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Modeling and Solving the Electric Vehicle Routing Problem with V2G Operation Planning

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ABSTRACT

This article proposes a route definition strategy for electric vehicles (EV) with V2G (vehicle-to-grid) technology based on a mixed integer linear programming (MILP) model. Considering the intelligent recharging system from V2G, the proposed PLIM model minimizes the costs of delivering products to consumers using routes with less energy purchased. In addition to the mandatory passage at delivery points, the model also considers stopping at recharging stations to fill up the vehicle or provide ancillary services to the local distribution network, such as importing (purchasing) and exporting (selling) energy. With this, operational costs can be reduced with the energy credits obtained during the recharge procedures. The case study uses a synthetic scenario considering a fleet with multiple V2G, serving a region with twelve consumers and four charging stations. The results show that the strategy defines the best delivery routes while using the stations to perform smart recharges and minimizes fleet operating costs.

KEYWORDS. Charging stations, electric vehicles, vehicle-to-grid, routing problems.

RESUMO

Este artigo propõe uma estratégia de definição de rotas para veículos elétricos (VE) com tecnologia V2G (do inglês, *vehicle-to-grid*), a partir de um modelo de programação linear inteira mista (PLIM). Considerando o sistema de recarga inteligente de um V2G, o modelo PLIM proposto minimiza os custos de entrega dos produtos aos consumidores utilizando as rotas com menor quantidade de energia comprada. Além da passagem obrigatória nos pontos de entrega, o modelo também avalia a parada em estações de recarga para abastecer o veículo ou prestar serviços ancilares a rede de distribuição local, como a importação (compra) e exportação (venda) de energia. Com isto, os custos operacionais podem ser reduzidos com os créditos de energia obtidos durante os procedimentos de recarga. O estudo de caso utiliza um cenário sintético considerando uma frota com múltiplos V2G, que atendem a uma região com doze consumidores e quatro estações de recarga. Os resultados mostram que a estratégia define as melhores rotas de entrega, enquanto utiliza as estações para realizar recargas inteligentes e minimiza os custos operacionais da frota.

KEYWORDS. Estações de carregamento, veículos elétricos, V2G, problema de roteamento.

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1. Introduction

Humanity's understanding of environmental protection, energy conservation, and emission reduction has changed in recent years, leading to an increasing trend of using electric vehicles (EVs) instead of fuel-powered vehicles yearly. Optimizing vehicle routing is essential for any supply chain in the freight transportation sector as it reduces logistics-related costs [Zhang et al., 2018b]. The standard Vehicle Routing Problem (VRP) [Dantzig e Ramser, 1959] aims to find the ideal set of routes to meet the demand for products of several customers, starting and ending at the depot. At present, multiple variations and applications of VRP attempt to approach real-life scenarios or fulfill specific needs. Some of the most well-known variations of VRP include vehicle carrying capacitated, time windows (it satisfies time constraints for visiting each client), and in recent years, EVs have been used to support the mitigation of climate changes [Zhang et al., 2022]. The Electric Vehicle Routing Problem (EVRP) is examined in this paper.

EVs are considered sustainable transport facilities for goods distribution, but they have significant challenges to face, such as initial investment, limitations in battery capacity, long waiting times for battery recharging, and an insufficient number of charging stations [Pelletier et al., 2019]. Several tailor-made solutions can be found in the literature to optimize EVRP while considering battery limitations. Zhang et al. [2018a] developed a mathematical formulation for EVRP that considers reducing vehicle energy consumption. Numerical experiments based on the ant colony metaheuristic satisfactorily solved instances of the model proposed. In addition to battery limitations, Zhang et al. [2018b] incorporated optional battery charging stations (and partial charging) on the EV routing and presented a mathematical model to minimize the total cost. Froger et al. [2022] proposed and solved an EVRP model considering the number of EVs simultaneously recharged at the charging station as a capacity constraint. Computational experiments based on local search algorithms solved the proposed model.

