Multi-depot Electric Vehicle Routing Problem with Half-Open Routes and Rotations: A Mathematical Formulation

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Abstract. The electrification spreads all around the world with the goal of global net zero emission, especially in transportation sector. As a natural consequence of this phenomenon, many countries and organizations announce their targets relating to the Electric Vehicles (EVs). Although shifting from fossil-fuel towards EVs is a major step forward, there are other precious actions to be taken, one of which is to integrate EVs into scientific studies along with the routing improvements. To this end, we introduce the Multi-Depot Electric Vehicle Routing Problem with Half-Open Routes and Rotations (MDEVRP-HORR) as an extension of the MDEVRP where the rotation refers to set of all routes assigned to an EV. EVs can be recharged at the depots or at the recharging stations along the route with full recharging strategy. The problem is formulated as a 0–1 mixed integer linear program (MILP) and existing procedures are applied to improve the model. The proposed model relaxes the restriction that the departure depot of the first route and arrival depot of the last route of an EV must be the same. It also avoids from creating dummy nodes for recharging stations and replenishment depots. We conducted experimental studies by using small-sized instances from the recent literature due to problem intractability. Out of 36 instances, results reveal that inclusion of half-open routes leads to a cost reduction for 20 instances. Besides, inclusion of both half-open rotations and half-open routes results in cost reduction for 28 instances.

Keywords: Electric Vehicle · Multi-Depot Electric Vehicle Routing Problem · Half-Open Route and Rotation

1 Introduction

Transportation is one of the foremost sectors that contribute to carbon emissions all around the world. As internal combustion engines dominated the transportation sector, concerns about their environmental impact raised. At this point, whilst the community converts to alternative fuel vehicles, Electric Vehicles (EVs) emerge as an effective way for fighting against air pollution and the climate change [1]. These recent developments have led to integration of environmental aspects into academic studies. When it comes

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to environmental aspects about the transportation, the Vehicle Routing Problem (VRP) and its variants offer worthwhile solutions, therefore there is a growing interest in this phenomenon in the literature [2]. In this regard, Electric VRP (EVRP) is one of the main variations since EVs are promising not only for reducing the pollution but also for reducing the transportation cost. Many countries like Norway, Netherlands, Germany, United Kingdom, Türkiye, France and Italy contemplate enforcing to brand new sales to be EV and ban the sales of internal combustion engine vehicle in the following years, even the purchase subsidies or tax benefits have already been applied recently and so on [3, 4]. However, the limited driving range, long recharging times and sparse available recharging options entail the EVRP to find optimal solutions by considering battery capacity, recharging times, and recharging options along with the locations. Regarding EVRP, there are growing bodies of literature studying the minimization of traveled distance [5–7], recharging cost [8, 9] or total time (travel, recharging etc.) [10, 11] or finding optimal locations for depots and recharging stations [12, 13].

Since the electricity is generated using thermal power in many countries, reduction in carbon emission resulting from penetration of EVs is limited [14]. For this reason, effective operations of EVs like resource sharing play an important role on curbing these indirect and adverse effects. The approach of half-open routes and rotations consists of sharing the vehicles among the depots and allows a vehicle to return to any depot contrary to the standard Multi-Depot VRP (MDVRP) [15]. Owing to this approach, the number of unnecessary and underloaded vehicles and a great deal of distribution cost could be significantly reduced [16]. On the other hand, integrating EVs to this approach leads to sharing not only the EVs but also the recharging stations among the depots. In this way, the opportunities of reducing the recharging costs and the number of recharging stations arise. While some studies include the sharing of EVs, others consider sharing the recharging stations or depots [2, 12, 17–20]. For this reason, sharing resources among multiple depots could be evaluated as a prominent strategy for logistics companies to gain competitive advantages [16], to reduce the traveled distance and energy consumption and to improve the distribution efficiency in the long run [14].

Yet, another usual extension of sharing vehicles is using the vehicles multiple times, which means a vehicle docks a depot at the end of a route and then can start a new route. This type of situation is often encountered when the duration of a single route is shorter as compared to working hours due to limited vehicle capacity or limited fleet size [21]. In practice, scheduling vehicles for multiple trips can provide a significant cost reduction, especially if the number of vehicles and hence drivers could be reduced or utilized with a higher rate. This situation may lead to a trade-off between scheduling/ routing related costs and number of vehicle/driver related costs [22].

Although there exist papers considering MDEVRP and resource sharing [7, 18], half-open approach in EVRP [14, 16] and even including good replenishment [23, 24], to the best of author's knowledge, the Multi-Depot Electric Vehicle Routing Problem with Half-Open Routes and Rotations (MDEVRP-HORR) is studied for the first time where the rotation refers to the set of all routes assigned to single vehicle [21]. We relax the restriction that the departure depot of the first route and arrival depot of the last route of an EV must be the same. To this end, a novel 0–1 Mixed-Integer Linear Programming (MILP) model is introduced, avoiding from generating dummy nodes of recharging stations and replenishment depots. This approach requires to add equations into mathematical model. The model also includes a decision variable controlling whether to receive recharging service at the depots.

The remainder of this paper is organized as follows. First, the related literature review outlining the extensions of our problem is presented in Sect. 2. Section 3 includes the problem description, illustrative example, and 0–1 MILP formulation. Computational results are given in Sect. 4. Finally, Sect. 5 concludes the paper.

2 Literature Review

The MDEVRP-HORR is a variation of a diverse well known VRPs in the literature. One of them is EVRP where EVs need to visit recharging stations to continue servicing the customers along the route. In this regard, Schneider et al. [5] expanded the Green VRP [25] by including EVs, introduced EVRP with time windows (EVRPTW) and proposed MILP model as well as hybrid heuristic including variable neighborhood search algorithm and tabu search. However they assume that the EVs can leave recharging stations only with full battery which is later relaxed by Keskin and Çatay [6] and partial recharging is allowed, a MILP model as well as Adaptive Large Neighborhood Search algorithm is introduced. Yet, they both employed dummy nodes to allow the recharging stations to be used multiple times.

