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A review on the electric vehicle routing problems

Elektrikli araç rotalama problemleri üzerine bir literatür incelemesi

Can Berk KALAYCI[1*], *Yusuf YILMAZ*[1]

[1]Department of Industrial Engineering, Faculty of Engineering, Pamukkale University, Denizli, Turkey.
cbkalayci@pau.edu.tr, yusufyilmaz@pau.edu.tr

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Abstract

The Electric Vehicle Routing Problem (EVRP) is an extension of the Vehicle Routing Problem (VRP), wherein electric vehicles (EVs) are utilized instead of internal combustion engine vehicles (ICEVs). Electric vehicles have a limited driving range due to their battery capacity and require recharging to complete their routes. Charging can take place at any battery level and can be done up to the battery capacity. Furthermore, the charging speed may vary depending on the technical infrastructure of the charging station (CS). In certain real-life applications, battery swap stations (BSSs) are used in conjunction with charging stations. This study specifically focuses on articles that discuss the use of electric vehicles in logistics activities, where they are charged during the route or through battery swapping. Firstly, the electric vehicle routing problem is introduced, explaining the evolution from the vehicle routing problem to the electric vehicle routing problem. Subsequently, a mathematical model for the electric vehicle routing problem is presented. The literature on the electric vehicle routing problem is then summarized using data and visuals, and classified based on different characteristics such as assumptions, constraints, problem types, and solution approaches. The emphasis is placed on the notable aspects and solution approaches within each category. Finally, future research opportunities are summarized.

Keywords: Electric vehicle routing problem, Heuristic algorithms, Literature review.

Öz

Elektrikli Araç Rotalama Problemi (EARP), içten yanmalı motorlu araçların yerine elektrikli araçların (EA) kullanıldığı Araç Rotalama Problemi'nin (ARP) bir genişlemesidir. Elektrikli araçlar, pil kapasitesi nedeniyle sınırlı bir menzile sahiptir ve rotayı tamamlamak için şarj edilmeleri gerekmektedir. Şarj, pil seviyesine bağlı olarak ve pil kapasitesine kadar herhangi bir miktarda gerçekleştirilebilir. Ayrıca, şarj istasyonunun (Şİ) teknik altyapısına bağlı olarak şarj hızı değişebilir. Gerçek hayatta bazı uygulamalarda, şarj istasyonları yanında pil değiştirme istasyonları (PDI) kullanıldığı durumlar bulunmaktadır. Bu çalışma sadece lojistik faaliyetlerde elektrikli araçların kullanıldığı ve rota üzerinde şarj edildiği veya pil değiştirme yöntemiyle şarj edildiği makaleleri ele almaktadır. İlk olarak, elektrikli araç rota problemi tanıtılmış ve araç rota probleminden elektrikli araç rota problemine geçişin evrimi açıklanmıştır. Ardından, elektrikli araç rota problemi için matematiksel bir model sunulmuştur. Sonra, elektrikli araç rota problemi literatürü, veriler ve görseller kullanılarak özetlenmiş ve varsayımlar, kısıtlamalar, problem tipleri ve çözüm yaklaşımları gibi farklı özelliklere göre sınıflandırılmıştır. Odak noktası, her sınıfa dahil olan önemli yönler ve çözüm yaklaşımları üzerindedir. Son olarak, gelecekteki araştırma fırsatları özetlenmiştir.

Anahtar kelimeler: Elektrikli araç rotalama problemi, Sezgisel algoritmalar, Literatür incelemesi.

1 Introduction

Today, reducing logistics operations' negative social and environmental impacts has become challenging for companies. According to the European Commission, approximately 27% of Europe's greenhouse gas emissions originate from logistics activities [1]. In addition, the main difficulty lies in that most companies' vehicles consist of conventional internal combustion engine vehicles (ICEVs). ICEVs cause air pollution and noise pollution due to carbon dioxide (CO2), nitrogen oxides (NOx), elemental carbon, and organic carbon emissions. Therefore, improving local air quality is one of the government's most critical short-term tasks. Furthermore, the World Health Organization has stated that poor air quality is a severe health risk [2].

On the other hand, electric vehicles (EVs) are attracting more and more attention from companies and governments as they can play an essential role in achieving this goal. In recent years, European countries have supported many projects and national initiatives to facilitate EV use. Likewise, well-established logistics companies have private initiatives that include EVs in their delivery operations [3]. The use of EVs has some advantages [4]. It contributes to logistics operations regarding environmental sustainability, as there are no greenhouse gas emissions locally, and they produce less noise than ICEVs. In addition, a zero-emission balance can be achieved when electricity is obtained using renewable energy sources. In addition, EVs have lower operating and maintenance costs than ICEVs [5].

Despite that, there are some barriers to using EVs. For example, EVs have a higher acquisition cost, shorter driving range, and longer charging time than ICEVs. These disadvantages affect operational decisions. In addition, the need for more charging infrastructure is considered an obstacle. However, EVs have become more competitive and an alternative to ICEVs due to technological advances, government subsidies, supportive policies, and regulations for greenhouse gas emissions [6].

With the widespread use of EVs, EVs' effects on operational decisions are also discussed in studies on the Vehicle Routing Problems (VRPs) [7]. Erdoğan and Miller-Hooks [8] first proposed a green vehicle routing problem (GVRP). The vehicle fleet consists of alternative fuel vehicles (AFV). The electric

*Corresponding author/Yazışılan yazar

vehicle routing problem was first described in the literature as the electric vehicle routing problem with time windows (EVRP-TW) presented by Schneider et al. [9]. The vehicle fleet consists of only EVs, and there are time windows where customers can receive service at the earliest and the latest. Authors have studied problems with different assumptions and constraints, such as mixed fleets of EV and ICEV, linear and nonlinear charging functions, full and partial charging, simultaneous EV routing, and charging station (CS) location selection.

This study examines the EVRP literature publications in-depth, considering the constraints, the developed models, and the solution methods used. In addition, this article presents a classification of solution methods and assumptions regarding the solution of EVRP to answer the following four research questions:

(i) Which models are most explored?

(ii) What constraints have been considered for EVRP?

(iii) How did the researchers address the problem constraints? (iv) Which methods are primarily used in the solution of EVRP, and which ones give convincing results?

In Chapter 2, EVRP is introduced, and a basic mathematical model is presented. Then, the relevant literature examined within the scope of this study is discussed and summarized from different perspectives in Chapter 3. Finally, solution methods are reviewed in Chapter 4, while the conclusion and future research opportunities are presented in Chapter 5.

2 Electric vehicle routing problem

EVRP is an extension of the problem defined as the VRP in the literature. VRP can be summarized as routing a fleet of internal combustion engine vehicles that leave a central depot and return to the same depot by meeting customer demands, as shown in Figure 1.

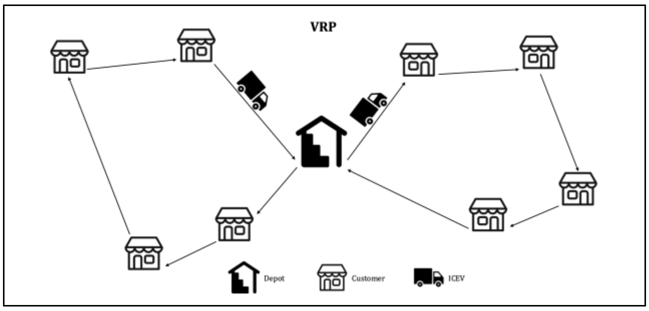

Figure 1. An example solution representation for the VRP.

With environmental sustainability coming to the fore, replacing ICEV's fleet with AFVs has become the forefront of the GVRP. An example illustration of GVRP is presented in Figure 2. EVRP, on the other hand, can be defined as routing and making charging decisions together to meet customer demands by EVs with limited load and battery capacity. The energy in the EVs' battery decreases in proportion to the distance traveled. Therefore, it may be necessary to visit one or more CSs and recharge the battery to continue the route. At this point, a decision must be made regarding which CS and the rate the EVs should be charged. In addition to these decisions, regarding full or partial charging of the battery, fast or standard speed charging, and whether a linear or nonlinear charging function will determine the elapsed time while charging should also be made.

