine a set of time intervals for the required AGV trips:

$$S = \left\{ \left[t_0 - \frac{1}{\sigma} d_{0i_0}, t'_0 + \frac{1}{\sigma} d_{j_0 0} \right], \left[t_1 - \frac{1}{\sigma} d_{0i_1}, t'_1 + \frac{1}{\sigma} d_{j_1 0} \right], \ldots, \left[t_l - \frac{1}{\sigma} d_{0i_l}, t'_l + \frac{1}{\sigma} d_{j_l 0} \right] \right\} \tag{16}$$

The number of required AGVs is then given by the maximum number of overlapping intervals over all points in time. Determining the minimum AGV fleet for the given picking tours equals determining the chromatic number in an interval graph (Golumbic 2004) and can be determined in polynomial time. The described approach can also be applied to determine the number of required AGVs if multiple pickers share a common AGV fleet. In this case, all pickers start their picking tours at the depot at the same time. The set S now contains time intervals for the trips of all pickers, and the required number of AGVs can be determined as before.

In the experiments, we vary the speed of the AGVs using σ values from 1 to 4 in steps of 0.5. For all combinations of the number of pickers (1, 5, 10, 20, 40) and σ, we conduct five runs of the described experiment and in each run, the order sequences of the original instances are randomly shuffled. The results are presented in Table 7. The reported values represent the average number of AGVs over five runs divided by the number of pickers.

As a main finding, we witness a pooling effect when the number of pickers increases, i.e., the number of AGVs scales less than linear with an increasing number of pickers. The effect somewhat saturates for a larger number of pickers: when doubling the number of pickers from 5 to 10, the required number of AGVs per picker drops by $\sim$10% (for $\sigma = 1$), from 10 to 20 pickers by $\sim$7%, and from 20 to 40 by $\sim$5%. As can

be expected, higher AGV speeds lead to a stronger reduction in fleet size. The AGV fleet needs to be slightly larger in case of CBD compared to UDD because the picker routes tend to be shorter for CBD, which in turn leads to more tightly packed time intervals for the AGV trips. Note that in our experiments we do not consider the actual time to pick individual items from their storage locations. Thus, in practice, the required number of AGVs are likely to be even lower than in our experiments and the difference between CBD and UDD even less pronounced.

In case AGVs are not shared between multiple pickers, two AGVs per picker seem to be a reasonable choice: although this number is not sufficient to reliably avoid waiting times in the experiments with $\sigma = 1$ (here more than two AGVs are needed on average), this rule of thumb should work well in practical settings with additional picking times. However, considerable reductions of the AGV fleet are possible, if AGVs are not fixedly assigned to their designated pickers but shared among the picking workforce. Since large e-commerce retailers employ hundreds of pickers per work shift (Boysen et al. 2019), even in a single picking zone, where an AGV sharing can easily be organized, a workforce of 40 pickers is quickly reached. Safety reasons restrict the maximum AGV speeds to walking speed (or allow only a slightly faster velocity), so that lower σ-values of 1.0 or 1.5 are the norm in real-world warehouses. Thus, AGV-per-picker ratios of about 1.5 seem a realistic rule of thumb to roughly approximate the investment costs for establishing an AGV-assisted order picking.

Table 7: Average required number of AGVs per picker for different numbers of pickers and AGV speeds on instance set Original.

# pickers	**AGV speed σ**						
	1.0	1.5	2.0	2.5	3.0	3.5	4.0
UDD							
1	2.00	2.00	2.00	2.00	2.00	2.00	2.00
5	1.92	1.84	1.72	1.64	1.60	1.56	1.56
10	1.76	1.62	1.54	1.48	1.40	1.36	1.36
20	1.63	1.48	1.42	1.35	1.32	1.29	1.28
40	1.54	1.37	1.30	1.26	1.23	1.21	1.19
CBD							
1	2.00	2.00	2.00	2.00	2.00	2.00	2.00
5	2.00	1.84	1.72	1.68	1.64	1.60	1.60
10	1.82	1.68	1.58	1.52	1.46	1.44	1.42
20	1.69	1.52	1.45	1.39	1.35	1.32	1.29
40	1.62	1.46	1.36	1.31	1.26	1.23	1.21

Summarizing, our results indicate that AGV-assisted order picking promises strong improvements in the order fulfilment process. Thus, it can be projected that this technology will gain importance in the next years, at least as a transitory technology, until finally a fully-automated order picking without human pickers becomes possible.

7 Conclusion

This paper considers AGV-assisted order picking, in which an AGV accompanies a human picker while collecting items from storage positions. Once an order is completed, the AGV returns the collected items to the depot, and the picker can directly meet with another AGV to start collecting the subsequent order. The resulting picker-routing problem is shown to be equivalent to the well-known clustered traveling salesman

problem (CTSP). We show that, contrary to the general CTSP, in single-block parallel-aisle warehouses, the resulting warehouse CTSP (WCTSP) with given cluster sequence is efficiently solvable in polynomial time. To do so, we extend the famous Ratliff and Rosenthal (1983) algorithm for order picking in single-block parallel-aisle warehouses and repeatedly solve it as part of a dynamic programming procedure. The developed procedure outperforms the high-quality TSP solvers Concorde and Lin-Kernighan-Helsgaun used together with a transformation of the instances. To also solve the WCTSP with open cluster sequence, we integrate our DP procedure into a greedy insertion heuristic and achieve decent solution quality in very short runtimes. Better-quality solutions within longer runtimes are obtained for this problem variant by using an instance transformation plus Concorde or Lin-Kernighan-Helsgaun.

From the practitioner's perspective, our main findings are the following:

- Compared to a traditional warehouse setting in which the picker has to return to the depot each time a pick list is completed, AGV-assisted order picking reduces the travel distance by about 20%, which indicates a potential of substantial cost savings in real-world warehouses.
- The additional gains that can be achieved by deciding the order sequence are only moderate. Therefore, a simple practical planning approach could determine order sequences by urgency, apply our solution procedure for the single-block WCTSP-GCS, and still gain considerably shorter travel distances compared to a traditional setting without AGVs.
- When opting for AGV-assisted order picking, the AGV-picker-tandems should not be routed using heuristic methods, i.e., S-shape or largest gap heuristic. When applying a heuristic routing, AGV-assisted picking barely leads to the same performance as optimal routing policies without AGV assistance.
- AGVs should not fixedly be assigned to designated pickers but shared among the picker workforce. The latter enables a pooling effect, so that in larger warehouses only about 1.5 AGVs per picker are required to avoid excessive idle time of pickers waiting for delayed AGVs.

AGV-assisted order picking leaves plenty of room for future research. Our basic picker-routing problem could, for instance, be extended by further characteristics of practical relevance. AGVs not being able to pass each other in narrow aisles have already been considered in other warehouse settings (Hong et al. 2012). Extending our problem by non-passing constraints requires the solution of a holistic problem in which all picker paths need to be coordinated. Furthermore, the following alternative routing policy could be evaluated. Instead of following a picker while completing an order, AGVs could stop at the relevant storage positions and wait there until some picker, that may vary from item to item, has placed the respective SKU onto the AGV. Again, a holistic problem coordinating all AGVs and pickers is to be solved. Such a flexible policy promises more efficient picker paths compared to our order-by-order policy. Its major drawback, however, is that once a delay occurs at some storage positions, this may induce further delays of all other AGVs and pickers, so that a complex online control system is required. A comparison of both policies with regard to the resulting picker travel times could illustrate the benefit of such a complex online control system.

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Picker routing in AGV-assisted order picking systems

Online appendix

A Proof of theorems

In this section we provide the proofs for the theorems from Sections 4.1–4.4. We repeat all theorems prior to their respective proofs.

A.1 Theorems of Section 4.1

Theorem 3 (Partial Path Subgraph Properties) A subgraph $T \subset L_i$ is an L_i PPS if and only if

1. every vertex in $T \setminus \{j, j'\}$ has even or zero degree,
2. the degrees of vertices $P'_s \cap L_i$ are nonzero and even in T,
3. vertices $L_i \cap \{j, j'\}$ have odd degrees in T,
4. excluding vertices with zero degree, T is either empty, has a single connected component containing at least one of e_i and e'_i or two connected components of which one contains e_i and the other one contains e'_i.

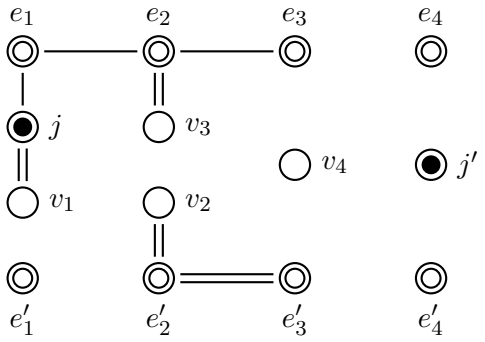
To make the proof of Theorem 3 more comprehensible, we first introduce the notion of PPS modes. This feature of a PPS has no equivalent in Ratliff and Rosenthal (1983), because it is a direct consequence from the extension to picking paths with non-identical start and end points. Let $A(v)$ be the aisle in which vertex $v \in V$ is located.

Lemma 3 (Partial Path Subgraph Modes) *For any subgraph $T \subset X_i$ with $X_i \in \{L_i^+, L_{i+1}^-\}$ that fulfills the conditions given in Theorem 3, we can distinguish two different modes depending on aisle i:*

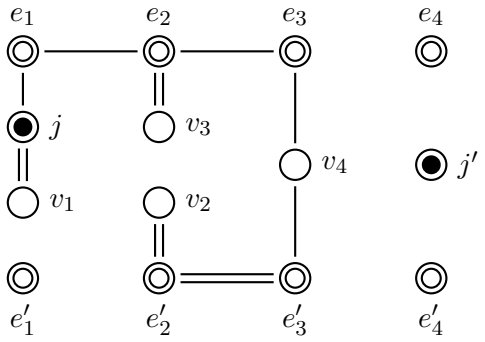
1. *If $i < \min\big(A(j), A(j')\big)$ or $i \geq \max\big(A(j), A(j')\big)$, the sum of the degrees of e_i and e'_i is even in T, and all X_i PPSs are said to be of even mode.*
2. *If $i \geq \min\big(A(j), A(j')\big)$ and $i < \max\big(A(j), A(j')\big)$, the sum of the degrees of e_i and e'_i is odd in T, and all X_i PPSs are said to be of odd mode.*

Proof of Lemma 3. The statement follows directly from the fact that, for any undirected graph, the sum of the degrees of all vertices is even, or equivalently, the number of vertices with odd degree must be even. Consider case 1. of Lemma 3: Either none or both of vertices j and j' are contained in the L_i PPS, both j and j' have odd degree, and all other vertices except for e_i and e'_i have even or zero degree. Thus, the sum of the degrees of vertices e_i and e'_i must be even. Now consider case 2. of Lemma 3: Exactly one of vertices j and j' is contained in the L_i PPS, thus the sum of the degrees of vertices e_i and e'_i must be odd. □

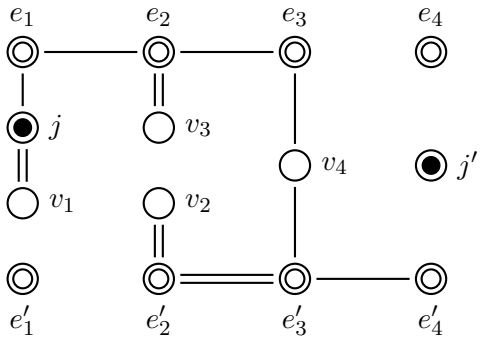
Note that according to Lemma 3, if $A(j) = A(j')$, every L_i PPS is of even mode for all aisles $i = 1, \ldots, r$, and, in any case, every L_r^+ PPS is of even mode. An illustration of L_i PPS modes is given in Figure 10.



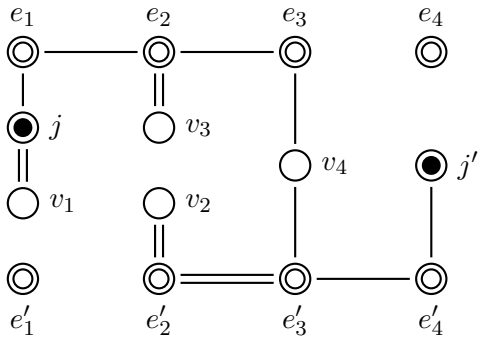
(a) L_3^- PPS, odd mode



(b) L_3^+ PPS, odd mode



(c) L_4^- PPS, odd mode



(d) L_4^+ PPS, even mode

Figure 10: Mode examples for L_3 and L_4 PPSs in a warehouse with 4 aisles.

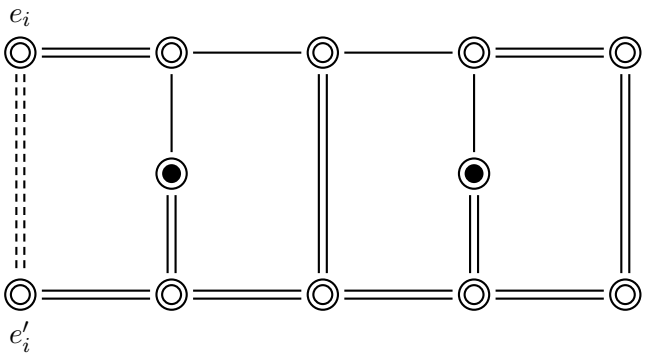
Proof of Theorem 3. To prove sufficiency of the conditions stated in Theorem 3, we show that a completion for any possible L_i PPS exists by following the schemes shown in Figure 11. The dashed parts are excluded for the completion of an L_i^+ PPS, and included for the completion of an L_i^- PPS. Figures (a)-(f) show completions for any L_i PPS of even mode, whereas (g) and (h) depict completions for any L_i PPS of odd mode. In (a)-(d), both end points are located to the right of aisle i. The completion schemes shown in (a) and (b) apply if the end points are located in different aisles, whereas (c) and (d) apply when the end points are located in the same aisle. (e) and (f) apply if both end points are located to the left of or within aisle i. There might be more or less aisles in the warehouse layout than depicted in the completion schemes in Figure 11. For aisles not shown in the schemes, a pair of parallel edges from the front to the rear of the aisle is inserted.

To prove necessity, we suppose that $(T \subset L_i) \cup (T^c \subset R_i)$ forms a valid PS. Because no arcs in T are incident with vertices in T^c except for possibly e_i and e'_i, T cannot have a connected component which neither contains e_i nor e'_i. □

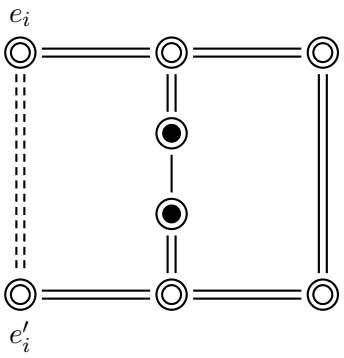
Theorem 4 (Equivalence Conditions) Two PPSs T^1 and T^2 of L_i are equivalent if

1. both e_i and e'_i have the same degree parity (even, odd, or zero) in T^1 and T^2,
2. excluding vertices with zero degree, both T^1 and T^2 have the same number of connected components.

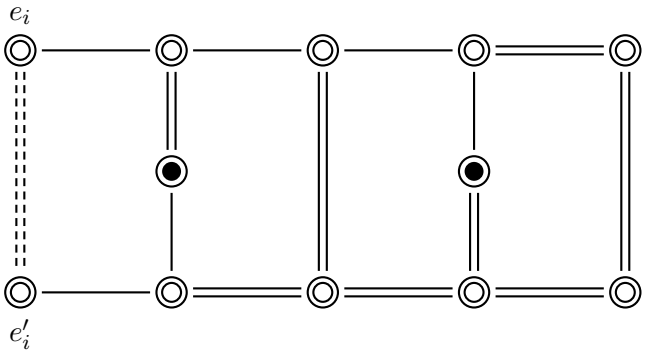
Proof of Theorem 4. Let $T^c \subset R_i$, such that $T^1 \cup T^c$ is a valid PS. Since e_i and e'_i, have the same degree parity in both T^1 and T^2, all vertices in $(T^2 \cup T^c) \setminus \{j, j'\}$ have even or zero degree, and j and j' have odd degree in $T^2 \cup T^c$. Contracting a connected component of a graph to a single vertex does not affect the connectivity of the graph. If we shrink the connected components of T^1 and T^2 in $T^1 \cup T^c$ and $T^2 \cup T^c$, the



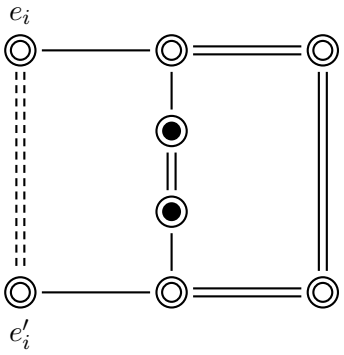
(a)



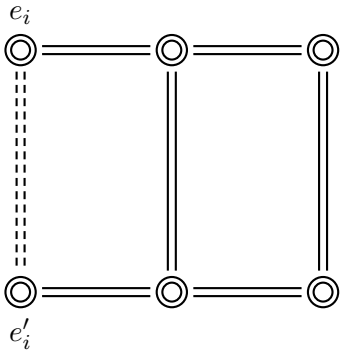
(c)



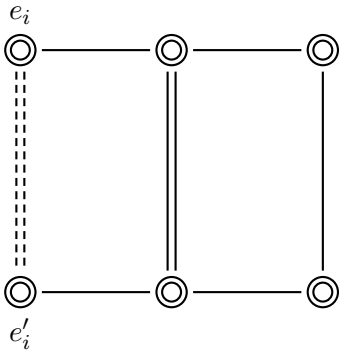
(b)



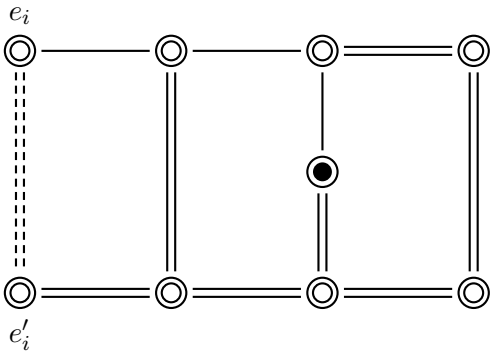
(d)



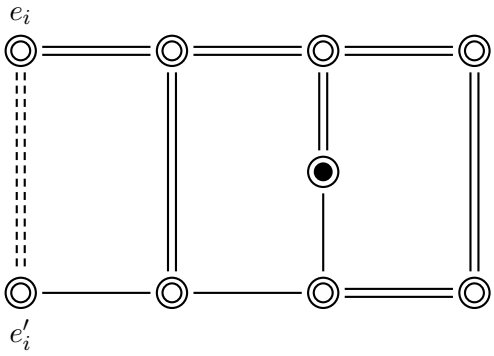
(e)



(f)



(g)



(h)

Figure 11: Completion schemes used in the Proof of Theorem 3.

resulting graphs are identical, namely, either T^1 and T^2 each shrink to a single vertex connected to e_i and e_i' in the same fashion or they each shrink to two vertices connected to e_i and e_i' in the same fashion. Therefore, because $T^1 \cup T^c$ is connected, $T^2 \cup T^c$ is also connected. It then follows from Theorem 2 that $T^2 \cup T^c$ is a valid PS. □

Theorem 5 (Possible Equivalence Classes) Every possible L_i PPS belongs to one of a set C of 14 equivalence classes

$$C = \{000,\ 001,\ E01,\ 0E1,\ EE1,\ UU1,\ EE2,\ UU2,\ U01,\ 0U1,\ UE1,\ EU1,\ UE2,\ EU2\}. \quad (17)$$

Proof of Theorem 5. The set of all potential equivalence classes is formed by

$$\bar{C} = 000 \cup \big(\{0, E, U\} \times \{0, E, U\} \times \{1, 2\}\big). \quad (18)$$

Thus, there are $|\bar{C}| = 19$ potential equivalence classes. Without loss of generality, suppose a parallel-aisle warehouse layout with $r = 1$. For each equivalence class c in C, there is an edge configuration in Figure 5 which belongs to c when interpreted as an L_1^+ PPS. For example, Figure 5 (1) belongs to equivalence class UU1. The equivalence class which corresponds to each edge configuration can be read from the first row in Table 2.

It remains to show that equivalence classes $002, E02, 0E2, U02$ and $0U2$ are empty. To this end, we only need to note that if there are two components in a subgraph $T \subset L_i$ and at least one of vertices e_i and e_i' has zero degree, there is at least one component in T which neither connects to e_i nor e_i'. Thus, T does not meet requirement 4 of Theorem 3 for being an L_i PPS. □

A.2 Theorems of Section 4.2

Lemma 1 (Maximum Vertex Degrees) A minimum length PS contains no more than two edges between any pair of vertices.