Other extension is MDEVRP where each EV is deployed at one of the depots, and each route starts and ends at the same depot [26]. Muñoz-Villamizar et al. [27] proposed a two-stage solution for collaboration among depots of logistics companies, analyzed the effect of EVs usage and introduced MILP model. Paz et al. [7] studied the MDEV location routing problem (LRP) with time windows and introduced three mathematical models where only the small sized-instances are solved. Koç et al. [2] addressed the EVRP where multiple companies collaboratively invest in the installation of recharging stations containing different technologies. Accordingly, each company has its own depot and EV fleet. Yet, the customers are pre-assigned, implying that customers have a single option for receiving service. Almouhanna et al. [12] addressed the LRP with a constrained distance by employing EVs and allowed them to be shared among the depots. They proposed both multi-start heuristic and a metaheuristic. Karakatič [10] introduced MDVRPTW and EVs with partial nonlinear recharging times and proposed a genetic algorithm. Londoño et al. [28] proposed a hybrid methodology of exact solution method and meta-heuristic for the MDEVRP and evaluated three different costs with trade-offs among each other. Wang et al. [17] studied the EV Charging Station LRP and resource sharing problem which consists of sharing the resources among depots within multiple service periods. Wang et al. [18] introduced collaborative MDEVRPTW and shared recharging stations. They reported that sharing both customers and recharging stations among the depots outperforms other scenarios in terms of cost, number of EVs and number of recharging stations used. Vahedi-Nouri et al. [29] addressed the collaborative EVRP and developed two MILP models for collaborative and non-collaborative strategies for companies and reported that collaborative strategy provides cost reduction.

MDEVRP with half-open routes is an extension of MDEVRP where starting and ending depot of an EV are not necessarily the same. Lijun et al. [14] addressed the Half-Open Time-Dependent MDEVRP, considered both battery recharging and swapping technologies, developed MILP model and presented simulated annealing algorithm. Their experimental studies show that the half-open route strategy reduces the total cost and carbon emissions notably. Fan [16] proposed a MILP model for Multi-Depot Half-Open time dependent EVRP, aiming to minimize the total distribution cost as well as a two-stage hybrid ant colony algorithm. Nevertheless, in the last two references, EVs are dispatched only once.

There are also other VRP variants studied extensively in which resource replenishment is considered without EVs. Crevier et al. [21] introduced the MDVRP with inter-depot routes (MDVRPI) where vehicles can be replenished with goods at replenishment facilities and can be assigned multiple routes. Tarantilis et al. [30] addressed the VRP with intermediate replenishment facilities and proposed three-step algorithmic framework including cost-saving construction heuristic, tabu search with variable neighborhood search and guided local search. Muter et al. [31] later studied the MDVRPI by relaxing the closed route and developed a branch-and-price algorithm to solve the problem. Che et al. [32] studied the Multi-Depot Petrol Station Replenishment with Open Inter-Depot Routes where each depot can act as an intermediate facility and multiple trips for the trucks are allowed.

There also exist papers considering both resource replenishment and EVs. Schneider et al. [23] are the first to introduce the VRP with intermediate stops which includes stops for replenishment/disposal, refueling/recharging or combined ones and developed an adaptive variable neighborhood search. Schiffer et al. [24] studied on location-routing problem considering intra-route facilities that offers different replenishment services and presented an adaptive large neighborhood search. They reported that combined facilities are useful to decrease the fleet size and reduce the total cost. They also classified the replenished resources as arc-based like energy for EVs and as node-based like load of the vehicle. Nevertheless, the last two references utilize dummy nodes in order to allow multiple visits to replenishment facilities.

Our paper differs from the existing literature in several aspects. First, it is the first study combining the EVs with half-open rotations. Second, our paper contains multi-depot, arc-based and node-based resource replenishment by adopting a pre-computing procedure which eliminates some of the recharging stations and replenishment depots. Eventually, this paper introduces a MILP model for a specified variant of EVRP problem without dummy nodes for recharging stations and replenishment depots.

3 Problem Definition

MDEVRP-HORR deals with (i) a set of customers with known demands and service times, (ii) homogeneous EVs with limited battery and load capacity, and (iii) multiple depots and creation of both half-open routes and rotations. The battery charge level of each EV depletes proportional to the distance traveled. The battery could be fully recharged both at depots [5] and recharging stations en-route [2]. For the sake of simplicity, the linear recharging is adopted [5, 33]. Each EV can perform multiple trips and be replenished with goods at any depot [23]. The duration of good replenishment is ignored. Each customer must be visited exactly once. The total demand of the customers in each route cannot exceed the EV load capacity. Recharging stations are assumed to be available at all times and could be visited more than one by any EV and simultaneous recharging is permitted as well [33]. The objective of the problem is to minimize the sum of the total traveled distance and the fixed EV cost per use.

The MDEVRP-HORR is formulated as 0–1 MILP model. Let $V = \{1, \ldots, N\}$ be the set of customers and F be the set of recharging stations. Vertices DD, AD, RD denote the departure, arrival, and replenishment depots respectively and are located in the same place. To indicate that a set contains departure or arrival depot, it is subscripted with DD or AD, i.e., $V_{DD} = V \cup \mathrm{DD}$ and $V_{AD} = V \cup \mathrm{AD}$. Thus, MDEVRP-HORR can be defined on a complete directed graph $G = \left(V_{DD,AD}, A\right)$ with the set of arcs $A = \{\ (i, j), | i \in V_{DD}, j \in V_{AD}, i \neq j\}$ where $V_{DD,AD} = V \cup \mathrm{DD} \cup \mathrm{AD}$.