In an attempt to address real cases where vehicles need to deliver orders to each customer within known time windows, the EVRP with time windows is developed. The authors in Roberti e Wen [2016] study the EVRP with time windows by proposing a mixed-integer linear formulation. They solved instances with 20 customers in quick computation times using a three-phase heuristic algorithm based on variable neighborhood search and dynamic programming. Hiermann et al. [2016] presented EVRP with time windows, heterogeneous transport fleets, battery size, and acquisition cost. To solve the problem, they used the branch-and-price method and proposed a hybrid heuristic that combines adaptive large neighborhood search with local search. Schiffer e Walther [2017] proposed an approach for EV routing incorporating decisions on the placement of charging stations. In the mathematical formulation, they considered minimizing the number of charging stations and the required number of EVs in addition to the distance traveled.

In recent decades, the demand for electrical energy has increased due to the growth of emerging economies, and technological advancements bring a set of challenges regarding energy consumption, which needs to be increasingly efficient to improve energy quality and network reliability. Nowadays, debating electrical energy demand without mentioning EVs is inevitable. In 2021, 5.6 million EVs were sold worldwide, representing an increase of 83% compared to 2020. Therefore, EVs should have a significant impact on distribution networks. To reduce the impact of EVs on electric grids, charging strategies are implemented to encourage users to recharge their EVs during times of lower energy demand and at charging stations with higher capacity. Furthermore, by applying vehicle-to-grid (V2G) technology, it is possible to return unused energy from EVs to the electric grid during peak demand periods [Tan et al., 2016].

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Some approaches integrating the EVRP and distribution networks appear in the literature. Ustun et al. [2013] defined the role of EVs as distributed storage devices and used the IEC-61850 universal communication standard to implement the plug-and-play concept in distribution networks. Singh e Tiwari [2020] investigated scheduling strategies for EVs with a cost-benefit analysis to achieve an optimal planning scheme. To minimize system losses, the authors addressed two scheduling strategies considering the dispatch of active and reactive power of EVs; the EVRP has also been studied considering the V2G technology. Abdulaal et al. [2016] incorporated V2G service options for EVRP, including a stochastic environment, multiple dispatchers, time windows, and simultaneous pickup and delivery. The results unveiled routes for EVs satisfying the constraints and providing ancillary grid services. Narayanan et al. [2022] considered EVRP with load capacity constraints, opportunity windows, and V2G power supply. The reinforcement learning technique was applied to solve the problem and compared with exact formulations based on metaheuristics and mixed-integer programming.

The central aspect of this contribution is developing a mathematical formulation and providing solutions to the integrated problem of EVRP with V2G technology, considering the scheduling of EV recharges for multiple vehicles, time windows, and vehicle capacity. Additionally, recharging and discharging the EV at the charging stations is flexible, as it can switch between the battery recharging and discharging functionality, considering the peak time and minimizing the total cost. Using the CPLEX solver in version 22.1.1 and the Python language, the model was tested by solving a synthetic instance in a laptop with CPU Intel(R) Core(TM) i5-8300H 2.3GHz e 8GB RAM. The numerical experiments achieved the optimal solution that concerns defining each vehicle route, visiting the customers, and optionally, the charging stations while satisfying the time windows, battery capacity, vehicle capacity, demand for products, and returning to the depot.

2. Mathematical modeling

2.1. Problem description

A mathematical model is proposed in this paper to integrate the EVRP with service options for distribution networks. The structure of the mathematical models proposed by Kucukoglu et al. [2021] is the main motivation. Additional constraints related to the use of V2G technology are incorporated into the model, including the ability to sell energy to the electrical grid) and varying recharge and discharge costs during peak time.

The studied problem consists of finding the routes for a fleet of electric vehicles, satisfying the demand of customers that must be served within a time window associated with a time interval $[e_i, l_i]$. The service (delivery) for each customer must start within the associated time window, and this service has a duration time s_i, during which the vehicle remains at the customer's location delivering the product. The time window to the depot is set as the total time for the vehicle to complete the route. The vehicles have a maximum capacity of products to carry, expressed in a unit of weight. Each vehicle leaves the depot with the battery charged at 100% and the recharge (or discharge to sell stored energy) occurs at any time only at charging station. Multiple vehicles can recharge or discharge at the same time at the charging station. The energy price is more expensive at peak times, but while it is mandatory to visit the customers, the visit to the charging stations is optional. The vehicle's battery can be partially or fully charged. The vehicles can also return stored energy to the grid to generate profit. Note that is advantageous to sell stored energy at the peak times.

