Electric Vehicles Routing Including Smart-Charging Method and Energy Constraints*

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***Abstract* — This paper presents an optimization-based approach for the Electric Vehicle Routing Problem considering Smart-Charging methods. The objective, based on the application of the model, is to obtain the shortest route for each of the electric vehicles that have to deliver freight to a set of customers minimizing the charging/discharging cost. Based on the Smart-Charging method, in which vehicles can charge/discharge energy from/to the grid, the power grid limits, and balancing needs are considered. In this way, both the charging points and the energy districts are prevented from exceeding the maximum allowed energy peak. A real case study in the Apulia Italian region (Italy) shows the effectiveness of the proposed optimization model.**

I. Introduction

Recently, with the growth of new technologies and, above all, after the pandemic, home delivery has been increasing as well as the vehicles dedicated to these tasks. Considering the importance of climate change and the level of pollution, many companies dedicated to delivery services have chosen to add electric vehicles (EVs) to their fleet of vehicles [1]. For this reason, a better organization in terms of deliveries is essential, since the autonomy of EVs, for now, is lower than that of combustion engine vehicles. In addition, in EVs a greater amount of time must be spent for charging the battery [2].

The Electric Vehicle Routing Problem (EVRP) has become a problem of great importance in the world of logistics in order to introduce this type of vehicles that contribute to the improvement of climate change. The goal is to minimize the cost of the vehicle journey considering various aspects such as the vehicle's charging time, autonomy, travelled distance, and so on.

There are some basic assumptions to describe EVRP [3]. In the considered node network, there are three types of nodes: depot node, customer node and charging station node.

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Each customer node must be served by a single EV [4] and each charging station can be visited by more than one EV [5].

Within the EVRP type classifications [6], this problem can be classified in different ways depending on the type of charging method. It can be considered a problem in which the vehicle does not charge and therefore travels within its battery limit.

Considering the load of the vehicle, this can be full charging policy [7], in which the vehicle has a fully charged battery after visiting a charging point, or partial charging policy [8].

In this context, an important and innovative aspect is related to the possibility of charging and discharging energy on the network, known as the Smart-Charging method. By offering to the vehicles the possibility of discharging energy, a network balance is achieved that allows the energy peak not to be exceeded.

Several studies focus on Smart-Charging from different points of view. In [9] the authors consider a fleet of EVs with the possibility of recharging at two different charging points. One of them offers renewable energy at a low price and the other the possibility of downloading energy obtaining a reward. In [10], the authors adapt the previous study considering prices that vary over time. In [11] a model is proposed in which stored energy is managed from renewable sources. The authors in [12] presented the EVRP with time windows under time-variant electricity prices.

In addition, the work [13] proposes a two-stage simulation-based heuristic that in the first stage, determines the EV routes using expected waiting time at the stations while in the second stage corrects the infeasible solution by penalizing the time-window violations and late returns to the depot. The EVRP is solved with a multi-objective optimization in [14] where travel time and energy are optimized considering the impact of weather and traffic conditions. Furthermore, [15] studies the EVRP considering non-linear charging time. The author develops an algorithm to minimize the total travel and charging times without approximating the charging time function. The proposed approach is demonstrated to solve moderate-size problem. On the contrary, in [16] the authors propose three exact approaches to solve a polynomial-sized formulation and compare the results with a hybrid algorithm, obtained by applying the branch-and-cut approach. The simulation results show how the polynomial-sized problem allows to resolve instances having up to 30 customer nodes and 21 charging stations while the hybrid algorithm is effective up to 100 customer nodes and 21 charging stations.

In this paper the EVRP is addressed for logistics application and is implemented integrating smart charging strategies. Starting from the EVRP solved in [12], this paper addresses the problem of determining the EVs fleet routing in logistics application, considering both the customers and the power grid requirements. In the considered model the node network includes the customer nodes to be visited by the EVs and the charging stations. Each EV travels to satisfy the customer demand and can be charged or discharged at the charging points based on the EV charge level needs and the power grid requirements. Indeed, in a smart charging strategy, the EV will be charged when the State of Charge (SoC) is not sufficient to reach the next node and can be discharged if it is needed by the power grid.