Proof of Lemma 1. Suppose a PS contains more than two edges between a pair of vertices v and v'. We construct a PS of shorter length the following way: remove two of the edges between v and v' as long as there are more than two edges between these vertices. Because the connectivity of the graph is preserved and removing an even number of edges between vertices v and v' does not change their degree parity, the resulting graph is still a valid PS. □

A.3 Theorems of Section 4.4

Theorem 6 (Picking Path Construction Procedure) Given a valid PS, a picking path can be constructed by the following procedure:

1. Start at vertex j.
2. If there is a pair of unused parallel edges incident to the current vertex, use one of them to go to the next vertex, then continue with step 2.

3. If there are any unused single edges (i.e., not one of a pair of parallel edges), use one of them to go to the next vertex, then continue with step 2.

4. If there is a pair of parallel edges with one edge used and one edge still unused, use the unused edge to go to the next vertex, then continue with step 2.

5. Stop. Now the currently visited vertex is j', and the order picking path is complete.

We prove the correctness of the procedure from Theorem 6 using the two following observations:

Corollary 2 (Incidence Patterns) *Given a valid PS of minimum length. As a consequence of Theorem 2 and Lemma 1, vertices j and j' are both incident with one single edge or with one single edge and two parallel edges, vertices P'_s are either incident with two single edges or two pairs of parallel edges, and vertices e_i and e'_i are either incident with two single edges, two single edges and a pair of parallel edges, two pairs of parallel edges, or three pairs of parallel edges.*

Lemma 4 (Path Subgraph Decomposition) *Let T be a valid PS of minimum length. Then T can be decomposed into a cycle-free path of single edges Π with start vertex j and end vertex j' and a set of cycles Θ such that $\Pi \cup \Theta = T$, where each cycle in Θ is of minimum length and connects to a single vertex in Π via a pair of parallel edges and each vertex in Π connects to at most one cycle from Θ.*

Proof of Lemma 4. Existence of Π can be proven inductively. From Corollary 2 it follows that j is connected to another vertex via a single edge. If this other vertex is j', we have found the desired path. If this other vertex is not j', it must be connected to yet another vertex via a single edge and so on. Π cannot have a cycle because a cycle with only single edges would imply that a vertex is incident with more than two single edges which violates Corollary 2.

If all edges in Π are removed from T, the degrees of j and j' are decreased by one, whereas the degrees of all other vertices in Π decrease by two. Hence, in the resulting graph, all vertices have even or zero degree, which means that all components in the remainder are Eulerian, i. e., they form a set of cycles. Because T is of minimum length, each cycle must be of minimum length.

Vertices j and j' are incident with one single edge, and all other vertices on Π are incident with two single edges. Thus, all cycles in Θ must connect to Π via a pair of parallel edges. Because of Corollary 2, each vertex in Π is incident with at most one pair of parallel edges, hence it connects to at most one cycle. □

We can now prove the correctness of the procedure described in Theorem 6.

Proof of Theorem 6. The procedure starts at vertex $v' = j$, which by definition belongs to Π. As Lemma 4 states, every cycle in Ω connects to exactly one vertex in Π and we note that steps 2-4 in the procedure above are the same as in the construction procedure presented in Ratliff and Rosenthal (1983). Thus, if there is a cycle which connects to v' via a pair of parallel edges, the procedure will construct a subtour which starts and ends at v' while visiting all other vertices in the cycle. Now if $v' \neq j'$, the procedure advances to the next vertex on Π. □

B Detailed results on benchmark instances

Tables 8–37 present the detailed results on the benchmark sets introduced in Section 6.1. We report for each instance the objective value f_0 when interpreting it as a traditional order picking problem instance and the

objective values f obtained by the different solution methods along with the respective runtime t in seconds when interpreting the instances as single-block WCTSP-GCS or WCTSP-OCS. We do not report objective values for CC for the WCTSP-GCS because they match those of DP on all instances. Underlined objective values denote optimal solutions. Table 38 shows the results of the heuristic picking policies (cp. Table 6) on the instance sets Centered Depot and Large Orders.

Table 8: Results on instance set Original with UDD and $l = 20$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	7148	6101	0.01	3.46	6101	30.14	5901	4.84	5901	22.43	5925	0.11	5835
2	6520	5407	0.00	1.24	5407	14.34	5175	1.41	5175	5.24	5247	0.07	5091
3	6852	5855	0.01	3.30	5855	28.76	5627	3.73	5627	22.70	5687	0.10	5528
4	6730	5671	0.01	2.29	5671	44.67	5453	2.54	5453	39.29	5485	0.08	5358
5	7002	5959	0.01	2.13	5959	43.13	5737	4.04	5737	31.69	5771	0.09	5651
6	7386	6373	0.01	3.23	6373	21.80	6185	3.50	6185	49.47	6243	0.13	6095
7	6702	5579	0.01	1.95	5579	22.09	5357	4.62	5357	26.66	5425	0.08	5259
8	6422	5347	0.01	1.28	5347	26.72	5143	4.49	5143	10.09	5243	0.07	5056
9	7432	6353	0.01	1.75	6353	17.00	6175	2.28	6175	41.40	6213	0.11	6101
10	6500	5467	0.01	2.33	5467	26.62	5221	4.90	5221	37.86	5295	0.08	5132
11	6526	5447	0.01	1.70	5447	22.61	5195	3.12	5195	12.46	5273	0.08	5114
12	7210	6163	0.01	1.81	6163	35.53	5909	2.43	5909	24.82	5957	0.11	5832
13	7342	6285	0.01	1.77	6285	21.69	6071	3.13	6071	35.92	6131	0.11	5997
14	6816	5683	0.01	1.73	5683	19.42	5477	15.22	5477	35.87	5531	0.09	5397
15	6446	5427	0.00	1.27	5427	23.10	5109	1.95	5109	28.98	5185	0.07	5002
16	6320	5329	0.01	1.32	5329	10.02	5131	9.01	5131	22.33	5165	0.07	5028
17	6914	5783	0.01	1.68	5783	30.95	5593	4.28	5593	19.56	5659	0.08	5512
18	6582	5527	0.01	2.54	5527	15.43	5325	1.96	5325	19.89	5381	0.08	5239
19	6654	5565	0.01	2.38	5565	22.54	5357	4.05	5357	31.92	5397	0.08	5281
20	6364	5353	0.01	1.52	5353	23.67	5133	5.31	5133	21.37	5193	0.07	5027
21	6694	5703	0.01	1.95	5703	17.90	5509	11.34	5509	22.33	5581	0.10	5417
22	6776	5703	0.01	2.04	5703	24.00	5477	7.96	5477	42.17	5551	0.09	5392
23	6396	5321	0.01	1.79	5321	18.79	5099	5.06	5099	27.23	5209	0.07	5033
24	6028	4935	0.00	3.38	4935	36.27	4693	1.97	4693	16.88	4767	0.06	4598
25	6914	5835	0.01	1.59	5835	29.60	5629	2.08	5629	14.41	5695	0.09	5555
26	6500	5509	0.00	1.83	5509	23.54	5263	3.49	5263	19.46	5295	0.07	5176
27	6420	5355	0.01	1.44	5355	15.27	5111	1.95	5111	35.94	5163	0.08	5031
28	6400	5299	0.01	1.70	5299	26.87	5087	3.15	5087	33.05	5135	0.07	5002
29	6602	5543	0.01	3.00	5543	10.62	5291	4.37	5291	16.05	5339	0.07	5214
30	6426	5349	0.01	1.63	5349	31.31	5163	2.95	5163	11.93	5237	0.08	5086
31	6550	5477	0.01	1.70	5477	17.97	5267	4.97	5267	36.08	5341	0.07	5180
32	6728	5707	0.01	1.99	5707	21.11	5457	32.96	5457	35.07	5515	0.09	5358
33	6720	5711	0.01	1.93	5711	49.53	5471	12.48	5471	21.16	5559	0.08	5401
34	7066	6049	0.01	3.27	6049	48.80	5845	6.20	5845	44.87	5895	0.11	5754
35	6306	5239	0.01	1.58	5239	24.60	5011	5.96	5011	25.26	5091	0.08	4922
36	6272	5163	0.01	1.08	5163	16.32	4903	3.59	4903	34.08	4985	0.07	4839
37	6730	5643	0.01	1.87	5643	25.04	5381	4.93	5381	26.92	5439	0.09	5307
38	6578	5573	0.01	1.60	5573	38.13	5337	5.94	5337	18.42	5393	0.08	5250
39	6622	5579	0.01	1.66	5579	18.79	5383	4.95	5383	59.54	5463	0.07	5306
40	6672	5683	0.01	1.84	5683	9.30	5449	12.04	5449	30.08	5497	0.08	5352

Table 9: Results on instance set Original with UDD and $l = 40$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	13462	11193	0.01	3.30	11193	54.86	10691	6.26	10691	30.64	10805	0.31	10605
2	13904	11645	0.02	4.81	11645	34.02	11253	81.25	11253	70.82	11383	0.38	11134
3	13962	11779	0.02	6.87	11779	54.18	11357	13.00	11357	61.13	11485	0.37	11253
4	13922	11819	0.01	5.22	11819	59.48	11353	9.14	11353	33.63	11453	0.35	11259
5	13576	11443	0.01	4.08	11443	29.43	10905	5.13	10905	47.51	11069	0.31	10817
6	13230	11101	0.01	3.86	11101	49.77	10617	6.10	10619	58.32	10741	0.28	10504
7	13604	11363	0.01	3.97	11363	55.57	10841	4.39	10841	64.13	10961	0.32	10737
8	12720	10709	0.01	4.25	10709	45.76	10197	10.24	10197	42.96	10313	0.26	10093
9	13342	11179	0.01	5.54	11179	43.56	10683	3.74	10683	35.94	10825	0.29	10580
10	13132	10853	0.01	3.77	10853	54.87	10455	12.98	10455	27.37	10573	0.29	10362
11	13920	11859	0.02	7.11	11859	101.02	11359	6.13	11359	44.36	11479	0.35	11274
12	14058	11963	0.02	8.17	11963	59.40	11503	9.78	11503	53.66	11645	0.40	11414
13	13138	11041	0.01	3.74	11041	23.37	10569	4.33	10569	36.47	10705	0.31	10451
14	13330	11233	0.01	5.68	11235	35.95	10645	7.32	10645	50.22	10773	0.31	10549
15	13700	11443	0.01	4.61	11443	65.80	10989	6.24	10989	51.78	11109	0.32	10897
16	13674	11535	0.02	7.80	11535	53.60	11059	4.67	11059	53.42	11153	0.36	10949
17	12794	10657	0.01	4.00	10657	30.28	10135	13.13	10135	55.12	10251	0.27	10040
18	12826	10839	0.01	4.05	10839	67.68	10251	6.66	10251	52.88	10369	0.28	10148
19	13700	11625	0.01	4.35	11625	29.12	11085	16.45	11085	44.20	11197	0.28	10996
20	13078	10805	0.01	3.65	10805	72.80	10259	4.34	10259	57.57	10399	0.26	10161
21	13752	11733	0.01	5.65	11733	34.30	11251	13.60	11251	60.19	11383	0.34	11150
22	13344	11117	0.01	4.50	11117	32.27	10635	4.43	10635	27.72	10741	0.31	10540
23	13600	11505	0.01	4.59	11505	23.94	11033	5.13	11033	47.20	11165	0.32	10954
24	13064	10949	0.01	4.25	10949	51.98	10377	11.03	10377	41.72	10485	0.28	10267
25	13796	11669	0.01	6.44	11669	29.28	11241	9.86	11241	32.55	11383	0.33	11158
26	13398	11217	0.01	4.09	11217	32.79	10791	9.41	10791	84.76	10881	0.31	10658
27	14332	12255	0.02	4.43	12255	65.71	11827	5.85	11827	41.39	11963	0.40	11726
28	12922	10681	0.01	10.08	10681	36.62	10177	4.66	10177	45.21	10319	0.27	10078
29	13146	10999	0.01	3.40	10999	20.81	10499	11.28	10499	33.13	10625	0.30	10406
30	13224	11163	0.01	6.77	11163	51.94	10669	11.51	10669	41.93	10769	0.32	10556
31	13392	11349	0.01	7.06	11349	35.96	10789	4.41	10793	56.20	10945	0.32	10697
32	13710	11539	0.02	6.08	11539	51.47	11053	98.27	11053	59.79	11207	0.34	10963
33	12798	10619	0.01	4.26	10619	23.79	10159	30.96	10159	47.36	10307	0.27	10061
34	12514	10415	0.01	6.67	10415	54.70	9889	7.87	9889	52.80	10037	0.27	9783
35	14108	11851	0.01	3.42	11851	25.80	11483	4.88	11483	40.13	11587	0.33	11391
36	13512	11265	0.01	4.34	11265	40.98	10847	19.17	10849	58.70	10931	0.29	10758
37	14012	11817	0.02	5.41	11817	35.38	11389	34.13	11389	48.21	11503	0.37	11271
38	13878	11815	0.01	5.58	11815	23.04	11373	6.01	11373	60.73	11497	0.33	11281
39	14146	11871	0.01	4.96	11871	33.52	11417	10.35	11417	38.15	11561	0.34	11324
40	13570	11529	0.02	5.09	11529	40.06	11091	30.52	11091	75.93	11223	0.37	10993

Table 10: Results on instance set Original with UDD and $l = 60$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	20298	17039	0.02	8.96	17039	45.47	16293	168.57	16293	73.64	16495	0.78	16181
2	20382	16837	0.02	6.16	16837	47.10	16147	39.87	16147	77.33	16313	0.69	16046
3	18310	14987	0.01	5.10	14987	38.54	14203	5.19	14203	37.73	14467	0.52	14069
4	19528	16263	0.02	7.33	16263	38.00	15519	21.70	15521	67.69	15725	0.63	15404
5	20284	16965	0.02	7.65	16965	48.38	16295	119.58	16295	52.62	16473	0.70	16174
6	20302	16987	0.02	6.05	16987	98.02	16279	98.19	16279	96.82	16473	0.71	16171
7	20930	17601	0.02	9.54	17601	49.45	16919	88.93	16919	108.66	17111	0.78	16818
8	20294	17149	0.02	9.51	17151	77.71	16381	21.67	16381	99.87	16579	0.75	16246
9	21540	18221	0.02	8.66	18221	74.31	17513	70.21	17515	112.24	17685	0.83	17415
10	21234	17963	0.02	8.28	17963	59.17	17251	15.22	17253	74.77	17435	0.78	17129
11	19936	16803	0.02	6.25	16803	54.47	16029	8.44	16029	48.40	16209	0.67	15924
12	21136	17957	0.02	9.46	17957	57.00	17225	9.36	17227	52.42	17441	0.78	17126
13	19904	16801	0.02	10.42	16801	54.53	16025	13.12	16025	66.72	16217	0.72	15915
14	19632	16481	0.02	9.70	16481	66.30	15705	9.71	15705	75.73	15905	0.68	15581
15	20814	17601	0.02	7.47	17601	105.79	16905	22.96	16905	128.54	17119	0.80	16800
16	19592	16375	0.02	8.94	16375	42.38	15659	13.15	15659	71.34	15859	0.65	15532
17	19744	16507	0.02	6.02	16507	40.01	15793	8.32	15793	76.78	15977	0.66	15666
18	19390	16151	0.02	7.16	16151	43.85	15353	10.73	15353	57.62	15571	0.67	15237
19	20274	17025	0.02	7.82	17025	62.34	16385	26.12	16387	115.72	16533	0.76	16263
20	20434	17149	0.02	9.21	17149	41.90	16399	236.97	16399	63.50	16627	0.72	16279
21	19942	16775	0.02	7.26	16775	44.29	16003	8.30	16005	76.36	16219	0.67	15905
22	20510	17235	0.02	15.28	17235	64.47	16555	13.37	16559	93.16	16759	0.72	16446
23	20948	17791	0.02	6.20	17791	36.15	17049	56.67	17049	79.76	17285	0.77	16933
24	19704	16313	0.02	6.45	16313	43.75	15617	15.61	15617	77.55	15821	0.65	15515
25	20218	16875	0.02	6.45	16875	41.85	16115	12.34	16115	97.00	16345	0.78	15997
26	19870	16775	0.02	7.16	16775	88.53	16021	59.85	16023	91.98	16215	0.72	15913
27	20360	16983	0.02	14.67	16983	59.08	16293	14.53	16295	99.22	16491	0.75	16176
28	20038	16873	0.02	7.95	16873	43.41	16169	19.85	16169	75.22	16371	0.76	16067
29	20160	16901	0.02	6.34	16901	64.59	16053	25.38	16055	95.22	16245	0.69	15933
30	19274	15901	0.02	6.48	15901	67.05	15075	7.57	15075	63.01	15301	0.56	14977
31	21178	17635	0.02	7.43	17635	49.96	17083	17.04	17083	86.91	17301	0.78	16967
32	19912	16421	0.02	7.69	16421	66.66	15733	7.06	15733	50.79	15947	0.63	15634
33	20824	17663	0.02	6.74	17663	58.06	16943	11.89	16943	56.00	17153	0.80	16835
34	20270	16999	0.02	9.18	16999	43.41	16311	42.47	16311	75.12	16543	0.76	16208
35	20656	17347	0.02	7.17	17347	98.98	16677	23.80	16677	76.36	16859	0.74	16578
36	19996	16731	0.02	8.29	16731	47.60	16073	37.42	16073	83.16	16309	0.67	15943
37	20102	16877	0.02	7.15	16877	39.78	16073	19.74	16073	68.01	16289	0.72	15953
38	19078	15869	0.02	5.41	15869	34.50	15027	24.16	15027	42.09	15223	0.59	14920
39	20020	16677	0.02	4.19	16677	55.05	15977	14.88	15977	93.77	16209	0.69	15889
40	19868	16667	0.02	6.83	16667	39.94	15937	22.59	15939	84.13	16159	0.65	15829

Table 11: Results on instance set Original with UDD and $l = 80$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	28690	24311	0.04	19.34	24313	61.24	23403	29.75	23403	88.29	23661	1.59	23289
2	27060	22799	0.03	9.85	22799	100.76	21699	12.18	21699	138.35	21959	1.38	21587
3	27590	23259	0.03	16.73	23259	82.94	22213	22.76	22213	123.78	22451	1.34	22107
4	27092	22567	0.03	8.70	22573	84.45	21505	11.46	21505	93.59	21799	1.32	21405
5	26360	21981	0.03	10.44	21981	69.80	21035	7200.00	21035	123.13	21335	1.23	20914
6	26636	22427	0.03	7.34	22427	70.58	21455	74.71	21455	93.90	21725	1.32	21339
7	27646	23183	0.03	10.87	23183	79.33	22103	29.94	22103	135.11	22343	1.41	21968
8	27192	22851	0.03	16.07	22851	77.96	21907	17.70	21907	105.27	22163	1.37	21793
9	26142	21877	0.02	10.48	21879	52.95	20889	69.73	20893	94.28	21173	1.16	20772
10	27936	23525	0.03	10.76	23525	69.00	22517	13.39	22517	104.11	22777	1.46	22421
11	27058	22785	0.03	15.42	22793	63.51	21711	30.91	21711	105.70	21997	1.34	21610
12	27450	22877	0.03	16.78	22877	78.10	21907	261.55	21907	96.54	22205	1.41	21799
13	26640	22443	0.03	10.30	22445	51.94	21403	99.23	21403	97.45	21671	1.38	21290
14	28170	23839	0.03	13.59	23843	50.27	22819	20.61	22819	81.64	23065	1.51	22712
15	25964	21483	0.02	7.27	21483	71.31	20467	25.36	20467	59.92	20767	1.18	20345
16	27302	22961	0.03	15.10	22961	53.85	21999	18.59	21999	57.25	22293	1.38	21873
17	27076	22799	0.03	14.88	22799	56.49	21793	21.66	21793	114.85	22087	1.32	21688
18	27052	22549	0.02	6.53	22549	60.17	21549	130.02	21549	122.48	21793	1.25	21422
19	26266	22021	0.03	10.68	22021	52.64	20929	55.31	20929	133.91	21193	1.25	20814
20	26470	22117	0.03	8.81	22117	35.30	21191	11.59	21191	65.89	21457	1.24	21083
21	26268	21799	0.02	9.26	21799	54.66	20941	126.23	20941	91.51	21239	1.21	20812
22	28494	24051	0.04	9.36	24051	61.45	23205	571.89	23205	144.26	23473	1.57	23093
23	26648	22393	0.03	14.81	22393	54.72	21419	9.95	21419	61.01	21679	1.30	21319
24	26106	21973	0.03	9.15	21973	80.73	20969	14.05	20971	122.03	21275	1.19	20861
25	26226	21871	0.02	9.09	21871	58.38	20849	53.93	20849	99.80	21159	1.18	20735
26	27346	22911	0.03	10.60	22911	81.69	21913	32.86	21913	82.75	22191	1.33	21787
27	26922	22457	0.03	10.64	22457	63.20	21455	183.07	21455	106.67	21705	1.35	21334
28	26938	22685	0.03	15.44	22685	124.44	21669	67.41	21669	117.49	21909	1.31	21551
29	27718	23341	0.03	11.79	23347	77.68	22263	24.02	22263	92.09	22519	1.35	22151
30	27456	22947	0.03	9.02	22947	50.60	22001	21.28	22001	98.12	22295	1.38	21892
31	27596	23175	0.03	10.89	23175	63.75	22223	69.18	22223	137.99	22479	1.37	22098
32	27030	22561	0.03	12.35	22561	81.51	21673	11.58	21675	114.83	21927	1.32	21552
33	26496	22095	0.03	13.65	22095	77.45	20991	22.82	20993	86.70	21259	1.31	20879
34	26764	22373	0.03	9.92	22373	62.15	21387	59.12	21389	124.26	21661	1.23	21269
35	25360	20889	0.02	11.64	20889	68.14	19895	47.04	19895	115.07	20155	1.08	19762
36	27092	22637	0.03	11.83	22637	72.93	21601	21.34	21601	105.43	21857	1.32	21497
37	26894	22465	0.03	9.09	22465	100.74	21559	137.87	21559	93.17	21813	1.27	21453
38	26494	22153	0.02	9.72	22153	90.88	21135	12.73	21135	41.62	21421	1.21	21031
39	27380	22833	0.03	7.71	22833	62.69	21953	21.13	21953	113.62	22253	1.35	21829
40	27044	22605	0.03	10.33	22605	64.70	21635	64.58	21635	89.81	21933	1.26	21531