2.2. Mathematical formulation

The following notations and input parameters are defined for the model.

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Sets and Parameters:

D	depot; $D := \{0\}$.
C	set of customers; $C := \{1,\ldots,nc\}$ and nc is the number of customers.
E	set of charging stations; $E := \{nc+1, nc+ne\}$ and ne is the number of charging stations.
K	set of vehicles; $K := \{1,\ldots,nv\}$; nv is the number of vehicles.
V	set of all customers, charging stations, end the depot; $V := D \cup C \cup E$.
DC	set of all customers and the depot; $DC := D \cup C$.
DE	set of all charging stations and the depot; $DE := D \cup E$.
CE	set of all customers and charging stations; $CE := C \cup E$.
n	peak times index; $n := \{0,1,2\}$, zero and two indicate outside and one inside the peak times.
r	energy purchase index; $r := \{0,1\}$, zero and one indicate the energy purchase and sale, respectively.
CI	purchase cost per unit of energy at the normal time.
CO	profit from sales per unit of energy at the normal time.
CIp	purchase cost per unit of energy at peak time.
COp	profit from sales per unit of energy at peak time.
RIO_r	energy recharge/discharge rate (s/kWh).
Q	battery capacity (kWh).
H	energy consumed per unit of distance.
d_{ij}	distance between node i and j.
t_{ij}	displacement time between node i and j.
e_i	the earliest time to start service on node i.
l_i	the later time to start service on node i; l_0 refers to the maximum time to return to the depot.
s_i	service time at the node i.
$G1_i$	start of peak time at the station i.
$G2_i$	end of peak time at station i.
qV	maximum load capacity (Kg) of the vehicle.
qC_i	customer demand i.

Decision variables:

x_{ij}^k	binary variable; x_{ij}^k=1 if the vehicle k travels from i to j, otherwise x_{ij}^k=0.
w_i^k	binary variable; w_i^k=1 if vehicle k arrives to the station i, otherwise w_i^k=0.
IP_{irn}^k	binary variable; IP_{ir}^k=1 if vehicle k recharges/discharges at the station i inside or outside the peak times, otherwise IP_{ir}^k=0.
y_i^k	battery level of vehicle k when arriving to node i.
Y_i^k	battery level of vehicle k before exiting node i.
p_i^k	starting time of vehicle k for customer service i.
WI_i^k	recharge quantity of vehicle k at the station i.
WO_i^k	discharge quantity of vehicle k at the station i.
z_{rin}^k	starting time for recharge/discharge of vehicle k at station i.
T_{rin}^k	time spent for recharge/discharge of vehicle k at station i.

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Mathematical formulation:

Minimizar
$$\sum_{i\in E}\sum_{k\in K}(T^k_{0i0}\cdot CI + T^k_{0i1}\cdot CIp + T^k_{0i2}\cdot CI)\cdot(1/RIO_0) - \sum_{i\in E}\sum_{k\in K}(T^k_{1i0}\cdot CO + T^k_{1i1}\cdot COp + T^k_{1i2}\cdot CO)\cdot(1/RIO_1) \quad (1)$$