Between nodes i and j, there are associated distance of d_{ij} and a travel time of t_{ij}. Each customer $i \in V$ has a positive demand q_i and service time s_i. EVs can carry a maximum load of C and have battery capacity Q. The battery charge is consumed by $h \cdot d_{ij}$ for each arc traversed, where h represents constant charge consumption rate. So, one unit of travelling distance, therefore, equals one unit of energy consumption and takes one unit of time [9]. Battery is recharged with a rate of g, meaning that recharging time is the product of g and the amount of recharge. The duration of a rotation cannot exceed the maximum duration T_{max}. Variables τ_i, u_i *and* y_i specify the arrival time, remaining load, and remaining charge level at node $i \in V_{DD,AD}$ respectively.

The binary decision variable x_{ij} is equal to 1 if arc (i, j) is traveled, and 0 otherwise. We inspire from the study of Schneider et al. [5] in developing our mathematical model and thus stick to the notation they used with an exception that we do not generate dummy vertices to allow multiple visits to recharging stations, requiring significant augmentation of the network. So, we follow similar procedure to the study conducted by Koç and Karaoglan [34] and Bruglieri et al. [33] and introduce the decision variable z^F_{ijk} which equals 1 if a EV travels from node i to j through the recharging station k. They reported the superiority of this method over generation of dummy nodes. Meanwhile, we apply the same logic for replenishment depots and introduce the decision variable z^D_{ijl} which equals 1 if an EV travels from node i to j through the replenishment depot l. The binary decision variable z^C_i is also introduced being equal to 1 if an EV visits a replenishment depot and is recharged after node i, and 0 otherwise.

Furthermore, we also follow a pre-computing procedure which eliminates some of the recharging stations between each pair of arcs. Similar procedures are applied by Bruglieri et al. [33] and Keskin and Çatay [9]. They reported that this procedure decreases the number of variables employed, which in turn leads to better performance of the model. The procedure results in having sets $\hat{F}_{ij}$ and initially, each $\hat{F}_{ij} = F$ which means each recharging station is available between nodes i and j. Now consider two recharging stations k and k^*. If conditions $d_{ik^*} > d_{ik}$ and $d_{k^*j} > d_{kj}$ hold, then it is certain that, recharging station k^* is not visited between nodes i and j in the optimal solution. Therefore, k^* is removed from $\hat{F}_{ij}$. These eliminations are conducted for each pair of departure depot-to-customer, customer-to-customer, and customer-to-arrival depot nodes. The same procedure is applied for replenishment depots as well. This time, initially each $\widehat{RD}_{ij} = RD$ and if conditions $d_{il^*} > d_{il}$ and $d_{l^*j} > d_{lj}$ hold, replenishment depot l dominates the replenishment depot l^* and therefore l^* is removed from $\widehat{RD}_{ij}$. These eliminations are conducted only for each pair of customer-to-customer nodes, mainly because visiting replenishment depot between departure depot and customer or between customer and arrival depot is not permitted.

3.1 Illustrative Example

In this section, an illustrative example depicting the relation between closed route and half-open route as well as closed rotation and half-open rotation is visualized in Fig. 1. D, C and RS denote the depot, customer, and recharging station, respectively. Part a includes two EVs i.e., two rotations which are closed as follow: (i) **D1**-*RS2*-C2-C5-**D1**-C1-C10-C6-**D1**-C9-C8-*RS3*-C4-C7-**D1** (ii) **D2**-C3-**D2**. The first and second rotations consist of three and one closed routes respectively. Part b includes one closed rotation where the first and third routes are half-open, and the second one is closed: (i) **D2**-C3-C7-*RS3*-C4-*RS3*-C8-C9-**D1**-C6-C10-C1-**D1**-C5-C2-*RS2*-**D2**. Finally, part c includes a half-open rotation where the first two routes are closed and the last one is half-open: (i) **D1**-C9-C8-*RS3*-C4-C7-**D1**-C1-C10-C6-**D1**-C5-C2-*RS2*-C3-**D2**. Consequently, part a is limited with closed route and closed rotation, the half-open route is allowed in part b, and both half-open route and rotation are allowed in part c.

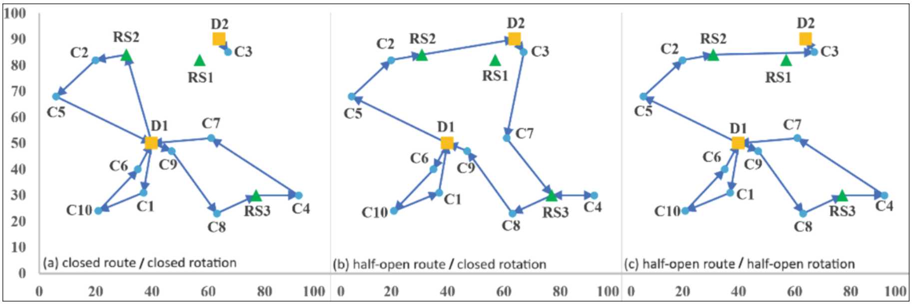

Fig. 1. Illustrations of closed and half-open routes and rotations

3.2 Mathematical Formulation

In what follows, first all sets, parameters, and decision variables of our model are given in Table 1, second the 0–1 MILP model is presented.