Table 12: Results on instance set Original with UDD and $l = 100$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	32734	27295	0.03	14.49	27295	81.38	25959	150.03	25959	131.96	26277	1.96	25825
2	34830	29293	0.04	26.26	29293	77.14	28055	59.75	28055	132.67	28407	2.41	27931
3	33330	27983	0.03	14.63	27983	71.56	26699	117.88	26699	145.29	27087	2.22	26571
4	35368	29765	0.04	22.01	29767	87.97	28521	30.10	28523	77.33	28845	2.44	28421
5	33558	28123	0.03	13.72	28123	71.84	26843	18.18	26843	83.51	27193	2.16	26721
6	33696	28135	0.03	14.42	28135	84.60	26851	139.79	26853	116.05	27179	2.15	26731
7	34216	28773	0.04	18.50	28773	77.42	27505	103.28	27505	123.59	27849	2.25	27405
8	33090	27641	0.03	16.22	27641	64.86	26233	41.99	26233	117.38	26607	2.09	26111
9	33010	27605	0.03	14.24	27605	89.36	26255	28.20	26255	87.97	26647	2.12	26128
10	33052	27437	0.03	13.48	27437	71.86	26207	379.68	26213	116.43	26531	2.07	26085
11	33316	27851	0.03	12.80	27851	65.04	26511	663.95	26513	120.05	26799	1.96	26395
12	34098	28525	0.04	11.84	28525	69.32	27367	148.94	27373	56.69	27675	2.22	27247
13	32556	27061	0.03	15.77	27061	67.70	25695	76.92	25695	122.03	26113	1.98	25576
14	32676	27213	0.03	17.67	27213	70.32	25949	31.75	25949	132.37	26343	1.93	25822
15	33288	27969	0.03	12.57	27973	50.09	26787	217.93	26787	107.29	27121	2.13	26673
16	33290	27777	0.03	14.26	27777	83.46	26565	37.75	26565	146.66	26869	2.00	26447
17	33478	28137	0.03	16.39	28139	100.57	26933	69.42	26933	120.64	27255	2.01	26816
18	33310	28007	0.04	16.05	28007	93.83	26735	29.59	26735	117.57	27055	2.21	26626
19	33092	27617	0.03	15.46	27617	102.73	26363	27.27	26367	125.89	26683	2.10	26245
20	34376	28885	0.04	17.31	28885	84.33	27697	32.53	27699	125.68	27993	2.32	27568
21	33972	28651	0.04	18.39	28651	93.98	27383	211.48	27385	118.46	27735	2.26	27259
22	33660	28127	0.03	13.19	28131	118.39	26931	52.01	26931	116.84	27241	2.17	26816
23	32812	27291	0.03	14.24	27291	58.83	25917	154.15	25921	95.41	26259	1.92	25779
24	34118	28449	0.03	14.47	28449	90.16	27229	86.24	27231	127.39	27529	2.09	27113
25	32808	27301	0.03	12.08	27301	69.81	26045	303.41	26045	161.83	26359	2.03	25909
26	34434	28741	0.03	18.67	28741	78.09	27471	28.10	27471	110.58	27805	2.22	27361
27	34524	28993	0.04	13.80	28993	83.07	27771	21.71	27771	124.72	28109	2.33	27675
28	33046	27485	0.03	17.65	27485	74.29	26273	241.74	26275	102.72	26623	1.95	26161
29	32362	26951	0.03	14.06	26951	43.26	25643	18.59	25643	128.86	25963	1.87	25518
30	33908	28371	0.03	18.34	28371	78.77	27129	300.16	27131	112.35	27439	2.23	26998
31	34576	29175	0.04	14.96	29175	107.31	27907	45.43	27907	138.12	28269	2.38	27794
32	34874	29469	0.04	14.09	29469	101.58	28235	682.10	28235	180.78	28531	2.39	28116
33	33444	27893	0.03	16.38	27893	76.85	26557	204.86	26557	108.45	26939	2.16	26425
34	34280	28919	0.04	12.02	28919	73.16	27649	117.00	27649	136.84	27991	2.27	27539
35	34304	28941	0.03	12.96	28941	145.05	27625	237.18	27629	130.20	27941	2.21	27509
36	33840	28071	0.04	11.59	28071	73.24	27043	25.46	27043	148.58	27431	2.22	26924
37	33030	27589	0.03	10.83	27597	106.25	26435	55.72	26435	103.85	26755	1.96	26329
38	34736	28993	0.04	14.06	28993	68.31	27849	43.77	27849	100.69	28181	2.33	27748
39	33504	27915	0.03	10.17	27915	73.92	26709	518.32	26709	166.83	27007	2.05	26579
40	33452	28141	0.03	18.82	28141	72.41	26857	24.98	26857	126.84	27233	2.03	26740

Table 13: Results on instance set Original with CBD and $l = 20$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	5244	4345	0.01	1.75	4345	26.15	4127	2.55	4127	37.38	4217	0.08	4044
2	4966	3945	0.00	1.16	3945	6.36	3715	1.63	3715	6.01	3787	0.05	3633
3	5468	4563	0.01	1.91	4563	19.23	4327	1.91	4327	11.40	4373	0.07	4260
4	5512	4511	0.01	1.29	4511	19.33	4287	2.63	4287	18.34	4331	0.07	4220
5	5476	4567	0.01	3.33	4567	23.66	4287	1.79	4287	10.98	4329	0.07	4211
6	5362	4491	0.01	2.24	4491	17.80	4311	3.71	4311	16.28	4345	0.09	4250
7	4828	3953	0.01	1.30	3953	8.91	3771	10.04	3771	19.83	3841	0.06	3696
8	4806	3965	0.00	1.78	3965	21.17	3713	5.35	3713	20.40	3795	0.05	3617
9	5470	4533	0.01	2.59	4533	25.14	4313	3.36	4313	21.58	4375	0.08	4254
10	5058	4163	0.01	2.29	4163	11.44	3949	12.19	3949	18.77	3989	0.06	3877
11	5356	4443	0.01	1.46	4443	26.91	4199	5.20	4199	19.40	4277	0.06	4127
12	5672	4821	0.01	1.61	4821	33.14	4603	4.12	4603	26.62	4635	0.08	4529
13	5484	4677	0.01	2.88	4677	34.09	4391	5.04	4391	22.89	4433	0.08	4311
14	5034	4141	0.01	1.60	4141	21.62	3923	2.10	3923	16.89	3991	0.07	3861
15	4884	3953	0.00	1.37	3953	16.90	3727	2.11	3727	18.03	3793	0.05	3648
16	4942	3983	0.00	1.45	3983	20.72	3751	1.54	3751	4.29	3849	0.05	3683
17	5476	4495	0.01	1.37	4495	17.40	4271	12.41	4271	18.04	4345	0.06	4180
18	4942	3991	0.01	1.26	3991	15.39	3789	5.07	3789	10.14	3849	0.06	3717
19	5082	4209	0.01	1.47	4209	9.85	4047	14.44	4047	26.95	4115	0.06	3957
20	5002	4093	0.00	2.00	4093	20.86	3855	1.73	3855	9.17	3941	0.06	3767
21	5692	4665	0.01	1.91	4665	16.66	4495	8.91	4495	21.06	4539	0.07	4438
22	5352	4373	0.01	2.06	4373	19.30	4169	4.92	4169	18.43	4225	0.07	4082
23	5168	4175	0.01	1.42	4175	14.49	3995	2.54	3995	24.08	4067	0.06	3914
24	4964	4035	0.00	1.70	4035	17.94	3843	3.51	3843	14.51	3863	0.05	3772
25	5480	4597	0.01	1.56	4597	13.96	4289	2.82	4289	17.55	4337	0.07	4222
26	5126	4263	0.00	1.42	4263	13.49	4039	1.80	4039	16.34	4127	0.05	3937
27	5122	4183	0.01	1.18	4183	9.39	3929	1.70	3929	12.40	4021	0.06	3865
28	5194	4299	0.01	1.51	4299	21.10	4043	1.26	4043	8.49	4149	0.06	3968
29	5048	4127	0.01	1.25	4127	14.18	3915	6.92	3915	8.41	3983	0.06	3822
30	5080	4183	0.01	1.92	4183	10.28	3937	2.22	3937	13.36	4001	0.06	3859
31	5014	4087	0.00	1.48	4087	19.17	3809	1.98	3809	12.01	3885	0.05	3734
32	5208	4287	0.01	1.57	4287	11.67	4121	3.43	4121	16.33	4161	0.06	4057
33	5120	4295	0.01	1.76	4295	17.89	4003	2.45	4003	5.21	4039	0.06	3934
34	5388	4527	0.01	3.25	4527	41.64	4283	3.00	4283	26.17	4357	0.08	4202
35	5224	4259	0.01	1.44	4259	12.70	4057	7.10	4057	18.81	4107	0.06	3978
36	5170	4145	0.00	1.28	4145	12.40	3975	1.56	3975	10.61	4053	0.05	3893
37	4932	4047	0.01	1.90	4047	22.71	3815	5.50	3815	14.66	3921	0.07	3717
38	5322	4339	0.01	1.49	4339	18.56	4145	3.22	4145	19.77	4207	0.06	4069
39	5226	4333	0.01	1.30	4333	12.75	4113	1.61	4113	9.41	4163	0.06	4044
40	5484	4543	0.01	1.76	4543	18.74	4367	4.37	4367	8.89	4401	0.07	4273

Table 14: Results on instance set Original with CBD and $l = 40$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	10486	8599	0.01	3.38	8599	42.76	8167	38.65	8167	18.97	8295	0.23	8070
2	11054	9159	0.02	6.56	9159	45.27	8745	20.64	8745	40.71	8855	0.28	8661
3	11148	9247	0.02	5.09	9247	21.36	8761	7.06	8761	27.07	8857	0.27	8684
4	10678	8787	0.01	4.68	8787	36.11	8261	6.08	8261	40.31	8375	0.25	8185
5	10640	8791	0.01	3.24	8791	22.27	8301	13.27	8301	26.05	8445	0.23	8191
6	10440	8431	0.01	5.11	8431	25.06	8013	4.08	8013	20.49	8145	0.22	7926
7	10980	9043	0.01	4.75	9047	20.62	8525	5.76	8525	19.24	8623	0.25	8454
8	10132	8343	0.01	2.54	8343	30.69	7821	4.61	7821	24.21	7957	0.20	7719
9	10494	8715	0.01	3.44	8715	21.18	8301	5.61	8301	29.08	8417	0.22	8205
10	9992	8111	0.01	3.09	8111	17.96	7641	5.82	7641	24.57	7769	0.22	7544
11	10960	8987	0.01	6.80	8987	34.84	8563	9.37	8563	24.74	8713	0.27	8486
12	10908	9151	0.01	4.88	9151	27.00	8659	9.81	8659	41.74	8765	0.28	8577
13	10628	8839	0.01	3.23	8839	17.48	8369	4.32	8369	27.29	8475	0.23	8284
14	10508	8631	0.01	4.04	8631	18.98	8031	4.24	8031	13.51	8233	0.24	7943
15	10868	9051	0.01	4.64	9051	24.67	8459	14.28	8459	25.85	8607	0.25	8363
16	10950	8921	0.02	2.86	8921	48.93	8489	26.96	8489	23.95	8637	0.27	8395
17	10278	8435	0.01	2.50	8435	26.04	7981	2.97	7981	17.31	8111	0.20	7896
18	10368	8515	0.01	3.82	8515	28.13	8089	7.02	8089	38.74	8255	0.22	7981
19	9970	8353	0.01	3.37	8353	22.01	7741	7.17	7741	18.49	7865	0.21	7651
20	9606	7855	0.01	3.04	7855	26.51	7413	13.47	7413	31.67	7547	0.19	7311
21	11052	9071	0.01	3.78	9071	29.44	8667	3.68	8667	22.89	8823	0.26	8598
22	10746	8849	0.01	3.47	8849	25.53	8391	21.29	8391	32.92	8559	0.23	8301
23	10484	8745	0.01	5.92	8745	22.45	8227	7.39	8227	31.90	8381	0.24	8133
24	10568	8639	0.01	2.90	8639	33.32	8137	6.92	8137	16.90	8257	0.20	8049
25	10626	8693	0.01	3.55	8693	22.87	8221	24.39	8221	31.57	8349	0.25	8122
26	10402	8533	0.01	3.33	8533	53.94	8117	7.88	8117	32.15	8243	0.22	8017
27	10972	9167	0.02	3.06	9167	33.20	8715	9.00	8715	33.95	8827	0.28	8618
28	10434	8465	0.01	4.04	8465	42.37	7975	39.55	7975	29.63	8075	0.21	7883
29	10524	8695	0.01	3.28	8695	27.84	8187	6.41	8187	19.93	8323	0.23	8090
30	10982	9157	0.01	2.82	9157	25.33	8739	8.80	8739	27.98	8855	0.25	8643
31	10752	8907	0.01	4.51	8907	35.49	8419	5.53	8421	17.90	8591	0.25	8316
32	10530	8767	0.01	4.61	8773	31.03	8255	4.51	8255	15.08	8431	0.26	8172
33	10538	8677	0.01	3.46	8677	27.39	8211	46.84	8211	32.44	8341	0.21	8130
34	10014	8271	0.01	2.67	8271	31.46	7797	10.75	7797	16.94	7963	0.19	7687
35	10562	8653	0.01	5.18	8653	27.84	8233	17.92	8233	43.88	8357	0.24	8157
36	10012	8123	0.01	3.62	8123	31.92	7631	4.16	7631	20.90	7741	0.22	7528
37	11048	9291	0.01	5.63	9291	35.23	8805	11.80	8805	23.79	8961	0.28	8718
38	10890	9003	0.01	4.33	9003	30.08	8577	6.52	8577	30.45	8683	0.24	8479
39	10918	8887	0.01	4.70	8887	29.05	8485	47.60	8485	23.04	8611	0.25	8385
40	11310	9417	0.02	4.11	9417	31.92	8945	7.01	8945	23.58	9081	0.29	8870

Table 15: Results on instance set Original with CBD and $l = 60$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	16374	13617	0.02	7.11	13617	47.45	12869	46.54	12869	41.50	13049	0.57	12750
2	15460	12685	0.02	6.13	12685	35.37	11917	19.60	11917	37.98	12143	0.50	11814
3	14988	12051	0.01	4.91	12051	26.32	11273	14.76	11273	33.65	11451	0.39	11171
4	15110	12421	0.02	8.19	12421	40.80	11551	21.45	11553	42.20	11755	0.47	11465
5	15768	13039	0.02	6.85	13039	39.61	12299	8.04	12301	32.64	12493	0.54	12210
6	15694	12861	0.02	5.53	12861	48.55	12117	16.32	12117	36.41	12319	0.54	12020
7	15932	13153	0.02	7.26	13153	38.68	12415	281.95	12415	40.51	12635	0.58	12328
8	15550	12883	0.02	7.94	12883	39.90	12013	12.42	12013	25.88	12227	0.55	11917
9	16522	13723	0.02	13.34	13723	77.81	13021	8.96	13021	32.50	13245	0.63	12929
10	16222	13459	0.02	7.51	13459	47.15	12755	18.68	12755	38.32	12943	0.59	12665
11	15578	12781	0.02	11.54	12781	38.27	11987	127.15	11987	36.13	12233	0.49	11895
12	16078	13363	0.02	5.78	13363	45.27	12603	115.80	12603	43.72	12773	0.58	12513
13	16168	13263	0.02	6.98	13265	57.16	12563	13.70	12563	25.15	12787	0.54	12447
14	15316	12549	0.02	6.00	12551	46.76	11693	50.33	11693	45.45	11867	0.52	11576
15	16176	13401	0.02	6.14	13401	38.36	12607	17.05	12607	46.79	12775	0.61	12519
16	15268	12575	0.02	8.45	12577	41.07	11797	77.60	11797	41.48	12013	0.47	11678
17	15118	12193	0.02	6.56	12193	29.95	11493	88.05	11493	44.00	11677	0.47	11386
18	15818	12889	0.02	5.30	12889	32.23	12103	28.31	12103	48.58	12325	0.52	12003
19	15646	12729	0.02	7.15	12729	57.69	12023	37.97	12023	57.54	12207	0.55	11921
20	15792	12893	0.02	12.57	12893	44.40	12107	9.66	12107	26.74	12297	0.53	12018
21	15424	12787	0.02	10.68	12787	33.91	12071	6.80	12071	27.70	12237	0.51	11983
22	16064	13407	0.02	5.88	13409	35.66	12663	20.76	12663	46.92	12843	0.57	12561
23	16152	13473	0.02	5.17	13473	52.13	12743	7.96	12743	46.83	12919	0.57	12663
24	15304	12511	0.02	6.71	12511	40.08	11759	62.96	11759	26.47	11991	0.47	11670
25	15620	12915	0.02	5.69	12917	43.22	12095	39.34	12095	35.12	12295	0.58	11996
26	16346	13551	0.02	8.26	13551	34.97	12795	34.81	12795	31.90	13015	0.56	12692
27	15772	13003	0.02	7.28	13003	38.42	12329	28.34	12329	42.99	12543	0.55	12228
28	15694	13087	0.02	8.46	13089	58.51	12319	278.23	12319	49.49	12509	0.56	12222
29	15494	12801	0.02	8.11	12801	47.86	12039	176.45	12039	39.77	12251	0.51	11935
30	14670	11843	0.02	5.07	11843	53.98	11143	30.16	11143	29.00	11325	0.43	11034
31	16208	13397	0.02	6.28	13397	48.42	12695	12.45	12695	40.64	12899	0.59	12582
32	16374	13439	0.02	5.65	13439	23.67	12753	28.23	12753	40.70	12989	0.50	12656
33	15920	13179	0.02	8.92	13179	36.26	12463	34.50	12463	37.81	12659	0.57	12358
34	15950	13247	0.02	7.20	13247	47.12	12493	24.59	12493	43.45	12681	0.56	12392
35	15754	13007	0.02	9.60	13007	33.90	12245	15.86	12245	26.05	12419	0.56	12160
36	15660	12981	0.02	5.06	12981	31.23	12253	15.01	12253	40.58	12459	0.50	12142
37	15780	12899	0.02	6.57	12899	49.50	12219	41.00	12219	36.45	12443	0.54	12126
38	15040	12161	0.01	4.78	12161	32.59	11305	36.22	11305	31.31	11491	0.45	11204
39	16116	13265	0.02	5.75	13265	48.25	12471	16.11	12471	21.88	12679	0.54	12375
40	15698	12911	0.02	7.87	12911	31.20	12135	31.53	12137	32.69	12333	0.50	12029

