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Electric Vehicle Routing Problem with industry constraints: trends and insights for future research

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Abstract

This paper presents and analyzes the one-to-many vehicle routing and scheduling problem with electric vehicles. Initially, focus is given on the problem formulation and the restrictions imposed in practice are examined. EVRP is NP-hard in the strong sense since it is natural extension of the well-known Capacitated Vehicle Routing Problem and requires substantial computational effort for determining optimal or near optimal solutions for medium and large scale problem instances. A comprehensive mathematical formulation is developed in order to model the EVRP and the multiple constraints appeared due to capacity limitations, time window restrictions and the predefined charging level of the vehicles. In addition, recent trends for the EVRP are analyzed producing valuable insights for future research regarding extra operational constraints, real-life data sets and solution frameworks that embody approximation algorithms for an efficient and effective search of the solution space.

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Keywords: Electric vehicles; routing and scheduling; mathematical formulation

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1. Introduction

In today's economy, markets tend to become increasingly open and competitive. The existence of an efficient, sustainable and environmental friendly freight transportation system is a vital factor for success. Environmental concerns and management issues related to the flows of freight have become crucial concerns for modern companies seeking to reduce energy consumption and the related production of greenhouse gas (GHG) emissions. The transport sector is responsible for 30% of the CO_2 emissions in EU while this share reaches the 40% in urban areas. For that reason, the efforts for technological improvements and innovation in transportation have been increased during the last decades and the electric delivery vehicles is the new trend in United States for many companies such as Fed Ex and UPS.

There is no doubt that urban cargo distribution with electric vehicles is beneficial to the environment. Cargo EV's are emission-free (except brake and tire wear) and perceived as more silent in operation. CEP and pharmaceutics services deliver with vans and small size trucks in regionally limited areas. Their daily distance range is below 140km. Therefore, EV's might potentially replace Commercial Vehicles (CVs) in delivery services in the near future (University of Duisburg-Essen, 2011). The cost competitiveness of electric trucks to conventional trucks is in the long term one of the most critical aspects to achieve a large-scale implementation of electric transport. Davis and Figliozzi (2013) did a study in the U.S. with three types of recent technology electric delivery trucks in order to examine their competitiveness to conventional trucks under varying scenarios. The study showed that electric trucks can be competitive in case the cost savings from the reduced operational cost are enough to overcome the significantly high purchase costs. Other parameters of cost increase, according to Jüchter (2011), are the significant costs for charging infrastructure in companies.

The process of recharging electric vehicles is an important issue as it greatly determines their use, both in terms of availability and flexibility. Regarding freight transport the charging techniques that get most attention so far are slow charging, fast charging, battery swop stations and inductive charging. Research in this field is so far addressing to applications for passenger cars. Still an unsolved problem related to charging process is the lack of compatibility of different chargers plugs. Standardization of charging plugs on a worldwide level is further discussed.

Limited literature discussing charging infrastructure for UFT indicates that since delivery vehicles tend to follow the same route each day and return to its company premise every night the possibility to recharge slowly during the night is a satisfying solution (Feng and Figliozzi, 2013; Ehrler and Hebes, 2012). The advantage of night charging is that public charging infrastructure has a lower demand than through the daytime (Schönewolf , 2011) and in some countries night current supply has a reduced cost. However, it occurred to be that the installation and operation of in-house charging infrastructure was technically challenging, therefore higher costs than initially planned (Schönewolf, 2011). In case charging is to take place outside the transport company premises (public charging infrastructure) logistic processes and vehicle routing need to be rescheduled (Schönewolf, 2011). Furthermore regaining energy through public charging stations, batteries should be quickly charged without damage (Schönewolf, 2011).

The key factors that determine the competitiveness of electric goods vehicles are the purchase price, fuel price, battery costs and lifetime and the vehicle utilization. Certainly rising conventional fuel costs in addition to falling battery costs will boost EV's market. At present electric vehicles are not competitive if routing constraints lead to the purchase of additional vehicles above the required number of conventional vehicles. Therefore, current priority until any future technological breakthrough is the optimization of delivery cargo EVs in urban environment.