Sujeito a
$$\sum_{j\in CE}\sum_{k\in K} x^k_{0j} = \sum_{i\in CE}\sum_{k\in K} x^k_{i0} \quad (2)$$
$$x^k_{ij} \le \sum_{j\in CE} x^k_{0j}, \quad i\in CE, \quad j\in CE, \quad k\in K \quad (3)$$
$$\sum_{\substack{i\in V\\ i\neq j}}\sum_{k\in K} x^k_{ij} = 1, \quad j\in C \quad (4)$$
$$\sum_{j\in V} x^k_{0j} \le 1, \quad k\in K \quad (5)$$
$$\sum_{\substack{i\in V\\ i\neq j}} x^k_{ij} = \sum_{\substack{i\in V\\ i\neq j}} x^k_{ji}, \quad j\in V, \quad k\in K \quad (6)$$
$$\sum_{i\in V}\sum_{j\in C} qC_j\cdot x^k_{ij} \le qV, \quad k\in K \quad (7)$$
$$p^k_i + s_i + (x^k_{ij}\cdot t_{ij}) \le p^k_j + (1-x^k_{ij})\cdot l_0, \quad i\in DC, \quad j\in V, \quad k\in K, \quad i\neq j \quad (8)$$
$$p^k_i + WO^k_i\cdot RIO_1 + WI^k_i\cdot RIO_0 + (x^k_{ij}\cdot t_{ij}) \le p^k_j + +(1-x^k_{ij})\cdot(l_0 + RIO_0\cdot Q), \quad i\in E, \quad j\in CE, \quad k\in K \quad (9)$$
$$p^k_i + s_i + (x^k_{i0}\cdot t_{i0}) \le l_0, \quad i\in C, \quad k\in K \quad (10)$$
$$p^k_i + WO^k_i\cdot RIO_1 + WI^k_i\cdot RIO_0 + (x^k_{i0}\cdot t_{i0}) \le l_0, \quad i\in E, \quad k\in K \quad (11)$$
$$e_i \le p^k_i \le l_i, \quad i\in DC, \quad k\in K \quad (12)$$
$$y^k_i + WI^k_i - WO^k_i = Y^k_i, \quad i\in E, \quad k\in K \quad (13)$$
$$x^k_{ij}\cdot d_{ij}\cdot H \le Y^k_i - y^k_j + (1-x^k_{ij})\cdot Q, \quad i\in V, \quad j\in V, \quad k\in K, \quad i\neq j \quad (14)$$
$$\sum_{\substack{i\in V\\ i\neq j}}\sum_{j\in V} x^k_{ij}\cdot d_{ij}\cdot H + \sum_{i\in E}(WO^k_i - WI^k_i) = Y^k_0 - y^k_0, \quad k\in K \quad (15)$$
$$w^k_i \ge (WI^k_i + WO^k_i)/2Q, \quad i\in E, \quad k\in K \quad (16)$$
$$w^k_j = \sum_{\substack{i\in V\\ i\neq j}} x^k_{ij}, \quad j\in E, \quad k\in K \quad (17)$$
$$Y^k_0 = Q, \quad k\in K \quad (18)$$
$$Y^k_i = y^k_i, \quad i\in C, \quad k\in K \quad (19)$$
$$T^k_{0in}/RIO_0 \le Q, \quad i\in E, \quad k\in K, \quad n\in N \quad (20)$$
$$T^k_{1in}/RIO_1 \le Q, \quad i\in E, \quad k\in K, \quad n\in N \quad (21)$$
$$IP^k_{irn} \ge T^k_{ri1}/(RIO_r\cdot Q), \quad j\in E, \quad k\in K, \quad r\in R, \quad n\in N \quad (22)$$

