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# Designing sustainable mid-haul logistics networks with intra-route multi-resource facilities

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**Abstract:** Location-routing problems (LRPs) with intra-route facilities have recently gained the attention of researchers and practitioners. Intra-route facilities are used in the context of city logistics or alternative fuel vehicle fleets to keep vehicles operational on routes. In this paper, we extend the LRP with intra-route facilities to handle so-called combined facilities at which different replenishment services are offered to visiting vehicles. We present an adaptive large neighborhood search which is enhanced by a lower bounding procedure that helps to efficiently explore promising facility configurations. We demonstrate the competitiveness of the algorithm on existing benchmark sets for the single-resource LRP with intra-route facilities. In addition, we design new benchmark sets to assess the impact of combined intra-route facilities in logistics networks. We find that combined facilities help to reduce both the overall costs of the operated logistics network and the fleet size.

**Keywords:** Routing, location routing, intraroute facilities, intermediate stops

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# 1 Introduction

Logistics service markets are on the move in a fast changing competitive business environment, especially in the small package shipping (SPS) sector. In recent years, the transport volume in SPS increased strongly, mainly due to an exploding growth rate of e-commerce (e.g. 25.5% of growth in sales in 2015, cf. Statista, 2016). Additionally, this growth in e-commerce results in more requests for same-day deliveries, or even deliveries within a couple of hours. As a consequence, major e-commerce players start to challenge established logistics providers to offer logistics services that better fit their needs (cf. Emeç et al., 2016). These changes lead to inefficient transportation in existing delivery structures with centralized depots. On average, trucks in the European Union (EU) show a load factor of 0.5, so that 50 % of potential transport volumes remain unused. This causes estimated costs of 160 billion euros (Cruijssen, 2013).

In addition, logistics fleet operators face new challenges due to increasing environmental awareness at the political level and in society. In the EU, transport activities are responsible for 25% of $CO_2$ emissions, 30% of particulate matters, and 60% of noxious emissions. Freight transportation remains the only sector in which the energy needed and the generated emissions are still rising (European Commission, 2014). This is mainly due to the fact that new technologies and efficiency-increasing methods and concepts (e.g. electric car sharing fleets) have been adapted in other sectors more quickly, often driven by governmental interests. In the field of freight transportation, technological as well as structural changes have not yet been implemented due to limited economic benefits. In this context, governments are applying measures like restricting the access for internal combustion engine vehicles (ICEVs) in city centers (cf. European Union, 2016) and levying penalty charges on emissions (European Commission, 2012). Logistics fleet operators must cope with these changes to keep their services operational in restricted areas and to make them as profitable as possible by limiting penalty charges. Therefore, the importance of sustainable transportation increases for logistics fleet operators also from an economical perspective. Pilot projects tackling these challenges have been undertaken, especially by using electric commercial vehicles (ECVs) for short-haul transportation (without recharging the vehicle on routes). Examples include projects in the domains of letter distribution and SPS by the Deutsche Post DHL Group (DPDHL, 2014) and United Parcel Service (UPS, 2013). In addition, retail companies are investigating the use of 12-tonne ECVs in medium-duty mid-haul transportation (Stütz et al., 2016).

Optimized decisions in this changing environment are essential for logistics fleet operators to remain efficient and competitive. These companies must consider the following aspects while designing a distribution network:

**Sustainable transportation** has to be used within these networks, in order to obtain (nearly) emission-free deliveries, e.g., by using ECVs. With this technology, intermediate stops at intra-route facilities are important for recharging on routes to keep vehicles operational.

**Efficient distribution network structures** that allow for high load factors should be designed to optimally operate vehicles. Intermediate stops at intra-route facilities in order to replenish freight and avoid detours to a central depot help to create such network structures.

**Flexible delivery structures** with respect to varying transport volumes and delivery-time horizons in SPS have to be created to keep the fixed costs of a logistics fleet as low as possible. Again, intra-route facilities that allow for intermediate stops help to reduce the number of necessary vehicles within this context.

Intra-route facilities have to be distinguished from intermediate facilities which are often used as synonyms for depots or hubs with cross-docking operations in two-stage logistics networks (cf. Cuda et al., 2015). Figure 1 depicts a network with intra-route facilities. As can be seen, intra-route facilities are neither hubs nor depots, but are visited by a vehicle on its route between customer visits. At these facilities the vehicle replenishes one or several resources (e.g., energy or freight) that are necessary to keep it operational. Intra-route facilities are planned on the same echelon as the customers. However, a second-echelon may be necessary to replenish the resource offered at an intra-route facility (cf. Figure 1). In some cases the second echelon is superfluous, e.g., for charging stations that are connected to the electrical grid. In this work, we neglect the intra-route facility replenishment and focus on a single echelon with visits to customers and intra-route facilities because the intra-route facility replenishment exceeds our one-day planning horizon.

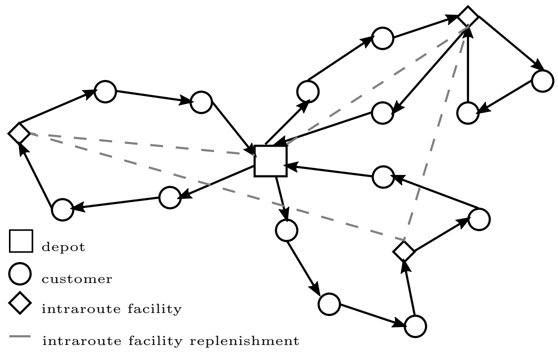


**Figure 1: Logistics network with intra-route facilities.**

The challenges just described have only partially been tackled in recent scholarly publications. A considerable amount of research has been carried out on the integration of ECVs into vehicle routing problems (VRPs) (e.g., Schneider et al., 2014; Desaulniers et al., 2016) or on city logistics (e.g., Crainic et al., 2009). In addition, new methods for tackling interdependencies between vehicle routing and the location of intra-route facilities have recently been proposed for ECVs (e.g., Yang and Sun, 2015; Schiffer and Walther, 2017). Schiffer and Walther (2016) introduced the location routing problem (LRP) with intra-route facilities (LRPIF), a general problem formulation that can be used to model location decisions either for satellite facilities in the context of freight replenishment, or for charging stations. However, solution concepts that focus on both freight replenishment and recharging at different or combined facility types are still missing from a strategic planning perspective.

Against this background, we introduce the LRPIF with multiple resources (LRPIF-MR) which allows for intermediate stops in order to replenish one or multiple resources. These resources can be divided into two categories. In the case of arc-based resources, consumption takes place on the arcs, while in the case of node-based resources it takes place at vertices. In the application under study, both arc-based (e.g., energy) and node-based (e.g., freight) resources, are considered. The option to replenish a resource depends on the type of the visited facility. Thus, we consider different facility types at which either energy (recharging facilities) or freight (replenishing facilities) or both (combined facilities) can be replenished. We present an adaptive large neighborhood search (ALNS) for the LRPIF-MR, which features a lower bounding technique to avoid extensively searching unpromising facility configurations. We present rules to efficiently calculate the feasibility violations caused by local search moves as well as vertex insertions and removals in the ALNS. We also provide benchmark instances based on a real-world example focusing on a mid-haul medium duty ECV logistics network and study the impact of replenishment facilities and combined facilities within this network structure. Our results highlight the significance of combined facilities for future logistics networks, showing that combined facilities reduce both the overall costs and the vehicle fleet size. In addition, we demonstrate the competitiveness of our algorithm by providing new best known solutions for existing LRPIF benchmarks and obtain faster computational times than Schiffer and Walther (2016).

The remainder of this paper is structured as follows: Section 2 provides a brief overview of recent research in the field of VRPs and LRPs with intermediate stops. In Section 3, we present a mixed integer linear program for the LRPIF-MR. Our algorithm is described in Section 4. The benchmark instances mentioned above and the discussion of results are presented in Section 5. Section 6 concludes the paper.

## 2 Literature review

This section provides a brief overview on related research on LRPs and VRPs with intermediate stops. We exclude papers on two-echelon distribution systems, because this paper focuses on single-echelon planning problems. For an overview of two-echelon problems, we refer to Cuda et al. (2015).

Schneider et al. (2015) proposed a generalized modeling approach for the VRP with intermediate stops (VRPIS), covering fixed vehicle costs, routing costs and time-dependent replenishment processes at intermediate facilities. Research on VRPIS variants can be classified into two streams: research on (i) intermediate freight (or waste) replenishment (or unloading) and (ii) on-route recharging for electric vehicles.

Angelelli and Speranza (2002) introduced the periodic VRP (PVRP) for waste collection including intermediate facilities, while Kim et al. (2006) provided a real-world case study on waste collection, considering issues like time windows and driver rest periods. Benjamin and Beasley (2010) developed an efficient variable neighborhood tabu search metaheuristic for the case study of Kim et al. (2006). Crevier et al. (2007) presented the multi-depot VRP with interdepot routes (MDVRPI) and were outperformed by a hybrid guided local search algorithm presented by Tarantilis et al. (2008). Kek et al. (2008) focused on the significance of intermediate stops in city logistics, providing a case study from Singapore. Crainic et al. (2009) gave a general overview on multi-depot VRPs (MDVRPs) in city logistics. Further applications for intermediate stops were proposed by Amaya et al. (2007) and Prescott-Gagnon et al. (2014) for road maintenance and the distribution of heating oil. In addition, Castro et al. (2013) and Divsalar et al. (2014) investigated hotel selection as an intermediate stop within an orienteering problem. We refer to Divsalar et al. (2014) for an overview of application cases for intermediate stops.

Focusing on alternative fuel vehicles (AFVs), Erdoğan and Miller-Hooks (2012) proposed the first model that considers additional vertices for charging processes as the green VRP (GVRP). In the context of ECVs, Schneider et al. (2014) were the first to study the electric VRP with time windows (EVRPTW) which allows for full recharges on routes. Several variants of the electric VRP (EVRP) have been published since. Work on partial recharging was conducted by Felipe et al. (2014), Bruglieri et al. (2015a), Bruglieri et al. (2015b) and Keskin and Çatay (2016). Montoya et al. (2017) additionally focused on non-linear charging. Desaulniers et al. (2016) presented an exact solution approach, providing a branch-price-and-cut algorithm for several EVRP variants. Work on mixed and heterogeneous fleets was presented by Goeke and Schneider (2015) and Hiermann et al. (2016). Mancini (2015) presented a first approach focusing on hybrid electric vehicles (HEVs) explicitly. For an extensive overview on goods distribution with ECVs, we refer the interested reader to Pelletier et al. (2016). For a review of battery characteristics and behavior, see Pelletier et al. (2017).

While the intermediate facilities at which replenishment can take place are given in the VRPIS, the location decisions for these facilities must be made simultaneously with the routing decision in the LRPIF (Schiffer and Walther, 2016). The authors presented a generic ALNS-based solution method with dynamic programming elements to solve different single-resource LRPIF variants. Publications focusing on LRPIF variants are still sparse. Schiffer and Walther (2017) introduced the electric LRP with time windows and partial recharging (ELRP-TWPR) that simultaneously considers the location of charging stations and ECV routing decisions. Yang and Sun (2015) proposed the battery swap station electric vehicle LRP (BSS-EV-LRP) that focuses on the problem of designing vehicle routes and locating battery swapping stations for ECVs. The BSS-EV-LRP can be seen as a special case of the ELRP-TWPR in which time-dependent replenishment, time windows, and maximum route durations are neglected. Hof et al. (2017) extended the adaptive variable neighborhood search (AVNS) of Schneider et al. (2015) to solve the BSS-EV-LRP.

All papers just reviewed focus on a single-resource that can be replenished. To the best of our knowledge, this paper is the first to study the LRPIF-MR.

## 3 Problem description

The mixed integer program (MIP) for the LRPIF-MR is defined on a directed and complete graph $G = (\mathcal{V}_{0,n+1}, \mathcal{A})$ with a set of vertices $\mathcal{V}_{0,n+1}$, including the depot vertex 0 and its duplicate $n+1$, and a set of arcs $(i,j) \in \mathcal{A}$. The set $\mathcal{C} = \{1, ..., n\}$ represents a set of customer vertices. Let $\mathcal{F}$ be a set of potential facility vertices, which comprises recharging facility vertices $\mathcal{F}_{\mathrm{R}}$, freight replenishment vertices $\mathcal{F}_{\mathrm{F}}$, and combined facility vertices $\mathcal{F}_{\mathrm{C}}$. Dummy vertices are used to allow for multiple visits to facilities. In this context, $\mathcal{S}_k$ denotes a set of dummy vertices for vertex $k$. Let $\mathcal{S} = \bigcup_{k \in \{\mathcal{C} \cup \mathcal{F}\}} \mathcal{S}_k$ be the set of all dummy vertices and let $\mathcal{V} = \mathcal{C} \cup \mathcal{F} \cup \mathcal{S}$. While recharging facilities can be sited at any vertex $i \in \mathcal{V}$, it is not allowed to site freight replenishment or combined facilities at customer vertices because obviously storing freight at its destination is not meaningful, i.e., $\mathcal{C} \cap \{\mathcal{F}_{\mathrm{C}} \cup \mathcal{F}_{\mathrm{F}}\} = \emptyset$ holds. In the following, we refer to any set $\mathcal{X}$ as $\mathcal{X}'$ if it includes dummy vertices. If the depot is included in any of the sets, the set is indexed by 0 for the start-depot and by $n+1$ for the vertex representing the end-depot. We define the cut set $\delta^+(i) = \{j \in \mathcal{V}_{0,n+1} : (i,j) \in \mathcal{A}\}$ to identify all successor vertices of vertex $i$ and define $\delta^-(i) = \{j \in \mathcal{V}_{0,n+1} : (j,i) \in \mathcal{A}\}$ for predecessors of $i$ respectively.