The new contribution of the paper is to deal with a complex EVRP problem including the following features:

- the EVs have different characteristics such as energy capacities, charging rates, freight capacities;
- the customers are of different types with respect to delivery times, weighs of delivery loads;
- the charge/discharge scheduling of the EVs has time-variant electricity prices;
- the charging stations have a maximum value of energy that can provide in a time slot;
- the charging stations belong to different energy districts characterized by different maximum value of energy that the district can provide in a time slot.

Including all these aspects in the model makes the proposed problem very realistic and able to provide operational decisions to support commercial EV fleet operators to lower the overall energy cost.

In this paper, the EVRP is modeled as an Integer Linear Programming (ILP) problem aiming at minimizing the total travel distance and the charging/discharging cost.

A real case study is described to validate the proposed optimization model and to show the obtained promising results.

The paper is structured as follows. Section II describes the optimization model for solving the considered EVRP. In addition, Section III presents a real case study to validate the proposed model and Section IV provides the results. Finally, Section V reports the conclusions and future work perspectives.

II. Model Description

In this section, the EVRP is presented and modeled as an ILP problem.

The EVRP is a problem in which it is decided the optimal route of a fleet of EVs that leave a depot and must satisfy the demands of customers. Not only the optimal route is decided in terms of total distance traveled, but also the coupling between the EV and the customer. EVs belonging to the set $K = \{1, \dots, N_K\}$ depart with full cargo and the battery fully charged from the Depot Node (D). Each EV travels through different nodes arriving to the destination known a priori. The objective of the EV is to reach the destination by delivering the customers using the shortest route. During the travel, if it is necessary, the EV can charge or discharge the battery in one or more charging stations.

Another fundamental element of the problem is the set of Customer Nodes (CN) $N = \{1, \dots, N_N\}$ where each element represents the node in which EVs make the delivery.

EVs stop at Charging Points (CP) included in the set $S = \{1, \dots, N_S\}$ at the time they need to charge or discharge energy in the network. Each $CP \in S$ belongs to a district in the set $P = \{1, \dots, N_P\}$.

The problem can be considered as a schedule of the day in which time is divided into time slots that belong to the set $T = \{1, \dots, T\}$.

In detail, a graph represents a network of nodes $U = N \cup S \cup D$, where each node is a real point of the trip (see Figure 1). In the node network, we define one departure point (depot node), the customer nodes including the arrival point, and the charge/discharge points. The nodes are connected through bidirectional arcs in which the distance is considered as their weight. The objective is to route the EVs fleet to satisfy the customer demand while applying a smart charging strategy to manage the charging/discharging operations for the EV batteries during the trip. In the EVs fleet, each EV has a cargo capacity and is used to serve the customers and participate to the charging/discharging strategy. In particular, the charging/discharging method is applied to respect the power grid requirements, in term of power balancing and not overcoming the maximum allowed demand peak overtime.

More in detail, the power balancing problem is considered both at charge point level and at district level. At charge point level, it is necessary to respect the local power constraint. On the other hand, at district level, a subset of charging station nodes is considered in which it is necessary to respect the district power constraints. To this purpose, the optimization model can decide the best strategy to charge or discharge an EV during the trip, always guaranteeing the necessary autonomy to complete journey.

In the proposed connected graph, the weight of each arc linking a node pair represents the real distance between two nodes in kilometers.

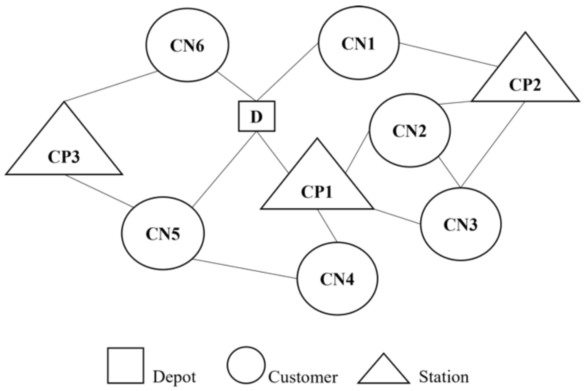

Figure 1. Example of nodes network

A. The EVRP Model

In this section the EVRP formalized by describing first the used sets, parameters and decision variables and then formalizing the ILP problem.