The focus of this paper is given on a modified vehicle routing problem using electric vehicles instead. Given a homogeneous fleet of depot-returning electric capacitated vehicles and a set of charge stations where vehicles recharge their battery, the goal is to design a set of routes that satisfy the delivery requirements of a set of geographically scattered customers. Each customer has a known demand for delivery and it must be serviced within a predefined time window that denotes the earliest and the latest times to begin the service. Vehicles are charged at the depot and can travel for a predefined distance before they need to visit a charging station in order to be fully recharged. Finally, each customer must be visited only once by exactly one vehicle and the load of the vehicle must not exceed its maximum capacity. The primary objective is to minimize the fleet size, while the secondary objective is to minimize the distance traveled since the goal is to minimize the total routing cost.

Considering the Electric Vehicle Routing Problem (EVRP), the practical perspective embodies multiple restrictions as well as operational constraints that enforced in practice for urban freight distribution using electric vehicles. The EVRP is NP-hard since it is derived from the well-known Capacitated Vehicle Routing Problem (Toth and Vigo, 2002) and thus, substantial computational effort is required for gaining high quality solutions even for medium scale instances. Fig. 1 depicts a simple example of the EVRP where there is only one electric vehicle, 2 charge stations and a set of 9 customers. The aim of this paper is to develop a comprehensive model that captures the realistic restrictions of the problem and also, to discuss and identify recent trends in transportation sector with respect to the electric vehicles. To this end, essential insights for future development are presented in an attempt to constitute the basis for future research inspired by industry needs.

The remainder of the paper is organized as follows: Section 2 provides an overview of the corresponding literature and then, Section 3 presents the definition and the notation of the problem that describes the aspects of the problem. Section 4 discusses and analyzes the problem variants that utilize electric vehicles as well as the proposed solution approaches presented in literature providing also pointers for future research. Finally, in Section 5 conclusions are drawn giving a summary of the EVRP potentials.

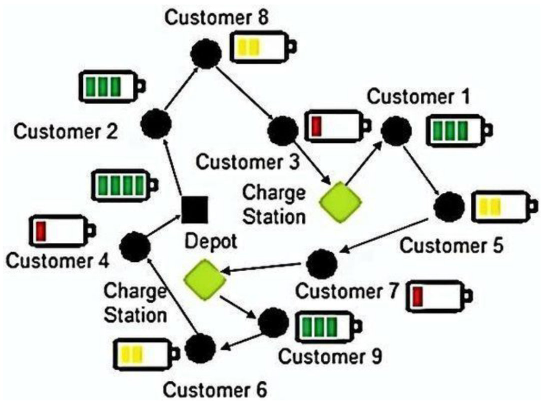

Fig. 1. A route of the EVRP

2. Literature Review

The EVRP is introduced the latest years due to the commercialization of electric vehicles and their use in urban freight distribution is imperative since the environmental protection and the minimization of the energy consumption constitute major concerns for governments. Literature provides some indications regarding distances travelled for urban deliveries and how this fits with the range of EVs. In the U.S. an average distance of 36 miles per day was found by FHWA (2009, 2010), while a report by FedeX (Barnitt, 2011) concluded to a distance of 41,4 miles, as the average travelled distance by delivery trucks. Both distances are significantly lower than the range achieved and claimed by EV manufacturers. EV's in CEP-services travel less than 40 km per day (Schönewolf, 2011). According to University of Duisburg-Essen (2011), the following commercial sectors might incorporate EVs in their fleets: CEP-Services, forwarding companies, and pharmaceutics, social services, newspaper and flower delivery. Simulation and analysis of freight transport activities indicated cargo delivery with EVs in CEP, postal and public cleaning services (University of Duisburg-Essen, 2011). Textile logistics also offer a large potential allowing multi-shift delivery (Schönewolf, 2011). Moreover, CEP service providers often work with sub-contractors who own their vehicle and use it privately.

Although the penetration of electric vehicles follows an accelerated pace, the literature about effective solution approaches for electric vehicle routing and scheduling appeared limited and there is still much room for contribution. Below, an overview of the studies encountered in literature is provided.

Artmeier et al. (2010) study the most economical plan of routing in terms of energy consumption rather than the shortest one in terms of traveled distance and propose a generic solution framework for the Shortest Path Problem considering trees of paths and an energy graph presenting the energy consumption. The proposed framework encompasses four different strategies (Dijkstra, Expand, FIFO and Expand-distance) that determine the next vertex to expand in an effort to obtain the energy-optimal route. It is the first attempt to introduce electric vehicles and the main interest lies on the energy consumption considering acceleration and deceleration costs as well as hard and soft constraints. The presented solution approach is implemented in a prototype navigation system that developed to generate the optimum route in terms of energy consumption.