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$$T^k_{0j0} + T^k_{0j1} + T^k_{0j2} = WI^k_j \cdot RIO_0, \quad j \in E, \quad k \in K \tag{23}$$
$$T^k_{1j0} + T^k_{1j1} + T^k_{1j2} = WO^k_j \cdot RIO_1, \quad j \in E, \quad k \in K \tag{24}$$
$$z^k_{0j0} = p^k_j, \quad j \in E, \quad k \in K \tag{25}$$
$$z^k_{rjn} = z^k_{r'j(n+r-1)} + T^k_{r'j(n+r-1)}, \quad j \in E, \ k \in K, \ n \in N, \ r \in R, \ r' \in R, \ r \neq r' \tag{26}$$
$$z^k_{ri0} + T^k_{ri0} \leq G1 + (1 - IP^k_{ir0}) \cdot l_0, \quad i \in E, \quad k \in K, \quad r \in R \tag{27}$$
$$z^k_{ri1} \geq G1 - (1 - IP^k_{ikr1}) \cdot l_0, \quad i \in E, \quad k \in K, \quad r \in R \tag{28}$$
$$z^k_{ri1} + T^k_{ri1} \leq G2 + (1 - IP^k_{ikr1}) \cdot l_0, \quad i \in E, \quad k \in K, \quad r \in R \tag{29}$$
$$z^k_{ri2} \geq G2 - (1 - IP^k_{ikr2}) \cdot l_0, \quad i \in E, \quad k \in K, \quad r \in R \tag{30}$$
$$x^k_{ij} \in \{0,1\}, \quad i \in V, \quad j \in V, \quad k \in K \tag{31}$$
$$w^k_i \in \{0,1\}, \quad i \in E, \quad k \in K \tag{32}$$
$$IP^k_{ir} \in \{0,1\}, \quad i \in E, \quad k \in K, \quad r \in R, \quad n \in N \tag{33}$$
$$y^k_i, Y^k_i, p^k_i \geq 0, \quad i \in V, \quad k \in K \tag{34}$$
$$WI^k_i, WO^k_i \geq 0, \quad i \in E, \quad k \in K \tag{35}$$
$$z^k_{rin}, T^k_{rin} \geq 0, \quad i \in E, \quad k \in K, \quad r \in R, \quad n \in N. \tag{36}$$

The objective function (1) minimizes the difference between the total energy cost (purchasing) required to complete the routes and the profit from selling energy to the electrical grid. Constraints (2) and (3) ensure that all vehicles depart from the depot and return at the end of the route. Constraint (4) guarantees that each customer is serviced by one vehicle. Constraint (5) ensures that each vehicle is assigned only one route. Constraint (6) relates to flow, stating that each vehicle entering node i must exit. Constraint (7) prevents exceeding the vehicle's load capacity (Kg). Constraints (8), (9), (10), (11) and (12) ensure the feasibility of time windows and prevent the creation of sub-routes. Constraint (8) provides that the service time at each customer is not exceeded, constraint (9) ensures the feasibility of charging/discharging times at the charging stations, constraints (10) and (11) guarantee that the vehicle returns to the depot within the maximum arrival time, and constraint (12) ensures that customers are serviced within their time window. Constraint (13) provides the feasibility of the battery level for each vehicle at the charging station. Constraints (14) and (15) track each vehicle's battery level and energy consumption. Constraint (14) ensures that the difference between the energy level when leaving node i and arriving at node j corresponds to the consumption during the route from i to j. Constraint (15) corresponds to the energy balance of the route for each vehicle. Constraints (16) and (17) detect energy sales or purchases at the station. Constraint (18) ensures that the vehicle departs with a fully charged battery (100%) from the depot. Constraint (19) ensures that the vehicle enters and exits the customer with the same battery level. Constraints (20) and (21) allow the vehicle to be charged or discharged within the minimum (0%) and maximum (100%) battery capacity. Constrain (22) active the index n. Constraints (23), (24), (25) and (26) ensure the feasibility of charging and discharging within index n for each charging station. Constraints (27), (28), (29) and (30) ensure the feasibility in peak time. Finally, constraints (31)–(36) refer to the domains of the variables.

3. Computational results

To validate the proposed mathematical model, 10 examples were solved. The instances were selected from the EVRPTW datasets by Schneider et al. [2014]. These datasets we re generated using the well-known Solomon datasets. The values for battery capacity, vehicle load capacity, energy consumption rate, recharge rate, demand, times windows, and service time are provided in

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the EVRPTW datasets. The energy costs and peak times used were based on those provided by the National Electric Energy Agency (ANEEL) website of Brazil.

An example solution by the model proposed is explained and illustrated to facilitate the reader's understanding of the problem. The example consists of a total of 17 nodes, which include a depot where the vehicles start and end the routes, 12 customers to be served within predefined time windows and demands, and 4 charging stations where vehicles can recharge (energy purchase) or discharge (energy sale). The energy purchase and sale prices vary between two time periods: normal and peak times. Three electric vehicles with the same load and battery capacity are used.