Table 16: Results on instance set Original with CBD and $l = 80$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	22154	18465	0.03	15.81	18465	54.56	17443	47.90	17443	45.65	17741	1.21	17342
2	21280	17513	0.03	11.72	17513	105.40	16543	12.87	16545	50.90	16797	1.07	16440
3	20870	17157	0.03	7.85	17157	60.42	16187	34.67	16187	52.28	16475	1.05	16087
4	21318	17719	0.03	8.15	17719	43.80	16655	60.11	16655	58.48	16895	1.05	16558
5	20970	17043	0.02	6.76	17043	45.70	16073	383.72	16075	53.53	16329	0.97	15970
6	20852	16999	0.02	8.45	16999	52.54	16021	15.48	16021	53.86	16279	0.99	15935
7	21732	17989	0.03	8.07	17989	46.09	17073	35.72	17073	39.64	17309	1.10	16974
8	22088	18293	0.03	11.37	18293	58.97	17229	27.44	17229	49.90	17487	1.09	17143
9	20254	16537	0.02	7.94	16537	36.97	15459	166.46	15459	31.23	15715	0.91	15361
10	22158	18433	0.03	17.23	18433	50.53	17445	249.66	17445	66.66	17715	1.20	17338
11	20892	17225	0.03	9.24	17225	53.27	16137	56.30	16137	43.39	16421	1.05	16033
12	22172	18281	0.03	8.10	18281	55.66	17315	48.65	17315	38.66	17543	1.12	17217
13	21012	17219	0.03	6.33	17219	41.30	16217	16.24	16217	44.42	16445	1.07	16126
14	21992	18253	0.03	7.77	18253	50.44	17421	137.42	17421	49.55	17685	1.16	17314
15	21490	17659	0.02	8.13	17659	57.65	16581	15.51	16581	46.97	16849	0.92	16473
16	21136	17409	0.03	11.23	17409	40.91	16535	104.21	16535	57.93	16755	1.06	16445
17	21444	17653	0.03	10.72	17653	50.31	16617	44.14	16617	65.36	16893	1.06	16529
18	20590	16863	0.02	11.78	16863	52.36	15697	19.62	15699	37.87	15973	0.96	15605
19	20898	17221	0.02	7.67	17221	45.21	16209	252.70	16209	57.59	16459	0.96	16112
20	20644	16945	0.02	6.76	16945	57.93	15831	15.45	15831	41.28	16133	0.98	15722
21	20992	17299	0.02	9.01	17301	49.80	16195	14.03	16195	43.60	16463	0.94	16087
22	22302	18697	0.03	9.98	18699	35.74	17753	341.33	17753	71.18	17969	1.21	17637
23	21048	17473	0.03	11.31	17473	62.35	16301	14.80	16301	42.13	16603	1.00	16205
24	20730	17083	0.02	6.74	17083	51.61	16035	62.90	16035	53.85	16275	0.92	15932
25	20486	16725	0.02	8.09	16727	49.27	15669	17.56	15669	40.65	15953	0.91	15579
26	21234	17499	0.03	10.38	17499	41.95	16497	142.44	16497	46.70	16763	1.03	16394
27	21504	17667	0.03	9.25	17667	58.48	16703	53.03	16703	60.24	16969	1.04	16608
28	20346	16577	0.03	18.76	16577	49.34	15621	115.36	15623	50.65	15917	0.98	15528
29	21192	17375	0.03	14.99	17377	62.65	16435	89.86	16435	55.15	16675	1.02	16340
30	21442	17619	0.03	8.19	17619	67.01	16675	860.20	16675	46.40	16927	1.07	16556
31	21378	17587	0.03	6.44	17587	45.36	16595	635.68	16595	46.71	16911	1.05	16488
32	20904	17193	0.03	10.63	17193	56.26	16163	86.36	16163	47.86	16415	1.02	16061
33	20662	16897	0.02	14.00	16897	109.72	15825	648.83	15825	66.07	16085	0.99	15718
34	20922	17183	0.02	10.36	17183	28.43	16177	62.95	16177	40.63	16431	0.97	16079
35	19726	16219	0.02	9.28	16219	41.17	15035	52.56	15035	40.06	15311	0.84	14915
36	21098	17441	0.03	8.02	17441	50.44	16487	10.72	16487	38.55	16755	1.03	16392
37	20694	17037	0.02	8.14	17037	55.82	15903	152.65	15903	40.29	16145	0.99	15801
38	20718	17043	0.02	7.66	17043	42.02	16007	16.36	16007	32.45	16301	0.97	15906
39	20732	16987	0.03	12.04	16987	53.37	16043	26.47	16043	54.77	16347	1.05	15935
40	21126	17455	0.02	8.36	17455	47.60	16299	11.98	16299	42.28	16535	0.97	16199

Table 17: Results on instance set Original with CBD and $l = 100$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	25692	20919	0.03	12.37	20919	61.38	19679	411.80	19681	61.87	19975	1.56	19569
2	26924	22115	0.03	14.93	22115	62.85	20833	18.63	20833	46.18	21193	1.91	20727
3	26298	21673	0.03	11.65	21673	66.09	20409	2412.88	20409	57.99	20727	1.79	20307
4	27234	22593	0.04	15.02	22593	77.40	21383	123.52	21383	69.93	21695	1.97	21286
5	25610	20889	0.03	24.69	20895	75.27	19605	49.74	19607	60.55	19857	1.71	19503
6	25844	21121	0.03	11.72	21121	45.15	19897	238.86	19899	54.14	20289	1.68	19773
7	26804	22035	0.03	13.61	22035	57.97	20725	6434.27	20725	58.70	21043	1.80	20641
8	25304	20661	0.03	13.46	20661	76.69	19345	76.94	19347	78.82	19677	1.63	19228
9	26846	22155	0.03	12.63	22155	72.89	20777	22.91	20777	61.38	21143	1.69	20684
10	25622	21141	0.03	20.18	21141	84.45	19825	38.61	19825	81.08	20145	1.63	19711
11	26072	21273	0.03	11.02	21273	49.17	20025	132.73	20027	49.06	20379	1.60	19938
12	26418	21657	0.03	12.38	21657	80.00	20565	16.69	20565	43.81	20859	1.83	20465
13	25184	20523	0.03	11.53	20523	62.74	19293	87.67	19299	50.08	19617	1.57	19197
14	25838	21253	0.03	12.45	21253	44.08	19991	17.14	19991	62.58	20297	1.53	19889
15	26474	21819	0.03	13.02	21819	61.35	20435	46.92	20435	58.97	20733	1.76	20329
16	26024	21433	0.03	9.45	21439	72.76	20043	1189.24	20043	42.99	20397	1.60	19936
17	25764	21177	0.03	16.28	21177	60.54	19911	45.38	19913	50.37	20249	1.62	19801
18	27094	22457	0.03	16.05	22457	89.99	21107	28.20	21107	73.66	21411	1.78	21009
19	26644	21829	0.03	10.38	21835	96.49	20629	25.58	20631	53.06	20941	1.69	20527
20	26650	21893	0.03	19.64	21893	69.46	20699	36.86	20701	74.86	21021	1.87	20597
21	26908	22193	0.03	12.61	22193	57.50	20947	145.44	20947	70.56	21265	1.85	20846
22	26614	21799	0.03	11.69	21799	88.07	20517	134.10	20517	53.28	20825	1.81	20412
23	26104	21337	0.03	18.40	21337	63.07	19993	18.39	19993	52.92	20289	1.55	19894
24	26722	22067	0.03	14.48	22067	62.72	20793	94.80	20793	55.50	21151	1.71	20699
25	25814	20985	0.03	14.51	20985	58.68	19731	56.60	19731	41.00	20073	1.61	19618
26	27454	22665	0.03	12.07	22665	58.24	21503	108.27	21503	57.84	21805	1.77	21405
27	26822	22031	0.04	13.84	22031	59.62	20779	59.76	20779	55.76	21123	1.91	20685
28	25792	21047	0.03	17.62	21049	77.52	19741	60.50	19743	62.07	20111	1.55	19629
29	25986	21223	0.03	12.93	21223	83.67	19903	68.71	19903	47.48	20225	1.56	19792
30	26022	21339	0.03	13.22	21339	63.27	20115	370.76	20115	67.32	20391	1.77	20003
31	27318	22553	0.04	11.15	22553	70.34	21403	16.53	21403	57.97	21725	1.96	21300
32	26322	21761	0.03	13.94	21761	58.28	20413	73.00	20415	82.79	20761	1.85	20321
33	26512	21985	0.03	9.75	21985	69.50	20625	14.64	20625	45.17	20981	1.72	20494
34	25914	21281	0.03	11.35	21281	47.20	20003	49.08	20003	52.45	20371	1.80	19890
35	26166	21447	0.03	15.03	21447	71.28	19999	96.93	20001	65.41	20349	1.71	19889
36	27018	22283	0.03	13.46	22285	58.30	21025	118.71	21027	52.37	21325	1.85	20927
37	26196	21635	0.03	9.57	21639	62.07	20261	65.79	20261	75.60	20559	1.58	20153
38	26652	22017	0.03	11.22	22017	56.31	20923	211.38	20923	69.93	21221	1.86	20824
39	25252	20623	0.03	17.13	20623	59.66	19277	24.41	19279	60.55	19565	1.64	19157
40	25840	20995	0.03	9.76	20995	52.46	19865	1199.05	19865	52.68	20221	1.63	19773

Table 18: Results on instance set Centered Depot with UDD and $l = 20$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	7066	6149	0.01	2.32	6149	27.30	5943	3.46	5943	29.11	5995	0.10	5853
2	6388	5461	0.00	1.67	5461	14.07	5229	2.07	5229	19.78	5303	0.07	5133
3	6740	5829	0.01	1.76	5829	14.42	5551	6.12	5551	22.07	5609	0.10	5450
4	6552	5619	0.01	1.23	5619	20.11	5415	1.86	5415	17.31	5437	0.08	5314
5	6922	5981	0.01	1.64	5981	29.14	5789	2.42	5789	27.60	5861	0.09	5691
6	7358	6355	0.01	1.52	6355	24.07	6197	12.30	6199	34.19	6245	0.13	6090
7	6634	5655	0.01	3.15	5655	22.65	5443	3.52	5443	26.73	5515	0.09	5329
8	6364	5329	0.01	1.64	5329	26.97	5119	3.13	5119	32.94	5175	0.07	5020
9	7310	6317	0.01	2.30	6317	37.54	6157	12.87	6157	28.94	6201	0.11	6071
10	6320	5387	0.01	1.47	5387	23.91	5187	9.71	5187	45.60	5247	0.07	5061
11	6364	5465	0.01	2.18	5465	24.99	5249	3.96	5249	25.02	5303	0.08	5146
12	7000	6093	0.01	2.92	6093	42.17	5853	15.22	5853	40.25	5905	0.11	5745
13	7262	6217	0.01	1.58	6217	24.22	5983	2.43	5983	41.18	6073	0.10	5891
14	6638	5643	0.01	2.21	5643	28.68	5451	22.30	5451	30.33	5485	0.09	5353
15	6262	5367	0.01	2.07	5367	29.61	5109	1.80	5109	14.28	5163	0.07	4997
16	6180	5357	0.01	1.55	5357	23.48	5117	2.38	5117	26.46	5183	0.07	4994
17	6816	5861	0.01	2.01	5861	31.44	5659	2.38	5659	35.50	5687	0.08	5567
18	6424	5549	0.01	1.55	5549	32.64	5369	2.07	5369	31.54	5409	0.08	5280
19	6530	5551	0.01	2.05	5551	22.84	5341	2.61	5341	35.31	5417	0.08	5245
20	6236	5369	0.01	1.34	5369	11.30	5145	3.77	5145	20.06	5227	0.07	5039
21	6622	5761	0.01	2.67	5761	17.67	5527	9.51	5527	24.75	5581	0.10	5427
22	6734	5743	0.01	1.58	5743	32.53	5571	2.12	5571	17.12	5657	0.08	5479
23	6202	5273	0.01	1.81	5273	10.42	5025	2.81	5025	21.15	5109	0.07	4930
24	5802	4921	0.00	2.41	4921	31.41	4681	3.90	4681	11.36	4745	0.06	4602
25	6728	5849	0.01	1.77	5849	13.68	5607	2.20	5607	17.30	5665	0.09	5534
26	6442	5597	0.00	2.48	5597	25.00	5321	2.33	5321	24.56	5393	0.07	5231
27	6304	5417	0.01	1.73	5417	26.69	5189	3.13	5189	48.97	5241	0.08	5103
28	6268	5301	0.01	1.38	5301	30.77	5123	7.39	5123	37.82	5181	0.07	5010
29	6344	5425	0.01	1.53	5425	15.83	5211	1.89	5211	12.13	5263	0.07	5121
30	6222	5289	0.01	1.61	5289	31.58	5037	1.50	5037	16.52	5147	0.07	4965
31	6460	5519	0.01	1.62	5519	20.97	5325	4.99	5325	31.76	5363	0.07	5226
32	6550	5643	0.01	2.17	5643	21.88	5443	2.23	5443	23.61	5487	0.09	5349
33	6582	5681	0.01	1.61	5681	27.48	5491	2.20	5491	31.02	5547	0.08	5398
34	6904	6049	0.01	3.53	6049	25.20	5815	12.19	5815	32.39	5869	0.11	5701
35	6188	5309	0.01	1.59	5309	40.81	5067	22.08	5067	39.47	5113	0.08	4958
36	6108	5207	0.01	1.39	5207	10.47	4957	2.55	4957	22.16	4989	0.07	4857
37	6622	5679	0.01	2.63	5679	26.71	5439	7.43	5439	30.24	5503	0.09	5339
38	6444	5569	0.01	1.30	5569	24.76	5325	3.48	5325	18.41	5395	0.08	5243
39	6534	5563	0.01	1.49	5563	14.34	5371	1.76	5371	13.37	5447	0.07	5276
40	6592	5701	0.01	5.60	5701	39.23	5475	3.40	5475	49.30	5539	0.08	5376

Table 19: Results on instance set Centered Depot with UDD and $l = 40$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	13300	11363	0.01	5.74	11363	45.15	10841	20.61	10841	52.43	10987	0.31	10732
2	13662	11697	0.02	4.95	11701	55.36	11179	5.11	11179	36.09	11291	0.38	11076
3	13866	11907	0.02	5.34	11907	39.05	11483	34.59	11483	52.51	11611	0.38	11382
4	13626	11757	0.01	5.05	11757	30.83	11333	7.75	11335	38.81	11459	0.35	11223
5	13382	11491	0.01	5.19	11491	45.55	10985	6.77	10985	40.18	11153	0.32	10870
6	12866	11033	0.01	4.82	11033	32.68	10555	4.85	10555	53.96	10667	0.28	10442
7	13374	11363	0.01	4.25	11363	29.03	10909	11.78	10909	59.50	11057	0.32	10790
8	12590	10677	0.01	3.32	10677	56.00	10199	3.64	10199	26.67	10337	0.26	10073
9	13034	11049	0.01	4.12	11049	37.09	10609	4.38	10609	57.73	10727	0.29	10490
10	12786	10861	0.01	5.40	10861	37.48	10443	7.68	10443	70.59	10587	0.29	10348
11	13828	11829	0.02	4.14	11829	34.62	11437	18.97	11437	47.43	11553	0.35	11306
12	13794	11779	0.02	4.77	11779	41.53	11367	5.57	11367	54.85	11499	0.40	11259
13	13098	11227	0.01	3.17	11227	18.75	10773	14.53	10773	43.65	10941	0.31	10652
14	13092	11173	0.01	4.26	11173	38.80	10677	6.03	10677	52.08	10765	0.31	10554
15	13338	11311	0.01	3.85	11311	25.28	10889	4.13	10889	49.39	10993	0.32	10768
16	13512	11531	0.02	5.36	11531	35.62	11067	6.33	11069	70.79	11211	0.36	10961
17	12586	10727	0.01	4.02	10727	34.88	10223	7.42	10223	45.52	10363	0.27	10096
18	12576	10721	0.01	3.41	10721	35.23	10195	8.18	10195	46.41	10351	0.29	10083
19	13352	11345	0.01	3.29	11345	19.33	10895	4.87	10895	40.60	11011	0.28	10795
20	12706	10697	0.01	4.65	10697	33.37	10201	13.08	10201	50.30	10319	0.27	10091
21	13568	11767	0.01	4.12	11767	30.69	11263	44.22	11263	62.16	11403	0.34	11135
22	13006	11071	0.01	4.76	11071	34.96	10653	8.38	10653	56.71	10807	0.30	10548
23	13468	11521	0.01	4.53	11521	37.10	11081	39.30	11081	63.69	11215	0.31	10966
24	12844	10885	0.01	3.03	10885	55.23	10437	120.80	10437	69.67	10563	0.28	10313
25	13534	11573	0.01	5.60	11573	53.13	11107	11.92	11107	93.09	11251	0.34	10993
26	13168	11171	0.01	3.35	11171	34.62	10775	7.67	10775	80.89	10915	0.31	10654
27	14154	12217	0.02	3.29	12217	36.22	11785	22.15	11785	49.62	11923	0.37	11678
28	12706	10743	0.01	2.93	10743	19.27	10305	4.62	10305	49.16	10441	0.27	10193
29	12812	10953	0.01	5.51	10953	41.81	10401	4.52	10401	61.40	10561	0.30	10266
30	12880	11125	0.01	4.62	11125	35.38	10569	14.56	10569	44.43	10719	0.32	10457
31	13238	11511	0.01	9.98	11511	35.31	10867	5.91	10867	55.74	10997	0.32	10789
32	13476	11643	0.02	4.39	11643	41.66	11167	12.70	11167	93.07	11283	0.34	11048
33	12334	10485	0.01	3.88	10485	20.57	10039	14.35	10039	41.72	10167	0.27	9924
34	12120	10323	0.01	3.33	10323	33.98	9867	6.55	9869	46.45	10041	0.27	9745
35	13804	11817	0.01	3.81	11817	69.10	11365	14.91	11365	50.50	11467	0.33	11242
36	13172	11241	0.01	5.27	11241	59.36	10693	23.12	10693	71.56	10831	0.29	10600
37	13770	11901	0.02	5.26	11901	74.19	11429	4.74	11429	46.08	11547	0.37	11312
38	13590	11721	0.01	3.64	11721	37.75	11261	12.71	11261	42.35	11375	0.32	11145
39	13848	11859	0.01	7.08	11859	22.76	11421	15.09	11421	36.13	11513	0.33	11298
40	13364	11437	0.02	4.92	11437	48.74	10965	4.87	10965	52.07	11107	0.37	10834

Table 20: Results on instance set Centered Depot with UDD and $l = 60$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	19952	17105	0.02	11.56	17105	57.87	16357	93.19	16357	69.36	16527	0.74	16235
2	20092	16935	0.02	6.61	16935	35.05	16259	76.63	16259	102.91	16447	0.69	16145
3	17914	15059	0.01	7.06	15059	41.23	14211	13.01	14211	54.67	14455	0.52	14082
4	18966	16099	0.02	12.32	16099	95.83	15359	63.81	15359	71.02	15589	0.62	15241
5	20018	16953	0.02	12.18	16953	50.43	16305	62.86	16305	49.02	16471	0.70	16179
6	20020	17069	0.02	9.37	17069	72.32	16277	8.30	16279	57.72	16539	0.71	16169
7	20370	17429	0.02	8.08	17429	44.05	16767	15.07	16767	87.14	16929	0.78	16659
8	20024	17267	0.02	7.67	17267	73.43	16461	27.96	16461	88.97	16647	0.76	16333
9	21068	18261	0.02	7.57	18261	52.13	17591	296.03	17591	102.80	17763	0.83	17478
10	20826	17921	0.02	8.51	17921	51.88	17269	16.13	17269	70.70	17441	0.77	17163
11	19500	16659	0.02	6.62	16659	40.81	15809	16.17	15809	30.97	15999	0.67	15687
12	20744	17863	0.02	15.04	17863	42.44	17175	25.04	17175	52.38	17363	0.79	17073
13	19530	16783	0.02	6.51	16783	54.11	16001	23.61	16003	72.35	16177	0.72	15867
14	19420	16487	0.02	7.48	16487	79.69	15751	49.34	15751	90.51	15993	0.68	15646
15	20564	17575	0.02	12.78	17575	63.29	16901	10.34	16903	124.36	17049	0.79	16804
16	19342	16467	0.02	7.97	16467	46.72	15679	20.30	15681	68.02	15905	0.65	15536
17	19268	16359	0.02	6.40	16359	47.99	15669	9.52	15673	78.56	15875	0.64	15553
18	19062	16227	0.02	5.91	16227	39.55	15429	21.88	15429	69.22	15591	0.67	15328
19	19884	17061	0.02	8.41	17061	58.22	16347	19.90	16347	70.46	16563	0.75	16228
20	20210	17129	0.02	7.11	17129	43.54	16447	10.16	16447	51.22	16645	0.72	16339
21	19584	16681	0.02	6.05	16681	90.51	15951	184.53	15953	86.94	16171	0.67	15840
22	20188	17259	0.02	9.20	17259	54.46	16557	41.75	16557	71.65	16783	0.72	16439
23	20670	17799	0.02	11.88	17799	49.77	17043	19.59	17043	54.33	17259	0.76	16921
24	19476	16579	0.02	6.17	16579	50.36	15815	15.01	15817	74.42	16011	0.65	15691
25	19946	17083	0.02	7.72	17083	65.93	16297	7.95	16297	48.12	16527	0.76	16200
26	19412	16679	0.02	9.92	16679	45.74	15873	44.99	15875	67.82	16063	0.71	15745
27	19858	16877	0.02	6.83	16877	73.31	16167	18.35	16167	69.05	16397	0.75	16063
28	19634	16869	0.02	13.96	16869	48.99	16129	18.58	16133	68.89	16309	0.75	15999
29	19534	16657	0.02	4.98	16657	88.38	15909	27.29	15909	66.62	16141	0.69	15798
30	18860	15919	0.02	6.33	15919	55.19	15175	63.04	15175	89.11	15375	0.57	15046
31	20770	17673	0.02	6.46	17673	49.95	16949	22.26	16949	72.19	17109	0.77	16836
32	19358	16415	0.02	8.18	16415	72.63	15743	22.53	15743	67.35	15947	0.64	15615
33	20472	17703	0.02	8.49	17703	48.18	16959	23.75	16959	88.12	17155	0.81	16860
34	20078	17157	0.02	9.75	17157	61.61	16497	27.42	16497	85.96	16679	0.76	16381
35	20386	17395	0.02	8.10	17395	45.75	16707	29.07	16707	56.85	16893	0.74	16583
36	19818	16903	0.02	14.66	16903	60.39	16257	23.40	16257	74.71	16469	0.68	16143
37	19914	16877	0.02	7.28	16877	54.02	16091	7.18	16091	43.59	16329	0.71	15971
38	18650	15883	0.02	5.00	15883	32.01	15029	12.29	15029	73.36	15215	0.59	14909
39	19510	16699	0.02	9.39	16699	64.71	15941	9.73	15941	125.40	16125	0.68	15839
40	19570	16829	0.02	7.02	16829	38.21	16079	20.34	16079	78.65	16309	0.66	15960