While the recharging time depends on the amount of energy recharged, the replenishment time for freight is constant. For energy, partial replenishment is allowed, whereas full replenishment is assumed for freight due to constant replenishment times. Recharging and providing service are carried out simultaneously if a refueling facility is sited at a customer vertex. The time needed for recharging at a vertex $i \in \mathcal{F}$ depends linearly on the amount of replenished energy $w_i$ and on the recharging rate $r$. Replenishing freight takes a constant amount of $g$ time units. The energy load at a vertex $i \in \mathcal{V}$ is denoted by $q_i$ and the freight load by $f_i$, respectively. Linear energy consumption is modeled by using the consumption rate $z$ and the arc related distance $d_{ij}$. For each arc $(i,j)$, a travel time $t_{ij}$ is given. For customer vertices $i \in \mathcal{C}$ a service time $s_i$ and a demand $p_i$ are known. Time windows $[e_i, l_i]$ are defined by the earliest $e_i$ and latest $l_i$ allowed start time of service at a customer vertex $i \in \mathcal{C}$. The variable $\tau_i$ is the arrival time at vertex $i \in \mathcal{V}$. The battery capacity of a vehicle is given by $Q$ and its freight capacity is given by $F$. Costs are separated into driving costs $c_{ij}$ for each arc, fixed costs for building a recharging facility $c_{\mathrm{R}}^{\mathrm{fix}}$ $(\forall i \in \mathcal{F}_{\mathrm{R}})$, fixed costs for building a freight replenishment facility $c_{\mathrm{F}}^{\mathrm{fix}}$ $(\forall i \in \mathcal{F}_{\mathrm{F}})$, fixed costs for building a combined facility $c_{\mathrm{C}}^{\mathrm{fix}}$, and fixed vehicle costs $c_{\mathrm{V}}^{\mathrm{fix}}$. All costs relate to the same planning horizon. The binary variables $x_{ij}$ indicate whether an arc $(i,j) \in \mathcal{A}$ is traversed. Location decisions are modeled by $y_i$ for recharging facilities, by $o_i$ for freight replenishing vertices, and by $v_i$ for combined facilities. If a recharging facility is located at vertex $i \in \mathcal{V}$, $y_i = 1$ holds. Otherwise $y_i = 0$ holds. Variables $o_i$ and $v_i$ hold analogously. Table 1 summarizes the notation just introduced.

**Table 1: Notation used for the LRPIF.**

| | |
|---|---|
| **Sets** | |
| $\mathcal{C}$ | set of customer vertices |
| $\mathcal{F}_{\mathrm{R}}$ | set of potential refueling facility vertices |
| $\mathcal{F}_{\mathrm{F}}$ | set of potential freight replenishment facility vertices |
| $\mathcal{F}_{\mathrm{C}}$ | set of potential combined facility vertices |
| $\mathcal{S}_k$ | set of dummy vertices for vertex $k \in \mathcal{F}$ |
| $\mathcal{S}$ | set of all dummy vertices $(\bigcup_{\kappa \in \{\mathcal{C} \cup \mathcal{F}\}} \mathcal{S}_\kappa)$ |
| $\mathcal{V}$ | set of all vertices without depot vertices $(\mathcal{C} \cup \mathcal{F} \cup \mathcal{S})$ |
| **Decision variables** | |
| $x_{ij}$ | binary: arc $(i,j)$ is traversed |
| $y_i$ | binary: refueling facility is sited at vertex $i$ |
| $v_i$ | binary: combined facility is sited at vertex $i$ |
| $o_i$ | binary: freight replenishment facility is sited at vertex $i$ |
| $\tau_i$ | arrival time at vertex $i$ |
| $w_i$ | amount of fuel replenished at vertex $i$ |
| $q_i$ | amount of energy when arriving at vertex $i$ |
| $f_i$ | freight load when arriving at vertex $i$ |
| **Parameters** | |
| $e_i$ | earliest start time of service allowed at vertex $i$ |
| $l_i$ | latest start time of service allowed at vertex $i$ |
| $s_i$ | service time at vertex $i$ |
| $p_i$ | demand at vertex $i$ |
| $t_{ij}$ | travel time of arc $(i,j)$ |
| $d_{ij}$ | distance of arc $(i,j)$ |
| $c_{ij}$ | travel cost of arc $(i,j)$ |
| $c_{\mathrm{R}}^{\mathrm{fix}}$ | fixed cost for installing a recharging facility |
| $c_{\mathrm{F}}^{\mathrm{fix}}$ | fixed cost for installing a freight replenishment facility |
| $c_{\mathrm{C}}^{\mathrm{fix}}$ | fixed cost for installing a combined facility |
| $c_{\mathrm{V}}^{\mathrm{fix}}$ | fixed cost of a vehicle |
| $r$ | refueling rate |
| $g$ | freight replenishment time |
| $z$ | fuel consumption rate |
| $Q$ | vehicle fuel capacity |
| $F$ | vehicle freight capacity |

With this notation, the MIP is defined as follows:

$$\text{minimize} \quad Z = \sum_{j \in \delta(0)} c_{\mathrm{V}}^{\mathrm{fix}} x_{0j} + \sum_{(i,j) \in \mathcal{A}} c_{ij} x_{ij} + \sum_{i \in \mathcal{F}_{\mathrm{R}}} c_{\mathrm{R}}^{\mathrm{fix}} y_i + \sum_{i \in \mathcal{F}_{\mathrm{C}}} c_{\mathrm{C}}^{\mathrm{fix}} v_i + \sum_{i \in \mathcal{F}_{\mathrm{F}}} c_{\mathrm{F}}^{\mathrm{fix}} o_i \tag{1}$$

subject to

$$\sum_{j \in \delta^+(i)} x_{ij} = 1 \qquad i \in \mathcal{C} \tag{2}$$

$$\sum_{j \in \delta^+(i)} x_{ij} \leq 1 \qquad i \in \{\mathcal{V} \setminus \mathcal{C}\} \tag{3}$$

$$\sum_{j \in \delta^-(i)} x_{ji} - \sum_{j \in \delta^+(i)} x_{ij} = 0 \qquad j \in \mathcal{V} \tag{4}$$

$$\tau_j \geq \tau_i + (t_{ij} + s_i)\, x_{ij} - l_0\,(1 - x_{ij}) \qquad i \in \mathcal{C}_0,\ j \in \delta^+(i) \tag{5}$$

$$\tau_j \geq \tau_i + t_{ij} x_{ij} + r w_i - (l_0 + rQ)\,(1 - x_{ij}) \qquad i \in \mathcal{F}'_{\mathrm{R}} \cup \mathcal{F}'_{\mathrm{C}},\ j \in \delta^+(i) \tag{6}$$

$$\tau_j \geq \tau_i + t_{ij} x_{ij} + g - (l_0 + g)\,(1 - x_{ij}) \qquad i \in \mathcal{F}'_{\mathrm{C}} \cup \mathcal{F}'_{\mathrm{F}},\ j \in \delta^+(i) \tag{7}$$

$$e_i \leq \tau_i \leq l_i \qquad i \in \mathcal{V}_{0,n+1} \tag{8}$$

$$0 \leq q_0 \leq Q \tag{9}$$

$$0 \leq q_i + w_i \leq Q \qquad i \in \mathcal{V} \tag{10}$$

$$0 \leq q_j \leq q_i + w_i - z d_{ij} x_{ij} + Q\,(1 - x_{ij}) \qquad i \in \mathcal{V},\ j \in \delta^+(i) \tag{11}$$

$$0 \leq f_i \leq F \qquad i \in \mathcal{V}_{0,n+1} \tag{12}$$

$$0 \leq f_j \leq f_i - p_i x_{ij} + F\,(1 - x_{ij}) \qquad i \in \{\mathcal{V}_0 \setminus \{\mathcal{F}'_{\mathrm{C}} \cup \mathcal{F}'_{\mathrm{F}}\}\},\ j \in \delta^+(i) \tag{13}$$

$$0 \leq f_j \leq f_i + F(v_i + o_i) + F\,(1 - x_{ij}) \qquad i \in \mathcal{F}'_{\mathrm{C}} \cup \mathcal{F}'_{\mathrm{F}},\ j \in \delta^+(i) \tag{14}$$

$$v_i + o_i \leq 1 \qquad i \in \mathcal{F}'_{\mathrm{C}} \cup \mathcal{F}'_{\mathrm{F}} \tag{15}$$

$$w_i \leq Q y_i \qquad i \in \mathcal{F}'_{\mathrm{R}} \tag{16}$$

$$y_i \geq y_j \qquad i \in \mathcal{F}_{\mathrm{R}},\ j \in \mathcal{S}_i \tag{17}$$

$$o_i \geq o_j \qquad i \in \mathcal{F}_{\mathrm{F}},\ j \in \mathcal{S}_i \quad (18)$$

$$v_i \geq v_j \qquad i \in \mathcal{F}_{\mathrm{C}},\ j \in \mathcal{S}_i \quad (19)$$

$$x_{ij} \in \{0;1\} \quad (i,j) \in \delta\left(\mathcal{V}_{0,n+1}\right) \quad y_i \in \{0;1\} \quad i \in \mathcal{F}'_{\mathrm{R}},$$
$$v_i \in \{0;1\} \quad i \in \mathcal{F}'_{\mathrm{C}} \quad o_i \in \{0;1\} \quad i \in \mathcal{F}'_{\mathrm{F}}\ . \quad (20)$$

The Objective (1) is to minimize total costs, consisting of investment costs for vehicles, driving costs, and investment costs for all types of facilities. Constraints (2) impose a single assignment for customers; single assignment is relaxed for other vertices by Constraints (3), and flow conservation is enforced by Constraints (4). The time-related constraints are given in (5)–(8): Constraints (5) hold for customer vertices, and Constraints (6) consider refueling times at recharging facilities and combined facilities; Constraints (7) account for freight replenishing times at freight replenishment and combined facilities; time windows are enforced by Constraints (8), and time windows for dummy vertices are set to the planning horizon; thus, recharging facilities at customer vertices are available during the whole planning period for all vehicles. Constraints for energy consumption and recharging are given by (9)–(11): battery capacity limits are enforced by (9) and (10); Constraints (11) limit the amount of energy and obtains the energy balance including recharges. Freight constraints are given by (12)–(14): Constraints (12) limit the residual freight at any vertex to the maximum freight capacity; the freight balance is given in (13) for all vertices at which neither a freight replenishment nor a combined facility can be sited; for freight replenishment and combined facilities, freight replenishment is considered in (14). Constraints (15) ensure that either a freight replenishment or a combined facility is built at a vertex. Constraints on the siting decisions are given by (16)–(19): Constraints (16) force a recharging facility to be built at vertex $i$ if recharging takes place because dummy vertices are used to allow multiple visits to a facility, Constraints (17) mirror siting decisions from real vertices to dummy vertices; siting decisions for freight replenishment and combined facilities are given by (18) and (19). Constraints (20) define the domains of the binary variables.

# 4 Adaptive large neighborhood search metaheuristic

This section starts with a general description of our algorithm for the LRPIF-MR. Single components are then explained in detail in Sections 4.1–4.4. In addition, Section 4.5 describes rules for efficient search move evaluations. Figure 2 provides the pseudo-code of our algorithm  and the notation is defined in Table 2. After

$\sigma \leftarrow InitialSolution(), InitializeParameters(), \iota \leftarrow 0$
**while** $(\iota < \eta^{\max})$ **and** $(\iota - \iota_{\mathrm{imp}} < \eta^{\max}_{\mathrm{noi}})$ **do**
  $\sigma' \leftarrow DestroyAndRepair(\mathcal{D}_{\mathrm{l}}, \mathcal{D}_{\mathrm{s}}, \mathcal{R}, \eta^{\mathrm{lrg}}\sigma)$
  **if** $(\lambda(\sigma') < \lambda(\sigma^*)(1+\delta))$ **then**
    $\sigma' \leftarrow LocalSearch(\sigma')$
  **if** $(\lambda(\sigma') < \lambda(\sigma))$ **then**
    $\sigma \leftarrow \sigma'$
    **if** $(\lambda(\sigma') < \lambda(\sigma^*))$ **then**
      $\sigma^* \leftarrow \sigma'$
    **if** $(\lambda(\sigma') < \lambda(\sigma^*_{\mathrm{f}}))$ **then**
      $\sigma'_{\mathrm{f}} \leftarrow GenerateFeasibleSolution(\sigma')$
      **if** $feasible(\sigma'_{\mathrm{f}})$ **and** $(\lambda(\sigma'_{\mathrm{f}}) < \lambda(\sigma^*_{\mathrm{f}}))$ **then**
        $\sigma^*_{\mathrm{f}} \leftarrow \sigma'_{\mathrm{f}}$
        $\iota_{\mathrm{imp}} \leftarrow \iota$
  $UpdateScores(\sigma'), UpdatePenalties(\sigma')$
  $SetNewScores(\eta^{\mathrm{al,l}}, \eta^{\mathrm{al,s}}, \eta^{\mathrm{p}})$
  $\iota \leftarrow \iota + 1$
$VRPphase$

**Figure 2: Pseudo-code of the adaptive large neighborhood search metaheuristic.**

Table 2: Parameters used in the ALNS.

| | |
|---|---|
| $\eta^{\mathrm{lrg}}$ | number of iterations after which a large destroy operator is applied |
| $\eta^{\max}$ | maximum number of iterations |
| $\eta^{\max}_{\mathrm{noi}}$ | maximum number of iterations without improvement |
| $\eta^{\mathrm{al,l}}$ | number of iterations after which the large operator probabilities are adapted |
| $\eta^{\mathrm{al,s}}$ | number of iterations after which the small operator probabilities are adapted |
| $\eta^{\mathrm{p}}$ | number of iterations after which the penalty weights are adapted |
| $\delta$ | percentage deviation in which the local search is applied |
| $\sigma'$ ($\sigma'_{\mathrm{f}}$) | (feasible) candidate solution |
| $\sigma$ | current solution |
| $\sigma^*$ ($\sigma^*_{\mathrm{f}}$) | best (feasible) solution |
| $\iota$ ($\iota_{\mathrm{imp}}$) | number of iterations (without improvement) |

removing infeasible arcs from $G$ (Section 4.1.1) and creating an initial solution (Section 4.1.2), a destroy-and-repair phase is applied (Section 4.2). In this phase, the destroy operators are separated into large destroy operators and small destroy operators. While the large destroy operators are able to modify the facility configuration, the small destroy operators only remove customers from routes. Whenever a large destroy operator is used, a lower bound is computed in order to avoid searching unpromising facility configurations (Section 4.3), i.e., a facility configuration is discarded if its lower bound is worse than the objective value of the best known feasible solution. After the application of a destroy operator, a repair operator is applied to create a new solution. In addition to the destroy and repair phase which is used for diversification, a local search component (Section 4.4) is applied for intensification. Local search is performed after every destroy and repair step involving a large destroy operator, but only after small destroy and repair steps if the objective value $\lambda(\sigma')$ of the candidate solution lies within a range of $(1+\delta)$ to the objective value $\lambda(\sigma^*)$ of the best known solution. To allow searching in infeasible regions of the solution space, we use a generalized cost function with penalty terms (Section 4.5), and we store feasible and infeasible solutions separately. At each iteration, the current solution is set to the candidate solution if it yields an improvement. In addition, if it improves the best known solution, $\sigma^*$ is substituted by $\sigma'$. If the candidate solution further improves the best known feasible solution, a feasible solution is yielded by $\sigma'$ (Section 4.1.3). If this solution still improves the best known feasible solution it is forwarded to $\sigma^*_{\mathrm{f}}$. The algorithm stops after a maximum number of iterations without improvement $\eta^{\max}_{\mathrm{noi}}$ or if a maximum number of overall iterations $\eta^{\max}$ is reached. Finally, a vehicle routing phase is applied to intensify the search on the best known facility configuration. In this phase, the same algorithm is applied for $\vartheta$ iterations but without using the large destroy operators.