Table 1 presents the time windows for the depot and customers, where s represents the service time at each customer and e denotes the earliest start time for service at each customer, and l represents the latest start time for service at each customer. This table also includes the demands for each customer, denoted as qC.

The energy prices during normal time are 0.3$/KWh for charging and 0.25$/KWh for discharging, while during peak time, they are 0.4$/KWh for charging and 0.35$/KWh for discharging. The peak time starts at 50 and ends at 70. The charging and discharging rate is 0.3 s/KWh. The energy consumption is 0.2 per unit of distance traveled. The battery capacity is equal to 250 kWh and the load capacity is equal to 500 kg.

Table 1: Time windows, service time and customer demand

	D	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
s	0	4	4	4	4	4	4	4	4	4	4	4	4
e	0	7	76	10	0	55	30	25	40	60	20	10	70
l	100	22	95	18	23	75	50	44	60	83	56	25	95
qC	–	15	20	30	25	15	10	25	30	20	25	15	20

In the following, a more detailed explanation of each vehicle route is provided. A graphical representation of the found solution can be seen in Figure 1. Additionally, the recharge levels in percentages are represented when arriving at a customer or charging station. For the charging stations, the recharge level when departing is also shown. The values of decision variables p, y, WI, WO and T for Vehicles 1, 2, and 3 are presented in Tables 2, 3, and 4, respectively. These values help to understand the problem's resolution better.

Figure 1 illustrates the route for Vehicle 1; it departs the route by leaving the depot and arriving at customer $C1$ with a battery level of 72.3%. It then proceeds to customer $C3$ with a battery level of 48.4%. The following customer visited is $C10$, whose battery level is 32.9%. The vehicle then arrives at the charging station $E3$ with a battery level of 12.9%, to understand what happens at the station, we take the variable p in Table 2 as a reference. We know that the vehicle arrives at a time $p = 26.5$ and charges for 23.5 units of time, at this point, the peak time begins ($p = 50$), and the vehicle discharges (energy sales) for 1.6 units of time. Considering the variables WI and WO, we observe that the vehicle charged 26.1% and discharged 1.72% of the battery, respectively. Thus, it departs from the station with a recharge level of 37.3%. Subsequently, the vehicle arrives at the customer $C8$, arriving with a battery level of 22.3%. Finally, the vehicles return to the depot with 0% battery charge.

Figure 1 illustrates the route for Vehicle 2, it departs from the depot and arrives at customer $C4$ with a battery level of 71.5%. It then proceeds to the customer $C7$ with a recharge level of 50.7%.