Table 21: Results on instance set Centered Depot with UDD and $l = 80$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	28374	24449	0.03	10.32	24449	146.71	23485	18.18	23487	138.75	23721	1.58	23367
2	26506	22751	0.03	12.65	22751	66.95	21681	33.62	21681	89.20	21945	1.37	21549
3	26932	23039	0.03	7.55	23039	49.31	22089	124.77	22089	100.77	22363	1.33	21959
4	26794	22667	0.03	13.52	22669	65.83	21721	12.98	21721	79.04	22017	1.31	21614
5	26106	22205	0.03	10.39	22205	52.57	21155	20.64	21155	119.15	21437	1.23	21030
6	26374	22573	0.03	9.57	22573	68.40	21595	21.31	21595	77.17	21889	1.29	21468
7	26994	23097	0.03	16.98	23097	72.48	22071	17.84	22073	100.53	22357	1.42	21951
8	26738	22919	0.03	12.79	22919	87.88	21843	124.61	21843	97.68	22099	1.37	21724
9	25530	21811	0.02	7.27	21811	44.75	20899	15.51	20903	127.94	21189	1.16	20784
10	27608	23691	0.03	11.04	23691	79.04	22721	21.31	22723	134.34	22975	1.45	22602
11	26458	22689	0.03	12.20	22689	52.98	21551	108.49	21551	115.62	21829	1.35	21431
12	27020	22917	0.03	12.10	22917	125.81	21999	25.04	22001	136.53	22273	1.40	21875
13	26298	22417	0.03	12.43	22417	67.96	21369	12.93	21369	85.15	21617	1.37	21248
14	27896	23845	0.03	19.08	23845	78.24	22865	4113.51	22865	89.78	23107	1.50	22738
15	25474	21669	0.02	8.01	21669	68.98	20573	78.21	20573	58.53	20815	1.18	20431
16	26728	22879	0.03	15.60	22879	73.15	21973	44.19	21973	106.62	22213	1.37	21852
17	26452	22597	0.03	11.15	22597	115.39	21611	181.73	21611	88.20	21901	1.32	21483
18	26450	22583	0.02	30.30	22585	59.23	21559	115.73	21561	73.77	21871	1.24	21445
19	25706	21859	0.03	7.46	21859	54.12	20907	13.09	20907	125.21	21173	1.25	20785
20	25894	22093	0.03	10.45	22093	130.04	21061	35.39	21061	104.33	21319	1.24	20928
21	25958	22061	0.02	12.82	22061	70.04	21139	93.64	21139	102.97	21395	1.21	21010
22	28060	24135	0.03	13.75	24135	66.52	23119	33.49	23119	95.53	23381	1.57	23011
23	26256	22499	0.03	10.30	22499	51.14	21459	115.85	21461	86.76	21725	1.32	21353
24	25716	22029	0.03	8.18	22029	83.60	20953	21.97	20953	69.83	21279	1.20	20819
25	25652	21729	0.02	7.65	21729	59.54	20675	95.34	20675	83.29	20945	1.17	20550
26	26786	22909	0.03	14.53	22909	58.59	21839	61.89	21839	96.84	22145	1.37	21711
27	26152	22247	0.03	16.45	22247	68.16	21265	42.51	21265	109.28	21547	1.33	21138
28	26454	22577	0.03	7.65	22577	72.99	21557	12.89	21557	136.43	21841	1.30	21414
29	27252	23261	0.03	15.57	23261	98.64	22203	10.74	22203	75.65	22463	1.35	22103
30	26890	23199	0.03	20.63	23199	69.86	22053	15.75	22053	128.49	22301	1.37	21940
31	27170	23189	0.03	7.01	23189	43.71	22191	31.55	22191	81.83	22461	1.38	22067
32	26508	22555	0.03	9.91	22555	59.26	21591	19.88	21591	90.03	21805	1.33	21477
33	25928	21975	0.03	7.98	21975	52.80	20999	33.89	21001	65.16	21235	1.31	20874
34	26184	22399	0.03	12.35	22399	55.37	21367	32.59	21367	94.51	21633	1.24	21252
35	24828	20939	0.02	5.71	20939	60.11	19963	14.78	19963	84.19	20239	1.07	19850
36	26496	22715	0.03	13.30	22715	73.86	21681	21.23	21685	59.46	21939	1.31	21552
37	26532	22553	0.03	10.13	22553	37.33	21619	9.26	21621	73.16	21887	1.28	21499
38	26026	22103	0.02	10.60	22105	54.08	21033	100.32	21033	85.21	21325	1.21	20914
39	26818	22837	0.03	8.80	22837	66.57	22005	36.81	22005	94.86	22247	1.34	21876
40	26708	22807	0.03	9.10	22807	84.78	21779	14.23	21779	77.48	22009	1.28	21677

Table 22: Results on instance set Centered Depot with UDD and $l = 100$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	31832	27169	0.03	16.74	27169	69.44	25861	72.12	25861	134.05	26269	1.94	25728
2	33994	29227	0.04	17.33	29227	85.65	28007	1176.28	28007	168.17	28295	2.41	27892
3	32744	28085	0.03	14.09	28085	65.03	26711	48.91	26713	108.22	27039	2.23	26583
4	35024	29849	0.04	21.03	29849	117.31	28719	64.76	28721	139.62	29043	2.42	28603
5	32814	27987	0.03	13.30	27987	74.68	26797	325.17	26799	93.92	27123	2.14	26648
6	33050	28215	0.03	11.10	28215	79.02	26867	58.43	26867	89.80	27157	2.15	26743
7	33574	28807	0.04	14.17	28807	87.81	27507	185.47	27507	136.82	27801	2.24	27390
8	32352	27539	0.03	12.00	27539	69.23	26143	37.35	26145	110.50	26503	2.07	26010
9	32406	27759	0.03	29.06	27759	101.57	26409	25.62	26413	104.90	26731	2.11	26286
10	32376	27685	0.03	22.40	27685	87.72	26359	966.51	26359	107.03	26797	2.07	26216
11	32864	27891	0.03	13.22	27891	75.83	26627	20.98	26627	126.96	26977	1.95	26498
12	33446	28457	0.04	12.54	28467	76.39	27271	107.79	27271	127.06	27545	2.23	27138
13	32040	27187	0.03	12.14	27187	74.50	25807	89.61	25809	131.23	26175	2.00	25678
14	31932	27217	0.03	11.53	27217	70.59	25965	43.96	25967	84.64	26289	1.93	25831
15	32590	27963	0.03	11.38	27963	97.69	26599	69.17	26599	134.44	26917	2.13	26479
16	32550	27763	0.03	18.05	27763	99.24	26439	27.55	26439	82.24	26787	2.00	26330
17	32982	27969	0.03	9.29	27973	82.10	26895	67.06	26897	141.49	27229	2.00	26770
18	32728	27981	0.03	14.87	27981	54.53	26607	266.25	26609	137.28	26947	2.19	26489
19	32530	27697	0.03	10.61	27697	75.87	26423	133.76	26427	147.43	26737	2.10	26287
20	33722	28779	0.04	14.44	28779	102.47	27617	176.84	27617	185.11	27895	2.31	27485
21	33384	28755	0.04	18.14	28755	70.26	27507	34.78	27513	130.80	27871	2.27	27379
22	33266	28389	0.03	32.14	28389	95.02	27225	2756.20	27225	141.74	27569	2.18	27102
23	31900	27101	0.03	13.01	27101	75.40	25665	52.74	25665	81.96	26011	1.90	25552
24	33376	28387	0.03	19.01	28387	86.70	27163	85.36	27163	139.69	27519	2.09	27025
25	32320	27551	0.03	11.01	27551	85.26	26085	186.22	26087	79.70	26429	2.01	25934
26	33732	28867	0.03	21.35	28867	85.72	27663	2212.61	27665	109.39	27969	2.22	27517
27	33936	28991	0.04	13.02	28991	90.67	27731	108.56	27731	95.94	28049	2.33	27625
28	32332	27283	0.03	19.51	27283	92.49	26027	77.17	26029	82.37	26383	1.94	25903
29	31868	27011	0.03	24.16	27011	52.70	25785	182.34	25785	107.25	26099	1.87	25644
30	33292	28439	0.03	18.30	28439	71.81	27099	380.99	27099	117.86	27475	2.24	26976
31	34086	29145	0.04	12.16	29145	70.40	27941	43.85	27943	103.62	28277	2.37	27832
32	34356	29409	0.04	16.66	29409	123.64	28141	20.31	28141	129.23	28523	2.40	28025
33	32976	28067	0.03	11.65	28071	85.11	26701	44.37	26701	88.99	27039	2.16	26554
34	33728	28897	0.04	18.59	28897	68.96	27653	19.78	27653	112.90	27985	2.28	27545
35	33940	29149	0.03	12.78	29151	76.99	27817	65.65	27817	106.16	28147	2.20	27696
36	33484	28179	0.04	14.26	28179	66.13	27083	46.68	27083	113.72	27409	2.24	26958
37	32564	27641	0.03	10.94	27641	79.52	26461	60.56	26461	117.90	26773	1.94	26327
38	34130	28969	0.04	12.55	28969	100.60	27839	43.49	27839	141.32	28201	2.34	27724
39	33008	28113	0.03	17.52	28117	81.44	26889	21.25	26889	154.27	27209	2.06	26769
40	32834	28023	0.03	11.80	28023	69.88	26705	7200.00	26707	83.67	27045	2.02	26577

Table 23: Results on instance set Centered Depot with CBD and $l = 20$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	5246	4343	0.01	5.01	4343	28.99	4083	3.25	4083	12.49	4171	0.07	3974
2	4824	3867	0.00	1.29	3867	9.88	3585	2.19	3585	12.37	3657	0.05	3472
3	5290	4419	0.01	2.44	4419	27.89	4117	2.87	4117	25.59	4199	0.07	4035
4	5458	4503	0.01	1.50	4503	8.94	4203	2.10	4203	11.59	4269	0.07	4115
5	5502	4473	0.01	1.40	4473	18.40	4261	5.85	4263	25.18	4319	0.07	4144
6	5398	4429	0.01	2.52	4429	8.14	4183	2.86	4183	28.09	4257	0.08	4092
7	4784	3913	0.01	1.64	3913	15.06	3627	15.60	3627	22.05	3725	0.06	3529
8	4768	3923	0.00	1.45	3923	10.77	3635	6.37	3635	23.71	3725	0.05	3515
9	5402	4407	0.01	2.34	4407	14.74	4155	32.22	4155	52.81	4219	0.08	4038
10	5036	4139	0.01	1.74	4139	18.64	3855	2.00	3855	14.54	3937	0.06	3769
11	5284	4387	0.00	3.15	4387	18.43	4113	14.55	4113	16.12	4191	0.06	3997
12	5682	4653	0.01	3.22	4653	19.00	4455	3.81	4455	36.75	4523	0.08	4364
13	5458	4533	0.01	1.73	4533	20.02	4273	10.37	4273	54.44	4331	0.08	4172
14	5116	4179	0.01	1.84	4179	6.97	3869	5.07	3869	25.98	3987	0.07	3762
15	4768	3839	0.00	1.59	3839	16.00	3597	1.47	3597	27.40	3685	0.05	3502
16	4748	3833	0.00	1.42	3833	6.01	3559	1.36	3559	8.93	3637	0.05	3454
17	5416	4495	0.01	2.22	4495	13.96	4169	3.99	4169	15.75	4257	0.06	4060
18	4842	3957	0.01	1.85	3957	9.10	3727	10.71	3727	22.71	3825	0.06	3599
19	5124	4075	0.01	1.69	4075	8.56	3893	2.14	3893	18.11	3977	0.06	3790
20	4990	4113	0.00	2.10	4113	18.06	3823	2.22	3823	16.15	3893	0.05	3720
21	5632	4643	0.01	2.70	4643	23.75	4383	20.12	4383	25.17	4453	0.07	4300
22	5150	4245	0.01	1.95	4245	14.80	4007	2.73	4007	18.24	4103	0.06	3896
23	4944	4023	0.00	1.69	4023	15.79	3797	1.74	3797	14.14	3841	0.05	3708
24	4738	3923	0.00	1.33	3923	13.78	3623	21.18	3623	19.67	3685	0.04	3497
25	5430	4597	0.01	3.06	4597	19.52	4227	17.25	4227	33.62	4287	0.07	4162
26	5032	4235	0.00	1.54	4235	14.33	3949	2.34	3949	17.20	4039	0.05	3839
27	5142	4217	0.01	2.04	4217	11.04	3979	5.08	3979	24.94	4019	0.06	3877
28	5076	4101	0.00	1.32	4101	15.14	3887	5.15	3887	34.36	3983	0.05	3771
29	4898	4003	0.00	2.47	4003	15.18	3693	2.39	3693	9.47	3773	0.05	3596
30	4964	4123	0.01	1.63	4123	11.45	3859	3.62	3859	19.86	3891	0.05	3742
31	4982	4041	0.00	1.48	4041	7.60	3709	1.91	3709	10.87	3785	0.05	3623
32	5124	4227	0.01	2.19	4227	17.96	3943	2.41	3943	23.05	4031	0.06	3850
33	4906	4085	0.01	2.19	4085	32.52	3779	1.78	3779	22.43	3863	0.06	3682
34	5350	4461	0.01	2.65	4461	35.41	4189	18.77	4189	27.22	4269	0.08	4051
35	5024	4173	0.00	1.78	4173	20.71	3881	7.11	3881	13.28	3987	0.05	3777
36	5016	4109	0.00	1.76	4109	9.66	3845	4.98	3845	22.43	3905	0.05	3743
37	4788	3995	0.01	2.76	3995	9.82	3673	3.63	3673	10.27	3753	0.06	3580
38	5230	4287	0.01	2.68	4287	16.11	4007	8.22	4007	37.08	4085	0.06	3887
39	5116	4161	0.01	1.89	4161	15.63	3945	10.17	3945	25.54	3999	0.06	3846
40	5432	4453	0.01	1.65	4453	18.06	4223	2.04	4223	16.17	4277	0.07	4118

Table 24: Results on instance set Centered Depot with CBD and $l = 40$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	10294	8445	0.01	3.24	8445	22.60	7899	3.95	7899	38.71	8127	0.22	7789
2	10876	8901	0.02	9.80	8901	24.23	8407	8.17	8407	49.96	8575	0.27	8308
3	11038	9043	0.02	4.64	9043	21.24	8513	16.93	8513	37.79	8661	0.27	8399
4	10506	8507	0.01	3.82	8507	25.62	7981	47.97	7981	62.71	8143	0.24	7872
5	10394	8649	0.01	4.37	8649	28.18	7979	26.88	7979	53.39	8161	0.23	7857
6	10134	8235	0.01	4.22	8235	24.82	7709	20.84	7709	36.28	7863	0.21	7593
7	10742	8859	0.01	5.52	8859	19.49	8293	7.57	8293	26.96	8457	0.23	8172
8	9908	8211	0.01	4.30	8211	33.28	7587	8.30	7587	62.99	7735	0.20	7459
9	10168	8465	0.01	4.29	8465	30.82	7813	10.69	7813	39.94	7949	0.21	7700
10	9834	8007	0.01	5.97	8007	31.05	7409	14.26	7409	48.99	7629	0.21	7308
11	10724	8763	0.01	5.04	8763	38.32	8243	6.33	8243	48.17	8419	0.25	8127
12	11016	8941	0.01	4.47	8941	24.88	8431	7.85	8431	58.93	8557	0.28	8314
13	10442	8657	0.01	4.13	8657	19.55	8005	9.81	8005	35.50	8155	0.23	7883
14	10344	8517	0.01	4.11	8517	33.35	7873	21.38	7873	24.62	8043	0.23	7755
15	10780	8957	0.01	6.63	8957	31.39	8327	25.18	8327	51.06	8467	0.24	8210
16	10864	8975	0.01	7.80	8975	28.58	8345	6.85	8345	28.62	8535	0.26	8224
17	10206	8323	0.01	6.08	8323	30.71	7691	3.44	7691	28.50	7891	0.20	7585
18	10106	8287	0.01	3.30	8287	19.59	7679	6.96	7679	40.60	7859	0.21	7554
19	9940	8209	0.01	5.02	8209	17.97	7469	23.95	7469	22.46	7645	0.21	7367
20	9480	7781	0.01	3.55	7781	21.90	7155	4.32	7155	45.73	7373	0.19	7065
21	10822	8847	0.01	5.56	8847	31.52	8267	16.49	8267	45.79	8429	0.26	8165
22	10710	8763	0.01	5.08	8763	24.99	8225	48.35	8227	72.71	8371	0.22	8095
23	10298	8535	0.01	3.30	8535	16.50	7951	3.64	7951	37.08	8119	0.23	7853
24	10522	8549	0.01	3.59	8549	29.95	7993	28.78	7993	58.87	8147	0.20	7870
25	10592	8593	0.01	4.34	8593	19.44	8005	14.15	8005	37.75	8205	0.24	7877
26	10428	8401	0.01	4.56	8401	17.47	7851	26.34	7851	36.78	8063	0.21	7733
27	10832	8907	0.01	3.70	8907	26.86	8337	18.83	8337	64.99	8503	0.27	8228
28	10230	8243	0.01	3.45	8243	16.89	7699	10.22	7699	42.57	7825	0.20	7580
29	10342	8541	0.01	4.18	8541	23.10	7945	32.82	7945	40.50	8105	0.22	7831
30	11030	9055	0.01	4.81	9055	32.63	8499	104.56	8499	71.44	8615	0.24	8393
31	10640	8781	0.01	8.09	8781	26.11	8181	32.62	8183	41.34	8309	0.25	8057
32	10450	8675	0.01	5.86	8675	29.78	8009	27.73	8009	47.53	8177	0.25	7906
33	10336	8525	0.01	3.55	8525	15.53	7843	11.78	7843	24.56	8007	0.21	7723
34	9842	8149	0.01	2.61	8149	29.97	7493	14.08	7493	33.55	7665	0.19	7370
35	10444	8485	0.01	6.10	8485	29.65	7955	4.87	7955	38.59	8147	0.24	7863
36	9830	7891	0.01	2.78	7891	21.31	7337	4.88	7337	25.24	7543	0.21	7218
37	10820	9075	0.01	5.96	9075	28.95	8459	7.26	8459	54.31	8603	0.27	8353
38	10906	8955	0.01	6.94	8955	28.98	8333	100.01	8333	72.44	8527	0.23	8243
39	10730	8835	0.01	4.55	8835	30.70	8211	7.77	8211	41.40	8399	0.25	8108
40	11188	9261	0.02	4.01	9261	39.96	8599	4.88	8599	45.85	8775	0.28	8489