Later, Conrad and Figliozzi (2011) present a Rechargeable Vehicle Routing Problem with time windows where vehicles can be recharged at customer locations during the service process and visits to customers are allowed only within a predefined time window. This problem constitutes the basis for the studied EVRPTW and the main objective is twofold; first, the minimization of the total number of vehicles and then, the minimization of the total routing cost including traveled distance, service time and recharging time. Bounds on the average traveled distance are established and based on the latter a regression analysis for the estimation of the average distance traveled is occurred.

In the context of the renewable sources of energy, Erdoğan and Miller-Hooks (2012) describe a generic Green Vehicle Routing Problem (GVRP) that encompasses the challenges associated with alternative fuel vehicles as the electric vehicles are with the aim to minimize the total distance travelled by the vehicles. They developed a modified Clarke and Wright construction heuristic based on geographical criteria (i.e. distance among customers) and a density-based clustering algorithm based on spatial properties (i.e. distribution of customers in the space) followed by a customized improvement technique that follows an inter- and intra- route exchange neighborhood search in order to deal with the GVRP.

More recently, Schneider et al. (2014) study a vehicle routing problem with intermediate stops which considers necessary visits at intermediate locations as the EVRP also requires. The main goal of the problem is to minimize the sum of the total travel cost and the fixed vehicle cost and an efficient solution scheme introduced incorporating a modified Clarke and Wright (1964) heuristic in order to generate the initial routes and also, adopts a metaheuristic Adaptive Variable Neighborhood Search algorithm for further improvement. The latter employs both an exchange and a relocate neighborhood structure, while the selection of customers is favored according to their previous performance within the search process.

On the other hand, Barco et al. (2012) study the EVRP from the public transport perspective and present a case study about carrying passengers from an airport to a hotel using electric vehicles and following the notation of the Dial-a-Ride Problem (DARP). A scheme that coordinates the routing, charge scheduling and operating costs is proposed taking into account the battery degradation as well as the recharging cost, while patterns allowing the increase in the battery lifetime were also obtained.

Finally, Baouche at al. (2013) present an alternative study for the EVRP and efficient tools are developed to minimize the energy consumption based on dynamic information in an effort to promote the use of electric vehicles in practice. Although there are also many studies in literature including Suzuki (2011), Xiao et al. (2012) and Li (2012) that are focused to energy consumption, their interest appears only on critical factors of the objective function for energy consumption (i.e. travel speed, load and distance) without considering alternative sources of energy (as electricity).

3. Problem Definition & Notation

According to the study of Davis and Figliozzi (2013), the most significant factors affecting commercial electric vehicle competitiveness are the route feasibility, minimum fleet size, minimum traveled distance, charging level, purchase costs and planning horizon. Inspired on the above and following the objective function of the classic VRPTW, this research study presents a detailed model of the EVRP that considers realistic operational constraints (i.e. vehicle capacity and time widows of customers) and captures the most important parameters for optimal routing where electric vehicles exist. It is an attempt to provide a complete mathematical model for the EVRPTW that incorporates the real-life processes and limitations that a company should contemplate for routing and scheduling a fleet of electric vehicles.

The EVRPTW is defined as a complete and indirect graph $G = (V, A)$, where V is a set of customers $C = \{c_0, c_1, ..., c_n\}$, the charge stations $S = \{s_1, ..., s_m\}$ as well as the depot d_o that acts also as a charge station; and A is a set of arcs $A = \{(i.j) \in V x V : i \neq j\}$. Each arc is associated with a travel distance $d_{ij,}$ and speed is assumed to be constant. Given a set of vehicles $K = \{k_1, k_2, ..., k_k\}$, each customer $i \in C$ is associated with a demand δ_i to be delivered, a service time p_i, and a time window $[e_i, l_i]$ that models the earliest e_i and the latest l_i times during the day that service can begin while for corresponding time window for the depot is $[E, L]$. During the service of the customers, all vehicles must remain at the customer locations for a predefined amount of time (service time) and in case that a vehicle arrives early; it has to wait w_i time until its service. Similarly, vehicles remain parked at the stations for a (charging) time h_i during charging. A route starts from the depot, visits a number of customers and a number of charging stations and returns to the depot as depicted in Fig 1. Note that each customer should be served by exactly one vehicle that can visit him only once while the depot acts also as charge station and can be visited many times for charging.