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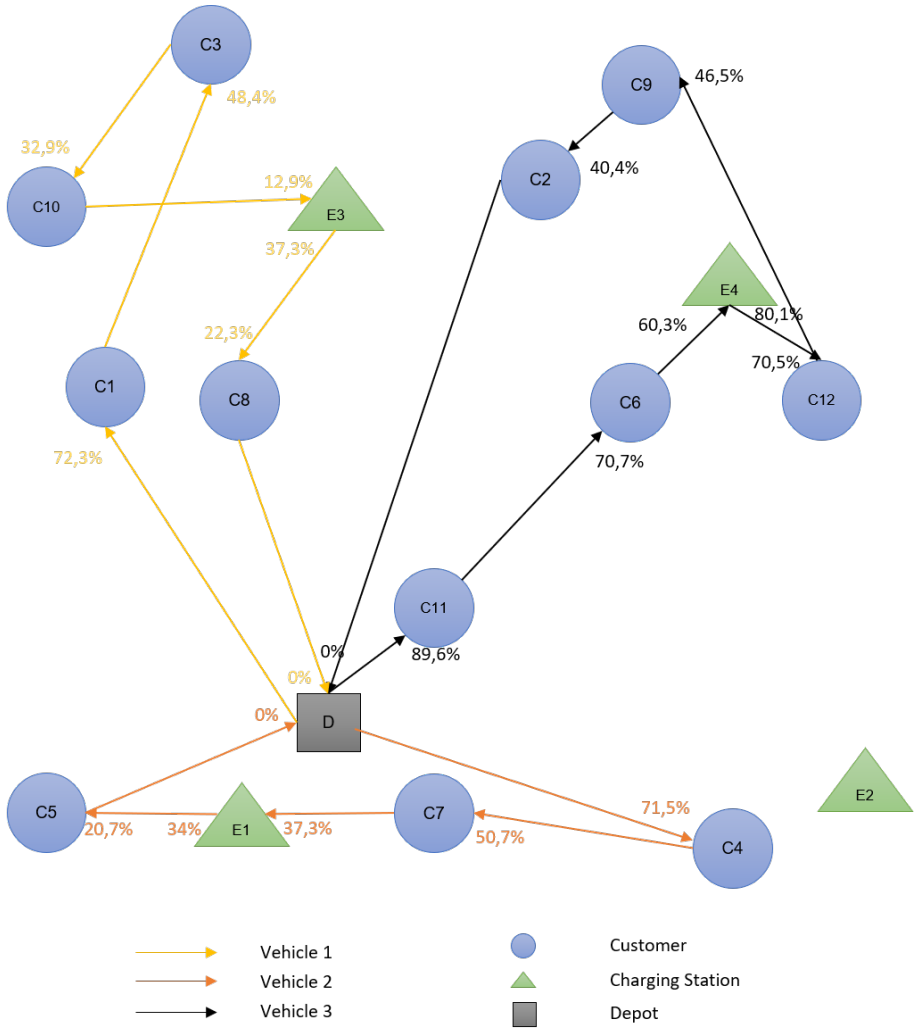


Figure 1: Example solution. Source: Authors

The following node visited was charging station $E1$, To understand what happens at the station, we refer to Table 3, where the battery level is 37,3%. Watching the variable p, we know that the vehicle arrives at the time $p = 33$ and recharges for 17 units of time, at this point, the peak time begins ($p = 50$), and the vehicle discharges for 20 units of time. When the peak time finished, the vehicle exited the charging station with 34% battery level. The total energy charged and discharged was 18,9% and 22,2%, respectively. Finally, visited the customer $C4$ with 20,7% and returned to the depot with 0% battery level.

Figure 1 also illustrates the route for Vehicle 3, it departs from the depot, it arrives at customer $C11$ with a battery battery level of 89.6%. It then proceeds to customer $C6$ with a battery level of 70.7%. The next node visited is charging station $E4$, where the battery level is 60.3%. To understand what happens at the station, we refer to Table 4, with the variable p, we know that the vehicle arrives at a time $p = 35.3$ and begins charging, using the variable T, it can be observed that it charges for 14.7 units of time, at this point, the peak time starts, and the vehicle still charging for 3,9 units of time. By examining the variable WI, we can determine that the vehicle has charged a total

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Table 2: Solution variables for Vehicle 1

	D	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	E1			E2			E3			E4		
p	66,8	7	0	14	0	0	0	0	60	0	20	0	0		0			0			26,5			0	
$y(\%)$	0	72,3	0	48,4	0	0	0	0	22,3	0	32,9	0	0		0			0			12,9			0	
$WI(\%)$	–	–	–	–	–	–	–	–	–	–	–	–	–		0			0			26,1			0	
$WO(\%)$	–	–	–	–	–	–	–	–	–	–	–	–	–		0			0			1,72			0	
T	–	–	–	–	–	–	–	–	–	–	–	–	–	0	0	0	0	0	0	23,5	**1,6**	0	0	0	0

Table 3: Solution variables for Vehicle 2

	D	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	E1			E2			E3			E4		
p	81,6	0	0	0	20,7	75	0	27,3	0	0	0	0	0		33			0			0			0	
$y(\%)$	0	0	0	0	71,5	20,7	0	50,7	0	0	0	0	0		37,3			0			0			0	
$WI(\%)$	–	–	–	–	–	–	–	–	–	–	–	–	–		18,9			0			0			0	
$WO(\%)$	–	–	–	–	–	–	–	–	–	–	–	–	–		22,2			0			0			0	
T	–	–	–	–	–	–	–	–	–	–	–	–	–	17	**20**	0	0	0	0	0	0	0	0	0	0

of 20.6%, resulting in a battery level of 80,1% upon leaving the station. It then heads to customer $C12$ with a battery level of 70,5%, followed by customer $C9$ with a battery level of 46.5%. The last customer visited was $C2$, whose battery level was 40.4%. Finally, the vehicle returned to the depot with a 0% charge.