The considered sets are the following:

$N = \{1, \dots, N_N\}$	Set of customer nodes
$S = \{N_N + 1, \dots, N_S\}$	Set of charging station nodes
$D = \{0\}$	Depot node
$T = \{1, \dots, N_T\}$	Set of time slots
$K = \{1, \dots, N_K\}$	Set of EVs
$P = \{1, \dots, N_P\}$	Set of districts
$U = D \cup N \cup S$	Set of nodes

The paraments of the ILP are:

$td_{ij} \in \mathbb{R}^+$	travel distance from node i to node j, $i, j \in U$ [km]
$tt_{ij} \in \mathbb{R}^+$	travel time from node i to node j, $i, j \in U$ [h]
$Q_k \in \mathbb{R}^+$	battery capacity of EV $k \in K$ [kWh]
$e_i \in \mathbb{R}^+$	earliest time to start service allowed at node $i \in U$ [time slot]
$l_i \in \mathbb{R}^+$	latest time to start service allowed at node $i \in U$ [time slot]
$C_k \in \mathbb{R}^+$	weight capacity of EV $k \in K$ [kg]
$g_k \in \mathbb{R}^+$	recharging rate of EV $k \in K$ [kW]
$q_i \in \mathbb{R}^+$	weight load of customer $i \in N \cup S. q_{i \in S} = 0$ [kg]
$s_i \in \mathbb{R}^+$	time required by the customer for delivery at the node $i \in N$ [h]
$\delta \in \mathbb{R}^+$	time slot duration [h]
$B_k \in \mathbb{R}^+$	amount of time to fully charge EV $k \in K$ [h]
$pr_t \in \mathbb{R}^+$	unit electricity buying price during time slot $t \in T$ [€]
$pd_t \in \mathbb{R}^+$	unit electricity selling price during time slot $t \in T$ [€]
$end_k \in U$	end node of EV $k \in K$
$c_{kij} \in \mathbb{R}^+$	energy consumption of EV $k \in K$ from node i to node j with $i, j \in U$ [kW]
$f_{kij} \in \mathbb{R}^+$	amount of time the EV $k \in K$ spends when travels from node i to node j with $i, j \in U$ [h]
$Pre_{kt} \in \mathbb{R}^+$	cost of charging EV $k \in K$ during time slot $t \in T$ [€]
$Pdis_{kt} \in \mathbb{R}^+$	cost of discharging EV $k \in K$ during time slot $t \in T$ [€]
$P\delta_i \in \mathbb{R}^+$	power of the charging station $i \in S$ [kW]
$emax_i \in \mathbb{R}^+$	maximum energy that the charging station $i \in S$ can provide in each time slot [kWh]
$emax\_d_p \in \mathbb{R}^+$	maximum energy that district $p \in P$ can provide [kWh]
$district_{pi} \in \{0,1\}$	if charging station $i \in S$ belongs to district $p \in P$ then $district_{pi} = 1$ otherwise $district_{pi} = 0$

The decision variables are the following:

$x_{ij}^k \in \{0,1\}$	if EV $k \in K$ travels from node i to node j $(td_{ij} > 0)$ then $x_{ij}^k = 1$ otherwise $x_{ij}^k = 0$, with $i, j \in U$
$\tau_{ki} \in \mathbb{R}^+$	arrival time of EV $k \in K$ at node $i \in U$ [h]
$r_{itk} \in \{0,1\}$	$r_{itk} = 1$ if EV $k \in K$ charges its battery at node $i \in U$ at time slot $t \in T$; $r_{itk} = 0$ otherwise.
$d_{itk} \in \{0,1\}$	$d_{itk} = 1$ if EV $k \in K$ discharges its battery at node $i \in U$ at time slot $t \in T$; otherwise $d_{itk} = 0$.
$u_{ki} \in \mathbb{R}^+ \cup \{0\}$	remaining cargo in EV $k \in K$ upon arrival to node $i \in U$ [kg]
$b_{ki} \in \mathbb{R}^+$	residual SoC (autonomy) in terms of time in EV $k \in K$ upon arrival to node $i \in U$ [h]

The EVRP objective function is composed of two parts. The first part aims at minimizing the journey of each EVs so that they can reach their destination using the shortest route and satisfying the needs of customers. The second part minimizes the total cost of the trip of each EV. The objective function is the following:

$$f(x_{ij}^k, r_{itk}, d_{itk}) = \sum_{i \in U} \sum_{j \in N \cup S} \sum_{k \in K} td_{ij} \cdot x_{ij}^k + \\ + \sum_{k \in K} \sum_{i \in S} \sum_{t \in T} \delta \cdot \left((r_{itk} \cdot Pre_{kt}) - (d_{itk} \cdot Pdis_{kt}) \right) \tag{1}$$