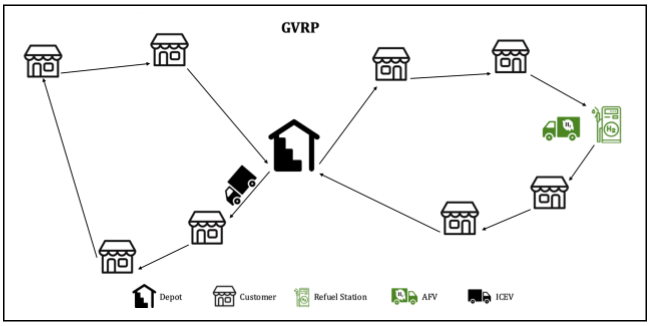

Figure 2. An example solution representation for the GVRP.

In its most general definition, EVRP aims to meet customer demands by using the least number of vehicles and by traveling the minimum distance, and to do by minimizing the total cost. An example solution illustration for EVRP is presented in Figure 3.

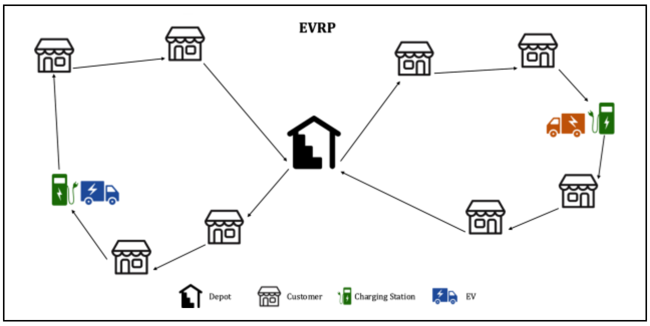

Figure 3. An example solution representation for the EVRP.

A mathematical model is given for the solution of EVRP. The model is created by removing SPD constraints from the model developed by Yilmaz and Kalayci [10]. The assumptions of the model are summarized below.

- All distribution requests of customers must be met,
- Splitting customer claims is not allowed,
- Each customer can only be visited by one electric vehicle,
- The customer visiting the CS leaves the CS with a full charge. Partial charging is not allowed,
- It is designed to minimize the total distance traveled by the objective function,
- The electric vehicle fleet is homogeneous,
- Electric vehicles start their tour from the depot and complete their tour in the depot,
- The load on the vehicle cannot exceed the vehicle capacity at any stage of the tour,
- Storage capacity of the depot is unlimited,
- Charging stations can be visited more than once by the exact electric vehicle,
- It assumed that EVs charged at a constant speed at the CSs,
- Each electric vehicle covers 1 unit of distance in 1 unit of time.

Notations, sets, parameters, decision variables, objective functions, and constraints of the developed model are presented below.

n_d = number of depots

n_r = number of charging stations

n_c = number of customers

n_k = number of EVs

N_D = the set of depot $\{1, \dots, n_d\}$

N_R = the set of charging stations $\{n_d + 1, \dots, n_d + n_r\}$

N_C = the set of customers $\{n_d + n_r + 1, \dots, n_d + n_r + n_c\}$

N_{RC} = the set of charging stations and customers $\{n_d + 1, \dots, n_d + n_r + n_c\}$

N_{DRC} = the set of depots, charging stations and customers $\{n_d, \dots, n_d + n_r + n_c\}$

N = the set of nodes $\{1, \dots, n_d + n_r + n_c\}$

N_k = the set of EVs at the depot $\{1, \dots, n_k\}$

d_{ij} = distance from node i to j

Q_k = maximum loading capacity of EV k

BC_k = maximum battery capacity of EV k

g_k = charging rate of EV k

h_k = energy consumption rate of EV k

D_j = delivery goods demand of customer j ($\forall j \in N_C$)

$x_{kij} = \begin{cases} 1, & \text{if node } j \text{ visited by EV } k \text{ after node } i \\ 0, & \text{otherwise} \end{cases} \quad (\forall k \in N_k, \forall i,j \in N_D \cup N_c)$

U_{kij} = amount of goods to be delivered by EV k on the arc (i,j) ($\forall i,j \in N, \forall k \in N_k$)

$BSCa_{ik}$ = charge level of EV k upon arrival at node i ($\forall i \in N, \forall k \in N_k$)

$BSCd_{ik}$ = charge level of EV k at departure from node i ($\forall i \in N, \forall k \in N_k$)

$$Min\ Z = \sum_{k\in N_k}\sum_{i\in N}\sum_{j\in N} d_{ij} * x_{kij} \tag{1}$$

$$\sum_{k\in N_k}\sum_{i\in N} x_{kij} = 1, \forall j \in N_C \tag{2}$$

$$\sum_{i\in N} x_{kji} - \sum_{i\in N} x_{kij} = 0, \forall k \in N_k, \forall j \in N \tag{3}$$

$$\sum_{j\in N_{RC}} x_{kij} \leq 1, \forall k \in N_k, \forall i \in N_D \tag{4}$$

$$\sum_{j\in N_{RC}} x_{kji} \leq 1, \forall k \in N_k, \forall i \in N_D \tag{5}$$

$$U_{kij} = 0, \forall i \in N_{RC}, \forall j \in N_D, \forall k \in N_k \tag{6}$$

$$U_{kij} = Q_k * x_{kij}, \forall i,j \in N, \forall k \in N_k \tag{7}$$

$$x_{kii} = 0, \forall i \in N, \forall k \in N_k \tag{8}$$

$$BSCa_{ik} \geq 0, \forall i \in N, \forall k \in N_k \tag{9}$$

$$BSCd_{ik} = BC_k, \forall i \in N_D, \forall k \in N_k \tag{10}$$

$$BSCa_{jk} \leq BSCa_{ik} - (h_k * d_{ij}) * x_{kij} + BC_k * (1 - x_{kij}), \forall i \in N_C, \forall j \in N, i \neq j, \forall k \in N_k \tag{11}$$

$$BSCa_{jk} \leq BSCd_{ik} - (h_k * d_{ij}) * x_{kij} + BC_k * (1 - x_{kij}), \forall i,j \in N, i \neq j, \forall k \in N_k \tag{12}$$

$$BSCa_{ik} \leq BSCd_{ik}, \forall i \in N, \forall k \in N_k \tag{13}$$

$$BSCd_{ik} \leq BC_k, \forall i \in N, \forall k \in N_k \tag{14}$$

$$BSCa_{ik} = BSCd_{ik}, \forall i \in N_C, \forall k \in N_k \tag{15}$$

$$BSCd_{ik} = BC_k, \forall i \in N_R, \forall k \in N_k \tag{16}$$

$$\sum_{i\in N} U_{kij} = \sum_{i\in N} U_{kji}, \forall j \in N_R, \forall k \in N_k \tag{17}$$

$$\sum_{k\in N_k}\sum_{i\in N} U_{kij} - \sum_{k\in N_k}\sum_{i\in N} U_{kji} = D_j, \forall j \in N_{RC} \tag{18}$$

$$d_{ij} \geq x_{kji}, \forall i,j \in N, \forall k \in N_k \tag{19}$$

$$x_{kij} \in \{0,1\}, \forall \mathrm{k} \in N_k, \forall \mathrm{i}, j \in N_D \cup N_R \cup N_C \tag{20}$$

$$U_{kij}, BSCa_{ik}, BSCd_{ik} \geq 0, \forall \mathrm{i}, j \in N, \forall \mathrm{k} \in N_k \tag{21}$$

The objective function (1) minimizes the distance traveled by EVs from the depot to the customers. Constraint (2) ensures that each customer is visited exactly once. Constraint (3) ensures that there are vehicle exits and vehicle entrances to each customer and CS and that EVs leaving the depot return to the depot. Constraint (4), constraint (5), and constraint (19) allow EVs in the depot to be used only when needed. Constraint (6) states that no products will be distributed in the vehicles returning from the customer to the depot. Constraint (7) states that the total load to be distributed in the vehicle cannot exceed the vehicle's capacity. Constraint (8) prevents the formation of a sub-tour with one element by preventing a movement from the current node to the node itself. Constraint (9) ensures that the vehicle charge level is not harmful when any node is reached. Constraint (10) shows that the vehicles leave with a full battery when leaving the depot. Constraints (11-16) are battery state constraints. Constraint (17) states that the amount of load distribution in an electric vehicle visiting the CS will remain the same. Constraint (18) ensures that the distribution demands of the customers are met by the relevant vehicles. Finally, constraints (20) and (21) describe the nature of the variables.