$$Min \sum_{i \in V_{DD}} \sum_{\substack{j \in V_{AD} \\ i \neq j}} \left(d_{ij}x_{ij} + \sum_{l \in \widehat{RD}_{ij}} (d_{il} + d_{lj} - d_{ij}) z^{D}_{ijl} + \sum_{k \in \hat{F}_{ij}} (d_{ik} + d_{kj} - d_{ij}) z^{F}_{ijk} \right) + \sum_{i \in DD} \sum_{j \in V_{AD}} c_{fix} x_{ij} \quad (1)$$

$$\sum_{\substack{j \in V_{AD} \\ i \neq j}} x_{ij} = 1 \qquad \forall i \in V \tag{2}$$

$$\sum_{\substack{i \in V_{AD} \\ i \neq j}} x_{ji} - \sum_{\substack{i \in V_{DD} \\ i \neq j}} x_{ij} = 0 \qquad \forall j \in V \tag{3}$$

$$\sum_{l \in \widehat{RD}_{ij}} z_{ijl}^{D} + \sum_{k \in \hat{F}_{ij}} z_{ijk}^{F} \leq x_{ij} \qquad \begin{matrix} \forall i \in V_{DD} \\ \forall j \in V_{AD} \\ i \neq j \end{matrix} \tag{4}$$

$$z_i^C \leq \sum_{\substack{j \in V_{AD} \\ i \neq j}} \sum_{l \in \widehat{RD}_{ij}} z_{ijl}^{D} \qquad \forall i \in V_{DD} \tag{5}$$

$$\begin{aligned} 0 \leq \tau_i + \left(t_{ij} + s_i\right)x_{ij} + \sum_{l \in \widehat{RD}_{ij}} \left(t_{il} + t_{lj} - t_{ij}\right) z_{ijl}^{D} \\ -T_{max}\left(1 - x_{ij} + z_i^C + \sum_{k \in \hat{F}_{ij}} z_{ijk}^{F}\right) \leq \tau_j \end{aligned} \qquad \begin{matrix} \forall i \in V_{DD} \\ \forall j \in V_{AD} \\ i \neq j \end{matrix} \tag{6}$$

$$\begin{aligned} 0 \leq \tau_i + \sum_{l \in \widehat{RD}_{ij}} \left(t_{il} + t_{lj} + s_i\right) z_{ijl}^{D} + \sum_{k \in \hat{F}_{ij}} \left(t_{ik} + t_{kj} + s_i\right) z_{ijk}^{F} \\ + g\left[Q - \left(y_i - \sum_{l \in \widehat{RD}_{ij}} d_{il} z_{ijl}^{D} - \sum_{k \in \hat{F}_{ij}} d_{ik} z_{ijk}^{F}\right)\right] \\ -(T_{max} + gQ)\left(2 - x_{ij} - z_i^C - \sum_{k \in \hat{F}_{ij}} z_{ijk}^{F}\right) \leq \tau_j \end{aligned} \qquad \begin{matrix} \forall i \in V_{DD} \\ \forall j \in V_{AD} \\ i \neq j \end{matrix} \tag{7}$$

$$\tau_i + t_{ij} + s_i - T_{max}\left(1 - x_{ij} + \sum_{k \in \hat{F}_{ij}} z_{ijk}^{F}\right) \leq T_{max} \qquad \begin{matrix} \forall i \in V \\ \forall j \in AD \end{matrix} \tag{8}$$

$$\begin{aligned} \tau_i + s_i + \left(\sum_{k \in \hat{F}_{ij}} \left(t_{ik} + t_{kj}\right) z_{ijk}^{F}\right) + g\left[Q - \left(y_i - \sum_{k \in \hat{F}_{ij}} d_{ik} z_{ijk}^{F}\right)\right] \\ -T_{max}\left(1 - \sum_{k \in \hat{F}_{ij}} z_{ijk}^{F}\right) \leq T_{max} \end{aligned} \qquad \begin{matrix} \forall i \in V \\ \forall j \in AD \end{matrix} \tag{9}$$

$$0 \leq u_j \leq u_i - q_j x_{ij} + C\left(1 - x_{ij} + \sum_{l \in \widehat{RD}_{ij}} z_{ijl}^{D}\right) \qquad \begin{matrix} \forall i \in V_{DD} \\ \forall j \in V_{AD} \\ i \neq j \end{matrix} \tag{10}$$

$$0 \leq u_j \leq C - q_j + C\left(1 - \sum_{l \in \widehat{RD}_{ij}} z_{ijl}^D\right) \qquad \begin{matrix} \forall i \in V_{DD} \\ \forall j \in V_{AD} \\ i \neq j \end{matrix} \tag{11}$$

$$u_i = C \qquad \forall i \in DD \tag{12}$$

$$\begin{aligned} 0 \leq y_j \leq y_i - h d_{ij} x_{ij} - h \sum_{l \in \widehat{RD}_{ij}} \left(d_{il} + d_{lj} - d_{ij}\right) z_{ijl}^D \\ + Q\left(1 - x_{ij} + z_i^C + \sum_{k \in \hat{F}_{ij}} z_{ijk}^F\right) \end{aligned} \qquad \begin{matrix} \forall i \in V_{DD} \\ \forall j \in V_{AD} \\ i \neq j \end{matrix} \tag{13}$$

$$\begin{aligned} 0 \leq y_j \leq Q - h\left(\sum_{l \in \widehat{RD}_{ij}} d_{lj} z_{ijl}^D + \sum_{k \in \hat{F}_{ij}} d_{kj} z_{ijk}^F\right) \\ + Q\left(1 - z_i^C - \sum_{k \in \hat{F}_{ij}} z_{ijk}^F\right) \end{aligned} \qquad \begin{matrix} \forall i \in V_{DD} \\ \forall j \in V_{AD} \\ i \neq j \end{matrix} \tag{14}$$

$$y_i \geq h\left(\sum_{\substack{j \in V_{AD} \\ i \neq j}} \sum_{l \in \widehat{RD}_{ij}} \left(d_{il} z_{ijl}^D\right) + \sum_{\substack{j \in V_{AD} \\ i \neq j}} \sum_{k \in \hat{F}_{ij}} \left(d_{ik} z_{ijk}^F\right)\right) \qquad \forall i \in V_{DD} \tag{15}$$