## 4.1 Basic components

In this section, we explain basic algorithmic procedures for preprocessing (Section 4.1.1), constructing an initial solution (Section 4.1.2), and deriving feasible solutions from infeasible ones (Section 4.1.3) during the search process.

### 4.1.1 Preprocessing

We remove infeasible arcs from $G$ according to (21)–(24) in order to reduce the neighborhood size and computational time in the search process:

$$i,\ j \in \mathcal{C} \quad \wedge \quad p_i + p_j \ > \ F \tag{21}$$

$$i \in \mathcal{V}_0,\ j \in \mathcal{V}_{n+1} \quad \wedge \quad e_i + s_i + t_{ij} \ > \ l_j \tag{22}$$

$$i \in \mathcal{V}_0,\ j \in \mathcal{V} \quad \wedge \quad e_i + s_i + t_{ij} + s_j + t_{jn+1} \ > \ l_{n+1} \tag{23}$$

$$i,\ j \in \mathcal{V}_{0n+1} \quad \wedge \quad z\, d_{ij} \ > \ Q. \tag{24}$$

While Constraints (21)–(23) identify infeasible arcs due to demand and time window constraints (Psaraftis, 1983; Savelsbergh, 1985; Schneider et al., 2014), Constraints (24) remove infeasible arcs if the constraints on the fuel resource are violated (Schiffer and Walther, 2016).

#### 4.1.2 Construction algorithm

We use a modified savings algorithm (Clarke and Wright, 1964) to construct an initial solution, in which the routes are allowed to be infeasible with respect to energy consumption, time windows and vehicle load. Thus, only the maximum route duration given by $l_0 - e_0$ remains as a stopping criterion while building routes. To construct the initial solution, the following steps are executed:

1. Back-and-forth routes for all customers are constructed.
2. Potential cost savings for merging routes are calculated. Afterwards, all possible merge moves are sorted in non-increasing order with respect to cost savings.
3. The two routes with the largest cost savings are merged if the maximum route duration is not exceeded. If all merge moves with positive savings have been executed or no feasible merge move remains, stop.
4. A local search procedure (Section 4.4) is applied once to improve the solution with respect to costs and violations.
5. Intra-route facilities are added to the initial routes in a hierarchical fashion. First, a combined replenishment facility is optimally inserted into routes for which freight penalties still exist. After repairing these freight violations, the remaining energy violations are calculated. Recharging facilities are then added in the respective routes to also repair these violations. For both steps, facilities are only added up to the maximum number of facilities (if their number is limited) or until no penalty for the respective resource remains.

#### 4.1.3 Generate feasible solution

To generate feasible solutions, we use the method described in Vidal et al. (2014). If a solution is infeasible, the local search procedure is executed after multiplying the current penalty weights by 100. If the solution remains infeasible, the local search procedure is reapplied, after multiplying the penalty weights by 10. If the solution remains still infeasible after this step, it is not forwarded to $\sigma_\mathrm{f}^*$ and the usual search procedure continues.

### 4.2 Destroy and repair phase

To handle changes in the facility configuration in the destroy and repair phase, we use two types of destroy operators: while small destroy operators from the set $\mathcal{D}_\mathrm{s}$ are only allowed to remove customers from the current solution, large destroy operators from the set $\mathcal{D}_\mathrm{l}$ are allowed to change the facility configuration by adding, removing or swapping facilities, before removing customers. After both types of destroy operators have been applied, a repair operator from set $\mathcal{R}$ is used to reinsert the removed customers in order to create a new solution. A large destroy operator is selected every $\eta^{\mathrm{lrg}}$ iterations in order to change the facility configuration. To avoid searching in unpromising facility configurations and thus increase the share of search iterations in promising configurations, a lower bound is computed for the facility configuration produced by a large destroy operator (see Section 4.3). If this lower bound $LB(\sigma')$ on the candidate solution $\sigma'$ is higher than the objective function value of the best known feasible solution value $\lambda(\sigma_\mathrm{f}^*)$, the respective facility configuration is discarded by reapplying a large destroy operator before resuming the search. If $LB(\sigma') < \lambda(\sigma_\mathrm{f}^*)$ holds, the candidate solution becomes the current solution $\sigma$ (even if it does not improve the latter) and is then improved by a local search procedure (Section 4.4). To select the operators according to probabilities that reflect their past performance, we use an adaptive learning mechanism as proposed in Ropke and Pisinger (2006) and implement the details as described in Schiffer and Walther (2016). Selection scores for the respective operators are updated after $\eta^{\mathrm{al,l}}$ iterations for large destroy operators and after $\eta^{\mathrm{al,s}}$ iterations for small destroy and repair operators.

To handle different facility types, we use the following large destroy operators. The `add` operator described in Hemmelmayr et al. (2012) is used, but it is split into an add operator handling combined facilities and an add operator handling charging facilities. Analogously, the `swap perfect` operator (Schiffer and Walther, 2016) that removes an arbitrary chosen facility and reinserts it in optimal fashion, is split for both types of facilities. A `swap perfect out` operator (Schiffer and Walther, 2016) is used like the `swap perfect` operator but closes facilities if reinserting them does not improve the solution. Furthermore, a drop operator that removes an arbitrarily chosen facility and afterwards removes customers on routes linked to the closed facility is used. In addition, we apply a swap facility type operator, which randomly selects a combined facility and a charging facility and swaps their types. After applying a large operator, an arbitrary chosen number of customer vertices out of $[1, \Omega_{\max}]$ are removed.

As small destroy operators, we use a worst remove (Ropke and Pisinger, 2006) and a related remove (Pisinger and Ropke, 2007) operator, as well as a route remove (Hemmelmayr et al., 2012) and a modified Shaw remove (Goeke and Schneider, 2015) operator. In addition, the station vicinity remove operator presented in Goeke and Schneider (2015) is used.

In the repair step, we apply the sequential insertion operator proposed in Hiermann et al. (2016). In addition, we use the sequential perturbed insertion operator (Schiffer and Walther, 2016), which extends the sequential insertion operator by perturbing the insertion costs within a range of $[0.8, 1.2]$

## 4.3 Lower bound

We calculate a lower bound depending on the facility configuration, which allows to reject a facility configuration if its lower bound is higher than the best feasible solution $\sigma_{\mathrm{f}}^*$ found so far. To estimate this bound, we need good estimations of the following components:

1. The minimum overall traveled distance $LB^{\text{distance}}$ is necessary to estimate routing costs and the minimum overall energy needed.
2. The minimum number of replenishment stops for loading freight or recharging energy is needed to estimate the minimum distance of additionally required detours.

Before obtaining subgraphs from $G$ in order to calculate minimal spanning trees for the necessary estimations, we remove infeasible arcs from $G$ as described in Section 4.1.1.

We first calculate a bound on the minimum overall traveled distance, using a minimal spanning tree on a subgraph $G^c$ of $G$ with $G^c = (\mathcal{C}_0, \mathcal{A}^c)$ with $\mathcal{A}^c = \{(i,j) \in \mathcal{A} : i \in \mathcal{C}_0, j \in \mathcal{C}_0\}$. On this incomplete connected graph $G^c = (\mathcal{C}_0, \mathcal{A}^c, d)$, weighted by the distance $d_{ij}$ of each arc, a minimum spanning tree is given by $T^c \subseteq \mathcal{A}^c$ with the minimum total weight. This total weight determines a lower bound ($LB^{\text{distance}}$) on the traveled distance:

$$LB^{\text{distance}} = \sum_{(i,j) \in T^c} d_{ij}. \tag{25}$$

With this bound, the minimum energy required can be estimated as

$$LB^{\text{energy}} = z \cdot LB^{\text{distance}}_. \tag{26}$$

To calculate a lower bound on the additional distance caused by detours due to replenishment stops, we require a lower bound on the amount of energy recharged on the routes ($LB^{\text{rch}}$) and a lower bound on the amount of freight reloaded on the routes ($LB^{\text{rpl}}$). Assuming that all vehicles start with a fully charged battery and fully loaded with freight, these bounds are estimated by the following Equations (27) and (28), depending on the number of vehicles $k$ of the current solution:

$$LB^{\text{rch}} = LB^{\text{energy}} - k \cdot Q \tag{27}$$

$$LB^{\text{rpl}} = \sum_{i \in \mathcal{C}} p_i - k \cdot F. \tag{28}$$

With these bounds, we can calculate the cost of additional detours for replenishing purposes. To this end, we use a second minimal spanning tree $T^{cf}$ of the subgraph $G^{cf} = \left(\mathcal{C}_0 \cup \mathcal{F}, \mathcal{A}^{cf}, d\right)$ with $\mathcal{A}^{cf} = \{(i,j) \in \mathcal{A} : i \in \mathcal{C}_0 \cup \mathcal{F}, j \in \mathcal{C}_0 \cup \mathcal{F}\}$, to account for additional facility vertices. We assume full replenishment at any replenishment vertex for each resource in order to obtain a lower bound on the number of replenishment visits. Because an energy recharge is considered for any freight replenishment process at combined facilities, detours due to freight replenishment are calculated first. The number of necessary replenishment processes is estimated as $\lceil LB^{\mathrm{rpl}}/F \rceil$. Thus, a subset $\mathcal{K}$ of $\mathcal{A}^{cf}$ with a cardinality equal to the number of necessary replenishment processes is sufficient to calculate a lower bound $LB^{\mathrm{det}}_{\mathrm{rpl}}$ on additional detours due to freight replenishment. As stated in Equation (29), $\mathcal{K}$ is limited to the arcs connecting customer vertices to combined facilities in order to extend $T^c$ for replenishment detours:

$$LB^{\mathrm{det}}_{\mathrm{rpl}} = \min \sum_{(i,j)\in\mathcal{K}} d_{ij}$$
$$\text{subject to} \quad |\mathcal{K}| = \left\lceil \frac{LB^{\mathrm{rpl}}}{F} \right\rceil \wedge \left(i \in \mathcal{F}^{\mathrm{O}}_{\mathrm{C}} \vee j \in \mathcal{F}^{\mathrm{O}}_{\mathrm{C}}\right) \wedge (i \in \mathcal{C} \vee j \in \mathcal{C}) \wedge \mathcal{K} \subseteq T^{cf}. \tag{29}$$

Analogously, additional detours for energy replenishment $LB^{\mathrm{det}}_{\mathrm{rch}}$ can be estimated through Equation (31), using set $\mathcal{L}$ and assuming a full recharge at each recharging station. Note that in this context, $LB^{\mathrm{rch}}$ has to be corrected for the amount of recharged energy $Q\left\lceil \frac{LB^{\mathrm{rpl}}}{F} \right\rceil$ that is already considered in $LB^{\mathrm{det}}_{\mathrm{rpl}}$, due to parallel charging and loading at combined facilities. Furthermore only the arcs that are not included in $\mathcal{K}$ are considered to construct $\mathcal{L}$:

$$\begin{aligned} LB^{\mathrm{det}}_{\mathrm{rch}} &= \min \sum_{(i,j)\in\mathcal{L}} d_{ij} \\ &\text{subject to} \\ |\mathcal{L}| &= \left\lceil \frac{LB^{\mathrm{rch}} - Q\left\lceil \frac{LB^{\mathrm{rpl}}}{F}\right\rceil}{Q} \right\rceil \wedge \left(i \in \mathcal{F}^{\mathrm{O}} \vee j \in \mathcal{F}^{\mathrm{O}}\right) \wedge (i \vee j \in \mathcal{C}) \wedge \mathcal{L} \subseteq T^{cf} \wedge \mathcal{L} \cap \mathcal{K} = \emptyset. \end{aligned} \tag{30}$$

Concluding, a lower bound on the overall traveled distance is given by (31):

$$LB^{\mathrm{D}} = LB^{\mathrm{distance}} + LB^{\mathrm{det}}_{\mathrm{rpl}} + LB^{\mathrm{det}}_{\mathrm{rch}}. \tag{31}$$

If the objective considers facility and vehicle costs, information on these cost terms can easily be considered in the lower bound estimation from the facility configuration and the number of vehicles from the current solution.

## 4.4 Local search

We apply a local search component to intensify the search in promising regions of the search space. It uses a composite neighborhood consisting of the 2-opt* operator (Potvin and Rousseau (1995)), the Or-opt operator (Or (1976)), and the exchange operator (Savelsbergh (1992)). In addition, we implement a station-in operator that inserts either a combined or a recharging facility in order to repair freight or energy violations and a station-out operator that removes unnecessary visits to facilities. Furthermore, we develop a new modify facility type operator, which allows to modify station configurations within the local search phase, by changing a facility type from combined to recharging and vice versa. A best improvement acceptance criterion is used, and the local search terminates if no further improving move can be found.

## 4.5 Penalty functions

In order to explore infeasible parts of the search space, we use a generalized cost function $\lambda_{\mathrm{gen}}(\sigma)$ to evaluate a solution $\sigma$ (see, e.g., Gendreau et al., 1994). Besides the objective value $\lambda(\sigma)$, we include penalty terms for violations of freight capacities ($FR$), time windows ($TW$) and energy capacity ($FL$), weighted by the penalty factors $\alpha$, $\beta$ and $\gamma$ respectively:

$$\lambda_{\mathrm{gen}}(\sigma) = \lambda(\sigma) + \alpha FR(\sigma) + \beta TW(\sigma) + \gamma FL(\sigma). \tag{32}$$

This generalized cost function contains penalties for node-based (freight) and arc-based (energy) resources. Note that within this context energy can be replaced by any other arc-based resource (e.g., driver time). Analogously, freight can be replaced by any other node-based resource (e.g., collected waste). In the following explanations, we use the terms energy and freight to simplify the discussion.

Because we allow for partial recharging of energy, time window feasibility becomes linearly dependent on the amount of energy that is recharged. Therefore, a corridor-based penalty approach is necessary to model these dependencies (see, Schiffer and Walther, 2016). To this end, we use a time corridor to check the feasibility of a route $\rho$, and model all resources using time units for consistency reasons in the following. We refer to the energy consumption along an arc $(i,j)$ as the time $h_{ij}$ needed to recharge the consumed energy, and to the battery capacity as the time $H = rQ$ needed to recharge the full battery capacity. Replenishing processes for freight take a constant amount of $g$ time units, independent of the amount of replenished freight. To refer to open facilities in the current facility configuration we use a superscript O, thus distinguishing the opened facility configuration $\mathcal{F}^{\mathrm{O}}$, $\mathcal{F}^{\mathrm{O}}_{\mathrm{R}}$, $\mathcal{F}^{\mathrm{O}}_{\mathrm{F}}$, and $\mathcal{F}^{\mathrm{O}}_{\mathrm{C}}$ from all potential facility vertices $\mathcal{F}$, $\mathcal{F}_{\mathrm{R}}$, $\mathcal{F}_{\mathrm{F}}$, and $\mathcal{F}_{\mathrm{C}}$.

