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A green logistics solution for last-mile deliveries considering e-vans and e-cargo bikes

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Abstract

The environmental challenges and the initiatives for sustainable development in urban areas are mainly focused on eco-friendly transportation systems. Therefore, we introduce a new green logistics solution for last-mile deliveries considering synchronization between e-vans and e-cargo bikes, developed as a Two-Echelon Electric Vehicle Routing Problem with Time Windows and Partial Recharging (2E-EVRPTW-PR). The first echelon represents an urban zone, and the second echelon represents a restricted traffic zone (e.g., historical center) in which e-vans in the first and e-cargo bikes in the second echelon are used for customers' deliveries. The proposed 2E-EVRPTW-PR model aims to minimize the total costs in terms of travel costs, initial vehicles' investment costs, drivers' salary costs, and micro-depot cost. The effectiveness of the proposed solution has been demonstrated comparing two different cases, i.e., the EVRPTW-PR considering e-vans for the first case, and the 2E-EVRPTW-PR considering e-vans and e-cargo bikes for the second case. The comparison has been carried out on existing EVRPTW-PR instances for the first case, and on novel 2E-EVRPTW-PR instances for the second case, in which customers of initial EVRPTW-PR instances have been divided into two zones (urban and restricted traffic zones) by using Fuzzy C-mean clustering. Moreover, results encourage logistics companies to adopt zero-emission strategies for last-mile deliveries, especially in restricted traffic zones.

Keywords: two-echelon electric vehicle routing problem; green logistics; electric cargo bikes; last-mile delivery;

1. Introduction and literature review

City logistics is facing everyday environmental challenges in promoting and developing a cleaner transportation environment focusing on emission, traffic noise, and congestion reduction. These challenges raised the concept of

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"green logistics" in urban areas that enhanced the movement of electric mobility considering various technologies, such as electric vehicles (EVs), e-cargo bikes, hybrid vehicles, etc. The substitution of internal combustion vehicles (ICVs) with zero-emission technologies achieves several benefits for companies such as lower maintenance and operational costs, accessibility in restricted traffic zones, such as historical centers, pedestrian zones, etc. (Taefi et al., 2015).

A novel formulation of the Electric Vehicle Routing Problem introduced the advantages of EVs regarding full recharge solution (Schneider et al., 2014) and partial recharge solution (Keskin and Çatay, 2016). To the best of our knowledge, only a few papers in the literature applied the Two-Echelon Electric Vehicle Routing Problem (2E-EVRP). Breunig et al. (2019) proposed a 2E-EVRP with Time Windows (2E-EVRPTW), where ICVs deliver goods to satellites in the first echelon, while customers are visited with EVs in the second echelon. Jie et al. (2019) proposed a combination of a column generation and an adaptive large neighborhood search for 2E-EVRPTW considering battery swapping stations (2E-EVRPTW-BSS). Wang et al. (2019) proposed 2E-EVRPTW-BSS with ICVs for the first echelon and EVs for the second echelon. On the other hand, different studies investigated the advantages and performance of e-cargo bikes (Gruber et al., 2014; Nocerino et al., 2016). Moreover, Anderluh et al. (2017; 2019) implemented the Two-Echelon Vehicle Routing Problem (2E-VRP) that involved the synchronization between vans and cargo bikes.

In this paper, we propose a novel formulation for Two-Echelon Capacitated Electric Vehicle Routing Problem with Time Windows and Partial Recharging (2E-EVRPTW-PR) based on Keskin and Çatay (2016), for the last-mile deliveries that highlights the usage of zero-emission technologies (e-cargo bikes and e-vans). We extended the mathematical formulation proposed by Keskin and Çatay (2016) to the two-echelon problem. The model aims at minimizing the total costs of two echelons considering travel costs, initial vehicles' investment costs, drivers' salary costs, and micro-depot cost. The proposed model highlights the advantages of using e-cargo bikes in restricted traffic zones in terms of energy and investment cost savings, which are scarcely considered in the literature.

The paper is organized as follows. In the second section, we described the problem that we considered, while the third section is devoted to the numerical experiments. Finally, conclusions and future developments are described in the fourth section.

2. Problem description

We formulated the proposed 2E-EVRPTW-PR as a mixed-integer linear programming model, where the first echelon is related to the urban zone, while the second echelon is related to the restricted traffic zone. The connection between the first and the second echelon is the transshipment point (micro-depot) t in which e-vans are delivering goods to the e-cargo bikes, according to the request of customers located in restricted traffic zones. Therefore, the transshipment point is the depot V_d^{II} for the second echelon, in which e-cargo bikes are parked. The first echelon set V_{d,N_1+1}^I is composed of the depot V_d^I, the set of customers V_c^I, the set of dummy stations $\tilde{V}_s^I$, and the transshipment point V_d^{II}. The set of dummy stations $\tilde{V}_s^I$ allows several visits to each recharging station. The synchronization between the first and the second echelon is established through the transshipment point, where the quantity of goods in the transshipment point is set as the sum of customers' demand in the second echelon. Consequently, the whole daily quantity of goods is delivered to the customers, and there are no inventory costs in the transshipment point.