Table 25: Results on instance set Centered Depot with CBD and $l = 60$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	16160	13299	0.02	8.85	13299	76.65	12341	33.14	12341	55.74	12525	0.56	12216
2	15262	12369	0.02	6.44	12369	25.20	11527	81.48	11527	84.75	11795	0.49	11409
3	14468	11773	0.01	3.82	11773	41.82	10849	7.20	10851	43.78	11025	0.37	10721
4	14778	12091	0.02	5.92	12091	30.08	11141	44.27	11141	58.02	11449	0.45	11020
5	15510	12673	0.02	11.79	12675	34.59	11777	13.71	11777	43.24	12053	0.52	11683
6	15482	12809	0.02	10.55	12809	46.38	11745	83.13	11745	74.44	12001	0.53	11623
7	15656	12895	0.02	9.84	12895	42.09	11921	21.00	11929	45.91	12153	0.56	11821
8	15232	12589	0.02	7.47	12589	125.65	11565	23.61	11565	105.60	11829	0.55	11443
9	16610	13609	0.02	7.23	13609	55.21	12781	47.45	12781	86.87	13011	0.62	12677
10	16242	13289	0.02	7.48	13289	33.69	12479	134.73	12479	72.00	12729	0.57	12364
11	15386	12533	0.02	5.43	12533	34.72	11601	23.86	11601	44.81	11835	0.48	11501
12	15806	12955	0.02	6.09	12955	59.07	11961	7.98	11961	53.89	12225	0.57	11842
13	15928	13033	0.02	12.52	13033	39.36	12105	9.71	12107	68.59	12321	0.52	12005
14	14806	12129	0.02	7.31	12129	35.09	11151	94.50	11153	59.80	11459	0.51	11037
15	15932	13199	0.02	8.59	13199	44.73	12157	15.12	12157	63.73	12461	0.59	12032
16	15076	12273	0.02	6.85	12273	33.91	11211	8.72	11211	46.59	11491	0.45	11124
17	14780	12059	0.02	7.41	12059	55.24	11119	8.73	11119	76.11	11337	0.46	11009
18	15684	12701	0.02	7.31	12701	25.70	11807	94.58	11807	67.32	12103	0.51	11700
19	15350	12615	0.02	8.65	12615	36.30	11597	56.94	11599	41.15	11845	0.55	11474
20	15572	12709	0.02	10.92	12709	36.97	11829	9.08	11829	45.67	12123	0.52	11722
21	15192	12577	0.02	8.58	12577	36.17	11591	15.86	11591	62.47	11841	0.51	11475
22	15756	12887	0.02	5.61	12887	42.49	12025	10.46	12025	52.96	12267	0.54	11920
23	16086	13191	0.02	7.86	13191	59.33	12307	10.11	12307	50.81	12553	0.58	12201
24	14996	12275	0.02	8.69	12275	40.92	11249	496.46	11251	50.06	11475	0.46	11127
25	15348	12637	0.02	8.36	12637	45.90	11691	49.21	11691	38.39	11941	0.56	11571
26	16248	13317	0.02	8.57	13317	38.30	12373	13.16	12373	59.76	12659	0.56	12238
27	15578	12785	0.02	8.12	12785	52.76	11833	7.14	11833	42.89	12127	0.54	11727
28	15510	12719	0.02	6.77	12719	32.02	11779	39.44	11779	63.07	12043	0.54	11660
29	15352	12585	0.02	12.39	12585	31.94	11613	51.41	11613	54.59	11851	0.51	11509
30	14246	11529	0.01	5.57	11529	37.00	10533	19.21	10533	54.36	10781	0.42	10408
31	16002	13129	0.02	10.70	13129	43.25	12259	8.92	12259	54.41	12501	0.57	12119
32	16006	13089	0.02	7.79	13097	35.31	12137	10.86	12137	48.47	12333	0.49	12022
33	15742	13083	0.02	8.68	13083	73.93	12107	55.29	12107	69.17	12333	0.55	11987
34	15766	12905	0.02	6.17	12905	36.67	12045	13.33	12045	48.78	12333	0.55	11917
35	15638	12881	0.02	11.78	12881	37.01	11881	47.82	11883	82.60	12119	0.55	11778
36	15402	12519	0.02	6.36	12519	40.63	11663	21.06	11663	100.47	11941	0.50	11538
37	15646	12885	0.02	7.67	12885	45.37	11853	1169.76	11853	66.89	12161	0.53	11744
38	14688	11943	0.01	4.74	11943	29.67	10897	16.43	10897	65.07	11191	0.43	10780
39	16032	13241	0.02	8.86	13241	57.46	12311	33.60	12311	80.63	12565	0.55	12192
40	15334	12423	0.02	6.49	12433	42.47	11509	14.06	11511	75.14	11743	0.49	11387

Table 26: Results on instance set Centered Depot with CBD and $l = 80$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	22022	18157	0.03	9.55	18169	58.85	16879	37.56	16879	68.59	17175	1.18	16767
2	21086	17249	0.03	9.88	17253	33.80	16083	17.13	16083	81.49	16447	1.05	15955
3	20836	16979	0.03	11.00	16979	37.16	15731	50.12	15731	112.62	16057	1.03	15618
4	21160	17351	0.02	11.03	17351	41.16	16035	127.02	16037	106.66	16395	1.03	15920
5	20614	16851	0.02	12.11	16855	44.02	15489	14.36	15489	108.53	15813	0.95	15383
6	20528	16777	0.02	10.97	16777	48.24	15527	140.25	15527	104.99	15869	0.97	15412
7	21586	17669	0.03	9.32	17669	43.48	16447	22.13	16447	38.83	16729	1.08	16326
8	21880	18033	0.03	14.90	18033	70.01	16753	46.84	16753	72.43	17095	1.08	16662
9	20072	16295	0.02	7.18	16295	50.32	15043	27.10	15045	87.12	15369	0.87	14934
10	21986	18113	0.03	10.46	18113	43.81	16791	25.12	16793	78.78	17101	1.18	16658
11	20516	16745	0.03	9.20	16745	58.58	15359	26.98	15359	56.45	15689	1.03	15233
12	22000	17915	0.03	13.04	17915	44.56	16795	7200.00	16791	68.76	17173	1.09	16677
13	20826	17083	0.02	9.49	17083	74.56	15887	108.69	15889	127.63	16229	1.06	15757
14	21860	17965	0.03	14.94	17965	36.92	16767	20.98	16767	68.57	17145	1.15	16645
15	21280	17429	0.02	8.35	17429	47.19	16119	132.41	16119	66.24	16455	0.91	16002
16	20776	17031	0.03	7.73	17033	45.94	15907	23.29	15907	96.83	16235	1.04	15791
17	21024	17183	0.03	8.94	17183	43.29	15939	149.80	15939	62.76	16335	1.02	15809
18	20384	16655	0.02	11.03	16655	44.37	15319	18.19	15321	49.73	15741	0.95	15210
19	20514	16867	0.02	10.54	16867	37.61	15585	13.48	15585	94.46	15969	0.94	15472
20	20342	16665	0.02	13.72	16665	40.44	15281	28.75	15285	74.83	15661	0.95	15174
21	20836	16831	0.02	10.70	16831	40.54	15639	14.92	15639	79.18	16023	0.93	15514
22	22274	18273	0.03	8.15	18273	45.35	17061	328.08	17063	72.42	17387	1.18	16951
23	20702	16927	0.02	9.41	16927	40.66	15631	44.90	15633	106.58	15963	1.00	15496
24	20406	16695	0.02	8.75	16695	38.44	15435	19.75	15435	74.11	15795	0.89	15318
25	19990	16333	0.02	7.65	16333	59.51	14981	23.29	14981	65.97	15313	0.89	14858
26	20760	17055	0.02	11.74	17055	50.64	15823	20.28	15823	54.36	16173	1.00	15715
27	21184	17385	0.02	15.57	17385	62.93	16039	26.04	16039	64.93	16361	1.02	15915
28	20022	16211	0.02	12.05	16211	48.32	14905	14.38	14905	60.71	15197	0.98	14760
29	20600	16847	0.03	7.77	16847	43.11	15579	170.12	15579	58.07	15971	1.03	15468
30	21174	17435	0.03	15.34	17435	47.53	16103	13.38	16103	54.19	16469	1.05	15995
31	21112	17203	0.02	9.94	17203	47.71	15983	66.80	15985	97.44	16291	1.03	15860
32	20660	16881	0.02	10.38	16881	39.57	15615	21.65	15615	97.49	15985	1.00	15500
33	20298	16775	0.02	15.99	16775	53.17	15281	139.02	15283	70.27	15623	0.96	15163
34	20502	16771	0.02	9.70	16771	41.04	15497	3868.82	15497	104.58	15825	0.95	15354
35	19304	15801	0.02	10.59	15801	32.68	14367	20.02	14367	88.57	14771	0.81	14257
36	21020	17289	0.03	25.85	17293	41.86	16023	241.21	16029	66.34	16319	1.01	15890
37	20194	16581	0.02	11.39	16581	35.37	15195	66.55	15195	72.83	15555	0.98	15077
38	20404	16601	0.02	10.04	16601	47.66	15313	22.28	15313	79.60	15645	0.95	15202
39	20272	16661	0.02	11.29	16661	55.26	15367	23.21	15367	65.99	15681	1.02	15246
40	20894	17025	0.02	8.44	17025	70.19	15687	103.84	15687	62.04	16037	0.96	15576

Table 27: Results on instance set Centered Depot with CBD and $l = 100$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	25212	20505	0.04	13.47	20505	60.08	19017	636.85	19019	82.18	19447	1.54	18895
2	26576	21745	0.03	16.83	21745	57.45	20139	338.64	20139	65.35	20599	1.87	20006
3	26040	21147	0.03	11.82	21147	68.19	19663	17.47	19663	90.62	20109	1.75	19543
4	26930	22113	0.04	15.94	22113	54.15	20583	20.47	20585	124.94	20957	1.95	20467
5	25198	20425	0.03	12.46	20425	63.35	18863	279.37	18865	90.55	19313	1.68	18737
6	25360	20605	0.03	29.85	20611	61.71	18989	83.99	18989	83.46	19439	1.67	18861
7	26434	21633	0.03	14.53	21633	77.89	20143	48.68	20143	84.59	20497	1.76	20023
8	24666	20081	0.03	12.41	20081	66.68	18477	117.73	18479	107.72	18897	1.58	18350
9	26328	21497	0.03	13.84	21497	74.86	19873	31.82	19875	79.91	20341	1.67	19758
10	25228	20625	0.03	10.53	20625	78.16	19011	41.85	19015	71.05	19469	1.60	18879
11	25638	21033	0.03	14.32	21033	77.28	19385	284.42	19385	64.74	19801	1.57	19267
12	26314	21453	0.03	13.51	21453	50.16	19991	83.70	19993	108.06	20373	1.81	19879
13	24642	20173	0.03	17.54	20173	62.38	18497	1383.14	18499	81.81	18949	1.54	18370
14	25712	20853	0.03	9.96	20865	52.30	19261	10.89	19261	45.68	19677	1.51	19139
15	25966	21319	0.03	30.05	21321	68.57	19677	450.79	19677	74.33	20135	1.70	19537
16	25670	21139	0.03	16.42	21141	58.29	19375	34.98	19375	68.46	19749	1.57	19256
17	25276	20719	0.03	13.66	20719	49.75	18999	7200.00	18999	81.15	19409	1.58	18874
18	26874	22175	0.03	12.75	22175	81.62	20585	174.58	20587	109.40	20927	1.74	20457
19	26186	21355	0.03	8.66	21355	97.20	19869	22.74	19869	84.86	20295	1.66	19763
20	26472	21641	0.03	13.60	21655	57.67	20145	109.15	20145	96.69	20551	1.80	20039
21	26510	21519	0.03	16.39	21519	60.75	20109	15.24	20109	87.43	20569	1.80	19975
22	26348	21381	0.03	33.31	21387	63.36	20003	48.26	20013	102.35	20429	1.78	19893
23	25676	21113	0.02	14.88	21113	60.57	19451	47.92	19451	75.98	19841	1.50	19347
24	26346	21663	0.03	13.63	21665	50.52	20011	84.59	20013	72.46	20389	1.67	19889
25	25218	20597	0.03	11.92	20597	56.60	18955	217.18	18955	78.11	19373	1.59	18849
26	27466	22335	0.03	13.13	22335	60.31	20941	95.04	20941	97.71	21339	1.77	20829
27	26094	21307	0.03	22.74	21307	61.82	19711	16.89	19715	112.37	20111	1.88	19581
28	25622	20865	0.03	12.51	20865	54.19	19119	18.36	19123	94.10	19523	1.55	19001
29	25528	20995	0.03	10.05	20995	44.18	19283	1042.27	19285	97.44	19685	1.51	19149
30	25732	21031	0.03	17.75	21031	51.90	19519	174.43	19519	105.53	19951	1.73	19393
31	27154	22309	0.03	29.84	22309	68.79	20783	128.36	20785	116.95	21159	1.91	20665
32	25854	21115	0.03	9.89	21117	52.94	19521	133.58	19521	83.31	19969	1.82	19401
33	26094	21435	0.03	16.19	21435	58.56	19793	42.28	19795	106.08	20211	1.69	19649
34	25696	20987	0.03	15.34	20987	54.36	19323	135.56	19323	87.38	19785	1.77	19189
35	25532	21039	0.03	13.92	21039	53.80	19243	127.71	19245	102.75	19645	1.67	19119
36	26710	21895	0.03	15.68	21901	75.39	20297	22.87	20297	69.40	20761	1.81	20182
37	25824	21125	0.03	18.64	21125	47.93	19563	166.74	19563	95.27	19985	1.53	19442
38	26320	21421	0.03	8.73	21421	51.36	20017	2069.90	20017	113.42	20421	1.83	19901
39	25132	20443	0.03	13.35	20443	69.51	18711	23.88	18711	119.59	19115	1.59	18595
40	25780	20827	0.03	17.91	20827	61.30	19333	56.92	19333	113.12	19771	1.61	19199

Table 28: Results on instance set Large Orders with UDD and $l = 20$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	8986	7879	0.03	5.25	7879	41.92	7713	3.98	7717	64.61	7779	0.31	7650
2	8828	7769	0.03	3.86	7769	34.57	7631	11.18	7631	97.07	7697	0.30	7562
3	8974	7881	0.03	5.72	7881	59.38	7729	14.18	7729	65.41	7799	0.32	7647
4	9266	8181	0.03	12.41	8181	60.36	8023	5.98	8023	102.30	8079	0.33	7963
5	9482	8377	0.04	6.10	8377	105.31	8231	17.26	8231	119.76	8271	0.41	8159
6	9276	8151	0.03	7.08	8151	41.17	7999	10.92	7999	69.72	8041	0.38	7932
7	8762	7611	0.03	4.26	7611	54.71	7455	8.26	7455	101.70	7499	0.28	7375
8	9208	8041	0.03	9.53	8041	63.69	7903	13.56	7903	76.07	7957	0.32	7838
9	9192	8095	0.03	4.21	8095	30.39	7939	15.43	7941	67.45	7999	0.33	7876
10	8602	7551	0.02	3.22	7551	41.89	7379	12.31	7379	68.53	7445	0.28	7306
11	9040	7967	0.03	5.61	7967	70.26	7809	4.84	7809	86.57	7863	0.32	7741
12	9514	8419	0.03	9.58	8419	58.01	8247	7.16	8247	66.03	8301	0.38	8187
13	9296	8185	0.03	6.31	8185	80.20	8021	6.68	8021	106.39	8095	0.39	7956
14	8846	7791	0.03	7.51	7791	71.92	7581	8.74	7581	98.11	7645	0.31	7517
15	8556	7549	0.02	5.56	7549	67.18	7371	4.65	7371	29.89	7415	0.25	7302
16	8842	7781	0.03	10.30	7781	59.46	7629	11.67	7629	67.51	7685	0.27	7564
17	8920	7743	0.03	3.70	7743	71.24	7655	5.16	7657	82.07	7715	0.29	7591
18	8742	7661	0.03	6.13	7665	43.69	7487	8.88	7487	75.29	7545	0.29	7416
19	8834	7747	0.03	5.41	7747	85.59	7567	66.31	7567	90.19	7605	0.29	7502
20	8750	7707	0.03	11.20	7707	61.53	7537	6.68	7537	61.86	7591	0.31	7473
21	8874	7705	0.03	8.20	7705	87.13	7557	6.18	7557	108.75	7581	0.34	7494
22	8868	7779	0.03	5.05	7779	60.81	7591	13.22	7593	59.14	7685	0.30	7534
23	8570	7535	0.02	5.68	7535	63.21	7359	5.11	7359	49.33	7399	0.25	7295
24	8592	7491	0.02	8.65	7491	52.57	7327	13.28	7327	50.35	7369	0.27	7254
25	8930	7849	0.03	2.80	7849	50.31	7691	588.86	7691	78.79	7751	0.29	7624
26	8774	7683	0.02	7.44	7683	59.88	7465	4.01	7465	39.66	7539	0.27	7408
27	8792	7603	0.02	3.22	7603	47.90	7441	4.26	7441	64.20	7507	0.29	7375
28	8724	7565	0.02	3.75	7565	35.35	7415	55.92	7415	74.22	7449	0.27	7344
29	8542	7465	0.02	9.59	7465	106.53	7293	27.97	7293	97.75	7337	0.27	7222
30	8770	7655	0.02	6.41	7655	61.98	7515	291.59	7515	64.60	7573	0.26	7439
31	8910	7861	0.03	6.89	7861	57.51	7667	8.32	7667	46.06	7717	0.30	7604
32	9106	8097	0.03	9.64	8097	80.52	7911	99.99	7911	88.80	7961	0.33	7833
33	9136	8095	0.03	9.55	8095	104.13	7941	22.16	7941	81.52	7997	0.35	7879
34	8854	7783	0.03	4.51	7783	30.63	7621	7.25	7621	65.03	7675	0.34	7558
35	8692	7655	0.02	3.78	7655	26.50	7497	94.97	7497	75.00	7549	0.27	7425
36	8660	7501	0.03	14.19	7501	72.19	7339	8.24	7339	88.64	7383	0.30	7278
37	9024	7873	0.03	4.61	7873	35.63	7717	25.02	7717	58.89	7785	0.31	7666
38	8746	7689	0.03	5.40	7689	72.07	7527	12.79	7527	60.92	7565	0.27	7457
39	9034	7941	0.03	4.60	7941	61.23	7753	34.14	7753	44.84	7799	0.28	7690
40	9256	8175	0.03	5.41	8175	88.34	7979	7.03	7979	55.96	7997	0.34	7910

Table 29: Results on instance set Large Orders with UDD and $l = 40$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	18248	15875	0.06	10.28	15877	85.06	15549	21.29	15549	139.10	15633	1.15	15470
2	18424	16073	0.07	20.52	16073	119.86	15725	52.42	15725	222.86	15835	1.30	15656
3	18234	16105	0.07	81.27	16105	136.27	15675	28.47	15675	124.16	15783	1.23	15597
4	18018	15829	0.06	20.92	15829	125.20	15429	1449.14	15429	200.85	15545	1.16	15346
5	17788	15575	0.05	30.10	15577	95.99	15203	13.50	15203	118.32	15321	1.05	15130
6	17986	15749	0.06	23.68	15755	64.35	15397	21.02	15397	76.84	15513	1.06	15339
7	17498	15377	0.05	25.44	15379	116.63	14975	27.05	14975	110.23	15123	1.01	14901
8	17274	15085	0.05	12.85	15087	81.42	14701	12.15	14701	119.33	14845	0.99	14631
9	17768	15591	0.06	15.87	15591	72.38	15245	43.44	15247	124.62	15341	1.03	15158
10	18406	16167	0.06	78.18	16177	110.22	15827	220.89	15827	131.97	15937	1.12	15751
11	18480	16231	0.07	13.41	16231	102.37	15871	38.73	15873	133.12	15989	1.27	15793
12	18354	16163	0.06	34.78	16167	89.29	15807	64.65	15807	149.90	15927	1.21	15729
13	17806	15591	0.06	25.47	15591	144.36	15199	25.19	15199	173.83	15291	1.08	15121
14	17700	15523	0.06	36.92	15531	155.45	15127	16.14	15127	132.65	15241	1.09	15054
15	18254	16037	0.06	8.52	16037	103.11	15665	215.19	15667	140.13	15765	1.18	15592
16	17714	15553	0.06	22.17	15553	81.19	15163	17.62	15163	131.68	15279	1.11	15079
17	17234	15051	0.05	35.26	15051	75.48	14671	264.19	14671	188.08	14803	0.96	14595
18	17634	15421	0.05	16.77	15425	79.91	15043	27.18	15043	98.25	15159	0.97	14964
19	17686	15443	0.05	17.60	15443	96.96	15089	21.85	15089	114.11	15185	0.94	15018
20	17910	15663	0.06	31.34	15673	104.94	15283	376.75	15283	157.14	15381	1.06	15181
21	18174	15963	0.06	36.41	15963	93.29	15577	82.72	15579	142.84	15675	1.11	15498
22	17968	15667	0.06	25.43	15667	115.28	15347	45.48	15347	161.66	15477	1.06	15272
23	17950	15687	0.05	21.92	15687	67.32	15331	39.71	15333	114.58	15457	1.03	15269
24	17890	15655	0.05	24.92	15655	74.22	15255	218.61	15255	138.09	15387	1.06	15184
25	18046	15873	0.06	10.14	15873	111.16	15509	25.76	15509	153.71	15615	1.11	15430
26	18334	16131	0.06	46.57	16135	136.80	15747	721.33	15747	178.89	15861	1.19	15677
27	18262	16057	0.06	15.32	16057	104.97	15753	63.64	15753	196.20	15847	1.12	15673
28	17448	15257	0.05	20.56	15257	119.09	14869	15.91	14869	49.34	14985	0.99	14782
29	17838	15593	0.05	18.55	15593	95.81	15203	278.48	15205	130.56	15349	1.05	15101
30	17312	15271	0.06	20.89	15275	139.46	14877	65.18	14877	176.46	14997	1.09	14794
31	17816	15623	0.06	19.86	15623	118.92	15215	185.14	15215	114.20	15301	1.14	15134
32	17458	15195	0.05	13.88	15195	113.31	14853	878.44	14853	162.26	14991	1.06	14769
33	17002	14925	0.05	17.36	14925	68.81	14505	50.04	14505	138.78	14623	0.93	14413
34	17902	15817	0.05	39.00	15817	139.67	15431	774.61	15433	184.46	15577	1.04	15352
35	18230	15955	0.06	18.81	15955	83.01	15649	35.14	15653	115.84	15737	1.08	15587
36	18292	16061	0.06	39.45	16061	77.17	15713	278.48	15713	159.61	15841	1.14	15639
37	18626	16335	0.06	29.61	16335	117.08	15997	45.62	15997	153.95	16121	1.21	15921
38	18368	16049	0.06	15.21	16049	88.38	15689	76.72	15693	68.51	15805	1.17	15619
39	18456	16067	0.06	12.81	16069	76.22	15753	19.09	15753	138.85	15895	1.24	15679
40	17782	15453	0.06	36.46	15461	81.26	15093	24.65	15093	126.31	15229	1.15	15026