To calculate the violations mentioned above, several resources that are related to each vertex of a route $\rho$ are necessary. In Section 4.5.1, we define these resources and explain penalty terms that are necessary to propagate these resources along a route $\rho$. Penalty terms for backward evaluations can be derived in an analogous fashion and are provided in Appendix A. To allow for time-efficient evaluations of the penalties while constructing new routes, concatenation rules are presented in Section 4.5.2.

#### 4.5.1 Forward penalties

To derive a corridor-based penalty approach, the following resources are used:

- $a_i^{\mathrm{e}}$ is used to track the energy that has been consumed on a route up to vertex $i$ and not been replenished at preceding charging stations or at combined facilities.
- $a_i^{\mathrm{f}}$ is analogously used to track the amount of freight that has been delivered and not been replenished at preceding combined facilities on a route up to vertex $i$.
- $a_i^{\min}$ denotes the earliest arrival time at vertex $i$ if freight is fully replenished at preceding combined facilities, and only as much energy as necessary to prevent the vehicle from running out of energy up to vertex $i$ is recharged at preceding facilities.
- $a_i^{\max}$ denotes the latest allowed arrival time at vertex $i$ if freight is fully replenished at preceding combined facilities, and as much energy as possible is recharged at preceding facilities on the respective route.

As introduced by Nagata et al. (2010) for point-based resource evaluations and extended by Schiffer and Walther (2016) to corridor-based resource evaluations, we use the concept of time-traveling to calculate penalty-corrected values for each vertex so that violations are considered only once on a route. To this end,

- $\tilde{a}_i^{\min}$ denotes the penalty-corrected value of $a_i^{\min}$,
- $\tilde{a}_i^{\max}$ denotes the penalty-corrected value of $a_i^{\max}$.

To propagate these resources along a route $\rho$ from vertex $i$ to vertex $j$, we compute two additional auxiliary values. In this context,

- $a_{ij}^{\mathrm{sl}}$ denotes the slack time arising after arrival at vertex $j$ before the earliest start time of service at $j$ when traversing arc $(i,j)$,
- $a_{ij}^{\mathrm{add}}$ denotes the additional amount of energy that has to be recharged at the last charging station or combined facility on a route to prevent the vehicle from running out of energy if arc $(i,j)$ is traversed.

These auxiliary values are computed as follows:

$$a_{ij}^{\mathrm{sl}} = \max\left\{0, e_j - \tilde{a}_i^{\min} - t_{ij}\right\}, \tag{33}$$

$$a_{ij}^{\mathrm{add}} = \begin{cases} \max\left\{0, \max\left\{0, a_i^{\mathrm{e}} - g - \max\left\{0, a_{ij}^{\mathrm{sl}} - g\right\}\right\} + h_{ij} - H\right\} & \text{if } i \in \mathcal{F}^{\mathrm{O}}_{\mathrm{C}} \\ \max\left\{0, \max\left\{0, a_i^{\mathrm{e}} - s_i - a_{ij}^{\mathrm{sl}}\right\} + h_{ij} - H\right\} & \text{if } i \in \mathcal{F}^{\mathrm{O}}_{\mathrm{R}} \\ \max\left\{0, \max\left\{0, a_i^{\mathrm{e}} - \min\left\{a_{ij}^{\mathrm{sl}}, \tilde{a}_i^{\max} - \tilde{a}_i^{\min}\right\}\right\} + h_{ij} - H\right\} & \text{else.} \end{cases} \tag{34}$$

Potential slack times are calculated in a straightforward fashion with respect to the earliest start time of service at vertex $j$, considering $\tilde{a}_i^{\min}$ and the driving time $t_{ij}$ in Equation (33). Slack times as well as idle times at combined facilities due to freight replenishment are implicitly considered as recharging times in Equation (34).

The resources are initialized for the depot vertex 0 to $a_0^{\min} = a_0^{\max} = a_0^{\mathrm{e}} = a_0^{\mathrm{f}} = 0$ and propagated along a route by Equations (35)–(40):

$$a_j^{\mathrm{e}} = \begin{cases} \min\left\{H, \max\left\{0, a_i^{\mathrm{e}} - g - \max\left\{0, a_{ij}^{\mathrm{sl}} - g\right\}\right\} + h_{ij}\right\} & \text{if } i \in \mathcal{F}_{\mathrm{C}}^{\mathrm{O}} \\ \min\left\{H, \max\left\{0, a_i^{\mathrm{e}} - s_i - a_{ij}^{\mathrm{sl}}\right\} + h_{ij}\right\} & \text{if } i \in \mathcal{F}_{\mathrm{R}}^{\mathrm{O}} \\ \min\left\{H, \max\left\{0, a_i^{\mathrm{e}} - \min\left\{a_{ij}^{\mathrm{sl}}, \tilde{a}_i^{\max} - \tilde{a}_i^{\min}\right\}\right\} + h_{ij}\right\} & \text{else,} \end{cases} \tag{35}$$

$$a_j^{\mathrm{f}} = \begin{cases} p_j & \text{if } i \in \mathcal{F}_{\mathrm{C}}^{\mathrm{O}} \cup \mathcal{F}_{\mathrm{F}}^{\mathrm{O}} \\ \min\left\{F, a_i^{\mathrm{f}}\right\} + p_j & \text{else,} \end{cases} \tag{36}$$

$$a_j^{\min} = \begin{cases} \max\left\{e_j, \tilde{a}_i^{\min} + t_{ij} + g\right\} + a_{ij}^{\mathrm{add}} & \text{if } i \in \mathcal{F}_{\mathrm{C}}^{\mathrm{O}} \cup \mathcal{F}_{\mathrm{F}}^{\mathrm{O}} \\ \max\left\{e_j, \tilde{a}_i^{\min} + t_{ij}\right\} + a_{ij}^{\mathrm{add}} & \text{else,} \end{cases} \tag{37}$$

$$a_j^{\max} = \begin{cases} \max\left\{e_j, \tilde{a}_i^{\min} + \max\left\{a_i^{\mathrm{e}}, g\right\} + t_{ij}\right\} & \text{if } i \in \mathcal{F}_{\mathrm{C}}^{\mathrm{O}} \\ \max\left\{e_j, \tilde{a}_i^{\min} + \max\left\{a_i^{\mathrm{e}} - s_i, 0\right\} + t_{ij}\right\} & \text{if } i \in \mathcal{F}_{\mathrm{R}}^{\mathrm{O}} \\ \max\left\{e_j, \tilde{a}_i^{\max} + t_{ij}\right\} & \text{else,} \end{cases} \tag{38}$$

$$\tilde{a}_i^{\min} = \min\left\{a_i^{\min}, a_i^{\max}, l_i\right\}, \tag{39}$$

$$\tilde{a}_i^{\max} = \min\left\{l_i, \min\left\{a_i^{\min}, a_i^{\max}, l_i\right\} + \max\left\{a_i^{\max} - a_i^{\min}, 0\right\}\right\}. \tag{40}$$

Analogously to (34), slack and idle times are accounted for recharging in Equation (35). Note that, within this context, $a_{ij}^{\mathrm{sl}}$ has to be corrected by $g$ to avoid circularities between $a_{ij}^{\mathrm{sl}}$ and $a_{ij}^{\mathrm{add}}$, because $g$ is not considered within $a_{ij}^{\mathrm{sl}}$. Furthermore, service times at customer vertices are considered as charging times if a charging station is sited at a customer vertex. The freight consumed on a route is described by Equation (36), considering freight replenishment at combined or freight replenishing facilities. The earliest arrival time $a_j^{\min}$ is propagated from vertex $i$ to vertex $j$, taking driving times and time window constraints into consideration. Furthermore, additional time due to recharging is considered by adding $a_{ij}^{\mathrm{add}}$. If vertex $i$ of arc $(i, j)$ is a combined or a freight replenishing facility, an additional idle time $g$ is considered due to freight replenishment processes in Equation (37). To forward the corridor of possible arrival times along a route, $a_j^{\max}$ is propagated along an arc $(i, j)$ considering the driving time as well as the earliest arrival time at vertex $j$. The time-traveled values of $a_i^{\min}$ and $a_i^{\max}$ are calculated by Equations (39) and (40).

With these variables, freight as well as time window and energy violations are calculated: to avoid the overestimation of violations, (41) considers only the minimum of $a^{\min}$ and $a^{\max}$ because the remaining violation is considered in (42):

$$\overrightarrow{TW}(\rho_i) = \sum_{v \in \rho_i} \max\left\{\min\left\{a_v^{\min}, a_v^{\max}\right\} - l_v, 0\right\}, \tag{41}$$

$$\overrightarrow{FL}(\rho_i) = \sum_{v \in \rho_i} \max\left\{a_v^{\min} - a_v^{\max}, 0\right\}. \tag{42}$$

Freight penalties are derived straightforwardly in (43):

$$\overrightarrow{FR}(\rho_i) = \sum_{v \in \rho_i} \max\left\{0, a_v^{\mathrm{f}} - F\right\}. \tag{43}$$

In this way, we derived forward penalties for energy and freight replenishment. Penalty functions for backward labeling can be derived analogously and with the same terminology. These penalty functions are referred to as $b^x$ with $x \in \{\min;\ \max;\ \mathrm{sl};\ \mathrm{e};\ \mathrm{f};\ \mathrm{add}\}$ (see, Appendix A).

### 4.5.2 Concatenation operators

Using the forward and backward penalty functions derived in Section 4.5.1 and Appendix A, we perform time efficient concatenation operations for most common search moves, concatenating two partial routes or inserting a single vertex between two partial routes. Since freight penalties are independent of energy penalties due to fixed freight replenishment times, concatenation operators can be derived straightforwardly as described in Schiffer and Walther (2016).

If two partial routes $\rho_1 =< 0, ..., x >$ and $\rho_2 =< y, ..., n+1 >$ are concatenated into a route $\rho_f =< 0, ..., x, y, ..., n+1 >$ without inserting an additional vertex, penalties for freight, time window, and energy violation are given by Equations (44)–(47):

$$\overrightarrow{FR}(\rho_e) = \begin{cases} \overrightarrow{FR}(\rho_1) + \overleftarrow{FR}(\rho_2) + \max\left\{0, a_y^{\mathrm{f}} - F\right\} \\ \qquad + \max\left\{0, b_y^{\mathrm{f}} - F\right\} & \text{if } v \in \mathcal{F}_{\mathrm{C}}^{\mathrm{O}} \cup \mathcal{F}_{\mathrm{F}}^{\mathrm{O}} \\ \overrightarrow{FR}(\rho_1) + \overleftarrow{FR}(\rho_2) + \max\left\{0, a_y^{\mathrm{f}} + b_y^{\mathrm{f}} - F\right\} & \text{else,} \end{cases} \tag{44}$$

$$TW(\rho_f) = \overrightarrow{TW}(\rho_1) + \overleftarrow{TW}(\rho_2) + \max\left\{0, a_y^{\min} - l_y - \max\left\{0, a_y^{\min} - a_y^{\max}\right\}\right\} + \max\left\{0, \min\left\{l_y, \max\left\{e_y, a_y^{\min}\right\}\right\} - b_y^{\min}\right\} , \tag{45}$$

$$FL(\rho_f) = \overrightarrow{FL}(\rho_1) + \overleftarrow{FL}(\rho_2) + \max\left\{0, a_y^{\min} - a_y^{\max}\right\} + D , \tag{46}$$

$$D = \begin{cases} \max\left\{0, a_y^{\mathrm{e}} + b_y^{\mathrm{e}} - H - \min\left\{H, \max\left\{0, b_y^{\min} - a_y^{\min}\right\}\right\}\right\} & \text{if } y \in \mathcal{F}_{\mathrm{R}}^{\mathrm{O}} \\ \max\left\{0, a_y^{\mathrm{e}} + b_y^{\mathrm{e}} - H - \min\left\{H, \min\left\{\max\left\{0, b_y^{\min} - a_y^{\min}\right\}, \right.\right.\right. \\ \left.\left.\left. \qquad \max\left\{0, a_y^{\max} - a_y^{\min}\right\} + \max\left\{0, b_y^{\min} - b_y^{\max}\right\}\right\}\right\}\right\} & \text{else.} \end{cases} \tag{47}$$

If a new route $\rho_e =< 0, ..., x, v, y, ..., n+1 >$ is constructed from two partial routes $\rho_1 =< 0, ..., x >$ and $\rho_2 =< y, ..., n+1 >$, inserting a vertex $v$, penalties for freight, time window, and energy violations can be calculated using Equations (48)–(51):

$$\overrightarrow{FR}(\rho_e) = \begin{cases} \overrightarrow{FR}(\rho_1) + \overleftarrow{FR}(\rho_2) + \max\left\{0, a_v^{\mathrm{f}} - F\right\} + \max\left\{0, b_v^{\mathrm{f}} - F\right\} & \text{if } v \in \mathcal{F}_{\mathrm{C}}^{\mathrm{O}} \cup \mathcal{F}_{\mathrm{F}}^{\mathrm{O}} \\ \overrightarrow{FR}(\rho_1) + \overleftarrow{FR}(\rho_2) + \max\left\{0, a_v^{\mathrm{f}} + b_v^{\mathrm{f}} - F\right\} & \text{else,} \end{cases} \tag{48}$$

$$TW(\rho_e) = \overrightarrow{TW}(\rho_1) + \overleftarrow{TW}(\rho_2) + \max\left\{0, a_v^{\min} - l_v - \max\left\{0, a_v^{\min} - a_v^{\max}\right\}\right\} + \max\left\{0, \min\left\{l_v, \max\left\{e_v, a_v^{\min}\right\}\right\} - b_v^{\min} - \max\left\{b_v^{\max} - b_v^{\min}, 0\right\}\right\}, \tag{49}$$

$$FL(\rho_e) = \overrightarrow{FL}(\rho_1) + \overleftarrow{FL}(\rho_2) + \max\left\{0, a_v^{\min} - a_v^{\max}\right\} + \max\left\{0, b_v^{\max} - b_v^{\min}\right\} + B, \tag{50}$$

$$B = \begin{cases} \max\left\{0, a_v^{\mathrm{e}} + b_v^{\mathrm{e}} - H - \min\left\{H, \max\left\{0, b_v^{\min} - a_v^{\min}\right\}\right\}\right\} & \text{if } v \in \mathcal{F}_{\mathrm{R}}^{\mathrm{O}} \\ \max\left\{0, a_v^{\mathrm{e}} + b_v^{\mathrm{e}} - H - \min\left\{H, \min\left\{\max\left\{0, b_v^{\min} - a_v^{\min}\right\}, \right.\right.\right. \\ \left.\left.\left. \qquad \max\left\{0, a_v^{\max} - a_v^{\min}\right\} + \max\left\{0, b_v^{\min} - b_v^{\max}\right\}\right\}\right\}\right\} & \text{else.} \end{cases} \tag{51}$$

Using Equations (44)–(51), penalties for freight, time window and energy violations can be calculated in $O(1)$ time for all neighborhood structures that can be constructed with the merge moves described above. Only for routes that are created by inserting more than one vertex at a time, penalties have to be calculated for the inserted route segment first. However, even in this case only a computational effort of $O(b)$ instead of $O(n)$ is necessary to evaluate the insertion of a route segment of length $b$.