In the first echelon, the set of homogenous vehicles (e-vans) $K^I = \{1, \dots, w^I\}$ is located at the depot V_d^I. The total number of vehicles (e-vans) w^I are starting the trip from $V_d^I = \{0\}$ and finishing at $V_d^I = \{N_1 + 1\}$, located at the same point. The second echelon set V_{d,N_2+1}^{II} includes the depot V_d^{II}, the set of customers V_c^{II}, and the set of charging stations V_s^{II} located in the restricted traffic zones. Thus, in the second echelon, the set of homogenous vehicles (e-cargo bikes) $K^I = \{1, \dots, w^{II}\}$ is located at the depot V_d^{II}. Each e-cargo bike starts its trip at $V_d^{II} = \{0\}$, and finishes at $V_d^{II} = \{N_2 + 1\}$, located at the same point. Thus, the 2E-EVRPTW-PR is defined on a directed graph $G_I = \left(V_{d,N_1+1}^I, A_I\right)$ for the first echelon, and on a directed graph $G_{II} = \left(V_{d,N_2+1}^{II}, A_{II}\right)$ for the second echelon, where sets of arcs A_I and A_{II} are defined as $A_I = \left\{(i,j) \mid i,j \in V_{d,N_1+1}^I, i \neq j\right\}$ and $A_{II} = \left\{(i,j) \mid i,j \in V_{d,N_2+1}^{II}, i \neq j\right\}$, respectively. All sets, parameters, and decision variables of the proposed 2E-EVRPTW-PR model are introduced in Nomenclature.

Nomenclature

Sets

$V_d^I \backslash V_d^{II}$	Depot of the 1st echelon, $V_d^I = \{0\}$ \ 2nd echelon, $V_d^{II} = \{t\}$, where t is the transshipment point
$V_s^I \backslash V_s^{II}$	Set of stations of the 1st echelon, $V_s^I = \{1, \dots, m^I\}$ \ 2nd echelon, $V_s^{II} = \{1, \dots, m^{II}\}$
$\tilde{V}_s^I \backslash \tilde{V}_s^{II}$	Set of dummy stations of the 1st echelon \ 2nd echelon
$V_c^I \backslash V_c^{II}$	Set of customers of the 1st echelon, $V_c^I = \{1, \dots, n^I\}$ \ 2nd echelon, $V_c^{II} = \{1, \dots, n^{II}\}$
$\tilde{V}_{N_1+1}^I$	Set of dummy stations, customers and transshipment point of the 1st echelon, $\tilde{V}_{N_1+1}^I = \tilde{V}_s^I \cup V_c^I \cup V_d^{II} \cup \{N_1 + 1\}$
$\tilde{V}_{N_2+1}^{II}$	Set of dummy stations and customers of the 2nd echelon, $\tilde{V}_{N_2+1}^{II} = \tilde{V}_s^{II} \cup V_c^{II} \cup \{N_2 + 1\}$
$\tilde{V}_d^I$	Set of depot, dummy stations, customers and transshipment point of the 1st echelon, $\tilde{V}_d^I = V_d^I \cup \tilde{V}_s^I \cup V_c^I \cup V_d^{II}$
$\tilde{V}_d^{II}$	Set of dummy stations, customers and transshipment point of the 2nd echelon, $\tilde{V}_d^{II} = \tilde{V}_s^{II} \cup V_c^{II} \cup V_d^{II}$
$K^I \backslash K^{II}$	Set of vehicles of the 1st echelon, $K^I = \{1, \dots, w^I\}$\ 2nd echelon, $K^{II} = \{1, \dots, w^{II}\}$
V_{d,N_1+1}^I	Set of all nodes of the 1st echelon, $V_{d,N_1+1}^I = V_d^I \cup \tilde{V}_{N_1+1}^I$
V_{d,N_2+1}^{II}	Set of all nodes of the 2nd echelon, $V_{d,N_2+1}^{II} = V_d^{II} \cup \tilde{V}_{N_2+1}^{II}$