$$y_i = Q \qquad \forall i \in DD \tag{16}$$

$$\sum_{i \in DD} \sum_{j \in AD} x_{ij} + \sum_{i \in DD} \sum_{j \in V} \sum_{l \in \widehat{RD}_{ij}} z_{ijl}^D + \sum_{i \in V} \sum_{j \in AD} \sum_{l \in \widehat{RD}_{ij}} z_{ijl}^D = 0 \tag{17}$$

$$\sum_{c \in V} x_{ic} - \sum_{c \in V} x_{jc} \leq 1 \qquad \begin{matrix} \forall i, j \in DD \\ i \neq j \end{matrix} \tag{18}$$

$$\sum_{c \in V} x_{ic} - \sum_{c \in V} x_{jc} \leq 1 \qquad \begin{matrix} \forall i, j \in AD \\ i \neq j \end{matrix} \tag{19}$$

$$\sum_{i \in D} \sum_{j \in V} x_{ij} + \sum_{i \in V} \sum_{\substack{j \in V \\ i \neq j}} \sum_{l \in \widehat{RD}_{ij}} z_{ijl}^D \geq \sum_{i \in V} q_i / C \tag{20}$$

$$x_{ij} \in \{0, 1\} \qquad \begin{matrix} \forall i \in V_{DD}, \forall j \in V_{AD} \\ i \neq j \end{matrix} \tag{21}$$

$$z_{ijl}^D \in \{0, 1\} \qquad \begin{matrix} \forall i \in V_{DD}, \forall j \in V_{AD} \\ \forall l \in \widehat{RD}_{ij}, i \neq j \end{matrix} \tag{22}$$

$$z_i^C \in \{0, 1\} \qquad \forall i \in V_{DD} \tag{23}$$

$$z_{ijk}^F \in \{0, 1\} \qquad \begin{array}{c} \forall i \in V_{DD}, \forall j \in V_{AD} \\ \forall k \in \hat{F}_{ij}, i \neq j \end{array} \tag{24}$$

The objective function in Eq. (1) minimizes the sum of total traveled distance and the fixed EV cost per use. Equation (2) ensures that each customer is visited exactly once. Equation (3) guarantees that the number of incoming and outgoing arcs to each node is equal. Equation (4) states that either replenishment depot or recharging station could be visited between nodes i and j providing that arc (i, j) is traversed. Equation (5) determines if the EV is recharged or not at replenishment depot during the good replenishment. Equation (6) ensures the time feasibility for arcs leaving customers in case of recharging is not provided, i.e., recharging station and replenishment depot is not visited, or recharging is not preferred while visiting the replenishment depot. The same argument is provided with Eq. (7) in the case that recharging is performed. Equations (6) and (7) prevent the formation of subtours as well. Equation (8) limits the arrival time at arrival depots to the maximum duration T_{max} providing that no recharging station is visited between the last customer and arrival depot. The same argument is ensured by Eq. (9) when a recharging station is visited between the last customer and arrival depot. Equation (10) guarantees that demands are met in the event that no replenishment depot is visited by assuring a nonnegative load level and same is ensured by Eq. (11) when a replenishment depot is visited. Equation (12) signifies that EVs depart from departure depots with full load capacity. Equation (13) guarantees that battery charge level is nonnegative and limited by maximum battery capacity in the case that EV is not recharged and the same is assured by Eq. (14) in the case that EV is recharged at replenishment depot or recharging station. Equation (15) ensures that the battery level is sufficient to reach the replenishment depot or recharging station if they are visited. Equation (16) guarantees that EVs depart from departure depots with full battery capacity. Equation (17) prohibits the travels between departure depots and arrival depots, departure depots and replenishment depots, replenishment depots and arrival depots. Equation (18) establishes a balance among departure depots and ensures that the difference between the number of EVs departing from each departure depot is at most 1. Equation (19) executes the same operation for arrival depots. Equation (20) provides a lower limit for the minimum number of EVs departing from departure depots and replenishment depots. Equations (21)–(24) define non-negativity constraints.

Table 1. Mathematical Notations and Definitions

Notation	Definition
Indices	
i, j, c	Customers
k	Recharging station
l	Replenishment depot
Sets	
DD	Set of departure depots
AD	Set of arrival depots
V	Set of customers
V_{DD}	Set of customers and departure depots ($V \cup DD$)
V_{AD}	Set of customers and arrival depots ($V \cup AD$)
F	Set of recharging stations
$\hat{F}_{ij}$	Set of available recharging stations between nodes i and j
RD	Set of replenishment depots
$\widehat{RD}_{ij}$	Set of available replenishment depots between nodes i and j
Parameters	
d_{ij}	Distance between nodes i and j
t_{ij}	Travel time between nodes i and j
q_i	Demand of customer i
s_i	Service time of customer i
C	Electric vehicle load capacity
Q	Electric vehicle battery capacity
h	Charge consumption rate
g	Recharging rate
T_{max}	Maximum duration
c_{fix}	Fixed cost per used electric vehicle
Decision Variables	
x_{ij}	1 if arc (i, j) is traversed and 0 otherwise
z_{ijl}^{D}	1 if an EV travels from node i to j through the replenishment depot l, and 0 otherwise
z_i^C	1 if an EV is recharged at depot after node i, and 0 otherwise
z_{ijk}^F	1 if an EV travels from node i to j through the recharging station k, and 0 otherwise
y_i	Remaining charge level at node i

(*continued*)

Table 1. (*continued*)

Notation	Definition
u_i	Remaining cargo level at node i
τ_i	Time of arrival at node i

4 Experimental Results

In this section, we present the results of numerical experiments. We conducted the experiments using the instances generated by Paz et al. [7]. In essence, their datasets are the modification of the instances generated by Schneider et al. [5]. Schneider et al. [5] modified the well-known VRPTW instances of Solomon [35] by adding recharging stations, battery capacity, energy consumption rate etc., and also derived the small sized instances from them. Later, Paz et al. [7] randomly added one depot for each of the small instances as well as one recharging station which is in the same location as the new depot to allow recharging at the depot.