# 5 Computational studies

This section contains the computational experiments on the LRPIF-MR and the LRPIF. First, we describe the benchmark instances we have used and our experimental setup in Section 5.1. Section 5.2 focuses on managerial insight for combined intra-route facilities. Based on these insights, we derive new benchmark classes with a varying number of facility types. Results on existing single-resource LRPIF benchmarks prove the competitiveness of our algorithm in Section 5.3.

## 5.1 Benchmark instances and experimental setup

Focusing on combined facilities, no benchmark sets exist so far. Thus, for contribution of this paper on LRPIF-MRs is twofold. First, we create new benchmark instances for the LRPIF-MR, by mapping the real-world application case presented in Schiffer et al. (2016) to the modified Solomon instances of Schiffer and Walther (2017). The derivation of these instances is described in Appendix B. Starting from a logistics network for ECVs that contains recharging facilities to cover the full territory, we investigate the effect of adding different types of facilities to the network. In a first step, we allow a certain number of $n \in \{1, 2, 3\}$ opened replenishment facilities in the solution at zero cost. Doing so, we analyze the cost savings potential that can be reached by allowing for freight replenishment. In an analogous fashion, we study the impact of adding $n \in \{1, 2, 3\}$ combined facilities instead of replenishment facilities. Second, we derive meaningful cost values for replenishment and combined facilities based on these initial results. Thus, we generate new benchmark instances in which all three types of facilities are available. Appendix C details the generation of the benchmark set and provides results of our algorithm as comparison values for future methods tackling the same problem.

To compare our algorithm with existing approaches, we computed results on the ELRP-TWPR and on the BSS-EV-LRP. For the ELRP-TWPR, we used the modified Solomon instances described in Schiffer and Walther (2016). Thus, 56 instances with 100 customers and 21 additional vertices were considered. For the BSS-EV-LRP, benchmark instances proposed by Yang and Sun (2015) are used. They contain a set of small-sized instances with 16 to 70 customers based on the instances provided by Augerat et al. (1995), 12 mid-size instances with 75, 100 and 150 customers based on the instances created by Rochat and Taillard (1995), and two large-size instances with 255 and 480 customers based on the instances of Golden et al. (1998). All of these benchmark instances for the single-resource LRPIF have been discussed in Schiffer and Walther (2016) and can be downloaded from http://www.om.rwth-aachen.de/data/uploads/lrpifinst.zip.

For all numerical experiments, we use a standard desktop computer with an Intel Core i7 3.60 GHz and 16 GB RAM running Ubuntu 16.04 LTS. Our solution method was implemented in C++ as a single core thread, using the same parameter setting for all computational runs. To provide a fair comparison between our algorithm and the algorithm of Schiffer and Walther (2016), we used the parameter setting of Schiffer and Walther (2016) to highlight the benefit of the lower bounding procedure.

## 5.2 Benefit of combined facilities

To identify the benefit of combined facilities, we proceed as described in Section 5.1 and we analyzed the different impact of dedicated replenishment and combined facilities first. In this course, we present results with cost terms for vehicles, traveling and recharging facilities, while keeping the number of replenishment or combined facilities fixed in Appendix C. Table 7 contains results for all instances with cost terms and no dedicated facilities, while Table 8 focuses on cost terms and dedicated combined facilities, and Table 9 contains results for cost terms and dedicated replenishment facilities. The box-whisker-plots in Figure 3 and Figure 4 depict these results by showing the potential improvement in overall costs for a certain number of replenishment facilities (Figure 3) or combined facilities (Figure 4). As can be seen, the benefit of combined facilities shows a median improvement between 8.66% (for one dedicated combined facility) and 21.47% (for three dedicated facilities), yielding maximum improvements of up to 45.74%. These improvements are significantly higher than the improvements for pure freight replenishment facilities that show a median improvement between 0.00% (for one dedicated replenishment facility) and 5.05 % (for three dedicated replenishment facilities). This large difference is mainly caused by the fact that additional freight replenishment stops only help to significantly reduce the number of vehicles and traveling costs if idle times for recharging and replenishing can be synchronized. Otherwise, the overall time horizon of a driver shift of nine hours is to short to deliver additional freight after replenishing.

Table 3 details the cost improvement potential for combined facilities and shows the average cost improvement $\overline{\Delta}n$ for a dedicated number of $n$ combined facilities for the different instance sets. These sets are separated into sets with clustered (c), random (r) and randomly clustered (rc) customer distributions. Furthermore, sets of type '100' feature smaller vehicle freight capacities then sets of type '200'. As can be seen, higher average cost savings are achieved for sets of type '100' independent of the respective customer distribution.

Concluding, our results show that, especially for ECVs that are operated in small time horizons and with small freight volumes, combined facilities offer a very high potential to save overall costs.

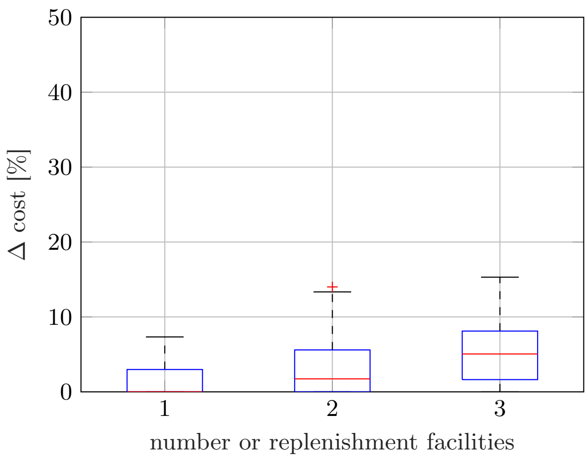


**Figure 3: Cost improvement with replenishment facilities.**

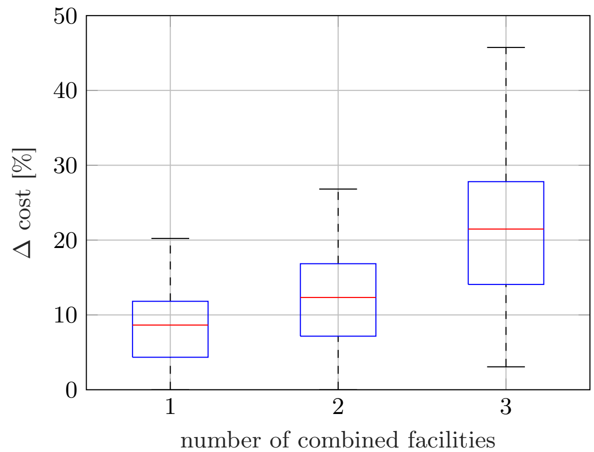


**Figure 4: Cost improvement with combined facilities.**

**Table 3: Set based cost improvements with dedicated combined facilities.**

| Set | $\overline{\Delta}1$ | $\overline{\Delta}2$ | $\overline{\Delta}3$ | Set | $\overline{\Delta}1$ | $\overline{\Delta}2$ | $\overline{\Delta}3$ |
|---|---|---|---|---|---|---|---|
| c100 | 11.13 | 19.20 | 32.16 | c200 | 6.48 | 9.53 | 14.85 |
| r100 | 10.70 | 14.04 | 22.87 | r200 | 3.56 | 7.15 | 13.43 |
| rc100 | 12.74 | 18.54 | 33.79 | rc200 | 3.68 | 5.87 | 10.76 |

Abbreviations hold as follows: Set - Instance set, $\overline{\Delta}n$ [%] - average cost improvement with $n$ combined facilities.

Based on these insights, we added cost terms for replenishment and combined facilities to the instances derived in Appendix B. For freight replenishment facilities we divided the average cost improvement per facility of all instances with three dedicated replenishment facilities. For combined facilities, we added an additional cost term for installing a charging station at a present facility as stated in Schiffer et al. (2016). The final instance set can be downloaded from http://www.om.rwth-aachen.de/data/uploads/lrpifinstmr.zip. Results that allow for algorithmic comparisons are given in Table 6 in Appendix C.

## 5.3 Results for the LRPIF with a single resource

Table 4 provides computational results for the BSS-EV-LRP. In addition to the initial BSS-EV-LRP results obtained by Yang and Sun (2015), results have also been provided by Hof et al. (2017) and Schiffer and Walther (2016). Since the latter results significantly outperform those of Yang and Sun (2015) for 23 out of 24 instances, we only compare the results of our algorithm (SSL) with the best known solution (BKS) and with the results of HGS (Hof et al., 2017) and SW (Schiffer and Walther, 2016). For each instance, we provide the number $n$ of customers, the best known solution value (BKS), and for each solution approach, the best solution found in 10 runs $\lambda^b$, the percentage gap $\Delta^b$ between $\lambda^b$ and the BKS, as well as the total runtime of these 10 runs $t^t$. As can be seen, the previously best algorithm with respect to solution quality is Schiffer and Walther (2016), which outperforms the algorithm of Hof et al. (2017). The algorithm proposed in this paper is capable of improving on average the results of Schiffer and Walther (2016). In addition, for five out of 24 instances it improves the BKS. The runtime is comparable to that of Schiffer and Walther (2016). For some instances, the runtime increases slightly because the search process repeatedly finds an improving solution which increases the total iteration count (see, e.g., results on GWKC_16). The algorithm of Hof et al. (2017) remains the fastest with respect to computational time. However, for a strategic planning task, all presented computational times are clearly acceptable.

**Table 4: Results on the BSS-EV-LRP benchmarks.**

| | | | HGS | | | SW | | | SSL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Instance | n | BKS | $\lambda^b$ | $\Delta^b$ | $t^a$ | $\lambda^b$ | $\Delta^b$ | $t^a$ | $\lambda^b$ | $\Delta^b$ | $t^a$ |
| P-n16-k8 | 16 | 1281.95 | 1282.38 | 0.03 | 1.66 | 1282.38 | 0.03 | 5.22 | 1282.38 | 0.03 | 3.66 |
| P-n19-k2 | 19 | 467.08 | 468.08 | 0.21 | 1.98 | 467.08 | 0.00 | 1.19 | 467.08 | 0.00 | 0.99 |
| P-n21-k2 | 21 | 471.74 | 472.74 | 0.21 | 1.93 | 471.74 | 0.00 | 1.00 | 471.74 | 0.00 | 1.42 |
| P-n23-k8 | 23 | 1346.04 | 1347.04 | 0.07 | 4.15 | 1346.04 | 0.00 | 12.88 | 1346.04 | 0.00 | 10.12 |
| P-n40-k5 | 40 | 856.71 | 857.70 | 0.12 | 8.42 | 856.71 | 0.00 | 13.96 | 856.71 | 0.00 | 12.09 |
| P-n45-k5 | 45 | 872.23 | 872.23 | 0.00 | 12.12 | 878.73 | 0.75 | 15.35 | 872.23 | 0.00 | 17.90 |
| P-n50-k7 | 50 | 1130.44 | 1130.44 | 0.00 | 15.18 | 1131.87 | 0.13 | 50.28 | 1131.87 | 0.13 | 35.16 |
| P-n55-k8 | 55 | 1170.04 | 1170.04 | 0.00 | 16.25 | 1173.39 | 0.29 | 49.10 | 1173.13 | 0.26 | 52.07 |
| P-n60-k10 | 60 | 1548.40 | 1556.38 | 0.52 | 33.57 | 1548.40 | 0.00 | 103.20 | 1548.40 | 0.00 | 100.51 |
| P-n70-k10 | 70 | 1621.19 | 1632.87 | 0.72 | 21.30 | 1621.19 | 0.00 | 118.57 | 1621.19 | 0.00 | 112.23 |
| Average | | | | 0.19 | 11.66 | | 0.12 | 37.08 | | 0.04 | 34.62 |
| tai75a | 75 | 1664.08 | 1664.08 | 0.00 | 8.84 | 1664.08 | 0.00 | 35.35 | 1664.08 | 0.00 | 30.34 |
| tai75b | 75 | 1468.73 | 1471.57 | 0.19 | 12.10 | 1468.73 | 0.00 | 24.92 | 1468.73 | 0.00 | 24.59 |
| tai75c | 75 | 1381.20 | 1381.20 | 0.00 | 18.11 | 1396.59 | 1.11 | 23.21 | 1396.59 | 1.11 | 14.94 |
| tai75d | 75 | 1399.03 | 1405.45 | 0.46 | 5.44 | 1399.03 | 0.00 | 20.47 | 1399.03 | 0.00 | 16.53 |
| tai100a | 100 | 2175.55 | 2179.28 | 0.17 | 19.79 | 2175.55 | 0.00 | 71.48 | 2175.55 | 0.00 | 49.22 |
| tai100b | 100 | 1940.61 | 1948.73 | 0.42 | 10.46 | 1940.61 | 0.00 | 62.92 | 1940.61 | 0.00 | 44.17 |
| tai100c | 100 | 1589.66 | 1598.72 | 0.57 | 27.76 | 1589.66 | 0.00 | 44.57 | 1589.66 | 0.00 | 51.07 |
| tai100d | 100 | 1609.06 | 1609.06 | 0.00 | 20.08 | 1609.70 | 0.04 | 49.81 | 1609.70 | 0.04 | 40.88 |
| tai150a | 150 | 3190.26 | 3194.41 | 0.13 | 58.89 | 3190.26 | 0.00 | 169.19 | **3189.94** | **-0.01** | 135.32 |
| tai150b | 150 | 2777.34 | 2815.80 | 1.38 | 45.23 | 2777.34 | 0.00 | 136.67 | **2773.03** | **-0.16** | 132.80 |
| tai150c | 150 | 2402.23 | 2403.41 | 0.05 | 43.44 | 2402.23 | 0.00 | 111.33 | **2401.56** | **-0.03** | 112.43 |
| tai150d | 150 | 2728.75 | 2744.54 | 0.58 | 84.91 | 2728.75 | 0.00 | 186.12 | **2725.94** | **-0.10** | 172.88 |
| Average | | | | 0.33 | 29.59 | | 0.10 | 78.00 | | 0.07 | 68.76 |
| GWKC_09 | 255 | 655.05 | 666.05 | 1.68 | 1017.08 | 655.05 | 0.00 | 1193.01 | 658.63 | 0.55 | 1181.53 |
| GWKC_16 | 480 | 1659.77 | 1693.34 | 2.02 | 262.64 | 1659.77 | 0.00 | 2122.16 | **1640.27** | **-1.17** | 2214.43 |
| Average | | | | 1.85 | 639.86 | | 0.00 | 1657.59 | | **-0.31** | 1697.98 |

Abbreviations are defined as follows: Inst. - instance, n - number of customers, BKS - best known solution, $\lambda^b$ - best solution value out of ten runs, $\Delta^b$ - percentage gap between the BKS and $\lambda^b$, $t^t$ [s] - total runtime out of ten runs, HGS - Hof, Goeke & Schneider, SW - Schiffer & Walther, SSL - Schiffer, Schneider & Laporte.