Parameters

$n^I \backslash n^{II}$	Number of customers of the 1st echelon \ 2nd echelon
$m^I \backslash m^{II}$	Number of stations of the 1st echelon \ 2nd echelon
$w^I \backslash w^{II}$	Number of vehicles of the 1st echelon \ 2nd echelon
$d_{ij}^I \backslash d_{ij}^{II}$	Distance between vertices i and j in the 1st echelon \ 2nd echelon
$t_{ij}^I \backslash t_{ij}^{II}$	Travel time between vertices i and j in the 1st echelon \ 2nd echelon
$C^I \backslash C^{II}$	Capacity of vehicles in K^I in the 1st echelon \ capacity of vehicles in K^{II} in the 2nd echelon
$g^I \backslash g^{II}$	Recharging rate of vehicles in K^I in the 1st echelon \ recharging rate of vehicles in K^{II} in the 2nd echelon
$h^I \backslash h^{II}$	Fuel consumption rate of vehicles in K^I in the 1st echelon \ Fuel consumption rate of vehicles in K^{II} in the 2nd echelon
$v^I \backslash v^{II}$	Average speed of vehicles in K^I in the 1st echelon \ average speed of vehicles in K^{II} in the 2nd echelon
$Q^I \backslash Q^{II}$	Battery capacity of vehicles in K^I in the 1st echelon \ battery capacity of vehicles in K^{II} in the 2nd echelon
$[e_i^I, l_i^I]$	Time window of each vertex $i \in \tilde{V}_{V_d^I,N_1+1}^I$ in the 1st echelon
$[e_i^{II}, l_i^{II}]$	Time window of each vertex $i \in \tilde{V}_{V_d^{II},N_2+1}^{II}$ in the 2nd echelon, where $[e_{V_d^{II}}^{II}, l_{V_d^{II}}^{II}] = [e_{V_d^I}^I, l_{V_d^I}^I]$
$s_i^I \backslash s_i^{II}$	Service time of each vertex $i \in \tilde{V}_{V_d^I,N_1+1}^I$ in the 1st echelon, where $s_{V_d^I}^I, s_{\tilde{V}_s^I}^I, s_{N_1+1}^I = 0$ \ service time of each vertex $i \in \tilde{V}_{V_d^{II},N_2+1}^{II}$ in the 2nd echelon, where $s_{V_d^{II}}^{II}, s_{\tilde{V}_s^{II}}^{II}, s_{N_2+1}^{II} = 0$
$q_i^I \backslash q_i^{II}$	Demand of each vertex $i \in \tilde{V}_{V_d^I,N_1+1}^I$ in the 1st echelon, where $q_{V_d^I}^I, q_{\tilde{V}_s^I}^I, q_{N_1+1}^I = 0$ and $q_{V_d^{II}}^I = \sum_i^{V_c^{II}} q_i^{II}$\ demand of vertex $i \in \tilde{V}_{V_d^{II},N_2+1}^{II}$ in the 2nd echelon, where $q_{V_d^{II}}^{II}, q_{\tilde{V}_s^{II}}^{II}, q_{N_2+1}^{II} = 0$
$c_e^{w^I} \backslash c_e^{w^{II}}$	Electric energy cost of vehicles w^I in the 1st echelon \ electric energy cost of vehicles w^{II} in the 2nd echelon
$c_v^{w^I} \backslash c_v^{w^{II}}$	Vehicle's w^I initial investment cost in the 1st echelon \ vehicle's w^{II} initial investment cost in the 2nd echelon
$c_d^{w^I} \backslash c_d^{w^{II}}$	Driver's salary cost of vehicles w^I in the 1st echelon \ driver's salary cost of vehicles w^{II} in the 2nd echelon
c_m	Cost of the transshipment point

Decision variables

$\tau_{ki}^I \backslash \tau_{ki}^{II}$	Arrival time at vertex $i \in \tilde{V}_{V_d^I,N_I+1}^I$ for all $k \in K^I$ in the 1st echelon \ arrival time at vertex $i \in \tilde{V}_{V_d^{II},N_2+1}^{II}$ for all $k \in K^{II}$ in the 2nd echelon
$u_{ki}^I \backslash u_{ki}^{II}$	Remaining cargo on arrival at vertex $i \in \tilde{V}_{V_d^I,N_1+1}^1$ for all $k \in K^I$ in the 1st echelon \ remaining cargo on arrival at vertex $i \in \tilde{V}_{V_d^{II},N_2+1}^{II}$ for all $k \in K^{II}$ in the 2nd echelon
$y_{ki}^I \backslash y_{ki}^{II}$	Remaining charge level on arrival at vertex $i \in \tilde{V}_{V_d^I,N_1+1}^I$ for all $k \in K^I$ in the 1st echelon \ remaining charge level on arrival at vertex $i \in \tilde{V}_{V_d^{II},N_2+1}^{II}$ for all $k \in K^{II}$ in the 2nd echelon
$Y_{ki}^I \backslash Y_{ki}^{II}$	Battery state of charge on departure from vertex $i \in \tilde{V}_{V_d^I,N_1+1}^I$ for all $k \in K^I$ in the 1st echelon \ battery state of charge on departure from vertex $i \in \tilde{V}_{V_d^{II},N_2+1}^{II}$ for all $k \in K^{II}$ in the 2nd echelon
$x_{kij}^I \backslash x_{kij}^{II}$	Binary decision variable in the 1st echelon, where $k \in K^I$ and $i, j \in \tilde{V}_{V_d^I,N_1+1}^I$ \ binary decision variable in the 2nd echelon, where $k \in K^{II}$ and $i, j \in \tilde{V}_{V_d^{II},N_2+1}^{II}$