3 Literature

Before presenting a comprehensive review of EVRP-related articles, previous review studies on EVRP were searched to demonstrate the contribution of this study to the literature clearly, and to the best of our knowledge, only four studies were found [11]-[14]. The focal points of the related studies are presented in Table 1.

Table 1. EVRP Review articles.

Study	Focus	Number of Studies Examined
Erdelić and Carić [13]	Other problems with EVRP and EAs	90
Qin et al. [12]	Solution methods in the Electric Traveling Salesman, YARP and EVRP literature	50
Xiao et al. [11]	EVRP energy consumption and charging patterns	30
Abid et al. [14]	EVRP solution methods	19

In addition to EVRP Erdelić and Carić [13], such as fleet optimization and energy management under fixed routes, EVs are also used without routing or charging decisions. Qin et al. [12] focused on solution methods in this study, which consists of 50 articles; in which Xiao et al. [11], on the other hand, examined 30 articles in terms of energy consumption and charging models. Abid et al. [14] considered only 19 papers in terms of solution approaches.

This study considers studies in which only EVs are used in logistics activities and battery swapping or charging on the route. A systematic classification has been made, considering the specific features of EVRP. Future research opportunities have been comprehensively revealed by including the approaches developed to solve the problem.

The literature search for EVRP was conducted to include articles published in scientific journals in English. The 59 articles examined within the scope of the study were analyzed in detail according to specific classification criteria, as indicated in

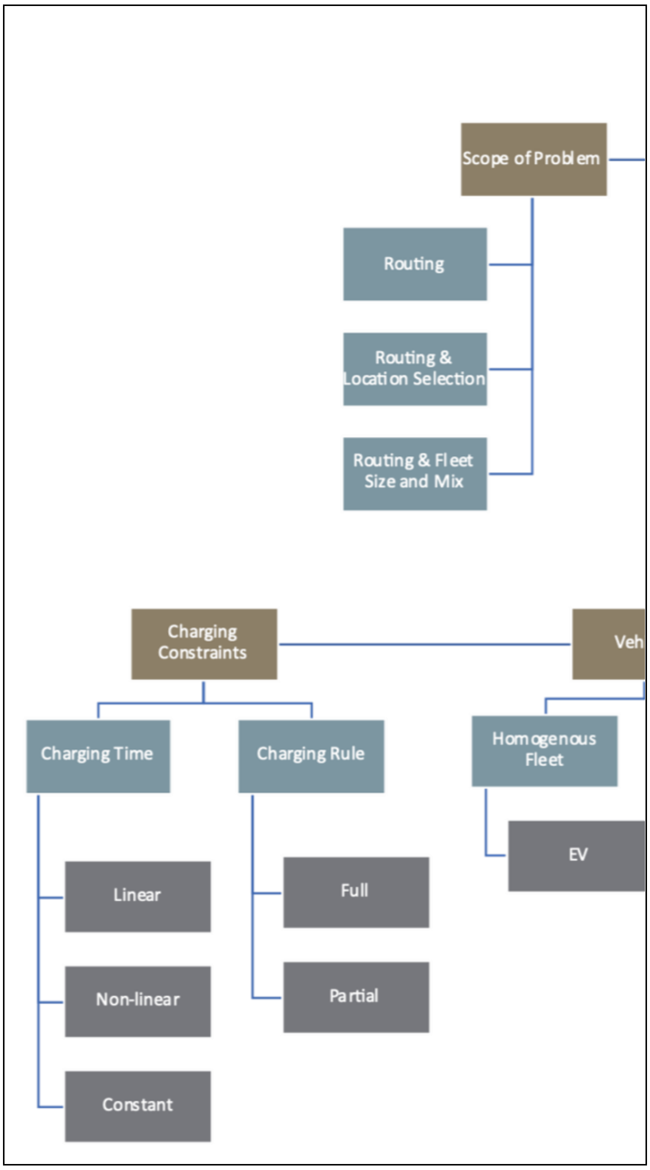

Figure 4. The scope, assumptions, and limitations of the studies are given in Table 2, and the solution methods suggested in the studies are given in Table 3.

When the literature is examined, there are different studies and approaches related to EVs. Considering the types of problems, there are problems such as vehicle routing, vehicle energy consumption estimation, battery swap station (BSS) selection, and charging decisions under fixed routes. In addition to the routing of EVs, there are studies on energy management and consumption forecasting [15]-[21]. In studies where different concepts are used to optimize energy management, factors such as weather conditions, topography, and traffic density on the route to be visited are taken into account. Larsson et al. [18] routing of the required vehicles by collecting them in a cloud-based environment and making specific calculations. De Cauwer et al. [16] used driving, road network, traffic density, weather, and elevation data to estimate energy consumption by analyzing real-life data. In addition, it tried to make a realistic consumption estimation by calculating the driver's vehicle usage profile on the route with artificial neural networks.

When the charge level of EVs decrease, EVs must go to the nearest CS and be charged. While 0% - 80% of the battery is charged linearly, after 80%, the charging speed gradually slows down due to technical reasons. This situation is defined as a nonlinear charge function in the literature. However, there are only six studies in which this assumption, which is a realistic approach, is considered [22]-[27].

Today, although EVs show differences in shape and speed, they are charged in almost the same way technologically, that is, with the help of sockets. However, in cases where time is of the essence, new technologies are being tested to avoid standing at the CS and waiting for the vehicle to charge. The most accepted of these are the technologies that can charge the vehicle on the go, thanks to the wireless charging equipment installed on the road. In the literature, six studies have presented solutions under the assumption of wireless charging of EVs [25],[28]-[32].

As the battery efficiency of EVs has increased compared to the past, it has started to be used in commercial areas and for individual use. The use of EVs in the internal logistics requirements of production facilities [33], public transportation, shared vehicle services [34],[35] and distribution networks is increasing day by day. Different solution methods were developed for routing these vehicles and deciding where and how many CSs, BSSs, or both should be opened.

The most important reason affecting the range of EVs used for individual purposes is the driver's driving style. The range is shortened at high speeds and extended at low speeds. Birrell et al. [36], Yang et al. [37], and Marmaras et al. [38]examined the relationship between drivers' driving behaviors and range. Companies must consider finding the size and characteristics of the fleet, such criteria as the customers' demands, the characteristics and amount of the loads to be transported, the legal obligations in the region to distribute, and the physical characteristics of the demand points. The literature defines this problem as Fleet Size and Mix (FSM) [39]-[41].

Bruglieri et al. [42] aimed to minimize the number of EVs used the total travel time, the total charging time, and the waiting time. Variable neighborhood search branching (VNSB) was applied to the developed model to obtain fast results in large-scale problems.

Goeke and Schneider [41] the time window and mixed fleet electric vehicle routing problem (EVRP-TW-MF). EVs are routed together with ICEV. A realistic model, which considers vehicle speed, road characteristics, load amount, and weather conditions, has been developed to estimate energy consumption for EVs and fuel consumption for ICEVs. ALNS was used to solve the problem.

Yang et al. [43] to EVRP with a different perspective. While making fast and standard charging decisions, it is aimed to minimize the time-based charging cost. A realistic energy consumption calculation that depends on vehicle load is also considered. A learning parthenogenesis algorithm (PGA) was developed to solve the proposed model.