Table 5 compares the ELRP-TWPR results presented in Schiffer and Walther (2016) to the results computed with our algorithm. It reports for each instance and method the best solution value out of ten runs $\lambda^b$, the average solution value out of these ten runs $\lambda^a$, and the total runtime $t^t$ as well as the average runtime $t^a$ out of these ten runs. Additionally, the percentage gap $\Delta^b$ between the best solution value obtained with our algorithm and the best solution value provided in Schiffer and Walther (2016) and the percentage gap $\Delta^a$ between the respective average solution values are given. As can be seen, our algorithm finds new BKS for 34 out of 56 instances and matches the BKS for 12 instances. A small gap between our solution value and the BKS value remains for only 10 instances. Our algorithm reduces the runtime by about 54%. Concluding, our algorithm provides competitive results with an average improvement of 0.36%, reducing the computational time significantly.

**Table 5: Results on the ELRP-TWPR benchmark.**

| | SW | | | SSL | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Instance | $\lambda^b$ | $\lambda^a$ | $t^a$ | $\lambda^b$ | $\Delta^b$ | $\lambda^a$ | $\Delta^a$ | $t^t$ | $t^a$ |
| c101_21 | 1045.35 | 1078.86 | 215.069 | **1037.91** | **-0.71** | 1041.53 | **-3.46** | 190.54 | 19.05 |
| c102_21 | 1011.76 | 1039.75 | 365.264 | **986.832** | **-2.46** | 1004.79 | **-3.36** | 666.92 | 66.69 |
| c103_21 | 956.94 | 987.304 | 245.359 | **951.659** | **-0.55** | 984.93 | **-0.24** | 848.84 | 84.88 |
| c104_21 | 874.46 | 886.134 | 90.915 | **872.937** | **-0.17** | 890.616 | 0.51 | 1011.83 | 101.18 |
| c105_21 | 1013.69 | 1055.75 | 194.813 | **1007.74** | **-0.59** | 1016.38 | **-3.73** | 258.42 | 25.84 |
| c106_21 | 1008.89 | 1022.46 | 162.044 | **993.8** | **-1.50** | 1003.36 | **-1.87** | 352.39 | 35.24 |
| c107_21 | 987.52 | 1003.56 | 118.281 | 991.201 | 0.37 | 1002.65 | **-0.09** | 340.81 | 34.08 |
| c108_21 | 974.49 | 983.018 | 107.628 | **973.726** | **-0.08** | 992.243 | 0.94 | 424.25 | 42.42 |
| c109_21 | 920.14 | 925.135 | 91.6276 | **918.866** | **-0.14** | 948.569 | 2.53 | 628.41 | 62.84 |
| c201_21 | 618.28 | 618.275 | 14.3838 | 618.275 | 0.00 | 618.275 | 0.00 | 105.45 | 10.54 |
| c202_21 | 618.28 | 618.275 | 20.0842 | 618.275 | 0.00 | 618.275 | 0.00 | 196.67 | 19.67 |
| c203_21 | 618.28 | 618.275 | 23.802 | 618.275 | 0.00 | 618.275 | 0.00 | 425.02 | 42.50 |
| c204_21 | 618.28 | 622.319 | 22.4058 | 618.275 | 0.00 | 619.23 | **-0.50** | 372.12 | 37.21 |
| c205_21 | 618.28 | 618.275 | 9.272 | 618.275 | 0.00 | 618.275 | 0.00 | 115.06 | 11.51 |
| c206_21 | 618.28 | 618.275 | 9.3649 | 618.275 | 0.00 | 618.275 | 0.00 | 133.28 | 13.33 |
| c207_21 | 618.28 | 618.275 | 12.9641 | 618.275 | 0.00 | 618.275 | 0.00 | 170.73 | 17.07 |
| c208_21 | 618.28 | 618.275 | 10.2851 | 618.275 | 0.00 | 618.275 | 0.00 | 156.43 | 15.64 |
| r101_21 | 1566.85 | 1597.67 | 768.736 | **1550.03** | **-1.07** | 1585.2 | **-0.78** | 704.36 | 70.44 |
| r102_21 | 1418.51 | 1435.19 | 441.968 | **1408.08** | **-0.74** | 1440.33 | 0.36 | 1548.88 | 154.89 |
| r103_21 | 1187.40 | 1199.72 | 542.843 | **1169.06** | -1.54 | 1217.15 | 1.45 | 1671.96 | 167.20 |
| r104_21 | 1012.56 | 1033.3 | 465.707 | 1016.04 | 0.34 | 1039.71 | 0.62 | 1746.65 | 174.67 |
| r105_21 | 1297.43 | 1327.18 | 374.951 | **1280.21** | **-1.33** | 1327.87 | 0.05 | 783.58 | 78.36 |
| r106_21 | 1202.39 | 1243.94 | 620.359 | 1207.5 | 0.42 | 1220.94 | **-1.85** | 1314.19 | 131.42 |
| r107_21 | 1064.98 | 1078.33 | 567.098 | 1070.43 | 0.51 | 1093.86 | 1.44 | 1916.87 | 191.69 |
| r108_21 | 956.36 | 985.813 | 575.739 | 956.52 | 0.02 | 989.02 | 0.33 | 1808.52 | 180.85 |
| r109_21 | 1133.91 | 1158.82 | 386.296 | **1114.51** | **-1.71** | 1141.73 | **-1.47** | 1216.78 | 121.68 |
| r110_21 | 1008.57 | 1029.24 | 597.099 | 1018.84 | 1.02 | 1040.56 | 1.10 | 1419.69 | 141.97 |
| r111_21 | 1021.60 | 1049.48 | 474.448 | **1008.24** | **-1.31** | 1043.04 | **-0.61** | 1516.82 | 151.68 |
| r112_21 | 954.847 | 974.956 | 482.236 | **942.721** | **-1.27** | 983.008 | 0.83 | 1633.73 | 163.37 |
| r201_21 | 1104.12 | 1110.54 | 36.747 | **1097.02** | **-0.64** | 1100.58 | **-0.90** | 242.894 | 24.29 |
| r202_21 | 994.158 | 999.608 | 68.452 | **992.546** | **-0.16** | 993.779 | **-0.58** | 384.744 | 38.47 |
| r203_21 | 863.266 | 872.644 | 72.6339 | **863.207** | **-0.01** | 868.698 | **-0.45** | 515.04 | 51.50 |
| r204_21 | 723.863 | 734.223 | 62.5765 | 724.59 | 0.10 | 731.812 | **-0.33** | 547.365 | 54.74 |
| r205_21 | 948.314 | 960.248 | 29.6976 | **948.265** | **-0.01** | 955.17 | **-0.53** | 288.672 | 28.87 |
| r206_21 | 885.636 | 901.077 | 59.4892 | 885.636 | 0.00 | 892.938 | **-0.90** | 426.519 | 42.65 |
| r207_21 | 792.623 | 811.096 | 47.576 | **791.331** | **-0.16** | 797.511 | **-1.67** | 469.289 | 46.93 |
| r208_21 | 714.93 | 723.299 | 42.5679 | **706.715** | **-1.15** | 723.522 | 0.03 | 525.253 | 52.53 |
| r209_21 | 852.833 | 867.701 | 50.3004 | 852.833 | 0.00 | 863.093 | **-0.53** | 431.777 | 43.18 |
| r210_21 | 835.219 | 847.855 | 44.9559 | **829.061** | **-0.74** | 838.294 | **-1.13** | 391.409 | 39.14 |
| r211_21 | 760.891 | 773.949 | 58.2968 | **758.741** | **-0.28** | 767.426 | **-0.84** | 498.692 | 49.87 |
| rc101_21 | 1602.88 | 1619.15 | 313.354 | **1590.99** | **-0.74** | 1620.32 | 0.07 | 500.335 | 50.03 |
| rc102_21 | 1448.22 | 1478.7 | 356.957 | **1447.19** | **-0.07** | 1469.79 | **-0.60** | 1300.18 | 130.02 |
| rc103_21 | 1285.16 | 1308.5 | 432.091 | **1273.76** | **-0.89** | 1297.58 | **-0.83** | 1862.13 | 186.21 |
| rc104_21 | 1111.11 | 1128.05 | 327.234 | 1111.48 | 0.03 | 1150.8 | 2.02 | 1413.85 | 141.39 |
| rc105_21 | 1385.28 | 1398.05 | 341.468 | **1370.66** | **-1.06** | 1404.49 | 0.46 | 588.492 | 58.85 |
| rc106_21 | 1343.32 | 1365.7 | 332.795 | **1341.78** | **-0.11** | 1361.64 | **-0.30** | 750.434 | 75.04 |
| rc107_21 | 1163.92 | 1195.71 | 471.804 | 1170.52 | 0.57 | 1199.88 | 0.35 | 1198.71 | 119.87 |
| rc108_21 | 1107.43 | 1128.48 | 326.185 | 1111.07 | 0.33 | 1146.23 | 1.57 | 1411.87 | 141.19 |
| rc201_21 | 1269.16 | 1272.77 | 24.7425 | **1258.17** | **-0.87** | 1265.08 | **-0.60** | 187.781 | 18.78 |
| rc202_21 | 1140.44 | 1150.53 | 37.7132 | 1140.47 | 0.00 | 1142.89 | **-0.66** | 315.101 | 31.51 |
| rc203_21 | 962.367 | 977.28 | 41.8573 | **956.783** | **-0.58** | 964.821 | **-1.27** | 434.852 | 43.49 |
| rc204_21 | 831.71 | 843.215 | 34.391 | **828.33** | **-0.41** | 832.848 | **-1.23** | 469.433 | 46.94 |
| rc205_21 | 1070.36 | 1087.77 | 23.2051 | 1070.36 | 0.00 | 1074.77 | **-1.20** | 284.931 | 28.49 |
| rc206_21 | 1073.5 | 1084.11 | 22.1072 | **1071.85** | **-0.15** | 1081.11 | **-0.28** | 273.534 | 27.35 |
| rc207_21 | 930.16 | 943.491 | 31.1486 | **925.301** | **-0.52** | 934.056 | **-1.00** | 365.112 | 36.51 |
| rc208_21 | 799.046 | 816.07 | 37.7233 | **798.019** | **-0.13** | 803.89 | **-1.49** | 434.701 | 43.47 |
| Average | | | 209.63 | | **-0.36** | | **-0.37** | | 71.77 |

Abbreviations are defined as follows: Inst. - instance, $\lambda^b$ - best solution value out of ten runs, $\Delta^b$ - percentage gap between both $\lambda^b$, $\Delta^a$ - percentage gap between both $\lambda^a$ , $\lambda^a$ - average solution value out of ten runs, $t^t$ [s] - total runtime out of ten runs, $t^a$ [s] - average runtime out of ten runs.

# 6 Conclusions

We have studied the LRPIF-MR in which three types of potential intra-route facilities, namely recharging, replenishment, and combined facilities are considered. These facilities allow for either recharging energy, or replenishing freight, or both recharging energy and replenishing freight. To solve large-size instances, we derived a hybrid of ALNS and local search (LS) that is enhanced by a lower bounding procedure to discard unpromising facility configurations at an early stage. In the numerical studies we found that adding both, pure replenishment as well as combined facilities reduces vehicle costs and routing costs in ECV logistics networks. Moreover, our algorithm is able to match or improve state-of-the-art results on LRPIF benchmarks.

# Appendices

# A Backward penalties

Backward penalties $b_i^x,\ x \in \{\text{min},\ \text{max},\ \text{sl},\ \text{e},\ \text{f},\ \text{add}\}$ to evaluate a route backward along arc $(i,j)$ from vertex $j$ to vertex $i$ can be derived from forward expressions swapping $e_i$ and $l_i$ and multiplying time-dependent components by $-1$. Note that for further mathematical conversions, $-\max\{x,y\} = \min\{-x,-y\}$, and $-\min\{x,y\} = \max\{-x,-y\}$ hold. Since time window constraints lead to additional asymmetries, further changes are necessary for $b_i^{\max}$, $b_i^{\text{e}}$ and $b_{i-1,i}^{\text{add}}$:

$$b_{ij}^{\text{sl}} = \max\left\{0, \tilde{b}_j^{\min} - t_{ij} - l_i\right\}, \tag{52}$$

$$b_i^{\text{e}} = \begin{cases} \min\left\{H, \max\left\{0, b_j^{\text{e}} - g\right\} + h_{ij}\right\} & \text{if } i \in \mathcal{F}_{\text{C}}^{\text{O}} \\ \min\left\{H, \max\left\{0, b_j^{\text{e}} - s_j\right\} + h_{ij}\right\} & \text{if } i \in \mathcal{F}_{\text{R}}^{\text{O}} \\ \min\left\{H, \max\left\{0, b_j^{\text{e}} - \min\left\{b_{ij}^{\text{sl}}, \tilde{b}_j^{\min} - \tilde{b}_j^{\max}\right\}\right\} + h_{ij}\right\} & \text{else,} \end{cases} \tag{53}$$

$$b_i^{\text{f}} = \begin{cases} p_i & \text{if } j \in \mathcal{F}_{\text{C}}^{\text{O}} \cup \mathcal{F}_{\text{F}}^{\text{O}} \\ \min\left\{F, b_j^{\text{f}}\right\} + p_i & \text{else,} \end{cases} \tag{54}$$

$$b_{i-1,i}^{\text{add}} = \begin{cases} \max\left\{0, \max\left\{0, b_j^{\text{e}} - g\right\} + h_{ij} - H\right\} & \text{if } i \in \mathcal{F}_{\text{C}}^{\text{O}} \\ \max\left\{0, \max\left\{0, b_j^{\text{e}} - s_j\right\} + h_{ij} - H\right\} & \text{if } i \in \mathcal{F}_{\text{R}}^{\text{O}} \\ \max\left\{0, \max\left\{0, b_j^{\text{e}} - \min\left\{b_{ij}^{\text{sl}}, \tilde{b}_j^{\min} - \tilde{b}_j^{\max}\right\}\right\} + h_{ij} - H\right\} & \text{else,} \end{cases} \tag{55}$$