The extended mathematical model of the proposed 2E-EVRPTW-PR based on Keskin and Çatay (2016) is formulated as follows:

$$f_1(x) = \left(c_v^{w^I} + c_d^{w^I}\right)\cdot w^I + \left(c_v^{w^I} + c_d^{w^{II}}\right)\cdot w^{II} + c_m + \sum_{k\in K^I}\sum_{i,j\in V^I_{d,N_1+1},\, i\neq j} d_{ij}^I \cdot c_e^{w^I}\cdot x_{kij}^I + \sum_{k\in K^{II}}\sum_{i,j\in V^{II}_{d,N_2+1},\, i\neq j} d_{ij}^{II}\cdot c_e^{w^{II}}\cdot x_{kij}^{II} \quad (1)$$

s.t.

$$\sum_{j\in V^I_{N_1+1}} x_{kij}^I = 1, \forall k\in K^I, \quad i\in V_d^I = \{0\},\ i\neq j \quad (2)$$

$$\sum_{j\in V^I_{N_1+1}} x_{kji}^I = 1, \forall k\in K^I, \quad i\in V_d^I = \{N_1+1\},\ i\neq j \quad (3)$$

$$\sum_{k\in K^I} x_{kij}^I + \sum_{k\in K^I} x_{kji}^I \le 1, \quad \forall i\in V_d^I,\ \forall j\in V^I_{N_1+1},\ i\neq j \quad (4)$$

$$\sum_{k\in K^I}\sum_{i\in V_d^I} x_{kij}^I = 1, \quad \forall j\in V_c^I,\ i\neq j \quad (5)$$

$$\sum_{k\in K^I}\sum_{i\in V^I_{N_1+1}} x_{kji}^I = 1, \quad \forall j\in V_c^I,\ i\neq j \quad (6)$$

$$\sum_{i\in V_d^I} x_{kij}^I - \sum_{i\in V^I_{N_1+1}} x_{kji}^I = 0, \quad \forall j\in V_c^I, \forall k\in K^I, i\neq j \quad (7)$$

$$\sum_{i\in V^I_{N_1+1}} x_{kij}^I \ge 0, \forall j\in V_s^I, \quad \forall k\in K^I,\ i\neq j \quad (8)$$

$$\sum_{i\in V^I_{N_1+1}} x_{kji}^I \ge 0, \quad \forall j\in V_s^I, \forall k\in K^I,\ i\neq j \quad (9)$$

$$\sum_{i\in V_d^I} x_{kij}^I - \sum_{i\in V^I_{N_1+1}} x_{kji}^I = 0, \quad \forall j\in V_s^I, \forall k\in K^I, i\neq j \quad (10)$$

$$x_{kij}^I + x_{kji}^I \le 1, \quad \forall i\in V^I_{N_1+1}, \forall j\in V_s^I, \forall k\in K^I,\ i\neq j \quad (11)$$

$$0\le u_{ki}^I \le C^I, \quad \forall k\in K^I, i\in V_d^I = \{0\} \quad (12)$$

$$0\le u_{kj}^I \le u_{ki}^I - q_{ki}^I\cdot x_{kij}^I + C^I\cdot\left(1-x_{kij}^I\right), \quad \forall i\in V_d^I, \forall j\in V^I_{N_1+1}, \forall k\in K^I,\ i\neq j \quad (13)$$

$$0\le y_{kj}^I \le y_{kj}^I - h\cdot d_{kij}^I\cdot x_{kij}^I + Q^I\cdot\left(1-x_{kij}^I\right), \quad \forall i\in V_d^I\cup V_c^I, \forall j\in V^I_{N_1+1}, \forall k\in K^I,\ i\neq j \quad (14)$$

$$y_{kj}^I \le Y_{ki}^I - h\cdot d_{kij}^I\cdot x_{kij}^I + Q^I\cdot(1-x_{kij}^I), \quad \forall i\in V_d^I\cup V_s^I, \forall j\in V^I_{N_1+1}, \forall k\in K^I,\ i\neq j \quad (15)$$

$$y_{ki}^I \le Y_{ki}^I \le Q^I, \quad \forall i\in V_d^I\cup V_s^I, \forall k\in K^I \quad (16)$$

$$\tau_{ki}^I + \left(t_{kij}^I + s_{ki}^I\right)\cdot x_{kij}^I - l_0\left(1-x_{kij}^I\right)\le \tau_{kj}^I, \quad \forall i\in V_d^I\cup V_c^I, \forall j\in V^I_{N_1+1}, \forall k\in K^I,\ i\neq j \quad (17)$$

$$\tau_{ki}^I + t_{kij}^I\cdot x_{kij}^I + g^I\cdot\left(Y_{ki}^I - y_{ki}^I\right) - \left(l_0 + g^I\cdot Q^I\right)\cdot\left(1-x_{kij}^I\right)\le \tau_{kj}^I, \quad \forall i\in V_s^I, \forall j\in V^I_{N_1+1}, \forall k\in K^I,\ i\neq j \quad (18)$$

$$x_{kij}^I \in \{0,1\}, \quad \forall i,j\in V^I_{d,N_1+1}, \forall k\in K^I,\ i\neq j \quad (19)$$

$$u_{ki}^I, y_{ki}^I, Y_{ki}^I, \tau_{ki}^I \ge 0, \quad \forall i\in V^I_{d,N_1+1}, \forall k\in K^I \quad (20)$$