To adapt those datasets to our problem, we first remove the recharging stations which are located at the same location of depots, since we already possess a decision variable controlling recharging at the depot. Second, since our problem does not involve time windows, we do not need them but the maximum duration T_{max}. So, we set the T_{max} to 600 unit of time for all the experiments. Third, since we investigate the multiple use of EVs, we set the EV load capacities as the two times of the highest customer demand for each instance. Besides, we set both routes and rotations to closed in Configuration-1 (C1), let routes be half-open in Configuration-2 (C2) and let both route and rotation be half-open in Configuration-3 (C3). These configurations correspond to parts a, b, and c respectively in Fig. 1 in Sect. 3.1. To set the configurations, we utilize some extra equations and notations. One is id_i, $i \in$ DD ∪ AD ∪ RD which denotes the depot identification number [7], and the id_i of each depot representing departure, arrival and replenishment are the same. Second, decision variable w_i, $i \in V_{AD}$ is used to follow the depot identification number of nodes. Last, the parameter NOD is utilized referring to the number of depots. To set C1, we add Eqs. (25)–(31) to our model which means EVs can return only to the same depot (closed rotation) and can only replenish their load at the same depot (closed route). For setting C2, we add Eqs. (25)–(29) to our model, making the rotations closed.

$$w_j \geq x_{ij} id_i - NOD\big(1 - x_{ij}\big) \qquad \forall i \in DD, \forall j \in V \tag{25}$$

$$w_j \leq x_{ij} id_i + NOD\big(1 - x_{ij}\big) \qquad \forall i \in DD, \forall j \in V \tag{26}$$

$$w_j \geq w_i - NOD\big(1 - x_{ij}\big) \qquad \begin{array}{c}\forall i \in V, \forall j \in V_{AD} \\ i \neq j\end{array} \tag{27}$$

$$w_j \leq w_i + NOD\big(1 - x_{ij}\big) \qquad \begin{array}{c}\forall i \in V, \forall j \in V_{AD} \\ i \neq j\end{array} \tag{28}$$

$$w_i = id_i \qquad \forall i \in AD \tag{29}$$

$$w_i \geq z_{ijl}^D id_l - NOD\left(1 - z_{ijl}^D\right) \qquad \begin{array}{c}\forall i, j \in V, l \in \widehat{RD}_{ij} \\ i \neq j\end{array} \tag{30}$$

$$w_i \leq z_{ijl}^D id_l + NOD\left(1 - z_{ijl}^D\right) \qquad \begin{array}{c}\forall i, j \in V, l \in \widehat{RD}_{ij} \\ i \neq j\end{array} \tag{31}$$

The experiments are carried out on a computer equipped with Intel Core i9-13900H Processor at 2.60 GHz and 16 GB of RAM. CPLEX solver embedded to GAMS version of 45.4.0 is used as the MILP-solver. The results of the experiments are presented in Table 2. While f denotes the objective function value, *td* denotes the total distance traveled, *t(s)* denotes the total run time in seconds, and *gap(%)* denotes the percentage gap between the lower and upper bound when the solver is complete in given maximum run time of 7200 s. The fixed cost per EV used c_{fix} is set to 100, 20 and 10 for the instances with 5, 10, and 15 customers, respectively. As the number of customers increases, we reduce the c_{fix} since we wish to reach optimal or near optimal solutions in a reasonable time to make a fair comparison between each pair of configurations. Such that, results of the pilot runs on 15 customers instances with c_{fix} equal to 50 reveal that no feasible solution is obtained in 3600 s, and it turns out that the average *gap(%)* is 31.42. Table 2 shows that the optimal solutions of all the instances with 5 and 10 customers are found. When customer number increases to 15, out of 12 instances, optimal solutions of 3, 4, and 4 instances are found for C1, C2, and C3 respectively. Out of 36 instances, results reveal that inclusion of half-open routes (i.e., from C1 to C2) leads to a cost reduction for 20 instances. Besides, inclusion of both half-open routes and rotations (i.e., from C1 to C3) results in cost reduction for 28 instances. On the other hand, in some instances, an improvement is observed although the distance is increased. For example, the total distance of C2 is higher than the one in C1 for RC204–15. However, the solution of C2 is better, which is because the number EV used in C2 is lower than the one in C1.

Table 2. Experimental Results for Small Sized Instances

Instance	Configuration-1			*gap(%)*	Configuration-2			*gap(%)*	Configuration-3			
	f	*td*	*t(s)*		*f*	*td*	*t(s)*		*f*	*td*	*t(s)*	*gap(%)*
C101-5	410.93	210.93	0.34	0	410.93	210.93	0.48	0	410.93	210.93	0.47	0
C103-5	358.96	158.96	0.36	0	358.96	158.96	0.36	0	358.96	158.96	0.33	0
C206-5	426.08	226.08	0.36	0	426.08	226.08	0.45	0	406.48	206.48	0.49	0
C208-5	382.45	182.45	0.8	0	382.45	182.45	0.83	0	382.45	182.45	1	0
R104-5	261.25	161.25	0.38	0	261.25	161.25	0.28	0	241.58	141.58	0.2	0
R105-5	256.08	156.08	0.38	0	240.70	140.70	0.34	0	222.95	122.95	0.47	0
R202-5	242.65	142.65	0.34	0	237.69	137.69	0.36	0	227.96	127.96	0.2	0
R203-5	295.63	195.63	0.23	0	279.68	179.68	0.22	0	273.05	173.05	0.2	0