Yang and Sun [44] aimed to simultaneously solve the Battery Swap Station Location Selection Problem (BSSLSP) and Electric Vehicle Routing Problem (EVRP) under battery-induced range constraints. The problem is formulated as an integer programming model and solved using a four-stage heuristic called SIGALNS and a two-stage taboo search-modified Clarke and Wright Savings heuristic called TS-MCWS. The objective function of the developed model aimed to minimize the sum of the cost of establishing the BSS and the freight transportation costs of the vehicles. Two different model definitions were made; in the first model, each EV's visit to the BSS was limited to one, while in the second model, it assumed that this limit does not exist.

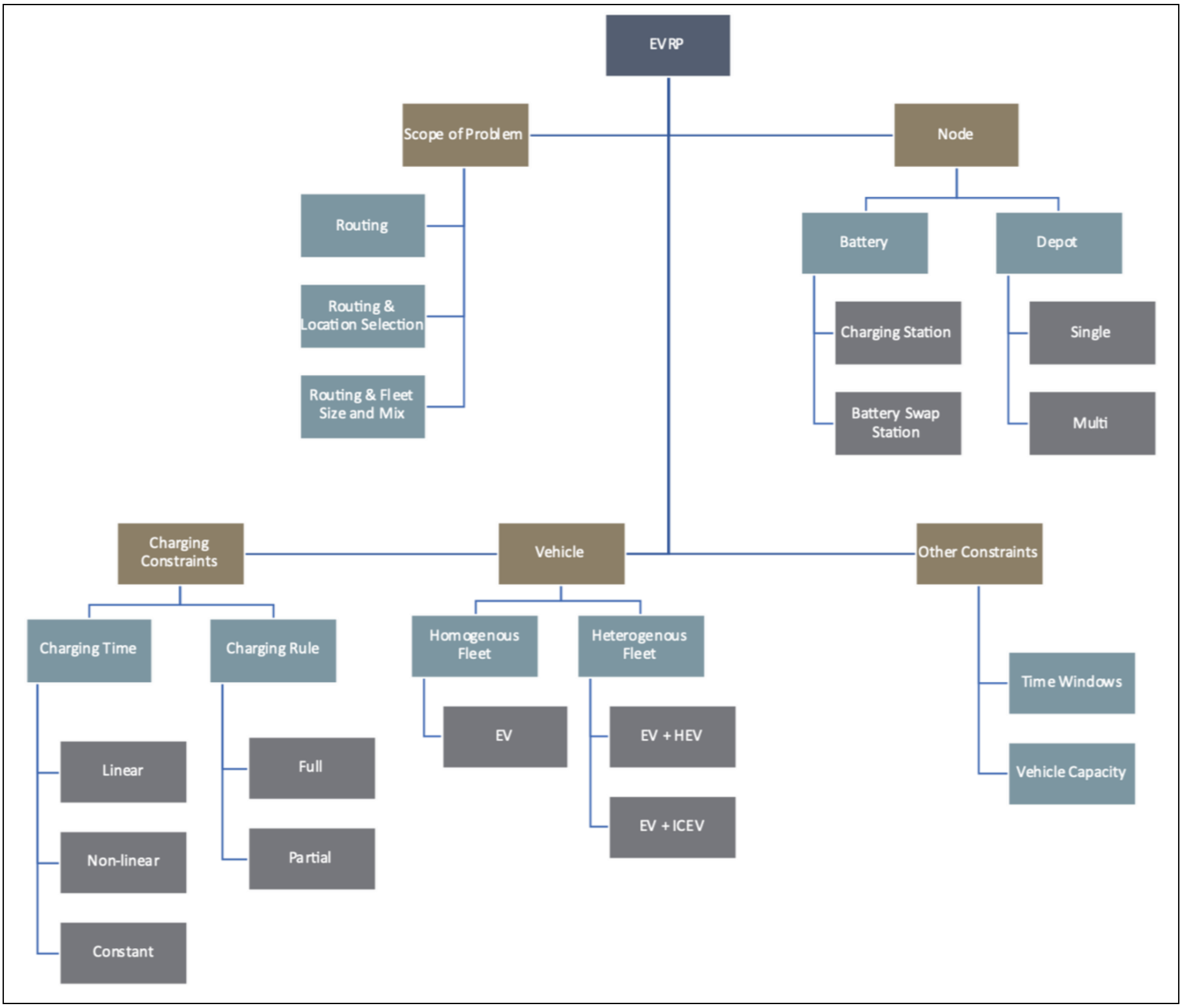

Figure 4. Literature classification criteria.

Table 2. EVRP literature (scope, assumptions, and constraints).

Study	2E	NL	PR	PD	SPD	TW	MD	HeF	BSS	CS	FSM	LRP
Felipe et al. [45]			+							+		
Schneider et al. [9]						+				+		
Bruglieri et al. [42]			+			+				+		
Goeke and Schneider [41]						+		+		+	+	
Li-Ying and Yuan-Bin [46]						+				+		+
Yang and Sun [44]									+			+
Desaulniers et al. [47]			+			+	+			+		
Grandinetti et al. [48]				+		+				+		
Hiermann et al. [39]						+		+		+	+	
Keskin and Catay [49]			+			+				+		
Lin et al. [50]				+						+		
Vaz Penna et al. [40]						+		+		+	+	
Barco et al. [51]		+				+				+		
Bruglieri et al. [52]		+	+			+				+		
Hof et al. [53]									+			+

Study	2E	NL	PR	PD	SPD	TW	MD	HeF	BSS	CS	FSM	LRP
Montoya et al. [26]		+	+							+		
Schiffer and Walther [4]			+			+				+		+
Shao et al. [54]										+		
Strehler et al. [27]		+	+							+		
Gatica et al. [55]										+		+
Keskin and Catay [56]			+			+		+		+		
Paz et al. [57]			+			+	+		+	+		+
Shao et al. [58]						+				+		
Zhang et al. [59]										+		
Agárdi et al. [60]	+							+		+		
Basso et al. [61]						+				+		
Breunig et al. [62]	+						+			+		
Cortés-Murcia et al. [63]			+			+				+		
Froger et al. [22]		+	+							+		
Goeke [64]			+	+		+				+		
Jie et al. [65]	+						+		+			
Keskin et al. [24]		+	+			+				+		
Koç et al. [25]		+	+			+	+			+		+
Zhao and Lu [66]				+		+		+		+		
Zuo et al. [67]		+				+				+		
Kancharla and Ramadurai [23]		+								+		
Lee [68]		+								+		
Lu et al. [69]						+				+		
Mao et al. [70]			+			+			+	+		
Meng and Ma [71]						+				+		
Raeesi and Zografos [72]						+			+			
Soysal et al. [73]				+					+	+		
Tahami et al. [74]										+		
Taş [75]						+				+		
Wang et al. [76]						+				+		
Zhang et al. [77]			+							+		
Zhao et al. [78]						+				+		
Ghobadi et al. [79]				+		+	+			+		
Karakatič [80]		+	+			+	+			+		
Keskin et al. [81]			+			+				+		
Lin et al. [82]			+			+				+		
Akbay et al. [83]	+					+				+		
Duman et al. [84]						+				+		
Guo et al. [85]		+	+							+		+
Raeesi and Zografos [86]						+			+	+		
Sánchez et al. [87]			+			+				+		+
Yang et al. [88]			+	+		+				+		+
Yilmaz and Kalayci [10]					+					+		
Zhang et al. [89]						+				+		

2E: Two Echelon, NL: Non-linear Charing, PR: Partial Recharge, PD: Pick-up and Delivery, SPD: Simultaneous Pick-up and Delivery, TW: Time Window, MD: Multi Depot, HeF: Heterogenous Fleet, BSS: Battery Swap Station, CS: Charing Station, FSM: Fleet Size and Mix, LRP: Location Routing Problem.

Table 3. EVRP Literature (Solution Approaches).