$$\sum_{j\in V^{II}_{N_2+1}} x_{kij}^{II} = 1, \forall k\in K^{II}, \quad i\in V_d^{II} = \{0\},\ i\neq j \quad (21)$$

$$\sum_{j \in V^{II}_{N_2+1}} x^{II}_{kji} = 1 \text{ , } \forall k \in K^{II} \text{, } \quad i \in V^{II}_{d} = \{N_2 + 1\} \text{, } i \neq j \tag{22}$$

$$\sum_{k \in K^{II}} x^{II}_{kij} + \sum_{k \in K^{II}} x^{II}_{kji} \leq 1 \text{ , } \quad \forall i \in V^{II}_{d} \text{, } \forall j \in V^{II}_{N_2+1} \text{, } i \neq j \tag{23}$$

$$\sum_{k \in K^{II}} \sum_{i \in V^{II}_{d}} x^{II}_{kij} = 1 \text{ , } \quad \forall j \in V^{II}_{c} \text{, } i \neq j \tag{24}$$

$$\sum_{k \in K^{II}} \sum_{i \in V^{II}_{N_2+1}} x^{II}_{kji} = 1 \text{ , } \quad \forall j \in V^{II}_{c} \text{, } i \neq j \tag{25}$$

$$\sum_{i \in V^{II}_{d}} x^{II}_{kij} - \sum_{i \in V^{II}_{N_2+1}} x^{II}_{kji} = 0 \text{ , } \quad \forall j \in V^{II}_{c} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{26}$$

$$\sum_{i \in V^{II}_{N_2+1}} x^{II}_{kij} \geq 0 \text{ , } \forall j \in V^{II}_{s} \text{, } \quad \forall k \in K^{II} \text{, } i \neq j \tag{27}$$

$$\sum_{i \in V^{II}_{N_2+1}} x^{II}_{kji} \geq 0 \text{ , } \quad \forall j \in V^{II}_{s} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{28}$$

$$\sum_{i \in V^{II}_{d}} x^{II}_{kij} - \sum_{i \in V^{II}_{N_2+1}} x^{II}_{kji} = 0 \text{ , } \quad \forall j \in V^{II}_{s} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{29}$$

$$x^{II}_{kij} + x^{II}_{kji} \leq 1 \text{ , } \quad \forall i \in V^{II}_{N_2+1} \text{, } \forall j \in V^{II}_{s} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{30}$$

$$0 \leq u^{II}_{ki} \leq C^{II} \text{, } \quad \forall k \in K^{II} \text{, } i \in V^{II}_{d} = \{t\} \tag{31}$$

$$0 \leq u^{II}_{kj} \leq u^{II}_{ki} - q^{II}_{ki} \cdot x^{II}_{kij} + C^{II} \cdot \left(1 - x^{II}_{kij}\right) \text{ , } \quad \forall i \in V^{II}_{d} \text{, } \forall j \in V^{II}_{N_2+1} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{32}$$

$$0 \leq y^{II}_{kj} \leq y^{II}_{kj} - h \cdot d^{II}_{kij} \cdot x^{II}_{kij} + Q^{II} \cdot \left(1 - x^{II}_{kij}\right) \text{ , } \quad \forall i \in V^{II}_{d} \cup V^{II}_{c} \text{, } \forall j \in V^{II}_{N_2+1} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{33}$$

$$y^{II}_{kj} \leq Y^{II}_{ki} - h \cdot d^{II}_{kij} \cdot x^{II}_{kij} + Q^{II} \cdot (1 - x^{II}_{kij}) \text{, } \forall i \in V^{II}_{d} \cup V^{II}_{s} \text{, } \forall j \in V^{II}_{N_2+1} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{34}$$

$$y^{II}_{ki} \leq Y^{II}_{ki} \leq Q^{II} \text{, } \quad \forall i \in V^{II}_{d} \cup V^{II}_{s} \text{, } \forall k \in K^{II} \tag{35}$$

$$\tau^{II}_{ki} + \left(t^{II}_{kij} + s^{II}_{ki}\right) \cdot x^{II}_{kij} \; - l_0 \left(1 - x^{II}_{kij}\right) \leq \tau^{II}_{kj} \text{ , } \quad \forall i \in V^{II}_{d} \cup V^{II}_{c} \text{, } \forall j \in V^{II}_{N_2+1} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{36}$$

$$\tau^{II}_{ki} + t^{II}_{kij} \cdot x^{II}_{kij} + g^{II} \cdot \left(Y^{II}_{ki} - y^{II}_{ki}\right) - \left(l_0 + g^{II} \cdot Q^{II}\right) \cdot \left(1 - x^{II}_{kij}\right) \leq \tau^{II}_{kj} \text{ , } \quad \forall i \in V^{II}_{s} \text{, } \forall j \in V^{II}_{N_2+1} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{37}$$

$$x^{II}_{kij} \in \{0,1\} \text{ , } \quad \forall i,j \in V^{II}_{d,N_2+1} \text{, } \forall k \in K^{II} \text{, } i \neq j \tag{38}$$

$$u^{II}_{ki}, y^{II}_{ki}, Y^{II}_{ki}, \tau^{II}_{ki} \geq 0 \text{ , } \quad \forall i \in V^{II}_{d,N_2+1} \text{, } \forall k \in K^{II} \tag{39}$$