$$b_i^{\min} = \begin{cases} \min\left\{l_i, \tilde{b}_j^{\min} - t_{ij} - g\right\} - b_{ij}^{\text{add}} & \text{if } j \in \mathcal{F}_{\text{C}}^{\text{O}} \cup \mathcal{F}_{\text{F}}^{\text{O}} \\ \min\left\{l_i, \tilde{b}_j^{\min} - t_{ij}\right\} - b_{ij}^{\text{add}} & \text{else,} \end{cases} \tag{56}$$

$$b_i^{\max} = \begin{cases} \min\left\{l_i, \tilde{b}_j^{\min} - \max\left\{b_j^{\text{e}}, g\right\} - t_{ij}\right\} & \text{if } i \in \mathcal{F}_{\text{C}}^{\text{O}} \\ \min\left\{l_i, \tilde{b}_j^{\min} - \max\left\{0, b_j^{\text{e}} - s_j\right\} - t_{ij}\right\} & \text{if } i \in \mathcal{F}_{\text{R}}^{\text{O}} \\ \min\left\{l_i, \tilde{b}_j^{\max} - t_{ij}\right\} & \text{else,} \end{cases} \tag{57}$$

$$\overleftarrow{FR}(\rho_i) = \sum_{v \in \rho_i} \max\left\{0, b_v^{\text{f}} - F\right\}, \tag{58}$$

$$\overleftarrow{TW}(\rho_i) = \sum_{v \in \rho_i} \max\left\{e_v - \max\left\{b_v^{\max}, b_v^{\min}\right\}, 0\right\}, \tag{59}$$

$$\overleftarrow{FL}(\rho_i) = \sum_{v \in \rho_i} \max\left\{b_v^{\max} - b_v^{\min}, 0\right\}, \tag{60}$$

$$\tilde{b}_i^{\min} = \max\left\{b_i^{\min}, b_i^{\max}, e_i\right\}, \tag{61}$$

$$\tilde{b}_i^{\max} = \max\left\{e_i, \max\left\{b_i^{\min}, b_i^{\max}, e_i\right\} - \max\left\{b_i^{\min} - b_i^{\max}, 0\right\}\right\}. \tag{62}$$

# B Benchmark instances

We created benchmark instances for the LRPIF-MR that cover both, real world data on energy consumption rates and charging times for medium-duty ECVs (cf. Taefi et al., 2016; Schiffer et al., 2016) and different customer patterns (randomly, clustered and randomly clustered) as well as dedicated nodes for intra-route facilities (Schneider et al., 2014; Schiffer and Walther, 2017). We scaled the instances used in Schiffer and Walther (2017) with the real-world information from Taefi et al. (2016) and the real world case from Schiffer et al. (2016) as follows:

1. Focusing on medium-duty mid-haul distribution, the distance between the depot and the customer farthest away from the depot is set to 120 $km$. All other distances are scaled accordingly.
2. The planning horizon is set to one working day, in our case one shift of nine hours.
3. We consider a 7.5-tonne ECV with a consumption rate of 0.76 $^{\mathrm{kWh}}/_{\mathrm{km}}$ (cf. Taefi et al., 2016).
4. The recharging rate is set to 0.73 $^{\mathrm{kWh}}/_{\mathrm{min}}$, assuming a 44 kW fast charger.
5. Assuming a discount rate of 5% and a planning horizon of five years, we calculate cost terms on a daily basis as proposed in Schiffer et al. (2016). Taking the investment costs from Taefi et al. (2016), vehicle costs of $c_{\mathrm{V}}^{\mathrm{fix}} = 36.66$ € result. The traveling costs are set to $c^{\mathrm{fix}} = 0.0522$ $^{€}/_{\mathrm{km}}$ (Schiffer et al., 2016). For recharging stations, investment costs of 27,000 € are used based on a personal communication with ABB. Thus, the cost coefficient for charging stations is set to $c_{\mathrm{R}}^{\mathrm{fix}} = 14.79$ €.

These instances are available at http://www.om.rwth-aachen.de/data/uploads/lrpifinstmr.zip with additional information on cost terms for replenishment and combined facilities.

# C Results for the LRPIF-MR experiments

**Table 6: Results on the LRPIF-MR with cost terms.**

| Instance | $\lambda^b$ | $\lambda^a$ | $t^t$ | Instance | $\lambda^b$ | $\lambda^a$ | $t^t$ | Instance | $\lambda^b$ | $\lambda^a$ | $t^t$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| c101 | 474.98 | 592.05 | 719.13 | r103 | 605.27 | 692.42 | 777.06 | r210 | 531.67 | 585.52 | 890.39 |
| c102 | 472.65 | 664.68 | 690.66 | r104 | 589.71 | 674.98 | 1332.42 | r211 | 546.78 | 591.64 | 937.22 |
| c103 | 576.75 | 680.37 | 615.57 | r105 | 505.22 | 558.42 | 897.96 | rc101 | 583.18 | 761.11 | 850.59 |
| c104 | 485.71 | 625.37 | 639.35 | r106 | 574.29 | 687.64 | 892.28 | rc102 | 653.97 | 749.34 | 872.79 |
| c105 | 506.24 | 601.13 | 907.54 | r107 | 622.39 | 696.43 | 697.04 | rc103 | 658.83 | 737.79 | 961.53 |
| c106 | 525.55 | 641.35 | 868.38 | r108 | 609.26 | 686.16 | 635.77 | rc104 | 686.62 | 770.08 | 866.86 |
| c107 | 531.37 | 605.21 | 819.99 | r109 | 572.18 | 676.01 | 764.20 | rc105 | 660.27 | 735.55 | 787.07 |
| c108 | 560.04 | 701.72 | 675.79 | r110 | 581.27 | 691.94 | 865.21 | rc106 | 640.32 | 732.39 | 732.04 |
| c109 | 512.09 | 606.86 | 739.51 | r111 | 580.14 | 692.96 | 827.90 | rc107 | 631.73 | 734.15 | 997.52 |
| c201 | 430.53 | 485.64 | 561.49 | r112 | 630.50 | 707.16 | 855.97 | rc108 | 663.12 | 780.65 | 974.08 |
| c202 | 459.92 | 496.57 | 643.57 | r201 | 592.76 | 680.99 | 799.67 | rc201 | 498.74 | 539.93 | 777.68 |
| c203 | 407.43 | 477.11 | 636.95 | r202 | 546.14 | 587.22 | 794.91 | rc202 | 439.08 | 525.59 | 691.43 |
| c204 | 438.86 | 496.87 | 580.24 | r203 | 515.69 | 597.72 | 909.72 | rc203 | 473.74 | 537.51 | 777.91 |
| c205 | 464.42 | 512.05 | 574.33 | r204 | 519.13 | 580.29 | 846.47 | rc204 | 506.32 | 557.31 | 662.80 |
| c206 | 444.18 | 485.06 | 558.20 | r205 | 516.84 | 573.49 | 850.45 | rc205 | 438.59 | 518.03 | 670.52 |
| c207 | 440.83 | 504.23 | 576.94 | r206 | 529.37 | 596.27 | 805.08 | rc206 | 492.27 | 537.21 | 731.25 |
| c208 | 443.95 | 497.56 | 627.47 | r207 | 573.98 | 601.53 | 862.07 | rc207 | 492.47 | 518.33 | 657.96 |
| r101 | 520.16 | 699.53 | 1058.58 | r208 | 532.88 | 580.32 | 751.87 | rc208 | 466.40 | 547.29 | 689.42 |
| r102 | 546.74 | 660.69 | 991.07 | r209 | 518.89 | 577.75 | 818.57 | | | | |

Abbreviations are defined as follows: $\lambda^b$ - best solution value out of ten runs, $\lambda^a$ - average solution value out of ten runs, $t^t$ [s] - total runtime out of ten runs.

**Table 7: Results on the LRPIF with recharging facilities.**

| Instance | $\lambda^b$ | $\lambda^a$ | $t^t$ | Instance | $\lambda^b$ | $\lambda^a$ | $t^t$ | Instance | $\lambda^b$ | $\lambda^a$ | $t^t$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| c101 | 670.63 | 729.82 | 988.25 | r103 | 667.51 | 712.12 | 1094.00 | r210 | 540.73 | 578.84 | 796.81 |
| c102 | 684.36 | 735.48 | 1708.84 | r104 | 650.28 | 729.18 | 1025.65 | r211 | 513.51 | 577.04 | 1032.46 |
| c103 | 622.92 | 711.09 | 1516.19 | r105 | 657.26 | 736.54 | 1370.50 | rc101 | 785.96 | 837.07 | 962.64 |
| c104 | 652.47 | 710.12 | 1096.86 | r106 | 683.63 | 719.22 | 1197.79 | rc102 | 754.37 | 829.54 | 922.12 |
| c105 | 670.85 | 717.11 | 1162.10 | r107 | 655.51 | 698.91 | 1375.40 | rc103 | 778.39 | 813.18 | 2523.90 |
| c106 | 671.84 | 698.29 | 1553.56 | r108 | 659.72 | 722.85 | 809.11 | rc104 | 772.12 | 819.37 | 1613.22 |
| c107 | 641.34 | 725.10 | 1617.87 | r109 | 658.90 | 709.47 | 1442.28 | rc105 | 736.00 | 843.57 | 1195.21 |
| c108 | 670.63 | 714.03 | 1419.45 | r110 | 651.89 | 725.23 | 804.33 | rc106 | 752.85 | 822.89 | 1310.18 |
| c109 | 628.99 | 697.50 | 1265.98 | r111 | 632.24 | 703.55 | 1209.00 | rc107 | 739.88 | 786.03 | 2041.47 |
| c201 | 465.99 | 492.66 | 682.80 | r112 | 680.35 | 726.35 | 1356.81 | rc108 | 735.42 | 804.16 | 1941.90 |
| c202 | 453.01 | 497.38 | 665.46 | r201 | 546.87 | 581.45 | 891.42 | rc201 | 473.14 | 526.26 | 712.29 |
| c203 | 438.32 | 479.61 | 495.10 | r202 | 543.65 | 581.86 | 862.77 | rc202 | 473.97 | 515.07 | 1189.81 |
| c204 | 454.00 | 486.18 | 687.91 | r203 | 513.12 | 567.27 | 768.97 | rc203 | 461.85 | 511.47 | 942.03 |
| c205 | 427.86 | 480.61 | 566.66 | r204 | 526.77 | 591.81 | 577.82 | rc204 | 474.24 | 500.73 | 1345.46 |
| c206 | 424.05 | 470.76 | 604.10 | r205 | 540.82 | 568.07 | 615.70 | rc205 | 462.21 | 500.69 | 1113.09 |
| c207 | 397.53 | 467.79 | 658.74 | r206 | 531.41 | 575.97 | 1123.81 | rc206 | 487.22 | 512.73 | 1056.15 |
| c208 | 440.36 | 476.64 | 781.62 | r207 | 514.67 | 566.71 | 862.56 | rc207 | 502.41 | 538.17 | 943.72 |
| r101 | 682.29 | 728.55 | 834.60 | r208 | 555.13 | 580.27 | 800.62 | rc208 | 490.88 | 538.70 | 914.70 |
| r102 | 654.75 | 725.50 | 1122.42 | r209 | 541.99 | 580.56 | 1112.61 | | | | |

Abbreviations are defined as follows: $\lambda^b$ - best solution value out of ten runs, $\lambda^a$ - average solution value out of ten runs, $t^t$ [s] - total runtime out of ten runs.