Study	Year	CPLEX	LNS	VNS	CW	LS	GA	ACO	TS	SA	Other
[45]	2014					+				+	
[9]	2014	+		+					+		
[42]	2015	+		+							
[41]	2015	+	+								
[46]	2015	+		+					+		
[44]	2015	+	+		+				+	+	
[47]	2016	+									
[48]	2016	+									
[39]	2016	+	+			+					
[49]	2016	+	+								
[50]	2016	+									
[40]	2016					+					
[51]	2017						+				+
[52]	2017	+		+							
[53]	2017	+		+		+					
[26]	2017	+				+					+
[4]	2017	+	+		+	+					
[54]	2017	+					+				
[27]	2017										+
[55]	2018										+
[56]	2018	+	+								
[57]	2018	+									
[58]	2018	+				+	+				
[59]	2018		+			+		+			
[60]	2019						+				
[61]	2019	+									
[62]	2019	+	+			+					
[63]	2019	+				+					
[22]	2019	+									+
[64]	2019	+							+		
[65]	2019	+	+								
[24]	2019	+	+								
[25]	2019	+	+								
[66]	2019		+								
[67]	2019	+									
[23]	2020	+	+								
[69]	2020	+		+							
[70]	2020	+						+			
[71]	2020	+						+			
[72]	2020		+								
[73]	2020	+									
[74]	2020	+									
[75]	2020	+									
[76]	2020	+		+							
[77]	2020		+								
[78]	2020							+			
[84]	2021	+									+
[79]	2021	+		+						+	
[80]	2021						+				
[81]	2021	+	+								
[68]	2021	+									
[82]	2021	+		+					+		
[85]	2022	+	+		+					+	
[86]	2022	+									+
[87]	2022	+									
[88]	2022										+
[10]	2022	+		+	+						
[89]	2022	+	+								

Hiermann et al. [39]focused on vehicle fleet size and mix while addressing EARP-TW. However, charging times and charging points decisions were also made. They tried to find a solution to the combination of EVRP-TW, Charging Station Location Selection Problem (CSLSP), and VRP with time windows and mixed fleet (VRP-TW-MF). Each vehicle can visit the charging point only once. Vehicles arriving for charging leave the station only after being fully charged. The charging time is determined linearly according to the empty part of the battery, and the charging speed is standard. A CS network does not consider separately. It is assumed that each customer has a CS. Local search and labeling procedure embedded, adaptive large neighborhood search (ALNS) meta-heuristic used to solve the problem.

Keskin and Catay [49] discussed EVRP-TW-PR with a scenario that allows for partial charging and a mathematical model developed in this context. In this study, the assumption that the vehicle fleet is homogeneous, partial charging is allowed with a standard charging speed. That energy consumption is only directly proportional to the distance traveled is accepted. EVRP and EVRP-PR are solved using the adaptive large neighborhood search (ALNS) heuristic. To test the performance of the employed solution approaches Schneider et al. [9]' s datasets were used, and better-than-best results were obtained for some problem types.

Lin et al. [50] routing strategy that tries to minimize travel time and energy costs. The paper is the first in the literature to consider the effect of load amount and speed on energy consumption. The mathematical model developed in the study aimed to minimize the sum of three different costs: charging cost, travel time cost, and waiting cost for charging. The charging cost is equal to the energy consumption cost. Each CS may be used by the same or different vehicles once, multiple times, or not used at all. A mixed fleet of EVs waits until fully charged. The speed between points is assumed to be constant. Time windows constraint is not considered. Although the developed model is solved with small test data, a heuristic method has yet to be developed for large problems. Different scenarios can be studied by considering a mixed fleet of ICEVs and EVs.

Sun and Zhou [90] try to minimize fuel consumption for a plug-in hybrid vehicle (PHEV) instead of an electric vehicle. In this study, the energy gained from the brake is also considered, unlike the routing of internal combustion vehicles (ICEV).

Hof et al. [53] employed an ALNS algorithm, proposed by Yang and Sun [44], to solve BSSLSP and EVRP simultaneously. They considered a homogeneous fleet, distance-based energy consumption, and time windows assumptions. Also, they used data sets of Yang and Sun [44]. The numerical results show that the proposed solution approach achieves quality solutions in a shorter time than the results of Yang and Sun [44] and CPLEX.

Montoya et al. [26] developed a mixed integer linear programming formulation, including a nonlinear charging function and a hybrid metaheuristic. In the developed model, the aim is to minimize the total time (traveling + charging). In this study, the route created, and the charging decisions have been made. In other words, a route is created by sorting for a vehicle first, then the fixed-route vehicle charging problem is solved, and it is determined how much to charge at which CS. A hybrid metaheuristic was developed in which iterative local search and heuristic aggregation were used to solve the problem.

Shao et al. [54] draw a realistic framework by considering variable charging and travel time in the EVRP literature. For this reason, realistic assumptions, such as dynamic traffic environment, vehicle capacity, time windows, charging cost, and penalty cost, are considered.

Strehler et al. [27] tried to find a solution by assuming the shortest path problem for routing electric and hybrid vehicles from a different perspective. In this context, a model has been developed for both types of vehicles, trying to find the shortest path using recyclable sources and CSs. For EVs, when using the model in which, only CSs are considered; For hybrid vehicles, both CSs and an internal combustion engine model are used, in which the charging status on the road is taken into account. The developed models were coded and solved in the MATLAB application.

Paz et al. [57] considered EVRP-TW with multi-depots and a homogeneous fleet in their study. They proposed a mixed integer linear programming model to solve the problem. In the developed model, Decisions have been made regarding; i) the number and location of CSs, ii) the number and location of depots, and iii) the number and route of EVs. In addition to charging by cable, BSSs are also where battery replacements are made. It assumed that each EV leaves the same depot and returns to the same depot, the charging time and battery swapping times are constant, and the charging time is always longer than the battery swapping time. It assumed that the vehicle speed is constant, and the energy consumption is directly proportional to the distance traveled. The model was solved with CPLEX using datasets of five, ten, and fifteen customers Schiffer and Walther [4]

For EVs to continue their distribution activities uninterruptedly, the batteries must be changed at the BSSs, or the batteries must be charged at the CSs. In this context, the concepts of charging with the battery swap station are explained below.

Battery charging time, one of the biggest obstacles to the spread of EVs, is still relatively long despite the emergence of new technologies. In addition to developing charging technologies, it tried to prevent waiting while charging at CSs with battery replacement. There are some obstacles to the spread of BSSs established in the United States and some European countries worldwide. The most important reason is that the initial setup cost of each BSS is over half a million dollars. In addition, keeping vehicle batteries with different characteristics in stock and ensuring that these batteries are full brings tremendous technical and economic burdens for station operators. Another problem encountered in BSSs is battery design. Batteries should be easily accessible and in a complete structure during battery replacement. To disconnect and reconnect power cables and cooling system equipment several times, the battery must be specially designed so that it can be easily and quickly removed from the vehicle and quickly reconnected. Cross-platform or brand compatibility is essential for a technology to be successful and become a dominant trend. For battery swapping to become widespread, different manufacturers must produce replaceable battery packs to the same standards. Manufacturers design their vehicles according to proprietary designs. Using a standard format battery limits the flexibility and innovation capacity of the manufacturer.

The infrastructure required for battery packs is large, much more complex, and more expensive than charging. First, all BSSs must charge their battery packs. Must have at least two battery packs; one must be available inside the car and the other at the BSS. This situation dramatically increases the cost of vehicles because battery packs are the most expensive component in an electric vehicle.

Battery performance decreases over time, so the range of EVs will be shortened after each charge. Considering that all vehicles will use the same battery pack format and power in the battery swapping scenario, BSS will have batteries with different energy storage capacities, mainly due to battery wear. Generally, most people will choose newer battery packs for battery replacement because of the more extended range. However, users may not be happy when their new battery is replaced with a lower-performance battery, as the range of lower-capacity batteries will differ from new ones. That will cause batteries to have shorter operating cycles, as low-performing battery packs will be replaced more quickly and significantly increase the cost of recycling to keep customers happy. Since EVs have a lower range than internal combustion vehicles and their battery capacities are low, they may need to be charged at CSs while serving customers.

