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ELECTRIC VEHICLE ROUTING PROBLEM: VARIANTS AND INDUSTRY IMPLICATIONS

Keywords

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Abstract

Transportation is the largest contributor to global greenhouse gas emissions. However, alternative-fuel powered vehicles can reduce pollutions and transportation cost as well. The focus of this study is on electric vehicles (EV) and particularly on one class of combinatorial problems: Electric vehicle routing problem (EVRP). The mathematical model for EVRP is presented, its variants are discussed and industry implications of EV are elaborated with special focus on battery-related issues, such as price, charging mechanisms and lifespan.

1. INTRODUCTION

The transport sector is responsible for 30% of the CO_2 emissions in European Union (EU), while this share reaches the 40% in urban areas [1]. At the same time, environmental concerns and operative issues in distribution process become key topics for many logistics companies that aim to reduce pollutions (greenhouse gas emissions) and transportation costs. The pollution problem (emissions of CO_2, SO_2, and NO_x) led to increase in research for more environmental transport solutions. From the industry perspective, many alternative-fuel powered vehicles are developed. They rely on the following energy sources: hydrogen, natural gas, electricity, etc. The focus of this study is on electric vehicles (EV) as they offer to reduce both, transportation costs and pollutions in comparison to fossil-fuel vehicles.

EVs are generally divided into battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs). An advantage of BEVs and HEVs is their ability to use their electric motor for regenerative braking to recuperate kinetic energy [2]. The process of recharging EV is an important issue as it greatly determines their use, both in terms of availability and flexibility. There are several different methods for charging: slow charging, fast charging, battery swop stations and inductive charging [1]. Hybrid EVs have recently been developed to reduce the necessary stops and dependence on infrastructure by using two different engines, a pure electric motor and an internal combustion engine [3].

That promising perspective of EVs to be included in everyday logistics processes, and particularly in last-mile delivery, motivated the authors to consider a specific class of combinatorial optimization problems: the electric vehicle routing problem (EVRP). The EVRP is approached from practical and scientific perspective.

The paper is organized in the following way. Section 2 presents a problem definition and mathematical model of EVRP. Section 3 overviews variants of EVRP and different algorithms that are used to solve EVRP. In Section 4 we present future perspectives of conventional and electric vehicles, and finally, Section 5 provides concluding remarks.

2. PROBLEM DESCRIPTION AND MODEL

The EVRP is an extension of the traditional vehicle routing problem (VRP) that specifically deals with finding optimized routes for electric vehicles, taking battery constraints and charging operations into account. The EVRP can be described as finding a set of vehicle routes, where each route services a set of customer nodes and starts and ends at a given depot node. The problem aims to find the best route plan for electric vehicles that minimizes a given cost function while satisfying a number of restrictions and operational procedures for electric vehicles [4]. An illustrative example of a route of the EVRP in shown in the Figure 1.

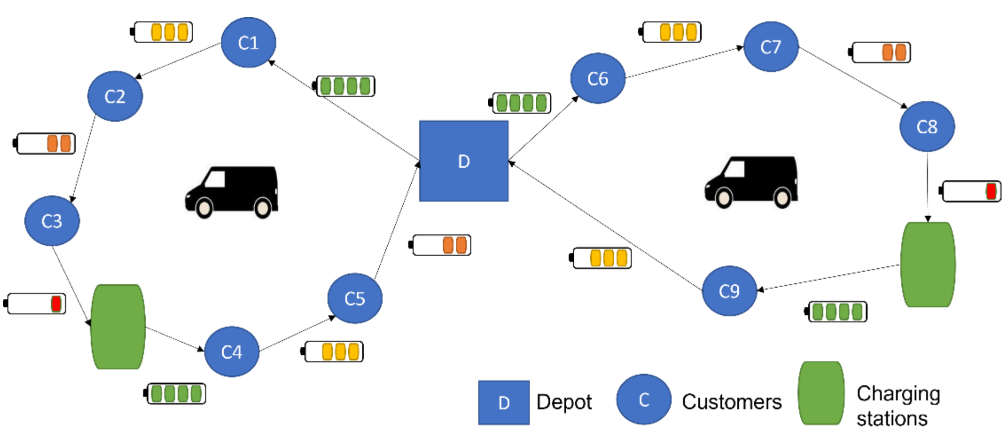

Figure 1. An illustrative example of a route of the EVRP

2.1. MATHEMATICAL MODEL

From the scientific perspective, the most often criterion in VRP and also EVRP is the minimization of total distance and consequently fuel consumption and CO_2 emissions. A mathematical formulation of the basic EVRP can formulated as follows.