The problem is defined as follows:

$$\min_{x_{ij}^k, r_{itk}, d_{itk}} f(x_{ij}^k, r_{itk}, d_{itk})$$

s.t.

$$\sum_{k\in K}\sum_{j\in N\cup S} x_{ij}^k = 1 \qquad \forall i \in N,\ i,j \neq end_k,\ i \neq j,\ tt_{ij} > 0 \tag{2}$$

$$\sum_{j\in N\cup S} x_{0j}^k = 1 \qquad \forall k \in K,\ j \neq end_k,\ tt_{0j} > 0 \tag{3}$$

$$\sum_{i\in N\cup S} x_{i,end_k}^k = 1 \qquad \forall k \in K,\ i \neq end_k,\ tt_{iend_k} > 0 \tag{4}$$

$$\sum_{i\in D\cup N\cup S} x_{ij}^k = \sum_{i\in N\cup S} x_{ji}^k \qquad \forall j \in N \cup S,\ i,j \neq end_k,\ i \neq j\ \forall k \in K \tag{5}$$

$$\sum_{i\in N\cup S}\sum_{j\in N\cup S} q_i \cdot x_{ij}^k \leq C_k \qquad \forall k \in K,\ tt_{ij} > 0 \tag{6}$$

$$\tau_{kj} \geq \tau_{ki} + \left(\left(tt_{ij} + s_i\right) \cdot x_{ij}^k\right) - M \cdot \left(1 - x_{ij}^k\right) \qquad \forall i \in N,\ \forall j \in N \cup S,\ \forall k \in K,\ td_{ij} > 0 \tag{7}$$

$$\tau_{kj} \geq \left(\begin{matrix}\delta \cdot t \cdot \\ (r_{itk} + d_{itk}) \cdot x_{ij}^k\end{matrix}\right) + \left(tt_{ij} \cdot x_{ij}^k\right) - M \cdot \left(1 - x_{ij}^k\right) \qquad \forall i \in S,\ \forall j \in N \cup S,\ \forall t \in T,\ \forall k \in K,\ td_{ij} > 0 \tag{8}$$

$$e_i \leq \tau_{ki} \leq l_i \qquad \forall i \in U,\ \forall k \in K \tag{9}$$

$$r_{itk} + d_{itk} \leq 1 \qquad \forall i \in S,\ \forall t \in T,\ \forall k \in K \tag{10}$$

$$\tau_{ki} - (t-1) \cdot \delta \leq M \cdot (1 - d_{itk} - r_{itk}) \qquad \forall i \in S,\ \forall t \in T,\ \forall k \in K \tag{11}$$

$$u_{kj} \leq u_{ki} - \left(q_j \cdot x_{ij}^k\right) + M \cdot \left(1 - x_{ij}^k\right) \qquad \forall i,j \in N \cup S,\ \forall k \in K,\ td_{ij} > 0 \tag{12}$$

$$u_{k0} \leq C_k \qquad \forall k \in K \tag{13}$$

$$b_{ki} = B_k \qquad \forall k \in K,\ i = 0 \tag{14}$$

$$b_{kj} \leq b_{ki} - \left(f_{kij} \cdot x_{ij}^k\right) + M \cdot \left(1 - x_{ij}^k\right) \qquad \forall k \in K,\ \forall j \in N \cup S,\ td_{ij} > 0 \tag{15}$$

$$b_{kj} \leq b_{ki} + \sum_{t\in T} \delta \cdot r_{itk} - \sum_{t\in T} \delta \cdot d_{itk} - \left(f_{kij} \cdot x_{ij}^k\right) + M \cdot \left(1 - x_{ij}^k\right) \qquad \forall k \in K,\ \forall i \in S,\ \forall j \in N \cup S \tag{16}$$

$$\sum_{t\in T} \delta \cdot r_{itk} \leq B_k - b_{ki} \qquad \forall k \in K,\ \forall i \in S \tag{17}$$

$$\sum_{t\in T} \delta \cdot d_{itk} \leq b_{ki} \leq B_k \qquad \forall k \in K,\ \forall i \in S \tag{18}$$