**Table 8: Results on the LRPIF-MR with dedicated combined facilities.**

| | 1 facility | | | 2 facilities | | | 3 facilities | | |
|---|---|---|---|---|---|---|---|---|---|
| Instance | $\lambda^b$ | $\lambda^a$ | $t^t$ | $\lambda^b$ | $\lambda^a$ | $t^t$ | $\lambda^b$ | $\lambda^a$ | $t^t$ |
| c101 | 598.93 | 671.47 | 1014.06 | 525.06 | 633.62 | 680.74 | 501.99 | 569.30 | 804.22 |
| c102 | 579.20 | 658.95 | 782.39 | 552.04 | 647.91 | 767.17 | 518.17 | 590.25 | 765.61 |
| c103 | 580.10 | 679.55 | 893.32 | 534.60 | 615.75 | 756.71 | 501.68 | 585.54 | 757.07 |
| c104 | 572.16 | 652.71 | 883.77 | 521.09 | 608.07 | 724.69 | 504.68 | 577.59 | 725.18 |
| c105 | 602.90 | 675.69 | 770.79 | 547.41 | 612.22 | 757.60 | 482.97 | 584.32 | 813.85 |
| c106 | 566.33 | 651.31 | 880.26 | 534.42 | 622.77 | 661.25 | 476.25 | 573.92 | 739.91 |
| c107 | 575.56 | 670.59 | 757.36 | 529.76 | 610.07 | 685.71 | 507.65 | 561.26 | 755.37 |
| c108 | 578.68 | 656.12 | 776.59 | 490.78 | 613.81 | 805.40 | 460.15 | 576.79 | 759.82 |
| c109 | 596.87 | 656.78 | 663.71 | 538.59 | 610.18 | 697.50 | 531.87 | 591.84 | 841.07 |
| c201 | 399.93 | 465.88 | 652.54 | 390.31 | 447.55 | 632.28 | 374.02 | 434.42 | 655.74 |
| c202 | 403.31 | 455.75 | 616.98 | 388.76 | 453.38 | 598.39 | 373.50 | 450.46 | 544.58 |
| c203 | 414.85 | 471.48 | 594.04 | 393.75 | 468.31 | 560.11 | 389.81 | 465.24 | 563.01 |
| c204 | 412.46 | 463.40 | 609.15 | 408.69 | 459.61 | 511.04 | 396.46 | 445.15 | 578.90 |
| c205 | 423.45 | 467.68 | 591.50 | 392.25 | 447.59 | 557.00 | 362.30 | 429.75 | 573.42 |
| c206 | 403.05 | 471.34 | 616.48 | 394.23 | 452.14 | 523.46 | 394.08 | 439.53 | 563.39 |
| c207 | 416.00 | 464.16 | 608.13 | 400.60 | 456.51 | 533.46 | 373.37 | 431.64 | 620.75 |
| c208 | 413.16 | 471.09 | 532.50 | 394.84 | 450.11 | 590.20 | 387.04 | 445.31 | 566.35 |
| r101 | 601.83 | 696.44 | 774.20 | 588.05 | 645.70 | 696.10 | 548.09 | 620.96 | 771.15 |
| r102 | 587.54 | 661.23 | 868.45 | 552.25 | 656.25 | 620.92 | 534.82 | 611.62 | 989.13 |
| r103 | 598.02 | 676.63 | 848.03 | 569.91 | 644.05 | 844.36 | 553.48 | 609.85 | 931.93 |
| r104 | 606.03 | 659.58 | 853.80 | 587.12 | 659.70 | 679.24 | 526.87 | 601.61 | 811.47 |
| r105 | 587.51 | 692.41 | 774.98 | 581.35 | 653.06 | 763.35 | 538.87 | 628.96 | 842.51 |
| r106 | 578.43 | 670.44 | 848.15 | 538.63 | 638.63 | 1002.31 | 526.21 | 614.80 | 870.59 |
| r107 | 604.03 | 666.28 | 709.48 | 573.56 | 645.52 | 685.35 | 543.20 | 622.47 | 786.53 |
| r108 | 590.92 | 686.13 | 903.57 | 574.22 | 659.14 | 800.23 | 538.13 | 616.99 | 778.07 |
| r109 | 601.70 | 701.91 | 809.18 | 551.58 | 654.13 | 1208.30 | 524.75 | 606.28 | 821.85 |
| r110 | 572.53 | 666.36 | 818.34 | 557.14 | 648.54 | 1191.04 | 529.55 | 619.70 | 823.24 |
| r111 | 577.83 | 663.71 | 763.69 | 571.57 | 648.78 | 683.22 | 542.37 | 614.18 | 839.44 |
| r112 | 575.76 | 672.89 | 896.00 | 571.52 | 681.05 | 758.21 | 552.67 | 586.27 | 799.52 |
| r201 | 505.70 | 574.34 | 832.61 | 489.66 | 560.75 | 1065.20 | 477.78 | 546.73 | 752.35 |
| r202 | 525.15 | 589.35 | 735.86 | 506.01 | 559.40 | 797.70 | 463.23 | 529.36 | 706.45 |
| r203 | 520.44 | 584.48 | 796.46 | 489.09 | 545.35 | 663.98 | 487.18 | 518.85 | 720.13 |
| r204 | 521.47 | 579.89 | 706.76 | 489.66 | 562.62 | 836.65 | 449.32 | 540.34 | 691.28 |
| r205 | 504.46 | 577.24 | 696.23 | 489.35 | 573.19 | 1006.50 | 462.99 | 519.72 | 695.50 |
| r206 | 530.50 | 570.87 | 773.47 | 517.87 | 562.67 | 833.98 | 476.74 | 543.66 | 637.82 |
| r207 | 494.40 | 578.28 | 808.05 | 477.25 | 534.60 | 822.07 | 465.87 | 551.69 | 771.20 |
| r208 | 516.15 | 575.66 | 859.92 | 505.50 | 564.26 | 890.10 | 501.13 | 540.40 | 656.23 |
| r209 | 517.07 | 566.69 | 671.04 | 464.31 | 544.02 | 831.67 | 445.49 | 545.22 | 760.04 |
| r210 | 515.07 | 573.18 | 937.93 | 514.20 | 551.59 | 917.08 | 505.06 | 546.36 | 732.70 |
| r211 | 515.79 | 583.07 | 760.09 | 502.86 | 544.62 | 797.11 | 446.26 | 544.81 | 824.71 |
| rc101 | 676.76 | 766.06 | 826.19 | 605.36 | 701.39 | 950.39 | 542.99 | 689.74 | 878.07 |
| rc102 | 677.72 | 757.77 | 1115.41 | 618.50 | 704.96 | 985.90 | 572.77 | 691.69 | 885.09 |
| rc103 | 693.68 | 759.20 | 982.82 | 593.24 | 685.55 | 856.23 | 566.10 | 676.13 | 993.10 |
| rc104 | 616.00 | 745.48 | 1029.52 | 608.54 | 702.98 | 957.09 | 586.16 | 657.37 | 980.87 |
| rc105 | 648.81 | 745.11 | 932.57 | 646.50 | 701.50 | 904.25 | 555.14 | 685.75 | 962.57 |
| rc106 | 650.44 | 783.15 | 986.04 | 604.70 | 724.21 | 888.37 | 596.76 | 693.83 | 989.35 |
| rc107 | 669.81 | 751.23 | 1139.59 | 674.27 | 730.68 | 812.66 | 555.16 | 689.94 | 890.91 |
| rc108 | 648.20 | 775.84 | 950.09 | 576.27 | 725.18 | 868.68 | 554.38 | 668.77 | 889.68 |
| rc201 | 479.69 | 509.66 | 659.78 | 455.01 | 504.89 | 685.45 | 443.73 | 488.43 | 727.45 |
| rc202 | 469.49 | 529.38 | 699.38 | 466.61 | 513.01 | 632.07 | 442.68 | 493.02 | 560.24 |
| rc203 | 465.73 | 517.80 | 626.96 | 450.21 | 518.10 | 821.90 | 448.11 | 515.48 | 658.91 |
| rc204 | 464.02 | 524.47 | 702.24 | 453.18 | 494.16 | 709.47 | 434.54 | 497.56 | 636.62 |
| rc205 | 444.62 | 505.77 | 769.59 | 435.84 | 512.85 | 658.02 | 426.81 | 496.53 | 739.18 |
| rc206 | 467.31 | 525.97 | 724.03 | 458.26 | 522.30 | 647.84 | 423.36 | 508.64 | 669.24 |
| rc207 | 436.84 | 501.79 | 670.40 | 435.88 | 506.08 | 582.86 | 410.28 | 503.45 | 602.64 |
| rc208 | 464.40 | 524.10 | 686.37 | 443.26 | 498.38 | 783.38 | 429.21 | 510.99 | 565.69 |

Abbreviations are defined as follows: $\lambda^b$ - best solution value out of ten runs, $\lambda^a$ - average solution value out of ten runs, $t^t$ [s] - total runtime out of ten runs.

**Table 9: Results on the LRPIF-MR with dedicated replenishment facilities.**

| | 1 facility | | | 2 facilities | | | 3 facilities | | |
|---|---|---|---|---|---|---|---|---|---|
| Instance | $\lambda^b$ | $\lambda^a$ | $t^t$ | $\lambda^b$ | $\lambda^a$ | $t^t$ | $\lambda^b$ | $\lambda^a$ | $t^t$ |
| Instance | fb | fa | to | fb | fa | to | fb | fa | to |
| c101 | 629.23 | 725.18 | 1032.44 | 581.17 | 655.98 | 749.70 | 574.01 | 681.37 | 762.19 |
| c102 | 634.20 | 736.94 | 828.24 | 588.52 | 663.13 | 870.79 | 582.10 | 710.80 | 929.85 |
| c103 | 662.91 | 752.49 | 786.42 | 623.70 | 712.92 | 905.26 | 606.11 | 725.43 | 768.07 |
| c104 | 625.41 | 740.52 | 829.86 | 607.50 | 680.57 | 743.69 | 553.71 | 673.94 | 889.56 |
| c105 | 651.66 | 714.37 | 786.80 | 594.80 | 716.18 | 791.22 | 577.18 | 698.37 | 890.78 |
| c106 | 642.36 | 718.17 | 728.68 | 616.69 | 687.81 | 898.74 | 578.85 | 688.75 | 864.64 |
| c107 | 632.77 | 753.70 | 823.26 | 624.48 | 697.50 | 869.09 | 607.55 | 675.75 | 736.48 |
| c108 | 622.86 | 701.61 | 771.55 | 604.66 | 703.73 | 863.26 | 567.97 | 659.60 | 728.34 |
| c109 | 642.69 | 722.25 | 811.68 | 607.31 | 661.06 | 825.63 | 579.03 | 666.30 | 729.03 |
| c201 | 443.18 | 482.18 | 523.81 | 431.74 | 489.68 | 611.10 | 429.02 | 499.55 | 659.96 |
| c202 | 446.22 | 506.12 | 546.49 | 444.66 | 518.33 | 659.55 | 439.20 | 486.17 | 473.23 |
| c203 | 431.54 | 491.69 | 539.38 | 428.70 | 466.81 | 532.63 | 405.89 | 473.31 | 487.79 |
| c204 | 433.22 | 464.17 | 484.07 | 429.36 | 488.35 | 568.04 | 416.17 | 481.32 | 480.93 |
| c205 | 435.20 | 475.02 | 557.33 | 419.71 | 500.43 | 655.01 | 401.15 | 490.45 | 617.68 |
| c206 | 440.52 | 504.72 | 619.74 | 438.37 | 470.29 | 503.12 | 433.80 | 497.62 | 676.37 |
| c207 | 444.58 | 499.96 | 515.50 | 434.43 | 471.21 | 515.17 | 413.97 | 485.72 | 470.54 |
| c208 | 444.77 | 486.76 | 549.02 | 439.99 | 484.58 | 642.45 | 429.19 | 480.21 | 547.82 |
| r101 | 645.72 | 729.17 | 739.92 | 629.31 | 713.92 | 715.35 | 617.25 | 713.40 | 809.63 |
| r102 | 687.58 | 770.45 | 667.11 | 674.91 | 739.88 | 681.13 | 663.51 | 726.25 | 746.57 |
| r103 | 664.79 | 761.05 | 696.83 | 658.65 | 746.49 | 781.45 | 643.21 | 717.90 | 768.41 |
| r104 | 686.43 | 755.66 | 859.17 | 662.18 | 750.43 | 765.61 | 657.62 | 717.98 | 884.69 |
| r105 | 623.43 | 752.59 | 676.12 | 612.88 | 696.67 | 824.31 | 611.75 | 671.15 | 703.22 |
| r106 | 717.58 | 775.04 | 674.33 | 692.77 | 747.07 | 811.67 | 648.31 | 705.89 | 721.69 |
| r107 | 661.69 | 732.11 | 769.17 | 604.01 | 710.82 | 771.01 | 587.22 | 720.64 | 734.81 |
| r108 | 686.90 | 764.48 | 822.55 | 677.38 | 732.46 | 911.92 | 671.79 | 733.25 | 738.17 |
| r109 | 687.93 | 764.24 | 759.01 | 674.55 | 742.02 | 780.46 | 615.01 | 712.61 | 673.84 |
| r110 | 696.37 | 760.30 | 767.98 | 631.25 | 710.06 | 786.43 | 591.77 | 697.22 | 720.73 |
| r111 | 677.50 | 748.15 | 821.14 | 668.45 | 748.90 | 774.89 | 644.29 | 734.07 | 765.53 |
| r112 | 658.30 | 739.61 | 861.16 | 631.21 | 717.16 | 801.81 | 626.24 | 732.59 | 778.14 |
| r201 | 547.83 | 598.41 | 636.31 | 533.97 | 603.24 | 683.38 | 519.84 | 587.05 | 666.88 |
| r202 | 573.35 | 613.12 | 623.94 | 558.82 | 591.42 | 715.87 | 533.46 | 603.33 | 585.86 |
| r203 | 531.21 | 590.25 | 718.83 | 529.78 | 608.85 | 674.85 | 517.47 | 586.47 | 662.93 |
| r204 | 559.16 | 594.08 | 636.09 | 548.04 | 587.40 | 667.28 | 519.44 | 585.37 | 713.48 |
| r205 | 558.90 | 600.41 | 634.49 | 531.78 | 602.08 | 753.53 | 493.32 | 560.12 | 582.54 |
| r206 | 545.00 | 593.43 | 708.22 | 534.26 | 594.00 | 708.50 | 510.24 | 570.92 | 701.31 |
| r207 | 532.24 | 578.79 | 629.88 | 520.21 | 579.46 | 658.63 | 515.21 | 555.41 | 642.75 |
| r208 | 550.02 | 583.21 | 802.89 | 533.24 | 583.74 | 659.75 | 518.26 | 604.26 | 748.73 |
| r209 | 524.17 | 578.09 | 750.36 | 519.64 | 589.38 | 698.77 | 512.79 | 570.55 | 644.11 |
| r210 | 546.32 | 603.27 | 620.35 | 531.51 | 579.59 | 686.13 | 520.94 | 586.10 | 718.53 |
| r211 | 545.35 | 606.24 | 689.61 | 545.30 | 594.00 | 792.53 | 531.77 | 591.11 | 676.17 |
| rc101 | 761.55 | 820.93 | 912.02 | 705.77 | 829.08 | 841.51 | 702.10 | 792.83 | 775.01 |
| rc102 | 741.89 | 804.66 | 1034.56 | 720.25 | 797.88 | 767.65 | 694.69 | 786.70 | 796.62 |
| rc103 | 779.08 | 859.21 | 945.13 | 764.29 | 812.83 | 837.75 | 722.78 | 826.87 | 736.95 |
| rc104 | 728.53 | 807.76 | 890.60 | 727.62 | 777.99 | 773.64 | 708.25 | 827.24 | 802.55 |
| rc105 | 781.45 | 850.97 | 1094.08 | 737.65 | 813.30 | 1004.09 | 732.88 | 811.03 | 978.07 |
| rc106 | 768.27 | 864.46 | 874.45 | 733.96 | 834.41 | 692.52 | 722.39 | 808.62 | 882.45 |
| rc107 | 747.32 | 839.43 | 849.61 | 734.16 | 817.72 | 880.91 | 692.30 | 778.47 | 700.70 |
| rc108 | 770.01 | 864.70 | 1002.46 | 762.88 | 840.64 | 753.41 | 735.53 | 806.55 | 700.24 |
| rc201 | 470.31 | 524.25 | 651.90 | 464.80 | 543.09 | 644.45 | 456.95 | 521.10 | 486.02 |
| rc202 | 482.53 | 525.26 | 642.98 | 470.03 | 524.00 | 566.53 | 463.89 | 554.23 | 575.76 |
| rc203 | 493.30 | 556.70 | 580.01 | 474.49 | 524.84 | 576.35 | 439.74 | 544.79 | 631.92 |
| rc204 | 494.77 | 547.08 | 658.56 | 494.20 | 540.77 | 597.35 | 467.90 | 522.22 | 534.47 |
| rc205 | 484.85 | 549.10 | 640.49 | 484.08 | 540.45 | 637.47 | 464.36 | 548.84 | 616.37 |
| rc206 | 511.18 | 545.92 | 649.35 | 492.71 | 546.04 | 622.17 | 471.28 | 514.75 | 485.43 |
| rc207 | 466.09 | 557.64 | 630.31 | 463.72 | 538.61 | 575.88 | 452.05 | 523.27 | 565.19 |
| rc208 | 512.42 | 552.20 | 621.18 | 493.50 | 549.21 | 551.41 | 470.59 | 537.11 | 571.38 |

Abbreviations are defined as follows: $\lambda^b$ - best solution value out of ten runs, $\lambda^a$ - average solution value out of ten runs, $t^t$ [s] - total runtime out of ten runs.

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