(*continued*)

Table 2. (*continued*)

Instance	Configuration-1			gap(%)	Configuration-2			gap(%)	Configuration-3			
	f	*td*	*t(s)*		*f*	*td*	*t(s)*		*f*	*td*	*t(s)*	*gap(%)*
RC105-5	332.00	232.00	0.36	0	326.79	226.79	0.49	0	303.20	203.20	0.33	0
RC108-5	353.93	253.93	0.23	0	350.13	250.13	0.2	0	339.80	239.80	0.23	0
RC204-5	287.69	187.69	0.26	0	287.69	187.69	0.12	0	287.69	187.69	0.25	0
RC208-5	300.18	200.18	0.34	0	300.18	200.18	0.33	0	290.42	190.42	0.34	0
C101-10	417.19	337.19	2179	0	417.19	337.19	4389	0	406.60	326.60	1466	0
C104-10	376.42	316.42	785	0	376.42	316.42	1128	0	343.56	283.56	93	0
C202-10	299.46	239.46	175	0	299.46	239.46	213	0	297.14	237.14	178	0
C205-10	305.83	245.83	59	0	305.83	245.83	144	0	305.83	245.83	78	0
R102-10	301.84	281.84	134	0	290.54	270.54	36	0	289.45	269.45	34	0
R103-10	222.85	202.85	199	0	216.22	196.22	74	0	214.29	194.29	56	0
R201-10	261.36	241.36	145	0	244.91	224.91	20	0	244.91	224.91	15	0
R203-10	287.90	247.90	34	0	257.87	237.87	2	0	257.87	237.87	3	0
RC102-10	386.62	366.62	31	0	374.11	354.11	6	0	372.07	352.07	5	0
RC108-10	351.64	311.64	7	0	340.82	320.82	4	0	326.66	306.66	0.9	0
RC201-10	308.83	268.83	27	0	297.67	277.67	13	0	286.66	266.66	4	0
RC205-10	431.93	391.93	155	0	431.93	391.93	339	0	431.93	391.93	151	0
C103-15	356.53	306.53	7200	18	356.53	306.53	7200	15	356.53	306.53	7200	14
C106-15	344.97	294.97	7200	10	344.97	294.97	7200	10	337.21	287.21	7200	6
C202-15	429.15	389.15	7200	14	429.15	389.15	7200	17	429.15	389.15	7200	14
C208-15	549.13	499.13	7200	32	549.13	499.13	7200	31	510.68	460.68	7200	25
R102-15	313.31	293.31	7200	8	299.93	289.93	6624	0	299.93	289.93	5652	0
R105-15	297.76	287.76	2063	0	274.37	264.37	21	0	274.37	264.37	20	0
R202-15	347.98	327.98	687	0	342.09	322.09	391	0	342.09	322.09	290	0
R209-15	369.89	349.89	7200	8	369.44	349.44	7200	9	369.44	349.44	7200	9
RC103-15	411.29	391.29	7200	6	409.57	389.57	7200	5	409.57	389.57	7200	5
RC108-15	494.24	474.24	7200	13	463.47	443.47	7200	8	463.47	443.47	7200	8
RC202-15	380.36	360.36	3208	0	379.34	359.34	4567	0	379.34	359.34	3253	0
RC204-15	538.22	508.22	7200	25	529.80	509.80	7200	24	525.41	505.41	7200	23

Meanwhile, the comparisons between each pair of configurations based on the results can be seen in Table 3. In panel C1/C2, while $\Delta f(\%)$ denotes the percentage improvement of C2 over the C1 for the objective function value, $\Delta td(\%)$ denotes the percentage improvement for the total distance traveled. The rest of the columns follow the same denotations. When C1 and C2 is comparatively investigated, one can observe that in 20 over 36 instances, C2 improved the solutions of C1. The maximum improvement with an 9.85 in traveled distance is a considerable one while the average improvements are 2.00 and 1.63 for the objective function and traveled distance, respectively. On the other hand, trade-off between routing cost and the fixed cost could also be observed. For instance, in RC108-10 while the $\Delta f(\%)$ equals 3.08, $\Delta td(\%)$ equals -2.95. This is because while two EVs are employed in C1, only one EV is employed in C2. So, although

f improves, td increases. When the C2 and C3 is comparatively investigated, no trade-off is observed. However, there is an improvement in 19 over 36 instances. On the other hand, the panel C1/C3 shows the overall superiority of applying half-open routes and rotations simultaneously. While the solutions of 28 over 36 instances are improved up to 12.94 for $\Delta f(\%)$ and 21.23 for $\Delta td(\%)$, the average improvements are 3.94 for $\Delta f(\%)$ and 4.35 for $\Delta td(\%)$. As one can observe from the results that the trade-offs occur in instances with 10 and 15 customers due to c_{fix}. When the c_{fix} increases, the number of trade-offs decreases and eventually reaches 0.

As is stated before, if the duration of a single route is shorter comparing to the whole working hours, using vehicles multiple times can yield cost saving. Besides, if the related organization has several depots or distribution centers, allowing half-open routes and rotation can lead to extra cost savings. On the other hand, the magnitude of the trade-off may differ according to the ratio between routing and vehicle cost. As is seen in Table 3, no trade-off occurs in the instances with 5 customers, but in the ones with 10 and 15 customers. The level of trade-off may be at different levels depending on the related logistics company, the sector, the type of vehicle used, and both the load and battery capacity of the electric vehicle. It may also vary depending on different strategies used such as half-open routes & rotations, and the decision to receive recharging service at the depot. In other respects, this paper considers only the full recharging and one type of recharging option. However, allowing partial recharging as well as multiple recharging options with different speeds may further improve the solution in terms of distance traveled and the number of electric vehicles employed.