The objective function (1) minimizes the total costs, such as travel costs, initial vehicles' investment costs, drivers' salary costs, and micro-depot cost of the first and the second echelon. Constraints (2) – (20), related to the first echelon, are explained as follows. Constraints (2) – (3) ensure that each vehicle starts and finishes its route at the depot. Constraints (4) avoid the cycles between nodes. Constraints (5) – (6) ensure that each customer should be visited by one vehicle once. Constraints (7) ensure the number of arcs leaving and entering at each customer node. Constraints (8) – (9) ensure that each station can be visited more times by one or more vehicles. Constraints (10) – (11) are related to the number of links entering and leaving from each station by avoiding cycles between stations. Constraints (12) – (13) are meeting the demand request at each node and ensure nonnegative remaining cargo load. Constraints (14) – (16) are related to the battery's partial charging for each vehicle at the station. Constraints (17) – (18) are related to the time window constraints and subtour elimination. Constraints (19) are related to the binary variables that are equal to 1 if the vehicle k is traveling on arc (i,j), 0 otherwise. Constraints (20) ensure that remaining cargo level u, remaining charge level y, battery state of charge Y, and arrival time τ are greater or equal than zero. Constraints (21) – (39) are related to the second echelon and are defined as the above-mentioned description of the first echelon constraints, following the same order. Furthermore, we created four cases to test and validate the proposed model, starting from the objective function f_1 and assigning different values to the costs, as follows:

- Case 1.a: The objective function f_2 (Eq. 40), with constraints (2) – (20), minimizes the total distance of the first echelon. We set up values of parameters $c_e^{w^I}$ equal to 1 and values $c_e^{w^{II}}$, $c_v^{w^I}$, $c_v^{w^{II}}$, $c_d^{w^I}$, $c_d^{w^{II}}$ and c_m equal to 0.

$$f_2(x) = \sum_{k \in K^I} \sum_{i,j \in V^I_{d,N_1+1},\, i \neq j} d^I_{ij} \cdot x^I_{kij} \tag{40}$$

- Case 1.b: The objective function f_3 (Eq. 41), with constraints (2) – (39), minimizes the total distance of both echelons. We set up values of parameters $c_e^{w^I}$, $c_e^{w^{II}}$ equal to 1 and values $c_v^{w^I}$, $c_v^{w^{II}}$, $c_d^{w^I}$, $c_d^{w^{II}}$ and c_m equal to 0.

$$f_3(x) = \sum_{k \in K^I} \sum_{i,j \in V^I_{d,N_1+1},\, i \neq j} d^I_{ij} \cdot x^I_{kij} + \sum_{k \in K^{II}} \sum_{i,j \in V^{II}_{d,N_2+1},\, i \neq j} d^{II}_{ij} \cdot x^{II}_{kij} \tag{41}$$

- Case 2.a: The objective function f_4 (Eq. 42), with constraints (2) – (20), minimizes the total costs of the first echelon. We set up the value of parameters of the second echelon $c_e^{w^{II}}$, $c_v^{w^{II}}$, $c_d^{w^{II}}$ and c_m equal to 0.

$$f_4(x) = \left(c_v^{van} + c_d^{van}\right) \cdot w^I + \sum_{k \in K^I} \sum_{i,j \in V^I_{d,N_1+1},\, i \neq j} d^I_{ij} \cdot x^I_{kij} \cdot c_e^{van} \tag{42}$$

- Case 2.b: The objective function f_1 (Eq. 1), with constraints (2) – (39), minimizes the total costs of both echelons.

3. Numerical experiments

We implemented the proposed mathematical formulation for all cases in CPLEX 12.10 that uses an exact method as a solution approach. The proposed model was run with an Intel(R) Core (TM) i7-8550U CPU (1.80GHz) and 16GB of RAM. Firstly, we validated the proposed model on the same three sizes instances (5, 10, 15 customers) used by Keskin (2016) and updated by Goeke (2019) considering Case 1.a with the objective function f_2 (Eq. 40). The comparison with benchmark solutions as represented in Table 1, ensures the effectiveness of the results in which optimality was reached for most instances.