Given that vehicles visit the charging stations more than once, an extra set $S' = \{s_{m+1}, s_{m+2}, \ldots, s_{m+h}\}$ is used to represent the multiple visits, and depot d_o is defined as a set $D = \{d_{o+1}, \ldots d_{o+t}\}$. Hence, the new graph $G' = (V', A')$ is created, where $V' = C \cup S \cup \{d_o\} \cup S' \cup D$ and $A' = \{(i.j) \in V' x V' : i \neq j\}$. Let x_{ij} be the binary variable that is defined as 1 if the vehicle k travels from i to j and 0 otherwise; y_i denotes the remaining electric energy after the visit at customer i or at charge station s and depot d_o; q_{ik} denotes the time when service starts at customer i by vehicle k; τ denotes the vehicle consumption rate, M the capacity and Q the battery level of charge; the mathematical formulation is presented as follows:

$$\min \sum_{k \in K} \sum_{(i,j) \in A'} d_{ij} x_{ijk} \tag{1}$$

Subject to:

$$\sum_{k \in K} \sum_{j \in V'} x_{ijk} = 1 \qquad \forall i \in C, \forall k \in K \tag{2}$$

$$\sum_{j \in V'} x_{ijk} - \sum_{j \in V'} x_{jik} = 0 \qquad \forall i \in V', \forall k \in K \tag{3}$$

$$\sum_{k \in K} \sum_{j \in V'} x_{ijk} \leq 1 \qquad \forall i \in V' \setminus C, \forall k \in K \tag{4}$$

$$x_{i,j,k}(q_{ik} + p_i + t_{ij} - q_{jk}) \leq 0 \qquad \forall k \in K, (i,j) \in A' \tag{5}$$

$$e_i(\sum_{j \in V'} x_{ijk}) \leq q_{ik} \leq l_i(\sum_{j \in V'} x_{ijk}) \qquad \forall k \in K, \forall i \in C \tag{6}$$

$$E \leq q_{ik} \leq L \qquad \forall k \in K, \forall i \in \{d_o\} \tag{7}$$

$$y_j \leq y_i - \tau d_{ij} x_{ijk} + Q(1 - x_{ijk}) \qquad \forall i \in V', j \in C, \forall k \in K, i \neq j \tag{8}$$

$$y_i \geq min\{\tau d_{io}, \tau(d_{ij} + d_{jo})\} \qquad \forall i \in C, \forall j \in S \bigcup S' \tag{9}$$

$$y_i = Q, \qquad \forall i \in d_o \bigcup D \bigcup S \bigcup S' \tag{10}$$

$$\sum_{j \in C} \delta_j \sum_{i \in V'} x_{ijk} \leq M, \qquad \forall k \in K \tag{11}$$

$$x_{ijk} \in 0,1, \qquad \forall i,j \in A', \forall k \in K \tag{12}$$

$$y_i \geq 0, \qquad \forall i \in A' \tag{13}$$

$$q_{ik} \geq 0, \qquad \forall i,j \in A', \forall k \in K \tag{14}$$

On the basis of the above, the objective function (1) indicates that there are two objectives, first to minimize the number of vehicles required to service all customers and then, to minimize the total distance traveled. The (2) constraint ensures that each customer is served by exactly one vehicle and constraint (3) present that the number of the vehicles that arrive at a node is equal to the number of the vehicles that depart from it, and constraint (4) presents the flow of a path followed by a vehicle k. Moreover, constraints (5), (6) and (7) represent the time windows constraints and (11) the capacity constraint, where M are the units of loading capacity. However, based on Cordeau et al. (2001), constraint (5) can be linearized as follows:

$$q_{ik} + p_i + t_{ij} - q_{jk} \leq (1 - x_{ijk}) B_{ij}, \qquad \forall i, j \in A', \forall k \in K \tag{15}$$

where B_{ij} represents large constraints that could be replaced by $max\{l_i + p_i + t_{ij} - e_j, 0\}$, $\forall$ $k \in K$, $(i,j) \in A'$. Constraint (8) represents the level of charge reduced according to the distance travelled; constraint (9) ensures that there is enough remaining energy to return to the depot either directly or via a charge station; and constraint (10) represents when a car is fully charged. Finally, the (12) is a binary constraint and either $x_{ijk} = 1$, in case that the vehicle k serves the customer i and then the customer j, or $x_{ijk} = 0$ if not.