Table 30: Results on instance set Large Orders with UDD and $l = 60$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	27088	23575	0.09	51.78	23577	167.68	23047	7200.00	23049	224.99	23241	2.57	22969
2	26036	22559	0.07	32.14	22559	117.84	22023	187.90	22023	173.90	22205	2.10	21941
3	25420	22039	0.07	17.01	22039	180.59	21447	42.33	21449	167.61	21593	1.97	21365
4	26382	23081	0.08	34.29	23081	156.95	22555	1210.61	22555	216.64	22743	2.34	22466
5	27224	23807	0.09	26.52	23811	119.47	23245	44.40	23247	197.39	23449	2.53	23168
6	27420	24025	0.09	17.77	24029	134.49	23515	49.18	23517	159.01	23735	2.67	23438
7	27666	24209	0.09	53.55	24215	182.89	23625	29.16	23629	191.28	23801	2.77	23557
8	27568	24163	0.10	69.07	24163	163.62	23647	263.30	23653	244.76	23803	2.87	23570
9	28116	24641	0.10	31.47	24641	121.56	24127	549.04	24127	150.45	24301	2.93	24058
10	27226	23973	0.09	68.21	23985	165.38	23381	188.11	23385	205.87	23547	2.53	23280
11	27506	24011	0.09	17.99	24011	130.38	23467	33.20	23467	202.46	23665	2.60	23400
12	27706	24439	0.09	27.75	24439	157.26	23887	62.31	23891	251.54	24063	2.71	23807
13	26840	23649	0.09	26.71	23649	143.64	23017	39.69	23019	239.96	23187	2.50	22931
14	26854	23607	0.09	59.31	23607	181.83	22993	182.92	22995	296.55	23151	2.60	22901
15	26776	23405	0.09	22.19	23405	145.61	22855	88.36	22857	183.33	23025	2.55	22783
16	26268	22883	0.08	18.96	22883	111.81	22313	666.50	22313	187.13	22529	2.28	22223
17	26472	23149	0.08	39.32	23149	159.80	22527	86.42	22529	211.19	22703	2.33	22451
18	26594	23223	0.09	88.30	23223	153.11	22683	43.01	22689	209.04	22853	2.57	22590
19	27362	24027	0.09	87.63	24027	134.09	23477	43.13	23481	226.62	23619	2.69	23397
20	27028	23675	0.09	174.90	23677	168.23	23117	32.01	23119	209.81	23275	2.49	23037
21	26742	23499	0.09	60.33	23507	147.63	22915	150.89	22915	162.60	23049	2.49	22839
22	27498	24133	0.09	17.59	24133	104.92	23547	507.69	23547	188.76	23711	2.70	23455
23	27162	23921	0.08	36.82	23921	165.62	23317	31.87	23321	236.75	23509	2.49	23237
24	27010	23561	0.09	24.82	23561	164.35	23071	1605.00	23075	274.23	23231	2.53	22983
25	26652	23385	0.09	74.99	23385	163.32	22841	5412.14	22843	243.67	23023	2.73	22760
26	27018	23593	0.09	28.70	23595	143.49	23043	179.72	23043	164.87	23209	2.64	22955
27	26738	23437	0.09	83.37	23437	150.43	22923	77.49	22929	176.12	23101	2.66	22842
28	27044	23757	0.09	63.45	23757	178.85	23153	65.25	23153	239.58	23321	2.56	23073
29	26596	23123	0.08	16.92	23123	136.72	22579	34.90	22585	124.40	22781	2.19	22509
30	27078	23521	0.08	29.29	23521	106.36	23023	159.87	23029	177.96	23193	2.44	22945
31	27190	23647	0.09	119.13	23647	180.88	23155	59.52	23159	151.77	23331	2.52	23078
32	27522	24227	0.09	52.89	24235	164.34	23663	41.22	23663	141.36	23839	2.57	23583
33	27374	23929	0.09	19.28	23937	163.40	23409	26.75	23411	195.08	23575	2.78	23326
34	26974	23521	0.09	70.67	23521	169.27	22975	34.94	22975	152.24	23129	2.71	22899
35	27194	23871	0.09	35.69	23871	204.61	23309	353.93	23309	237.77	23465	2.56	23216
36	26978	23641	0.08	34.86	23641	150.52	23065	70.33	23065	178.23	23223	2.50	22971
37	26168	22749	0.08	46.88	22749	143.19	22165	26.49	22169	190.47	22377	2.25	22082
38	26588	23157	0.08	21.39	23157	165.70	22601	66.10	22603	222.10	22757	2.24	22534
39	27076	23697	0.08	33.32	23697	113.05	23171	3038.82	23173	144.30	23375	2.44	23087
40	26872	23577	0.08	22.32	23577	134.09	23003	41.51	23003	212.81	23183	2.53	22913

Table 31: Results on instance set Large Orders with UDD and $l = 80$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	36746	32277	0.13	37.53	32293	170.96	31571	70.22	31573	273.06	31801	5.81	31492
2	36188	31683	0.12	163.70	31683	235.57	30865	552.75	30869	255.62	31099	5.23	30774
3	36318	31713	0.12	44.30	31713	199.01	30959	53.57	30967	272.90	31189	5.15	30872
4	35718	31155	0.11	55.82	31161	287.43	30421	69.52	30423	271.07	30643	4.93	30341
5	35368	30977	0.11	100.30	30977	243.30	30205	354.55	30205	298.16	30433	4.85	30115
6	36302	31823	0.12	40.15	31823	213.38	31011	67.64	31015	317.23	31215	5.27	30919
7	36226	31765	0.13	88.44	31765	260.66	30953	74.89	30961	307.97	31221	5.44	30877
8	35402	30965	0.11	107.68	30965	191.92	30211	70.26	30211	251.70	30447	4.89	30126
9	35994	31543	0.11	81.80	31543	204.43	30749	178.13	30759	377.80	31019	4.96	30668
10	36508	31865	0.12	140.28	31869	199.32	31145	52.89	31151	294.43	31395	5.51	31071
11	36308	31685	0.12	64.09	31685	225.11	30977	62.04	30981	301.43	31207	5.40	30879
12	36396	31659	0.12	61.56	31659	144.03	30975	340.20	30987	220.61	31197	5.46	30886
13	36510	32001	0.13	55.52	32005	184.75	31257	920.62	31261	278.64	31465	5.64	31172
14	36220	31739	0.12	67.60	31739	165.68	30973	107.40	30983	287.97	31193	5.20	30872
15	35614	31183	0.11	59.78	31183	193.64	30435	3619.77	30439	262.17	30669	4.89	30338
16	36432	32161	0.12	138.22	32165	195.49	31369	549.47	31375	285.74	31583	5.23	31283
17	35890	31359	0.11	45.75	31359	187.61	30559	37.54	30567	254.76	30785	4.91	30474
18	35494	30963	0.11	108.45	30963	181.57	30229	132.52	30233	269.40	30427	4.78	30141
19	35096	30755	0.11	272.99	30757	195.34	29947	159.06	29955	311.97	30201	4.83	29859
20	35626	31157	0.11	197.60	31157	187.54	30387	2315.24	30389	336.01	30613	4.71	30318
21	36594	31915	0.12	35.11	31915	187.23	31239	145.61	31241	246.50	31463	5.39	31155
22	36696	32193	0.13	38.92	32193	238.79	31397	136.79	31403	270.51	31617	5.60	31314
23	35170	30817	0.11	28.85	30817	224.48	30069	7200.00	30069	305.76	30291	4.76	29974
24	35064	30679	0.10	47.60	30679	232.61	29937	410.25	29941	256.70	30169	4.50	29841
25	35482	31019	0.11	40.54	31019	190.17	30223	297.50	30231	302.57	30457	4.82	30146
26	35844	31307	0.12	86.57	31307	224.63	30481	64.38	30483	258.64	30743	5.12	30382
27	35972	31535	0.12	41.87	31535	205.44	30795	121.65	30797	352.30	31043	5.28	30703
28	36490	31817	0.12	116.44	31825	189.67	31085	93.70	31089	236.56	31331	5.17	30995
29	36346	31715	0.12	91.96	31727	185.16	30941	50.79	30943	243.83	31187	5.24	30863
30	36742	32143	0.12	116.94	32143	195.02	31417	52.83	31423	338.12	31643	5.38	31330
31	36686	32009	0.12	146.74	32015	162.94	31275	224.25	31277	227.81	31499	5.25	31184
32	36008	31505	0.11	92.19	31505	197.41	30789	70.13	30799	327.66	31015	5.07	30714
33	35388	30867	0.11	48.15	30867	179.53	30087	214.19	30093	296.75	30325	4.95	29986
34	35468	31087	0.10	34.84	31091	164.40	30335	118.58	30335	215.75	30597	4.46	30257
35	34882	30225	0.10	62.32	30229	145.13	29537	76.03	29539	227.50	29767	4.62	29442
36	36362	31633	0.11	43.29	31637	198.15	30851	139.83	30853	229.81	31067	5.06	30767
37	36066	31527	0.11	47.12	31527	215.17	30835	7200.00	30825	278.27	31035	4.79	30730
38	35872	31431	0.11	231.73	31431	170.15	30697	4561.55	30707	378.20	30937	4.89	30612
39	36286	31859	0.11	137.65	31871	202.30	31083	31.16	31087	282.76	31349	4.98	31006
40	36970	32407	0.13	48.96	32409	207.69	31663	53.92	31671	373.08	31873	5.50	31577

Table 32: Results on instance set Large Orders with UDD and $l = 100$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	45192	39527	0.14	221.98	39527	267.36	38619	145.30	38621	303.28	38891	8.75	38531
2	45652	39965	0.16	70.51	39965	184.89	39065	226.36	39071	376.58	39313	9.49	38972
3	45732	40089	0.16	95.68	40089	222.49	39081	118.60	39091	334.36	39391	9.54	38991
4	45820	40131	0.15	67.89	40131	244.12	39189	113.25	39193	437.12	39443	9.32	39115
5	45400	39611	0.14	156.18	39611	311.81	38705	83.15	38711	315.36	38991	8.68	38644
6	45578	39785	0.15	40.84	39785	205.70	38855	7200.00	38843	442.98	39151	8.94	38757
7	45118	39391	0.14	135.18	39391	209.80	38339	109.81	38341	340.06	38629	8.78	38246
8	44106	38545	0.14	117.22	38545	261.89	37549	523.50	37551	390.32	37833	8.60	37454
9	44488	38891	0.14	81.14	38893	280.75	37829	7200.00	37833	305.51	38113	8.51	37758
10	44878	39031	0.13	141.90	39031	255.51	38165	389.27	38167	321.19	38461	8.35	38070
11	44520	38779	0.14	70.49	38779	209.98	37811	7200.00	37811	286.21	38119	8.52	37716
12	44066	38447	0.14	78.27	38447	233.13	37503	498.83	37509	289.38	37777	8.52	37417
13	44056	38499	0.13	167.97	38503	272.35	37493	126.99	37493	342.85	37819	7.90	37402
14	44024	38457	0.13	84.58	38457	251.28	37517	336.93	37525	285.11	37821	8.15	37436
15	44288	38635	0.14	130.59	38641	194.11	37733	773.36	37743	327.21	38019	8.44	37646
16	44512	38879	0.13	292.08	38881	242.08	37991	95.58	38015	329.61	38259	8.12	37911
17	44700	39189	0.14	176.40	39193	210.72	38275	301.93	38287	427.49	38571	8.58	38191
18	44662	39033	0.14	78.76	39033	257.56	38077	984.65	38081	411.48	38411	8.64	38000
19	45082	39507	0.15	219.21	39507	285.22	38567	758.08	38579	363.49	38835	9.06	38467
20	45274	39633	0.16	285.19	39639	292.26	38677	142.95	38687	247.35	38973	9.24	38579
21	45206	39453	0.15	121.36	39453	239.99	38541	7200.00	38541	375.52	38829	9.11	38435
22	44812	39013	0.13	151.20	39021	285.69	38163	71.71	38165	321.70	38445	8.22	38080
23	44632	38881	0.14	361.21	38883	239.76	37867	182.27	37875	275.29	38159	7.99	37778
24	44150	38539	0.14	121.02	38539	204.62	37627	79.89	37637	360.67	37927	8.25	37526
25	44754	39069	0.15	140.15	39079	242.82	38089	3213.60	38097	355.14	38353	8.58	38003
26	45656	39811	0.16	92.65	39833	234.71	38901	6926.96	38901	346.79	39167	9.37	38808
27	44742	39119	0.14	51.20	39119	215.48	38207	111.85	38211	299.03	38521	8.63	38128
28	43568	38009	0.13	80.62	38009	271.13	37015	375.15	37019	347.25	37311	7.71	36915
29	44326	38795	0.13	298.93	38795	246.71	37809	2629.73	37817	236.93	38117	8.26	37719
30	44734	39069	0.15	496.08	39073	242.61	38231	192.70	38241	393.16	38549	9.01	38144
31	45586	40037	0.16	136.52	40065	288.16	39083	314.60	39089	461.22	39383	9.61	38994
32	45334	39833	0.15	269.57	39835	226.50	38891	7200.00	38893	445.20	39139	9.25	38800
33	44816	39177	0.15	65.51	39177	211.08	38215	96.54	38227	282.00	38533	8.97	38127
34	45554	39849	0.15	60.29	39851	249.68	38913	6040.08	38925	350.61	39187	8.99	38821
35	45440	39795	0.15	79.96	39821	280.31	38813	7200.00	38809	347.70	39095	9.14	38714
36	44738	39183	0.14	122.16	39183	222.06	38315	7200.00	38325	391.05	38591	8.48	38233
37	45202	39325	0.14	191.99	39325	204.84	38417	7200.00	38419	364.90	38691	8.86	38321
38	45238	39429	0.15	82.12	39429	257.26	38527	52.79	38533	347.69	38835	8.88	38449
39	44482	38863	0.14	397.18	38863	291.44	37931	1106.37	37933	416.98	38209	8.28	37850
40	44444	38867	0.13	132.21	38877	259.14	37895	92.24	37907	272.96	38207	8.01	37812

Table 33: Results on instance set Large Orders with CBD and $l = 20$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	6652	5761	0.02	4.68	5761	76.11	5569	6.18	5569	47.79	5613	0.21	5494
2	6732	5755	0.02	9.73	5755	38.10	5593	15.11	5593	37.81	5649	0.21	5534
3	7192	6195	0.03	4.02	6195	63.07	6035	14.83	6035	46.31	6099	0.25	5981
4	7046	6087	0.03	5.48	6091	45.75	5915	3.13	5915	28.18	5963	0.25	5865
5	7090	6191	0.03	20.95	6191	113.07	6013	88.20	6013	90.40	6057	0.27	5946
6	6768	5815	0.03	5.81	5815	34.87	5699	20.56	5699	100.97	5743	0.25	5633
7	6400	5485	0.02	6.22	5485	41.87	5311	4.18	5311	59.93	5373	0.19	5257
8	6772	5833	0.03	4.70	5833	38.42	5697	21.11	5697	96.36	5737	0.22	5646
9	7120	6087	0.03	5.74	6087	45.71	5961	4.19	5961	47.67	5999	0.25	5909
10	6776	5769	0.02	3.29	5775	35.38	5617	9.91	5617	36.49	5671	0.21	5560
11	7314	6327	0.03	3.57	6327	61.03	6227	27.64	6227	81.46	6253	0.25	6173
12	7168	6251	0.03	3.92	6251	104.78	6079	89.03	6079	67.31	6123	0.26	6015
13	6922	6011	0.03	3.53	6011	37.00	5877	6.64	5877	40.73	5919	0.25	5822
14	6594	5675	0.02	3.38	5675	48.18	5541	6.07	5541	68.57	5581	0.20	5478
15	6272	5261	0.02	3.17	5261	75.00	5111	24.05	5111	63.18	5149	0.18	5057
16	6780	5771	0.02	5.66	5771	65.24	5623	3.96	5623	48.70	5663	0.19	5568
17	6690	5749	0.02	3.32	5749	39.52	5571	5.47	5571	43.46	5629	0.21	5520
18	6698	5731	0.03	3.38	5731	72.29	5589	3.55	5589	60.06	5611	0.20	5541
19	6588	5657	0.02	4.42	5657	100.73	5509	4.18	5509	55.53	5551	0.19	5441
20	6948	5973	0.02	5.37	5977	51.45	5821	7.73	5821	91.07	5873	0.22	5760
21	7248	6181	0.03	4.58	6181	62.52	6045	42.61	6045	87.32	6083	0.24	5993
22	6794	5823	0.02	5.82	5823	79.68	5689	23.97	5689	71.00	5753	0.20	5623
23	6478	5575	0.02	3.24	5575	60.93	5405	4.29	5405	38.43	5445	0.17	5337
24	6646	5673	0.02	3.24	5673	45.46	5513	4.84	5513	40.96	5569	0.19	5462
25	6880	5973	0.02	4.89	5973	42.91	5775	6.50	5775	47.04	5817	0.20	5723
26	6688	5749	0.02	4.22	5749	61.02	5619	8.18	5619	83.25	5655	0.20	5559
27	6758	5873	0.02	3.84	5873	106.19	5691	4.54	5691	52.77	5715	0.20	5630
28	6678	5801	0.02	4.69	5801	42.26	5627	38.25	5627	80.75	5661	0.19	5560
29	6688	5743	0.02	3.36	5757	38.42	5597	4.22	5597	50.63	5641	0.20	5544
30	6632	5677	0.02	3.76	5677	55.46	5547	4.65	5547	38.42	5581	0.18	5476
31	6952	5977	0.02	4.04	5977	73.93	5841	77.48	5841	39.19	5889	0.19	5791
32	6796	5907	0.03	6.87	5907	37.68	5767	7.44	5767	65.87	5815	0.21	5716
33	6760	5875	0.03	7.44	5875	67.84	5745	9.55	5745	64.50	5793	0.24	5673
34	6932	5967	0.03	4.18	5967	79.08	5813	4.35	5813	49.99	5849	0.25	5763
35	6790	5773	0.02	4.11	5773	67.60	5613	3.69	5613	39.56	5693	0.19	5558
36	6618	5673	0.02	4.45	5673	36.13	5509	32.62	5509	53.78	5547	0.19	5459
37	6728	5779	0.03	8.01	5779	46.57	5595	7.70	5595	43.47	5629	0.21	5529
38	6652	5761	0.02	3.17	5761	33.91	5607	18.79	5607	28.62	5655	0.19	5533
39	7002	6173	0.02	4.90	6173	90.84	5981	6.09	5981	68.56	6037	0.21	5920
40	6858	5957	0.03	5.43	5957	105.78	5765	6.32	5765	54.00	5821	0.24	5695