$$0 \leq b_{ki} \qquad \forall k \in K,\ \forall i \in N \cup S \tag{19}$$

$$b_{kj} \leq B_k \cdot \sum_{i\in D\cup N\cup S} x_{ij}^k \qquad \forall k \in K,\ \forall j \in N \cup S \tag{20}$$

$$\sum_{k\in K} P\delta_i \cdot (r_{itk} - d_{itk}) \leq emax_i \qquad \forall i \in S,\ \forall t \in T \tag{21}$$

$$\sum_{k\in K} P\delta_i \cdot (r_{itk} - d_{itk}) \cdot district_{pi} \leq emax\_d_p \qquad \forall i \in S,\ \forall t \in T,\ \forall p \in P \tag{22}$$

Constraints (2) handle the connectivity of customer nodes and charging stations. Constraints (3) and (4) ensure that EVs follow only one route plan ending at the arrival node. Equation (5) controls the flow of EVs.

By equation (6) the model ensures that EVs do not exceed their cargo capacity. Constraints (7) and (8) handle the EV travel time among each node pair and constraints (8) consider the charging/discharging time.

By equation (9) the model makes sure that the time windows of the nodes are respected. Equation (10) controls the charging and discharging battery of the vehicle in the node, allowing only one of the two actions to be carried out in the specific instant.

Constraint (11) guarantees that the charging or discharging of the EV battery does not start before its arrival at the charging station. Equation (12) makes sure that the demands of all customers are satisfied.

Constraint (13) Indicates that the vehicles, before starting the route, cannot exceed the maximum cargo and constraint (14) indicates that all EVs are fully charged before starting the travel.

Constraints (15) and (16) track the battery level at customer and charging stations nodes. Constraint (17) guarantees that EV does not exceed battery charge level. And constraint (18) ensures that the battery of the EV is not discharged to a level below 0. Constraints (19) and (20) controls the limit of EVs energy.

Finally, equations (21) and (22) balance the network to avoid exceeding the maximum energy peak. In the case of equation (21), the charging station is not allowed to exceed the maximum peak energy, while in equation (22), the district is not allowed to exceed the maximum peak energy.

III. Case Study

A. The system description

This section presents a real case study describing a network of nodes in the Apulia region, in Southern Italy.

The node network shown in **Errore. L'origine riferimento non è stata trovata.** is composed of a Depot Node (from where all the EVs depart), N_N = 15 customer nodes of set $N = \{CN1, \ldots\ldots CN15\}$ and $N_S = 5$ charging station nodes for EVs of set $S = \{CP1, \ldots CP5\}$.

The EVs start their route at the Depot Node and visit the nodes of *N* and *S* to reach the destination node, which belongs to one of the customer nodes, minimizing the total traveled distance.

TABLE I. DISTANCE BETWEEN THE CONNECTED NODES

	td_{ij} [km]					
CN1	***CN7***	***CN13***				
	22	59				
CN2	***DEPOT***	***CN5***	***CP2***			
	38	49	21			
CN3	***DEPOT***	***CP3***	***CP4***			
	72	63	48			
CN4	***CN14***	***CP3***				
	29	31				
CN5	***CN2***	***CN14***	***CP2***			
	49	27	53			
CN6	***CN12***	***CP4***	***CP5***			
	51	19	63			
CN7	***DEPOT***	***CN1***	***CP2***			
	64	22	38			
CN8	***DEPOT***	***CN9***				
	59	53				
CN9	***CN8***	***CN15***				
	53	32				
CN10	***DEPOT***	***CP4***	***CP5***			
	41	67	21			
CN11	***DEPOT***	***CN13***	***CP1***			
	61	97	51			
CN12	***CN6***	***CP3***	***CP4***			
	51	38	59			
CN13	***DEPOT***	***CN1***	***CN11***	***CP1***		
	103	59	97	73		
CN14	***CN4***	***CN5***				
	29	27				
CN15	***CN9***	***CP1***	***CP5***			
	32	66	73			
CP1	***CN11***	***CN13***	***CN15***			
	51	73	66			
CP2	***CN2***	***CN5***	***CN7***			
	21	53	38			
CP3	***CN3***	***CN4***	***CN12***	***CP4***		
	63	31	38	68		
CP4	***DEPOT***	***CN3***	***CN6***	***CN10***	***CN12***	***CP3***
	73	48	19	67	59	68
CP5	***DEPOT***	***CN6***	***CN10***	***CN15***		
	51	63	21	73		

Table I shows the distance [km] between the connected pair of nodes. It is important to note that the arcs that link a pair of nodes are considered bidirectional arcs.