Table 1. Comparison of the EVRPTW-PR model with benchmark instances

Instances	EVRPTW-PR							Instances	EVRPTW-PR						
	Keskin (2016)			*Proposed model Obj. fun. f_2*					*Keskin (2016)*			*Proposed model Obj. fun. f_2*			
	w	*f*	*t(s)*	*w*	f_2	*t(s)*	Δf		*w*	*f*	*t(s)*	*w*	f_2	*t(s)*	Δf
C101-5	2	257.75	0.31	2	257.75	0.29	0.00	R201-10	1	241.51	11.40	1	241.51	18.59	0.00
C103-5	1	175.37	2.73	1	175.37	0.38	0.00	R203-10	1	218.21	1.62	1	218.21	1.28	0.00
C206-5	1	242.56	5.38	1	242.56	0.45	0.00	RC102-10	4	423.51	3.07	4	423.51	11.42	0.00
C208-5	1	158.48	1.37	1	158.48	0.11	0.00	RC108-10	3	345.93	2.90	3	345.93	13.83	0.00
R104-5	2	136.69	0.47	2	136.69	0.16	0.00	RC201-10	1	412.86	7200	1	412.86	7200	0.00
R105-5	2	156.08	3.39	2	156.08	0.24	0.00	RC205-10	2	325.98	3.26	2	325.98	1.33	0.00
R202-5	1	128.78	0.95	1	128.78	0.09	0.00	C103-15	3	348.46	1008.00	3	348.46	7200	0.00
R203-5	1	179.06	1.12	1	179.06	0.08	0.00	C106-15	3	275.13	0.47	3	275.13	4.56	0.00
RC105-5	2	233.77	3.06	2	233.83	4.66	0.06	C202-15	2	383.62	24.07	2	383.62	1457.61	0.00
RC108-5	2	253.93	3.76	2	253.93	0.53	0.00	C208-15	2	300.55	0.92	2	300.55	15.61	0.00
RC204-5	1	176.39	2.17	1	176.39	0.25	0.00	R102-15	5	412.78	7200	5	412.78	7200	0.00
RC208-5	1	167.98	1.05	1	167.98	0.20	0.00	R105-15	4	336.15	1.39	4	336.15	531.27	0.00
C101-10	3	388.25	50.26	3	388.25	845.36	0.00	R202-15	2	358.00	462.89	2	358.00	1678.48	0.00
C104-10	2	273.93	5.15	2	273.93	8.78	0.00	R209-15	1	313.24	610.64	1	313.24	1624.87	0.00
C202-10	1	304.06	7.52	1	304.06	3.92	0.00	RC103-15	4	397.67	20.27	4	397.67	1428.67	0.00
C205-10	2	228.28	2.01	2	228.28	0.66	0.00	RC108-15	3	370.25	101.45	3	370.25	7200	0.00
R102-10	3	249.19	1.83	3	249.19	648.25	0.00	RC202-15	2	394.39	113.43	2	394.39	7200	0.00
R103-10	2	206.12	6.76	2	206.12	189.06	0.00	RC204-15	1	403.38	7200.00	1	403.38	7200	0.00

Secondly, we compared Case 2.a (EVRPTW-PR), and Case 2.b (2E- EVRPTW-PR) in which we considered the e-van fleet for Case 2.a and e-vans and e-cargo bikes for Case 2.b since the goal of the proposed model was to introduce a novel green logistics solution for last-mile deliveries. Parameters and values used in objective functions f_1 and f_4 are proposed by Ploos van Amstel et al. (2018) and by Nocerino et al. (2016). In particular, the micro-depot cost c_m is set as 2.74 €/day. The other values are represented in Table 2.

Table 2. Parameters used in the objective functions $f_1$and f_4

Description	Parameter		Value	
	e-van	*e-cargo bike*	*e-van*	*e-cargo bike*
Vehicle's initial investment cost (€/day)	$c_v^{w^I}$	$c_v^{w^{II}}$	69.863	0.274
Driver's salary cost (€/day)	$c_d^{w^I}$	$c_d^{w^{II}}$	125	80
Electric energy cost (€/km)	$c_e^{w^I}$	$c_e^{w^{II}}$	0.0318	0.0006

We created new instances with 10 and 15 customers by modifying Goeke (2019) instances, named Colovic and Prencipe (2020), to ensure the optimal solution with reasonable computation time. Colovic and Prencipe (2020) instances test could lead to a solution in which realistic values related to the fuel consumption rate of vehicle h are high enough to ensure the deliveries to the customers without visiting recharging stations. Generated instances are available at the following URL: https://bit.ly/3feuMA8. We set the values of the parameter h to ensure the visit of at least one recharging station m according to the type of vehicle. Moreover, we set C^I, v^I , Q^I, and g^I for e-vans equal to 700 kg, 25 km/h, 40 kWh, and 4.44 kWh/h, respectively. Then, we set C^{II}, v^{II}, Q^{II}, and g^{II} for e-cargo bikes equal to 80 kg, 17 km/h, 40 kWh, and 4.44 kWh/h, respectively (see Nocerino et al., 2016). The Fuzzy C-mean clustering, proposed by Tilson et al. (1988), was applied to obtain two clusters of customers related to urban and restricted traffic zones. The Euclidian distances d_{ij}^I for Case 2.a and d_{ij}^{II} for Case 2.b, expressed in kilometers, was obtained dividing the initial instances by 30 in order to have more realistic urban and restricted traffic zones' distances. We calculated the coordinates of the transshipment point V_d^{II} as the half between the first and the second clusters' centroids. The time windows $[e_i^I, l_i^I]$ for Case 2.a and $[e_i^{II}, l_i^{II}]$, for Case 2.b expressed in hours, were obtained dividing initial instances by 200 in order to fit daily scheduling and driver's working hours. The service time s_i is adjusted according to the type of vehicle used in urban and restricted traffic zones. For Case 2.a, we obtained service time s_i^I dividing the initial service time s_i by 200 for e-vans entering in the urban zone, and by 100 for e-vans entering in the restricted traffic zone. In this case, we assumed higher time for serving customers in the restricted traffic zone due to difficulties for e-vans to access in narrow streets, pedestrian areas, unavailable parking spaces, etc. For Case 2.b, we obtained the service time s_i^{II} dividing the initial service time s_i by 200 for e-vans in the urban zone, and by 400 for e-cargo bikes in the restricted traffic zone. Additionally, these new instances have been used for the Case 1.a and the Case 1.b in order to provide optimal solutions as a benchmark for future comparisons. The comparison between results obtained from Case 2.a and Case 2.b is represented in Table 3.