Table 34: Results on instance set Large Orders with CBD and $l = 40$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	13956	11983	0.06	11.12	11983	79.94	11693	63.45	11695	120.87	11771	0.86	11615
2	14398	12401	0.07	12.13	12401	141.85	12059	26.98	12059	98.92	12183	0.95	12001
3	14244	12293	0.06	14.46	12293	104.00	11955	20.81	11955	83.32	12053	0.89	11892
4	13664	11829	0.06	14.47	11829	114.24	11497	12.02	11497	133.81	11621	0.82	11433
5	13676	11707	0.05	11.45	11707	60.82	11399	23.75	11399	88.38	11487	0.77	11344
6	13854	11811	0.05	7.20	11811	69.42	11577	20.97	11577	126.67	11675	0.78	11508
7	13726	11869	0.05	10.05	11869	85.58	11489	391.11	11489	127.45	11585	0.75	11423
8	13674	11779	0.05	18.68	11779	74.21	11419	29.17	11419	157.04	11517	0.74	11333
9	13380	11487	0.05	21.93	11487	81.19	11175	21.46	11175	108.07	11247	0.75	11104
10	13520	11659	0.05	14.60	11659	117.63	11295	19.22	11295	103.81	11407	0.83	11225
11	14332	12459	0.06	14.44	12459	121.51	12131	13.29	12137	137.29	12235	0.94	12059
12	13938	12093	0.06	16.68	12093	139.60	11725	18.17	11725	98.40	11819	0.86	11660
13	13570	11649	0.05	9.96	11649	49.07	11319	38.12	11319	76.95	11427	0.79	11256
14	13872	12055	0.05	12.75	12055	63.10	11677	18.20	11677	103.35	11793	0.82	11596
15	13762	11891	0.06	11.59	11891	123.89	11473	17.73	11473	72.20	11559	0.87	11399
16	13718	11853	0.05	9.20	11853	93.38	11515	25.32	11515	93.30	11603	0.82	11446
17	13480	11599	0.05	8.89	11599	79.74	11267	118.31	11267	89.54	11373	0.71	11186
18	13456	11673	0.05	8.15	11673	69.26	11327	27.27	11327	94.35	11415	0.73	11246
19	12886	11047	0.04	16.06	11055	56.83	10709	273.57	10709	95.21	10833	0.69	10626
20	13906	11951	0.05	10.91	11951	60.59	11645	22.76	11645	89.08	11753	0.77	11576
21	14070	12195	0.05	10.36	12195	66.59	11885	484.49	11887	73.11	11979	0.86	11815
22	13862	11971	0.05	7.77	11971	87.34	11633	11.36	11633	87.44	11749	0.80	11557
23	13762	11847	0.05	7.67	11847	60.14	11535	14.70	11537	69.33	11631	0.75	11467
24	13824	11823	0.05	7.81	11823	85.45	11493	12.61	11493	63.39	11593	0.79	11424
25	13646	11711	0.06	12.03	11711	89.27	11377	45.03	11377	103.61	11485	0.79	11299
26	13950	12005	0.06	19.01	12005	55.25	11701	88.59	11703	117.36	11805	0.85	11629
27	13782	11779	0.06	12.54	11779	110.55	11469	26.66	11469	132.11	11575	0.83	11391
28	13480	11637	0.05	10.12	11637	70.92	11287	20.03	11287	81.85	11377	0.74	11220
29	14056	12077	0.05	16.82	12077	119.39	11751	11.07	11751	63.68	11847	0.83	11690
30	13974	12089	0.05	19.47	12089	95.50	11751	11.87	11751	72.29	11853	0.86	11697
31	13782	11841	0.06	15.81	11843	119.71	11473	15.47	11475	94.70	11595	0.85	11414
32	13740	11777	0.05	7.65	11777	80.42	11455	63.43	11455	105.22	11579	0.79	11381
33	13554	11669	0.04	6.72	11669	55.99	11365	19.61	11365	79.58	11477	0.70	11288
34	13502	11633	0.05	22.84	11639	117.37	11321	60.27	11321	98.38	11419	0.76	11250
35	13210	11335	0.05	10.37	11335	91.68	10945	25.22	10947	133.75	11051	0.77	10865
36	13620	11793	0.06	14.29	11793	88.28	11443	27.19	11445	132.15	11523	0.86	11369
37	14256	12351	0.06	10.90	12351	106.87	12025	48.41	12027	105.49	12123	0.89	11951
38	14432	12375	0.06	14.49	12375	59.07	12115	19.69	12115	94.09	12209	0.85	12048
39	14382	12353	0.06	16.11	12355	67.92	12011	334.47	12013	100.58	12109	0.91	11950
40	14106	12157	0.06	11.49	12157	67.97	11817	18.21	11817	96.71	11937	0.87	11759

Table 35: Results on instance set Large Orders with CBD and $l = 60$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	20702	17903	0.08	18.57	17905	95.81	17333	41.70	17333	167.01	17491	1.89	17247
2	19652	16871	0.07	13.63	16871	72.42	16297	17.87	16297	108.86	16461	1.52	16213
3	19564	16749	0.06	10.96	16749	154.53	16145	39.55	16145	108.97	16333	1.49	16073
4	19910	17053	0.07	37.66	17053	112.78	16455	77.02	16455	185.33	16607	1.76	16394
5	20538	17719	0.08	20.67	17719	151.43	17227	3405.69	17227	137.72	17369	1.92	17147
6	20612	17657	0.09	13.11	17657	80.60	17133	40.11	17135	154.75	17271	2.00	17063
7	20502	17609	0.09	37.72	17609	147.67	17049	52.42	17049	154.34	17193	2.02	16968
8	20700	17859	0.09	25.15	17859	167.21	17323	42.83	17325	163.82	17443	2.12	17256
9	21188	18383	0.09	22.48	18383	165.60	17885	121.82	17885	180.23	18015	2.16	17813
10	20670	17827	0.08	15.83	17829	89.51	17311	290.57	17313	149.10	17447	1.87	17238
11	20968	18047	0.08	37.09	18047	91.99	17531	132.34	17531	100.88	17675	1.93	17464
12	21164	18165	0.09	15.29	18165	84.10	17681	132.81	17681	122.74	17825	2.08	17607
13	20604	17783	0.08	28.65	17783	172.11	17217	55.60	17219	165.22	17343	1.83	17148
14	20110	17335	0.08	39.83	17339	174.80	16733	32.53	16735	162.90	16895	1.99	16666
15	20418	17493	0.08	17.76	17493	148.97	17013	18.26	17015	140.54	17179	1.89	16956
16	20158	17317	0.07	15.00	17317	151.26	16791	259.81	16791	117.15	16959	1.68	16727
17	20114	17251	0.07	30.32	17251	149.79	16715	29.83	16715	96.49	16883	1.75	16644
18	20608	17639	0.08	21.23	17641	90.18	17133	23.79	17133	116.49	17279	1.92	17066
19	20502	17661	0.09	25.25	17661	95.96	17101	459.32	17101	205.32	17247	1.93	17019
20	20840	17923	0.08	28.88	17923	124.71	17437	289.75	17441	116.25	17601	1.87	17365
21	20290	17557	0.08	23.08	17557	119.79	16967	26.11	16969	108.96	17125	1.88	16901
22	21088	18237	0.09	21.52	18237	142.98	17755	7200.00	17755	182.49	17891	1.98	17678
23	20608	17647	0.08	23.63	17647	154.15	17191	36.74	17193	179.77	17335	1.86	17113
24	20194	17355	0.08	38.56	17355	128.57	16859	413.78	16859	162.86	16985	1.85	16789
25	20964	18003	0.08	33.14	18003	151.07	17499	28.88	17499	158.29	17651	2.04	17420
26	20968	18169	0.08	38.71	18171	125.54	17593	63.88	17595	130.71	17729	2.02	17519
27	20688	17913	0.09	23.74	17913	186.87	17357	25.40	17357	160.92	17493	2.01	17284
28	20400	17503	0.08	25.06	17503	125.43	16967	94.28	16969	150.26	17089	1.94	16893
29	19638	16803	0.07	21.55	16803	102.86	16215	13.79	16215	125.03	16359	1.72	16148
30	19848	17007	0.08	29.53	17007	82.90	16411	28.80	16411	134.55	16587	1.83	16337
31	21060	18161	0.08	30.99	18161	87.56	17669	20.82	17669	121.86	17813	1.93	17604
32	20942	18011	0.08	24.47	18011	94.01	17527	37.18	17527	120.90	17667	1.95	17460
33	20948	18045	0.09	31.08	18045	215.63	17561	34.84	17561	183.29	17699	2.09	17495
34	20560	17799	0.09	19.49	17799	105.90	17267	31.47	17269	146.04	17411	1.98	17194
35	20812	17963	0.08	18.03	17963	161.51	17441	2255.16	17445	208.98	17593	1.93	17368
36	20504	17503	0.08	15.14	17503	115.37	17089	7200.00	17089	146.26	17231	1.95	17016
37	20046	17137	0.07	36.08	17147	111.28	16567	29.91	16569	120.66	16723	1.73	16492
38	20532	17503	0.07	14.13	17509	142.96	16947	30.86	16947	117.22	17111	1.73	16877
39	20568	17621	0.08	20.53	17625	130.95	17149	16.89	17149	150.53	17285	1.91	17074
40	20898	17967	0.08	15.65	17967	88.95	17437	3180.71	17437	166.16	17583	1.88	17372

Table 36: Results on instance set Large Orders with CBD and $l = 80$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	27902	24065	0.12	72.19	24065	190.01	23373	158.74	23377	265.28	23557	4.38	23287
2	27382	23473	0.11	44.67	23473	115.48	22807	7200.00	22807	173.12	22989	4.08	22718
3	27274	23365	0.11	20.96	23365	108.08	22745	2042.32	22745	232.71	22951	3.96	22674
4	27554	23765	0.10	67.40	23765	178.31	23011	66.66	23017	160.81	23197	3.84	22951
5	27034	23113	0.10	25.09	23113	180.87	22461	34.90	22461	144.58	22645	3.72	22386
6	27750	23925	0.11	59.32	23929	196.27	23169	3390.38	23173	191.09	23337	3.99	23082
7	28102	24249	0.12	31.77	24261	198.73	23577	42.84	23577	212.03	23761	4.21	23506
8	28250	24321	0.10	67.18	24321	161.78	23643	109.57	23649	170.98	23851	3.65	23573
9	27772	23969	0.11	26.11	23969	108.75	23297	83.42	23299	272.72	23491	3.80	23215
10	28134	24235	0.12	30.88	24235	172.91	23549	7200.00	23547	146.56	23711	4.25	23471
11	28128	24173	0.11	110.24	24173	187.72	23467	7200.00	23465	227.43	23653	4.17	23386
12	28236	24275	0.11	33.06	24277	186.51	23559	258.16	23559	259.61	23763	4.20	23479
13	27742	23827	0.12	74.78	23829	148.05	23165	216.96	23165	211.37	23361	4.25	23070
14	28056	24187	0.11	52.51	24203	124.73	23453	203.79	23453	173.38	23635	3.85	23376
15	27738	23823	0.10	26.70	23823	179.44	23089	42.66	23089	157.84	23297	3.74	23023
16	27804	23905	0.11	41.45	23905	209.02	23289	509.03	23291	208.13	23515	4.04	23229
17	26972	23197	0.10	35.31	23197	132.25	22399	7200.00	22399	196.27	22599	3.86	22318
18	27264	23413	0.10	20.36	23413	179.76	22753	1036.40	22753	127.75	22929	3.58	22675
19	27052	23251	0.10	20.30	23251	194.39	22501	61.77	22503	179.14	22713	3.73	22415
20	27082	23253	0.10	60.97	23253	169.23	22569	118.11	22575	194.23	22799	3.61	22484
21	28004	24169	0.11	87.64	24169	188.39	23477	44.19	23479	184.33	23659	4.14	23400
22	27948	24161	0.12	41.56	24161	120.19	23455	369.12	23455	215.78	23641	4.23	23368
23	27210	23403	0.10	53.91	23403	201.74	22731	943.50	22731	166.08	22917	3.71	22654
24	26864	23011	0.10	24.42	23021	191.03	22265	524.35	22265	169.07	22461	3.48	22189
25	27108	23161	0.10	39.79	23165	132.66	22447	98.61	22447	170.61	22635	3.64	22381
26	27724	23899	0.11	20.96	23899	233.91	23289	265.28	23289	209.34	23475	3.91	23213
27	27406	23625	0.11	34.57	23625	206.59	22953	159.79	22955	207.85	23135	3.89	22877
28	26970	23075	0.11	61.55	23077	182.67	22465	410.64	22465	276.29	22661	3.77	22391
29	27722	23731	0.11	32.22	23731	232.24	23089	519.76	23089	194.06	23265	4.00	23006
30	28174	24313	0.11	43.97	24313	139.00	23651	1317.62	23655	199.86	23857	4.03	23586
31	27496	23621	0.11	23.49	23621	147.20	22893	328.55	22897	177.34	23091	3.96	22820
32	27468	23605	0.10	31.97	23605	166.76	22935	76.31	22939	225.34	23129	3.74	22855
33	27158	23349	0.10	34.17	23359	119.77	22641	59.30	22641	143.50	22857	3.76	22555
34	26554	22709	0.09	58.10	22709	179.19	21933	70.42	21935	154.62	22179	3.41	21854
35	26808	23053	0.10	24.13	23053	119.49	22409	5189.33	22409	203.89	22559	3.52	22340
36	27442	23595	0.10	36.69	23595	167.47	22809	1970.76	22815	193.49	23015	3.85	22725
37	26814	22939	0.10	40.47	22939	167.54	22187	57.24	22187	118.83	22379	3.68	22124
38	27116	23245	0.11	43.96	23245	133.20	22561	211.23	22561	207.00	22725	3.84	22488
39	27154	23305	0.10	29.18	23309	149.10	22619	7200.00	22625	225.51	22815	3.88	22534
40	28232	24399	0.11	27.45	24399	172.30	23757	76.61	23757	203.17	23931	4.22	23679

Table 37: Results on instance set Large Orders with CBD and $l = 100$.

#	f_0	WCTSP-GCS					WCTSP-OCS						
		DP		CC	CLKH		CC		CLKH		BI		LB
		f	t	t	f	t	f	t	f	t	f	t	f
1	34070	29233	0.13	74.50	29233	244.08	28345	94.39	28349	229.53	28599	6.95	28256
2	34560	29645	0.14	54.85	29649	252.86	28835	309.55	28841	358.95	29069	7.41	28736
3	35020	30133	0.15	81.75	30133	239.71	29265	600.47	29273	292.32	29497	7.91	29182
4	34206	29439	0.14	58.72	29441	311.75	28513	7200.00	28513	290.67	28745	7.53	28428
5	33354	28523	0.13	36.46	28523	144.77	27695	6078.72	27697	257.51	27937	6.85	27619
6	34514	29613	0.13	97.21	29613	237.88	28787	7200.00	28787	352.36	29031	7.17	28711
7	33998	29077	0.13	38.46	29081	218.28	28215	2405.48	28221	233.25	28463	6.92	28121
8	34224	29381	0.13	36.08	29381	198.90	28411	247.95	28415	225.92	28645	6.71	28331
9	34036	29373	0.12	37.04	29375	193.24	28447	236.76	28449	222.81	28745	6.66	28371
10	33628	28955	0.12	55.96	28957	153.29	28011	382.89	28013	246.46	28253	6.39	27931
11	34532	29555	0.13	50.34	29555	191.49	28745	512.49	28745	210.42	28995	6.99	28681
12	33552	28851	0.13	127.95	28851	168.23	27873	104.75	27875	225.47	28101	6.67	27793
13	33558	28729	0.12	32.69	28729	212.93	27827	261.42	27827	253.98	28057	6.13	27737
14	34508	29679	0.13	38.31	29679	145.69	28799	68.02	28807	228.67	29059	6.60	28719
15	34018	29173	0.13	53.85	29173	154.82	28193	7178.56	28199	210.95	28457	6.77	28107
16	33758	29003	0.13	141.78	29011	153.26	28049	493.00	28055	200.14	28329	6.38	27967
17	34292	29545	0.13	31.89	29567	147.16	28669	171.23	28677	195.42	28929	6.84	28607
18	34882	30111	0.13	64.37	30111	177.63	29227	120.21	29227	224.13	29447	7.04	29155
19	34574	29829	0.14	126.97	29829	177.67	28975	3053.92	28977	265.86	29227	7.30	28901
20	34920	30039	0.15	94.49	30039	249.42	29175	3391.71	29177	240.37	29417	7.60	29086
21	34704	30035	0.14	49.21	30035	218.80	29105	131.43	29107	278.17	29337	7.49	29027
22	34296	29469	0.13	101.32	29469	181.08	28597	281.55	28605	247.44	28855	6.71	28514
23	34670	29869	0.12	60.76	29869	149.19	28941	199.78	28945	189.86	29211	6.40	28868
24	34132	29537	0.13	71.01	29537	162.87	28607	141.10	28611	253.32	28847	6.66	28530
25	34464	29635	0.13	237.55	29641	134.80	28763	1051.04	28769	231.27	29013	6.89	28682
26	35422	30519	0.14	66.16	30519	260.46	29733	840.90	29735	290.10	29963	7.53	29648
27	34458	29623	0.13	48.76	29627	159.65	28723	49.96	28727	253.39	28977	7.11	28640
28	34318	29431	0.12	38.88	29431	133.12	28521	929.94	28523	206.55	28787	6.15	28457
29	34148	29475	0.12	45.87	29477	167.50	28603	7200.00	28607	234.80	28829	6.77	28515
30	34532	29795	0.14	51.92	29795	213.35	28905	201.73	28909	267.07	29173	7.51	28821
31	34950	30057	0.15	76.71	30059	240.73	29161	1585.24	29161	294.24	29433	7.78	29077
32	34726	29869	0.14	59.57	29869	246.45	29017	7200.00	29023	279.22	29251	7.22	28948
33	34048	29253	0.14	135.43	29253	258.53	28255	292.89	28259	239.04	28503	7.06	28161
34	34098	29215	0.14	58.04	29215	218.97	28333	7200.00	28339	261.42	28575	7.12	28246
35	34628	29755	0.14	100.53	29755	174.66	28853	4731.69	28853	207.35	29075	7.15	28782
36	35186	30287	0.13	35.77	30287	194.87	29455	2437.09	29457	258.77	29661	6.90	29374
37	34510	29741	0.13	41.42	29747	152.66	28869	1567.49	28871	309.19	29127	6.96	28797
38	33898	29129	0.14	102.92	29129	186.00	28181	344.65	28187	237.71	28433	7.02	28089
39	33402	28503	0.12	52.30	28503	142.43	27543	156.54	27543	204.58	27757	6.70	27466
40	33678	28941	0.12	28.08	28949	126.40	28031	127.80	28035	205.03	28295	6.35	27962

Table 38: Comparison of results on instance sets Centered Depot and Large Orders when applying the modified S-shape and largest gap heuristics.

Instance Group	**Exact**	**S-Shape**		**Largest Gap**	
	WCTSP-GCS	WCTSP-GCS	Traditional	WCTSP-GCS	Traditional
Centered Depot, UDD					
$l = 20$	-14.13	10.95	30.81	5.02	10.30
$l = 40$	-14.51	10.56	30.42	3.84	9.77
$l = 60$	-14.63	10.07	30.67	4.20	10.11
$l = 80$	-14.64	9.97	30.25	4.26	10.09
$l = 100$	-14.71	10.04	30.42	3.90	9.99
Avg.	-14.52	10.32	30.52	4.24	10.05
Centered Depot, CBD					
$l = 20$	-17.82	2.64	27.07	6.70	15.39
$l = 40$	-17.91	2.22	27.51	6.78	15.44
$l = 60$	-18.08	1.79	26.91	6.80	15.50
$l = 80$	-18.15	1.79	26.84	6.94	15.49
$l = 100$	-18.29	1.93	27.31	6.56	15.30
Avg.	-18.05	2.08	27.13	6.76	15.42
Large Orders, UDD					
$l = 20$	-12.25	3.76	24.78	7.03	14.84
$l = 40$	-12.38	2.98	24.26	6.64	15.04
$l = 60$	-12.51	2.50	24.10	6.57	15.08
$l = 80$	-12.54	2.69	24.31	6.50	14.94
$l = 100$	-12.62	2.69	24.53	6.42	15.02
Avg.	-12.46	2.92	24.40	6.63	14.98
Large Orders, CBD					
$l = 20$	-13.90	4.54	33.76	3.31	18.24
$l = 40$	-13.86	4.00	33.79	2.36	18.03
$l = 60$	-14.00	3.71	33.48	2.27	18.11
$l = 80$	-14.04	3.57	33.43	2.25	18.06
$l = 100$	-14.02	3.75	33.82	2.11	17.89
Avg.	-13.96	3.91	33.66	2.46	18.06