Notation:

Depot nodes: *N*
Set of charging stations: *F*
Set of customers: *V*
Set of vehicles: *K*
Energy consumption rate of the vehicles per unit distance: *h*
Battery capacity of the vehicles: *Q*
Traveling distance from node i to node j: *dij*

Objective function:

$$\sum_{i \in V_0'} \sum_{j \in V_{N+1}'} \sum_{k \in K} d_{ij}\, x_{ij}^k \rightarrow min \tag{1}$$

Subject to:

$$\sum_{j \in V_{N+1}'} \sum_{k \in K} x_{ij}^k = 1, \forall\, i \in V \tag{2}$$

$$\sum_{j \in V_{N+1}'} \sum_{k \in K} x_{ij}^k \leq 1, \forall i \in F' \tag{3}$$

$$\sum_{j \in V'} x_{0j}^k \leq 1, \forall k \in K \tag{4}$$

$$\sum_{i \in V_0'} x_{ij}^k = \sum_{i \in V_{N+1}'} x_{ij}^k\,, \forall j \in V', \forall k \in K \tag{5}$$

$$y_j^k < \ y_i^k - \left(h * d_{ij}\right)x_{ij}^k + Q\left(1 - x_{ij}^k\right),, \forall i \in V, \forall j \in V_{N+1}', \ \forall k \in K \tag{6}$$

$$y_j^k < \ Q - \left(h * d_{ij}\right)x_{ij}^k\,, \forall i \in F' \cup \{0\}, \forall j \in V_{N+1}', \ \forall k \in K \tag{7}$$

$$y_0^k < \ Q, \forall k \in K \tag{8}$$

The objective function (1) aims to minimize the total distance of electric vehicles. Constraints (2) handle the connectivity of the customer nodes. Constraints (3) ensure that each dummy charging station can be visited at most once. Constraints (4) make sure that each electric vehicle can be used only in one route plan. Constraints (5) ensure that the total number of outgoing arcs is equal to the total number of incoming arcs at customer and charging station nodes, which provides continuity in the routes. Constraints (6)-(8) track the battery level of the electric vehicles and their battery state after the recharging operations at the charging stations following a full charging policy. Described model considers capacity of the battery as the only constraint. In the case of a capacitated EVRP, EVRP with time window, and EVRP with a heterogeneous fleet additional constraints need to be added.

3. VARIANTS OF EVRP

The maximum driving range of most EVs is between 160 and 240 km [5]. However, it decreases significantly by the impact of weather conditions (e.g. low temperatures) and terrain configuration (e.g. hills). As a direct consequence, the driving range of EVs is often not sufficient to complete logistics services and charging stations need to deployed throughout the transportation network. It basically depends on the capacity of the battery, specific logistics task (objective function), available fleet (EV, hybrid vehicles, drones), and so on. From the practical and scientific perspective, at least three different classes of EV problems can be highlighted (Table 1).

Table 1. Variants of EVRP [6]

Variant	Decision Variables	Constraints	Objectives
Fleet size and mix	(1) The number and type of EVs to be purchased. (2) The ideal composition of the heterogeneous fleet.	(1) Environmental standards and price incentive to acquisition of EVs. (2) Fixed and variable charging times. (3) Limited budget to renew the fleet of vehicles.	(1) Minimize the acquisition and operating costs of new EVs. (2) Maximize the satisfaction of customer needs. (3) Minimize the environmental impact.
Charging networks	(1) Number and geographical position of recharging stations. (2) Capacity of recharging stations. (3) Technology of recharging stations (low or fast recharge). (4) Swapping or recharging of batteries.	(1) Limited budget to install new recharging stations. (2) Needs of EVs to recharge or exchange batteries.	(1) Minimize the investment and operating costs of charging networks. (2) Maximize the level of service to customers.
Routing	(1) The number of visits to recharging stations. (2) The timing of visits to recharging stations. (3) Available recharging resources to vehicles in recharging stations. (4) The option of recharging or swapping batteries.	(1) Geographical position of recharging stations. (2) Capacity of recharging stations. (3) Fixed or variable recharging/swapping times.	(1) Minimize routing cost considering recharging operations. (2) Minimize routing times considering recharging operations. (3) Minimize recharging and swapping costs.

To solve previously mentioned aspects of EVs many exact and approximate algorithms have been developed (Figure 2). Approximate algorithms can be analyzed as heuristics and metaheuristics.