Table 3. Comparison between EVRPTW-PR model and 2E-EVRPTW-PR model

Instances	EVRPTW-PR				Instances	2E-EVRPTW-PR					gap
	Case 2.a			*Case 1. a*		*Case 2. b*				*Case 1. b*	$\Delta f = f_1 - f_4$
	w^I *(e-van)*	f_4 *(€/day)*	*t(s)*	f_2 *(km)*		w^I *(e-van)*	w^{II} *(e-cargo bike)*	f_1 *(€/day)*	*t(s)*	f_3 *(km)*	***(€/day)***
1E-C101-10	2	390.15	11.00	13.49	2E-C101-10	2	1	473.01	2.75	12.72	82.86
1E-C104-10	2	390.01	2.72	8.72	2E-C104-10	1	1	278.02	0.16	9.18	-111.99
1E-R102-10	2	389.96	6.11	7.63	2E-R102-10	2	1	472.90	0.25	7.52	82.94
1E-R103-10	2	389.92	2.69	6.21	2E-R103-10	1	1	277.96	0.03	5.12	-111.96
1E-RC102-10	2	390.12	1.11	12.17	2E-RC102-10	1	1	278.15	0.16	13.34	-111.97
1E-RC108-10	2	390.07	1.14	10.77	2E-RC108-10	1	1	278.09	0.13	11.35	-111.98
1E-C103-15	3	584.95	37.85	11.23	2E-C103-15	1	2	358.34	4.91	12.37	-226.61
1E-C106-15	3	584.93	3.13	10.37	2E-C106-15	2	1	472.90	0.50	9.92	-112.03
1E-R102-15	4	779.83	212.95	11.92	2E-R102-15	2	2	553.22	8.06	11.52	-226.61
1E-R105-15	2	390.18	7200	14.28	2E-R105-15	1	2	358.33	1.36	11.34	-31.85
1E-RC103-15	2	390.08	7200	13.09	2E-RC103-15	1	1	278.19	147.59	14.01	-111.89
1E-RC108-15	2	390.06	92.44	10.69	1E-RC108-15	1	2	358.33	0.19	12.76	-31.73

Additionally, we provided solutions of Case 1.a and Case 1.b (minimization of the total distance) using proposed instances. According to the difference Δf between the objective functions f_1 and f_4, the proposed 2E- EVRPTW-PR model (Case 2.b) resulted in lower costs for most instances, as represented in Table 3. Results obtained from Case 2.b demonstrate the effectiveness of the proposed logistics solution in which the implementation of e-cargo bikes in restricted traffic zones results in the minimization of overall costs. The model performs better for instances with a higher number of customers. However, instances with 15 customers resulted in high computation time for Case 1.a, while the computation time for Case 1.b is significantly lower. Moreover, as shown for instances 1E-R105-15 and 1E-RC108-15, from an economic point of view, one e-van could be substitute by two e-cargo bikes with a cost reduction of about 31 $€/day$.

4. Conclusions

In this paper, we proposed a Two-Echelon Electric Vehicle Routing Problem with Time Windows and Partial Recharging (2E-EVRPTW-PR) model for last-mile urban deliveries, where the first echelon represents an urban zone, and the second echelon represents a restricted traffic zone (e.g., historical center). Therefore, e-vans and e-cargo bikes are used for customers' deliveries in the first and second echelon, respectively. We carried out a comparison between the EVRPTW-PR model (Case 2.a) and the 2E-EVRPTW-PR model (Case 2.b) to minimize the total costs related to travel costs, initial vehicles' investment costs, drivers' salary costs, and micro-depot cost. The comparison was tested on a new set of instances (Colovic and Prencipe, 2020). According to numerical application results, the proposed green logistics solution (Case 2.b) could benefit logistics companies with a higher number of daily requests. The results highlighted the advantage of using e-cargo bikes in restricted traffic zones considering the minimization of total costs. Additionally, we provided the benchmark instances solutions for the EVRPTW-PR model (Case 1.a) and the 2E-EVRPTW-PR model (Case 1.b), that minimize the total distance for city distribution. In future developments, we intend to propose a heuristic algorithm to solve the proposed model for large-size problems and to carry out a sensitivity analysis related to parameter settings and different types of vehicles.

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