The objective function value obtained was 31.66, and the computational time required for solving the instance was 90 seconds.

Table 4: Solution variables for Vehicle 3

	D	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	E1			E2			E3			E4		
p	96,8	0	87,8	0	0	0	30	0	0	83	0	23,6	76		0			0			0			35,3	
$y(\%)$	0	0	40,4	0	0	0	70,7	0	0	46,5	0	89,6	70,5		0			0			0			60,3	
$WI(\%)$	–	–	–	–	–	–	–	–	–	–	–	–	–		0			0			0			20,6	
$WO(\%)$	–	–	–	–	–	–	–	–	–	–	–	–	–		0			0			0			0	
T	–	–	–	–	–	–	–	–	–	–	–	–	–	0	0	0	0	0	0	0	0	0	14,7	3,9	0

The information for each example and the results obtained can be seen in Table 5. For each example, this table shows the number of vehicles used, the number of customers, the number of charging stations, the total energy purchased and sold, the total distance traveled, the total cost, and Gap. The gap represents the distance between the best integer solution found and the best-relaxed solution. It is interesting to see how the optimal solution was found for almost all the examples except for c208c15, which obtained a gap of less than 5%. Also, it can be observed how, with a greater number of charging stations, the energy quantity bought and sold increases; this may be due to the fact that vehicles have more possibilities of places to recharge and discharge. The examples with the most computational time were those with 10 or more customers; the examples r103C10 and c208c15 took more than 7000 seconds to find the optimal solution. The largest examples (15 customers) have the most distance traveled.

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Table 5: Information and results of each example

Example	Vehicles	Customers	C. Station	E. Purchased (kWh)	E. Sold (kWh)	Distance	Cost($)	C. Time	Gap (%)
*c*103*C*5	1	5	2	147,9	50,1	175,6	109,3	0,1	0
*c*206*c*5	1	5	4	368,5	189,1	257,1	42,6	1,1	0
*c*208*c*5	1	5	3	272,1	185,5	164,3	73,0	0,2	0
*c*202*c*10	2	10	4	521,0	355,9	320,6	93,8	8,9	0
*c*101*c*10	3	10	5	430,6	245,1	274,8	124,3	923	0
*r*102*C*10	2	10	4	258,4	154,8	276,5	123,5	538	0
*r*103*C*10	3	10	3	300,3	323,2	158,9	48,5	7372	0
*c*106*c*15	3	15	3	274,6	197,1	308,6	58,3	100	0
*c*208*c*15	3	15	4	524,3	536,8	305,8	54,1	7703	5
*r*202*c*15	1	15	6	156,4	184,2	361,7	203,3	573,3	0

4. Conclusion and future work

This paper studied the problem of electric vehicle routing integrated with V2G operation planning. A mathematical model was proposed to minimize the difference between the total cost of energy purchases and the total profit from energy sales to the electrical grid of the vehicle fleet. Ten examples were solved to evaluate the model, and feasible results were obtained. The model also includes time windows, battery and load vehicle capacities, customer service, flexible ancillary services, and other requirements. The solution of the model accurately defined the route for each vehicle used. The vehicles charged energy at the charging station as needed to reach the next customer/deposit, and they sold energy at peak times. Therefore, it can be concluded that the proposed model is viable and capable of obtaining satisfactory solutions for the studied applications. Some interesting issues can be explored as further research. For example, to increase the size of the instances, to include multiple depots and multi-periodicity, and to apply heuristic or metaheuristic methods. Furthermore, it would be interesting to test different types of objective functions, such as minimizing distance traveled or minimizing time.

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