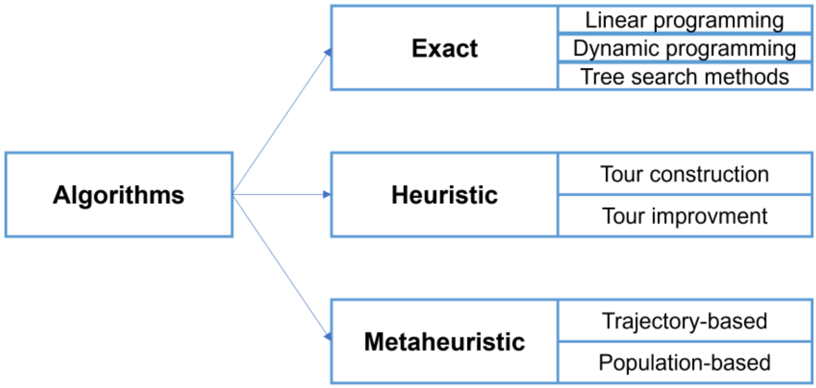

Figure 2. Algorithms used to solve different EVRPs

Exact algorithms for EVRP include branch and bound, cutting planes, dynamic programming, linear programming, and other methods. Exact algorithms are mostly used to address small scale EVRPs, as their complexity increases exponentially with the number of nodes. Approximate algorithms encompass heuristics and metaheuristics approaches. Heuristic algorithms for EVRP include tour construction and tour improvement algorithms. Metaheuristic algorithms for EVRP include a wide range of methods, including trajectory-based and population-based search. One of the classifications is presented in the Figure 2.

4. INDUSTRY IMPLICATIONS

According to the 2019 report of the world energy outlook series, the future estimation of energy systems indicates that a serious loss will happen by 2040 [7]. Tremendous progress and development of information and communication technologies (ICT), particularly in security aspects, offer opportunities for ICT-supported energy transition, including investigation of hydrogen and renewable energy However, there are predictions that the share of electric energy in final consumption will exceed the oil by 2040 [8], mainly due to EVs. Having that in mind, EU has targeted a 40% reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 (European Commission, 2014). This will be a great challenge for the transportation sector and logistics companies.

The main aspects that determine the competitiveness of EV are the purchase price, battery costs and lifespan, and practical implications of vehicle operations. Between them, battery-related issues, such as specific energy, specific power, and price will have the major role in development of the ecosystem for EV. While future lithium-ion cells' specific energy could reach 300 Wh/kg, development of technologies such as lithium-sulfur (Li-S) and lithium-air (Li-air) batteries should allow reaching values above 500 Wh/kg [9]. Zinc-air (Zn-air) batteries are another option in development that could improve specific energy [10]. Projections for different BEV battery types are provided in Table 2.

Table 2. Projections for promising BEV battery types [11]

Battery type		**Li-S**	**Zn-air**	**Li-air**
Specific energy (Wh/kg)	< 2025	400	250	500
	> 2025	500	350	1000
Specific power (W/kg)	< 2025	300	Unknown	Unknown
	> 2025	400	Unknown	Unknown
Cost ($/kWh)	< 2025	Uncertain	Uncertain	Uncertain
	> 2025	250-500	100-300	350-700
Issues		Safety Cycle life	Specific power Charge efficiency	Specific power Cycle life Safety

To make the use of electric vehicles as accessible as possible the price of mostly-used lithium-ion batteries need to decrease over time. In the Table 3 the prediction of price range for lithium-ion batteries is presented.

Table 3. Projections for Lithium-Ion Battery Pack Cost [12]

Period	2010-11	2012-13	2015	2020	2025	2030
Estimate ($/kWh)	650-1000	500-800	400-700	300-500	225-400	200-300

Two more important aspects are battery lifespan and battery charging. Lithium-ion batteries' health can be negatively influenced by the way they are used and stored, and, therefore, the vehicle's range can be decreased. The most common way of charging batteries is with cable and connector. Charging modes are defined by the communication protocol between the vehicle and the charging equipment [12].

5. FINAL REMARKS AND FUTURE WORK

EVs reduce transportation costs and pollutions more efficiently in comparison to conventional vehicles. On the other side, EVs have one main disadvantage compared to conventional vehicles: they have batteries that need to be charged which limits their range and often cause long charging periods. Therefore, EVs and particularly EVRP are attracting growing interest from researchers, practitioners, non-profit organizations, and governments.

By introducing EVs in distribution and logistics processes, urban transportation is faced with transition. Infrastructure, traffic network, signalization, and traffic regulations will need to be adapted to create transportation ecosystem for EV.

The future work could focus on extending the research on detailed investigation of algorithms used to solve EVRP. In addition, battery technology, charging technology, and regulatory consideration can be further explored.

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