The distribution of the 59 articles examined within the study's scope by years is presented in Figure 5. While the first study was published in 2014, 52 articles were published in the eight years until 2022. Considering the number and scope of the articles in the EVRP literature, many more researchers must conduct research in this field.

Figure 6 shows that 37 journals contributed to the publication of 59 articles. It observed that 30 of these identified articles were published in the first eight journals, corresponding to 51% of the total articles. Among the journals, Computers & Operations Research and the European Journal of Operational Research dominate, representing 20.4% of all published articles.

As indicated in Figure 7, 46, corresponding 78% of the studies focused only on routing, within the scope of the Electric Vehicle Routing Problem and Fleet Size and Mix Optimization (EVRP-FSMO), in which the fleet size and types of vehicles in the fleet were optimized together with routing. There are three studies available [39]-[41]. Within the scope of the Electric Vehicle Routing and Charging Station Location Selection Problem (EVRP-CSLSP), in which routing and the location selection of charging stations are handled together, there are ten studies representing 16.9% of the studies examined [4],[25],[44],[46],[53],[55],[57],[85],[87],[88].

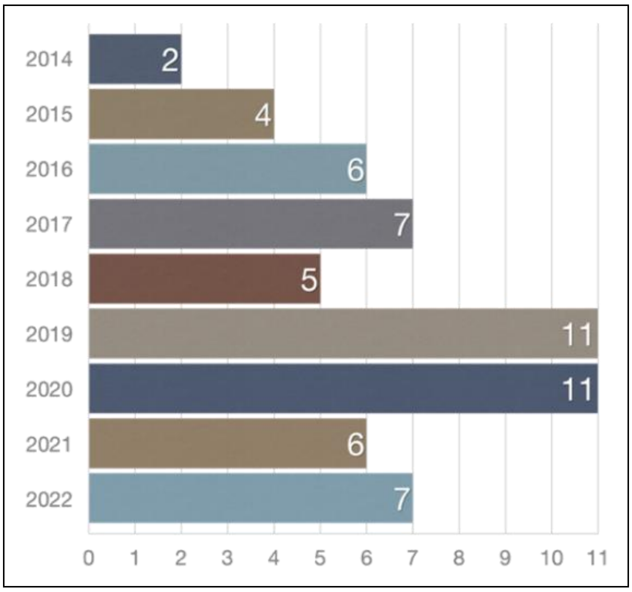

Figure 5. Number of publications by year.

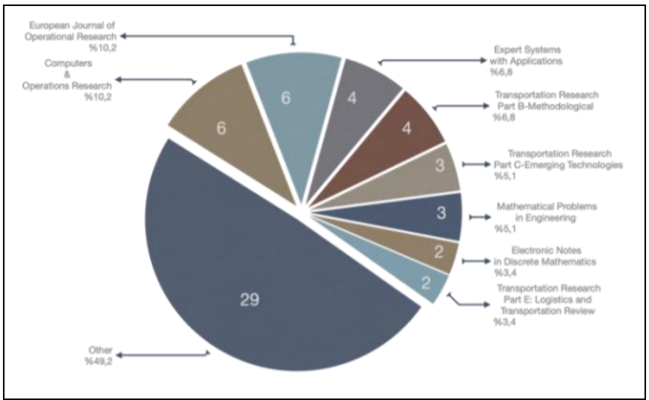

Figure 6. The Number of publications by journals.

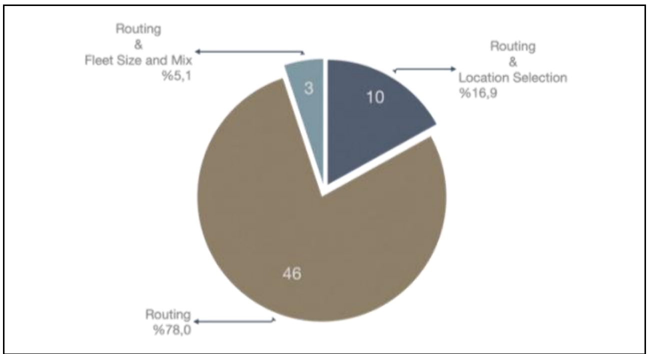

Figure 7. Distribution of publications according to the scope of the problem.

While 91.5% of the studies in the literature accept the assumption that the load capacity of EVs is limited, in 5 studies ([22],[25]-[27],[55]) corresponding to 8.5%, the vehicle load capacity is assumed unlimited (Figure 8).

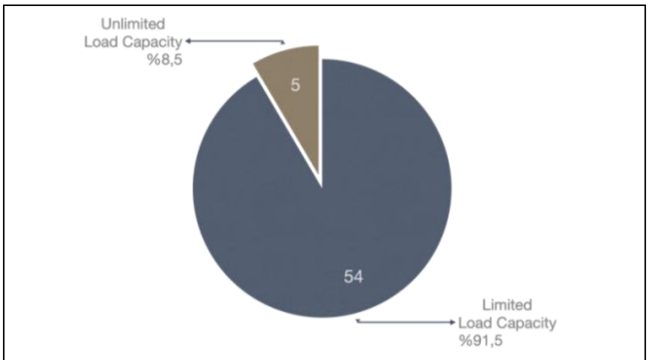

Figure 8. The number of publications assumes of the load capacity of EVs is limited.

As can be seen from Figure 9, although the single depot assumption was taken into account with a significant rate of 88.1% in 52 studies in the EVRP literature, the multiple depot assumption was taken into account in 7 studies corresponding to 11.9% of the studies examined [25],[47],[57],[62],[65],[79],[80].

In the upcoming segments of the literature review, various facets of electric vehicle routing problems (EVRPs) are explored, drawing upon both foundational and recent works in the field. It begins with "Time Windows" where the effects of scheduling and time constraints on the planning and optimization of EVRP are examined.

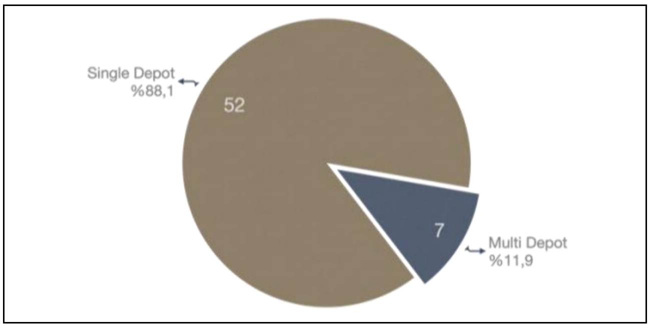

Figure 9. Distribution of publications based on the assumption of the number of depots.

This is followed by "Simultaneous Pickup and Delivery" where the implications of this crucial logistics feature on energy consumption and the efficiency of EVs are discussed. Attention is then given to "Battery Swap Station," an innovative solution to the range limitations of electric vehicles. The focus then shifts to the "Non-linear Charging Function," where the impact of charging characteristics on EVRP is analyzed. In the subsequent "Partial Charging" section, the strategies and impacts of only partially recharging the battery during a route are delved into. A diverse set of vehicles with different capabilities and characteristics is discussed in the "Heterogeneous Fleet" section. The final section, "2E-EVRP," a type of EVRP that includes both energy consumption and emission considerations, is presented. Each section is a critical component of the complex EVRP landscape, contributing to our collective understanding and shaping future developments in this burgeoning field.

3.1 Time Windows

The time windows constraint is one of the most considered constraints in the EVRP literature. This constraint, which includes the earliest and latest time intervals that can be visited for the customers served, makes the solution of EVRP even more difficult. As presented in Figure 10, 67.8% of the examined studies were handled within the scope of the Electric Vehicle Routing Problem with Time Windows (EVRP-TW), while the time windows constraint was not taken into account in 19 studies to a rate of 32.2%.