Regarding the energy consumption, the *operating mode* of the vehicle constitutes a crucial factor that should be taken into consideration to estimate the y_i remaining electric energy of each vehicle after the visit at a customer i. Based on Davis and Figliozzi (2013), the energy consumption E_c of a vehicle with average speed υ (km/h) and weight w_e (kg) due to the operating mode could be defined as:

$$E_c = \frac{\rho \cdot ul \cdot fv \cdot \upsilon^3}{2} + f \cdot \upsilon \cdot w_e \cdot \upsilon + g \cdot w_e \cdot \upsilon \tag{16}$$

where ρ represents the air density (km/m^3), ul is the coefficient of drag, g is the average road gradient (%) and fv is the frontal area of the vehicle (m^2) which depends on the average speed of the vehicle.

4. Current trends and motivations for future research

In this section the recent trends and observations about the EVRP are presented and discussed. Among these special consideration is given on future research and directions are drawn with respect to industry needs and technological developments.

To begin with, a shift towards more energy-efficient problems can be observed and an intense interest of the research community belongs to EVRP. However, comparisons are not feasible since different objective functions and constraints are encountered. This calls for an integrated study of the problem by researchers that requires a systematic analysis of the real-world environment to capture the industry perspectives and exploit the scientific background.

Towards this direction, dynamic information about travel times and customer requests could go the research a step further in an effort to capture the dynamic nature of real problems encountered in practice. Studies dealing with realistic constraints are still limited and the study of a real-world problem appeared in industry could enhance future research. Another critical research pointer is the study of the cooling/heating usage for the freight EVs with respect to the energy consumption. The energy effect of the cooling/heating usage could be examined under different weather conditions (standard, cold and hot) since recent outcomes for passenger electric cars (Bütler and Winkler, 2013) prove the importance of this factor and particularly, it is observed that the heating usage appears a higher impact on energy consumption compared to the cooling.

Similarly, the benchmark data sets used for evaluation are derived from instances previously generated for the known capacitated VRP (such that instances generated by Christofides and Eilon (1969) and used for the EVRP by Schneider et al. 2014) since industry information is not available. Therefore, a valuable pointer to future research is the input of practitioners. Empirical studies dealing with small or large scale problems could play an important role in the development of robust and effective solution methods.

Additionally, the proposed mathematical model could be enriched considering extra constraints such that a heterogeneous fleet of vehicles, battery degradation as well as costs of recharge. Another possible modification of studying the EVRP is to consider the possibility that customers own charging infrastructure offering fast charges for a reduced transport fee of goods when delivery lasts longer than 20-30 minutes. This is an innovative idea due to the restrictive use of the EVs and it could be really efficient for EV owners and cost-saving for customers.

Besides operational constraints, the practical perspective of a distribution – collection system is to route and schedule these activities in a way that increases the possible synergies of combining pickup and delivery customers. For this reason, merging products brought to the customers as well as products brought back to the depot is a realistic case that seems to interest the logistics industry sector and it should be employed by researchers in near future.

Due to the computational complexity of the EVRP, the current trend predominately belongs to approximate methods (such that the Clarke and Wright heuristic, the density-based clustering algorithm and the Adaptive Variable Neighborhood Search) that sacrifice the optimum solution for the sake of getting high quality solutions in a significantly reduced amount of time. Comparison can be done by looking at the different results achieved for the same benchmark instances. As it is already mentioned, comparisons for EVRP are not possible while in case of GVRP, the modified benchmark data sets proposed by Erdoğan and Miller-Hooks (2012) are also used by Schneider et al. (2014) and new best results are reported. Nonetheless, the evaluation of the proposed methods depends on multiple criteria i.e. accuracy, speed, flexibility and simplicity (Cordeau et al. 2005). Thus, researchers should consider a four-level analysis to develop more sophisticated solution procedures that embody approximation algorithms, memory structures, operators and efficient search mechanisms of the solution space in a way that enhances robustness and minimizes complexity.

5. Conclusions

Over the last years with increasing environmental consciousness, the use of electric vehicles has become critical due to the economic and environmental importance for an effective and an energy-efficient urban freight distribution. This paper draws essential observations about the recent trends of the EVRP and proposes a mathematical model inspired of the known VRPTW. The main effort is to provide an outline of the literature and the available solution frameworks identifying promising directions for future research that appear an intense interest in practice. The latter reveal that moving towards more realistic and rich problems, real case studies are of great interest and real-life data sets will provide the basis for the evaluation and the comparison of different solution approaches. Finally, the development of more sophisticated solution schemes that render considerable efficiency may also ensure future increase and effectiveness in use of the electric vehicles.

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