Based on the electric power grid configuration, two districts are considered, i.e., $P = \{1,2\}$. The charging station nodes *CP1* and *CP2* belong to district 1 and *CP3*, *CP4* and *CP5* belongs to district 2.

In this network, the EVs fleet is the set $K = \{EV1, \ldots, EV7\}$ composed of N_K=7 vehicles that have to satisfy the customers' requests. The problem considers a heterogeneous fleet of EVs, which means that each EV has different characteristics. Table II shows the EVs data. However, all the 7 EVs considered in the network have the same average speed of 100 km/h.

TABLE II. ELECTRIC VEHICLES DATA

	Electric Vehicles						
	EV1	***EV2***	***EV3***	***EV4***	***EV5***	***EV6***	***EV7***
Q_k	58	100	80	52	52	60	100
B_k	3.8	5.5	4.4	2	3.4	3.3	8.3
C_k	300	350	400	250	450	600	300
g_k	43	22	22	22	43	22	43
end_k	CN1	CN15	CN6	CN12	CN4	CN14	CN7

Considering a time horizon of 12 hours and time slots of 20 minutes, the model is developed contemplating 36 time slots, three per hour. For each of them there is a recharging and discharging battery price. Both the customer nodes and the charging stations have an earliest and latest time to start the service allowed.

The customers node also provided information about the amount demand and the time that service requires at node.

IV. The EVRP Model Results

This section presents the results obtained by applying the proposed EVRP model that is implemented by Cplex with a CPU Intel I7 3.4 GHz and a RAM of 16GB and the solution is found in few minutes.

Table III shows the nodes of the EV optimal path and the total travel distance.

TABLE III. ELECTRIC VEHICLES OPTIMAL PATHS

EV	**Intermediate nodes**	end_k	**Total travel distance [km]**
EV1	CN7	CN1	86
EV2	CN10 – CP5	CN15	135
EV3	CP4	CN6	92
EV4	CN3 – CP3	CN12	173
EV5	CN2 – CN5 – CN14	CN4	143
EV6	CP4 – CN6 – CN12 – CP3 – CN4	CN14	241
EV7	CN8 – CN9 – CN15 – CP1 – CN11 – CN13 – CN1	CN7	393

To reach their destination, the EVs, leaving from the Depot Node, follow different paths in which they make deliveries to the CNs and, if necessary, charge or discharge energy at the CPs, considering the time-variant electricity prices and respecting the peaks of both the column and the district.

Analyzing the obtained results in terms of smart charging it is important to highlight EV4 and EV6 solutions. The EV4 discharges energy into CP3, the same column used by the EV6 for charging the battery. This allows the CP3 not to exceed the imposed energy peak.

The EV6, due to its route (see Figure 2), needs to charge twice in two different charging points, both belonging to the same district. In order not to exceed the energy peak of District 2, since the EV2 has a high battery capacity, it discharges energy into CP5 so that EV6 can charge the battery at CP4.

Figure 2. EV6 optimal path

V. Conclusion and Future Research

In this paper, an optimization model focused on the Electric Vehicle Routing Problem considering a Smart-Charging method is presented. The main objective is to minimize the travel distance of each of the EVs that belong to a vehicle fleet that must deliver freight to customers and to charge/discharge EV batteries without exceeding the imposed energy peak.

A case study shows that the model provides the optimal timetable for a fleet of EVs traveling through a network of nodes in the Apulia region, in Italy. It results that there are both charging and discharging operations. In this way, the balance of the network is maintained, and the maximum peak established at charging point level and district level (to which one or more charging points belong) is not exceeded.

For future research there are some open issues to be investigated. The Pareto front can be studied considering that the model has a multi-objective function. The reservation of the charging points could be added to the problem. In this way, the calculation of the route would be based on the charging point availability and would give the possibility of adding vehicles not belonging to the fleet.

In addition, both non-electric vehicles and private electric vehicles can be added to delivery vehicles.

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