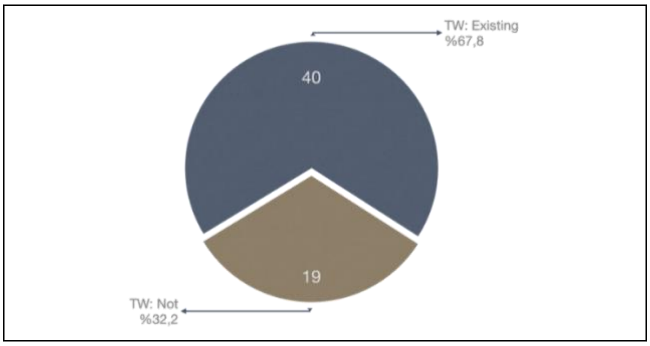

Figure 10. Distribution of publications according to time windows constraints.

3.2 Simultaneous pickup and delivery

Although the service demand of the customers is usually on the distribution side, in some industries and scenarios, a customer may have a pickup-only or both pickup and delivery demand together. The fact that some of the customers served by the same EV have a delivery demand and some a pickup demand is called the Electric Vehicle Routing Problem with Pickup and Delivery (EVRP-PD) in the literature. The scenario where the same vehicle provides pickup and delivery services to the same customer is considered EVRP with simultaneous pickup and delivery (EVRP-SPD). Of the studied studies, 7 ([48],[50],[64],[66],[73],[79],[88]) were EVRP-PD, and 2 of them ([10],[91]) covered in the EVRP-SPD (Figure 11).

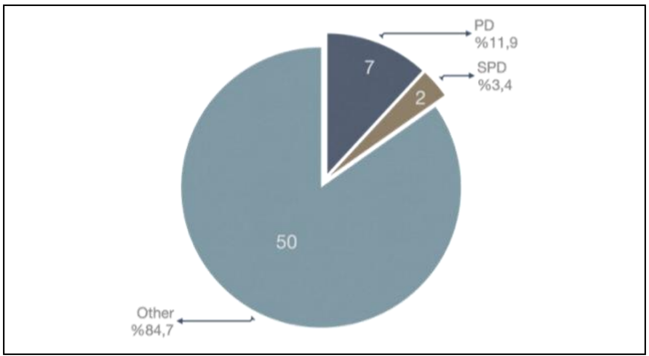

Figure 11. Number of publications considering PD and SPD constraints.

3.3 Battery swap station

Although it is assumed that 88.1% of the studies examined to meet the energy needs of EVs by charging them at the charging station, four studies ([44],[53],[65],[72]) BSSs taken into account instead of the CS. In 3 studies ([57],[70],[73]), both BSSa and CSs were considered together (Figure 12).

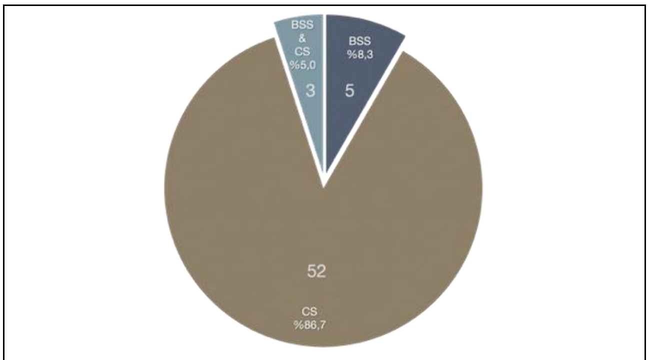

Figure 12. Distribution of publications according to charging/battery swapping.

3.4 Non-linear charging function

In the EVRP literature, it is possible to collect the assumptions about the charging time under three main headings: constant, linear, and non-linear charging times. Under the assumption of constant charging time, it assumed that when the EV comes to the CS, it leaves the CS fully charged in a constant time, regardless of the battery charge level. In the linear assumption, the charging rate is assumed to be constant. Most current EVRP models assume a linear relationship between battery charge level and charging time. For example, the charging time of a 20kW battery with a socket charging at 2kW/hr is expected to be 10 hours, but in reality, the relationship is not linear generally, while the battery charges at a linear rate up to 80% charge level-the 20% charge level charges more slowly and with a decreasing acceleration [92]. The numerical and proportional distributions of the studies that take into account the assumptions about the charging time are shown in Figure 13. While the linear charging function was the most accepted assumption at a high rate of 61.8%, the non-linear charging function, which is more suitable for real life, was considered at 23.6%. In 8 studies ([54],[58-60],[66],[69],[75],[79]), which correspond to a 14.5% rate, the assumption of constant charging time was used.

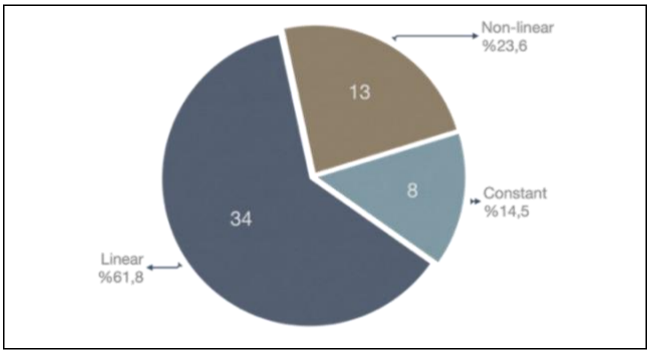

Figure 13. Distribution by charge function.

It should be noted that while the total number of studies classified within the scope of the charging function is 55, the number of studies examined within the scope of this article is 59. As seen in Figure 12, there is no charging operation in 4 studies; only the assumption of a battery exchange station is considered.

3.5 Partial charging

In the literature, there are different approaches for leaving EVs from the CS by charging them at full capacity or charging them as needed. Particularly in studies where the time windows constraint is considered, the partial charge assumption is more considered. Therefore, in addition to the charging function classification, the classification with the assumption of full or partial charge is given in Figure 14. The linear charging function was used in 16 of 25 studies, and the nonlinear charging function was used in 9 studies, which considered the partial charging assumption. Likewise, out of 31 studies considering the full charge assumption, linear charging time is valid in 19, nonlinear in 4, and constant charging time in 6 studies.

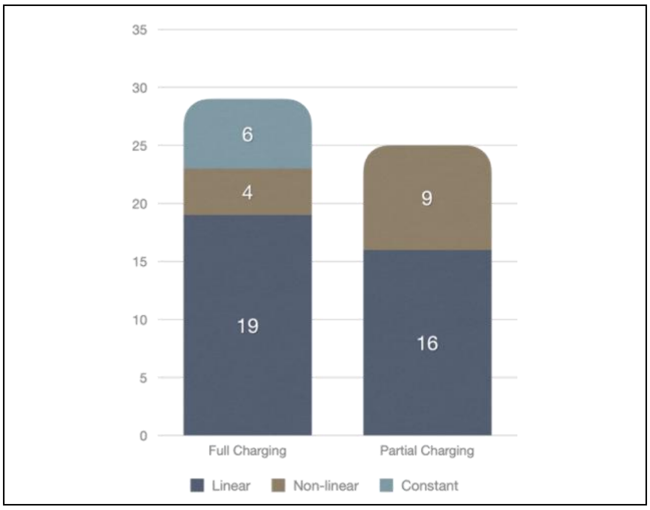

Figure 14. The Number of publications based on the charging assumptions.

3.6 Heterogeneous fleet

In order to meet customer demands, 89.8% of the same load and battery capacity. While using identical fleets with features such as 10.2%, in 6 studies ([39]-[41],[55],[60],[66]), mixed fleets consisting of non-identical EVs were used in Figure 15.

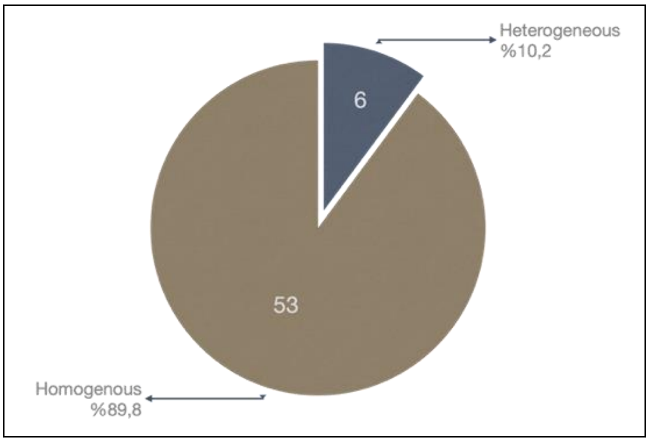

Figure 15. Distribution of publications according to fleet type.