Table 3. Comparisons of Configurations for Small Sized Instances

Instance	C1/C2		C2/C3		C1/C3		Instance	C1/C2		C2/C3		C1/C3	
	Δf (%)	Δtd (%)	Δf (%)	Δtd (%)	Δf (%)	Δtd (%)		Δf (%)	Δtd (%)	Δf (%)	Δtd (%)	Δf (%)	Δtd (%)
C101-5	0.00	0.00	0.00	0.00	0.00	0.00	R201–10	6.29	6.82	0.00	0.00	6.29	6.82
C103-5	0.00	0.00	0.00	0.00	0.00	0.00	R203–10	10.43	4.05	0.00	0.00	10.43	4.05
C206-5	0.00	0.00	4.60	8.67	4.60	8.67	RC102–10	3.24	3.41	0.55	0.58	3.76	3.97
C208-5	0.00	0.00	0.00	0.00	0.00	0.00	RC108–10	3.08	-2.95	4.15	4.41	7.10	1.60
R104-5	0.00	0.00	7.53	12.20	7.53	12.20	RC201–10	3.61	-3.29	3.70	3.97	7.18	0.81
R105-5	6.01	9.85	7.37	12.62	12.94	21.23	RC205–10	0.00	0.00	0.00	0.00	0.00	0.00
R202-5	2.04	3.48	4.09	7.07	6.05	10.30	C103–15	0.00	0.00	0.00	0.00	0.00	0.00
R203-5	5.40	8.15	2.37	3.69	7.64	11.54	C106–15	0.00	0.00	2.25	2.63	2.25	2.63
RC105-5	1.57	2.25	7.22	10.40	8.67	12.41	C202–15	0.00	0.00	0.00	0.00	0.00	0.00
RC108-5	1.07	1.50	2.95	4.13	3.99	5.56	C208–15	0.00	0.00	7.00	7.70	7.00	7.70
RC204-5	0.00	0.00	0.00	0.00	0.00	0.00	R102–15	4.27	1.15	0.00	0.00	4.27	1.15

(*continued*)

Table 3. (*continued*)

Instance	C1/C2		C2/C3		C1/C3		Instance	C1/C2		C2/C3		C1/C3	
	Δf (%)	Δtd (%)	Δf (%)	Δtd (%)	Δf (%)	Δtd (%)		Δf (%)	Δtd (%)	Δf (%)	Δtd (%)	Δf (%)	Δtd (%)
RC208-5	0.00	0.00	3.25	4.88	3.25	4.88	R105–15	7.86	8.13	0.00	0.00	7.86	8.13
C101-10	0.00	0.00	2.54	3.14	2.54	3.14	R202–15	1.69	1.80	0.00	0.00	1.69	1.80
C104-10	0.00	0.00	8.73	10.38	8.73	10.38	R209–15	0.12	0.13	0.00	0.00	0.12	0.13
C202-10	0.00	0.00	0.77	0.97	0.77	0.97	RC103–15	0.42	0.44	0.00	0.00	0.42	0.44
C205-10	0.00	0.00	0.00	0.00	0.00	0.00	RC108–15	6.23	6.49	0.00	0.00	6.23	6.49
R102-10	3.74	4.01	0.38	0.40	4.10	4.40	RC202–15	0.27	0.28	0.00	0.00	0.27	0.28
R103–10	2.98	3.27	0.89	0.98	3.84	4.22	RC204–15	1.56	-0.31	0.83	0.86	2.38	0.55
							Average	2.00	1.63	1.98	2.77	3.94	4.35

5 Results and Discussion

In this paper, we investigated the effect of half-open routes and half-open rotations for the MDEVRP-HORR and introduced a novel 0–1 MILP model. For experimental studies, we used the small-sized instances up to 15 customers provided by Paz et al. [7]. These instances are the modification of the ones by Schneider et al. [5] based on well-known Solomon [35] instances. We first solved the instances with closed routes and rotations, second let routes be half-open and finally let them both be half-open. The results show that half-open routes and rotations lead to an improvement in terms of the total distance traveled, number of EV utilized and on 28 out of 36 instances total cost reduces. Further, in some instances, trade-off between the routing cost and fixed cost of using an EV is observed especially when the fixed cost is lower. This result may lead to interesting investigations for half-open routes and rotations in different sectors where the number of EVs utilized and the fixed cost vary. In this context, critical contributions of this paper can be listed as follows;

- The half-open rotation concept which allows EVs to be assigned multiple routes and flexibility to complete the tour at a different depot than the departure depot is adopted,
- A recharging station and replenishment depot elimination procedure is implemented in the MDEVRP which significantly reduces the number of variables employed,
- A procedure which helps avoid from using dummy recharging stations and depots and eventually obstruct network augmentation is applied.

Since the VRP belongs to class of hard combinatorial optimization problem and the MDEVRP-HORR is an extension of it, we carried out experimental studies on small sized instances. However, number of customers in small sized instances are lower as compared to real-life settings. Therefore, to solve our problem with medium and large sized instances, heuristic and metaheuristic algorithms including swarm intelligence (Particle swarm or ant colony optimization), evolutionary algorithms (genetic or memetic algorithm) or neighborhood structured algorithms (variable or adaptive large neighborhood search algorithm) must be developed. Besides, the trade-off between the routing cost and fixed EV cost per use could be examined according to the different logistics service areas. Besides, this paper adopted full recharging strategy. However, there are many other strategies in real life which are also often utilized in the literature such as partial recharging, battery swapping, or hybrid ones etc. So, integration of these different strategies to tackled problem is worth studying.

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