3.7 2E-EVRP

In parallel with the countries' economic growth, there is a rapid increase in logistics activities. With the increase within the scope of environmental sustainability, local governments and states create intermediate facilities around the city, called satellites, and impose restrictions on large trucks to stay away from city centers.

Distribution is made from a central depot to the satellites around the city by larger vehicles and from satellites to customers by smaller EVs. Distribution decisions are made at two levels: determining which EVs will serve customers from which satellites. This problem is included in the literature as a two-echelon vehicle routing problem (2E-VRP). In 2E-EVRP, vehicles in the second stage consist of EVs. There are also CSs for charging EVs on the route. For this reason, it is necessary to decide how long the EVs will be charged in which CS. An example illustration of 2E-EVRP is given in Figure 16.

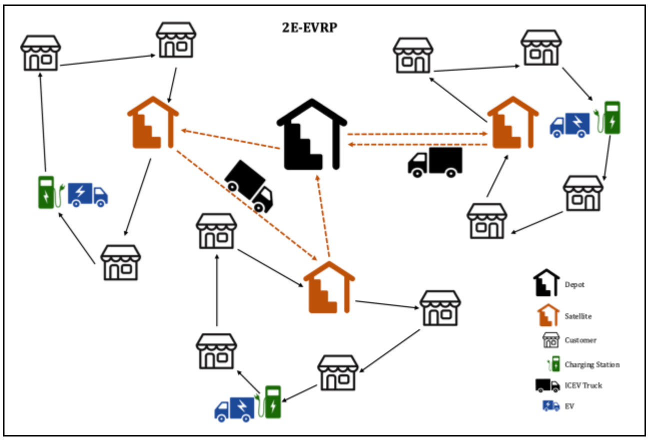

Figure 16. An Example representation of 2E-EVRP.

When the literature is carefully examined, it is seen that only four studies have been conducted on the 2E-EVRP ([60],[62],[65],[83]). Jie et al. [93] assumed that instead of charging EVs at the CS, the battery is swapped at the BSS. Since the battery swapping process has a standard processing time, it is a less complex problem than the linear, non-linear charging time and constant charging assumptions in the CS. Breunig et al. [62] sought a solution to 2E-EVRP with the assumption of CS usage and took into account linear charge time/full charge assumptions. Agárdi et al. [60] aimed to minimize the route length. Time windows constraint is not taken into account. In addition, although the concept of a CS is used, no variable related to the vehicle's charging status has been defined. There is no detail on charging consumption, charging time, and charging type. Akbay et al. [83], on the other hand, handled 2E-EVRP with a time windows constraint and reached effective solutions with the Variable Neighborhood Search (VNS) algorithm, in which Large Neighborhood Search (LNS) operators also employed in order to solve large-sized data sets quickly.

4 Solution approaches

The solution methods and heuristic algorithms used in the studies examined, apart from the problem scopes, constraints, and assumptions, are grouped according to the frequency of use. As seen from the pie chart in Figure 17, 11 of the 59 studies examined had only exact solution results, and 13 of them only the results of the proposed heuristic algorithm or algorithms. In comparison, the experimental results of the developed mathematical model and the proposed heuristic algorithm(s) were given in 35 studies.

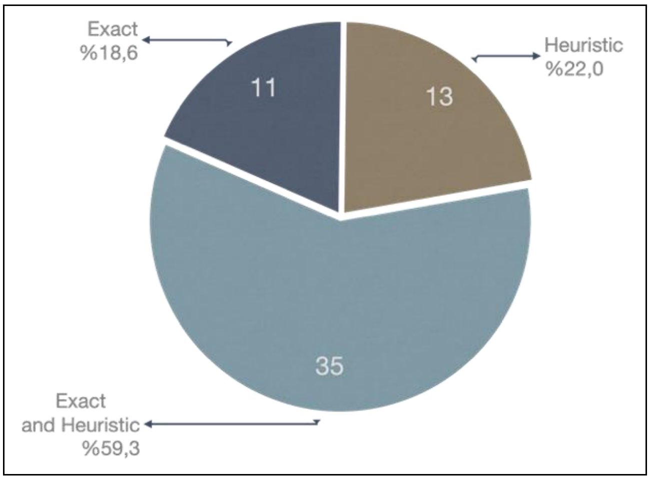

Figure 17. Distribution of publications according to solution approaches.

Among the heuristic algorithms proposed as a solution method in the studies examined, it is the most widely used large neighborhood search (LNS) algorithm with 26.8%. In addition, the variable neighborhood search (VNS) algorithm was used with 16.9%, the local search (LS) algorithm with 14.1%, tabu search (TS) algorithm with 8.5%. Since more than one heuristic algorithm is used in most studies, the total number in Figure 18 is higher than the number of studies examined. Therefore, it would be helpful to examine Table 3 to see which solution approaches were used in each study. In addition, the meanings of the abbreviations in Figure 18 are given below in Table 3.

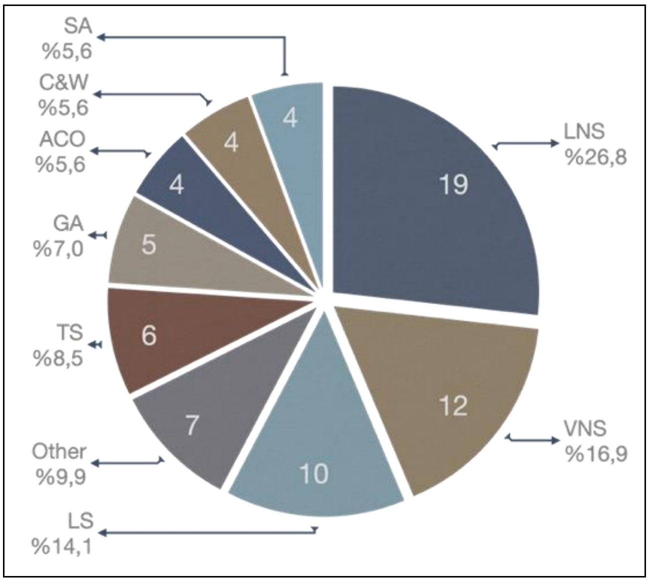

Figure 18. Distribution of heuristic solution methods.

5 Conclusions

There is yet to be comprehensive and extensive scientific literature on EVs, which are no longer the technology of the future and are rapidly becoming widespread and used in different fields. Therefore, more researchers can contribute to this field. Furthermore, opportunities to study different topics are available for further research. For example, more flexible solutions can be found by considering mobile charging stations in the models. Furthermore, almost all conventional ICEVs can be converted to electric or replaced. Therefore, other variants of the Vehicle Routing Problem (VRP) can be considered and investigated under the EVRP. Another area for improvement observed in this study is that research on exact solution methods is scarce and more researchers are needed to design approaches for optimal solutions to problems. It is impossible to say that the developed heuristic solution algorithms reach the solution quickly in large-sized data sets. Although the number and variety of datasets used in the literature are low, there are few studies using real-world data. Therefore, there is a need for studies that consider realistic assumptions and constraints using real-life data. Finally, new problems related to the routing of EVs will arise due to the development of such technologies as autonomous vehicles, 5G, and the internet of things (IoT), and new models and algorithms can be proposed and investigated.

6 Author contribution statements

In the study carried out, Can Berk KALAYCI in the formation of the idea, the design, the literature review, checking the spelling, and checking the article in terms of content; Yusuf YILMAZ contributed to the review and classification of articles, creation of figures and diagrams for literature analysis, and interpretation of results contributed.

7 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person/institution in the article prepared.

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