A pickup and delivery problem with a fleet of electric vehicles and a local energy production unit

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Extended abstract submitted for presentation at the 11th Triennial Symposium on Transportation Analysis conference (TRISTAN XI)
June 19-25, 2022, Mauritius Island

April 11, 2022

Keywords: pickup and delivery, electric vehicles, routing, energy production

1 INTRODUCTION

We study a problem in which a set of capacitated Battery Electric Vehicles (BEVs) carry out pickup and delivery operations with time windows constraints. The energy needed to recharge the batteries of these vehicles is produced in a production unit (p.u.) that is also the depot of the vehicles. Additional batteries are available at the depot, where vehicles can go and swap their batteries. Pickup and delivery operations must be planned over a time horizon divided into periods. In each period it must be decided how much energy to give to the batteries that are at the production unit. Also, if the energy produced is in excess of that required by the batteries, this excess can be sold to the general network at a profit. If the energy required by the batteries is greater than the energy produced, an unlimited amount of energy can be bought from the general network. The objective of the problem is to plan vehicle routes to meet all pickup and delivery demands while maximizing the profit that is made from the energy sold over the time horizon.

We now briefly cite the relevant literature. Gonçalves *et al.* (2011) is one of the first papers to study pickup and delivery problems with a mixed fleet of BEVs and Internal Combustion Engine Vehicles. In Grandinetti *et al.* (2016) the electric Pickup and Delivery Problem with Time Windows (E-PDPTW) is studied. In the context of people transportation, one of the first studies on Dial-a-Ride problems with electric vehicles is Chabrol *et al.* (2008). In Masmoudi *et al.* (2018) the authors address the DARP with electric vehicles and a battery swapping policy. Since our problem deals with the management of the energy produced, it can be seen as an integrated problem sharing similarities with the Inventory Routing Problem (IRP) Dror *et al.* (1985) or the Production Routing Problem (PRP) Adulyasak *et al.* (2014).

2 PROBLEM DESCRIPTION AND MILP MODELLING

The problem can be formally described as follows. We have a complete directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, where $\mathcal{N}$ is the set of all nodes and $\mathcal{A} = \{(i,j) : i,j \in \mathcal{N}, i \neq j\}$ is the set of arcs connecting each pair of nodes. The set of nodes $\mathcal{N} = \{0, 2n+1\} \cup \mathcal{P} \cup \mathcal{D}$ consists of two copies of the depot/production plant $(0, 2n+1)$, the set of pickup nodes $\mathcal{P} = \{1, \ldots, n\}$ and the set of delivery nodes $\mathcal{D} = \{n+1, \ldots, 2n\}$. Every route begins and ends at the depot. There are n transportation requests that have to be served over a planning horizon $\mathcal{H}$ of H periods $\{1, \ldots, H\}$, each of duration τ. Periods can be interpreted as hours. The time horizon can be interpreted as a whole day, and nothing happens between two time horizons. The state of the fleet/system at the end of the time horizon is exactly the state of the system at the beginning of the following time horizon. An arc (i,j) in set $\mathcal{A}$ has an associated non-negative energy cost e_{ij} and a non-negative travel time τ_{ij}. We assume that a fleet $\mathcal{V}$ of $|\mathcal{V}| = V$ homogeneous BEVs is available at the depot, each of capacity Q. Vehicles can swap their batteries at the depot. We assume that vehicles move at constant speed on the network. K batteries are available, each of capacity Q_e. Among them, V batteries are located on the vehicles and $K - V$ are located at the depot. In each period h, p_h is the energy produced, and it is available at the beginning of the period. If a battery is recharged during a period, it is available only at the end of the period. Moreover, if a vehicles visits the depot to swap its battery, the latter can be recharged only from the following period on. Anyway, vehicles are allowed to visit the depot and wait for the end of the period. The recharging rate is denoted by λ, and corresponds to the maximum quantity of energy that a battery can get in a period. The average state of charge of a battery is the same at the beginning and at the end of the time horizon. We make this hypothesis because the idea is to define a sustainable/domestic production and consumption of the energy that vehicles use. In fact, the production unit can be imagined as a solar power plant. Every transportation request specifies an origin s_i, a destination t_i, a time window $[r_i, d_i]$ and a demand q_i, where this demand at each delivery is equal to $q_{n+i} = -q_i$. Each user node must be visited exactly once, while the depot may be visited multiple times. Moreover, the depot must be visited at the beginning and at the end of each tour. The time window to visit the depot is set to $[0, L]$, where L is length of the planning horizon ($L = H\tau$). Moreover, we assume that the number of stops that a vehicle can make to swap its battery is not limited. Vehicles are allowed to wait at any node in the graph.

At the beginning of each period h, the energy p_h must be split among the batteries located at the depot and the general network. If the energy is assigned to the general network there is a profit. If in a period h the energy produced p_h is not sufficient to recharge the batteries, additional energy can be bought from the general network. Obviously, the energy cannot be bought and sold to the general network in the same period h. The quantity of energy that can be bought from the general network is not limited. The energy cost is different for each period h: α_h denotes the unitary selling cost and β_h denotes the unitary purchasing cost ($\beta_h > \alpha_h$ significantly). The objective is to satisfy all transportation requests at maximal revenue. The revenue is defined as the difference between the quantity of energy sold to and the quantity of energy bought from the general network. The side-effect is that the energy used by the vehicles must be minimised.

We now introduce the notation used in the problem formulation. We call trip a couple $t = (r, h)$ where r is a path between two nodes and h is the starting period of the path. All trips are made up by paths where the depot is the starting and ending node. In what follows, we make the simplifying hypothesis that trips can only start (end) at the beginning (at the end) of a period. We denote the set of trips with $\mathcal{T}$. Let ϵ_{it} denote a parameter that is equal to 1 if request i belongs to trip t and δ_{th} is equal to 1 if trip t is active during period h. Let c_{th} denote the cost of trip t in period h. Let γ_k denote the state of charge of battery k at the beginning of the time horizon. For each period h, let the continuous variables s_h denote the quantity of energy sold, b_h the quantity of energy bought and l_{kh} the state of charge of battery k at the end of period

h. Let a_{kh} denote the quantity of energy given to battery k in period h. Let u_{kh} be a binary decision variable equal to 1 if battery k is at the depot *for an entire period* h. Let x_{kt} denote a binary decision variable equal to 1 if battery k is used in trip t. Note that if $\sum_{k\in\mathcal{K}} x_{kt} = 0$ then trip t is not selected.

The formulation is as follows:

$$\max \sum_{h\in\mathcal{H}} \alpha_h s_h - \sum_{h\in\mathcal{H}} \beta_h b_h \tag{1}$$

s.t.:

$$\sum_{k\in\mathcal{K}} a_{kh} + s_h = p_h + b_h \qquad h\in\mathcal{H} \tag{2}$$

$$a_{kh} \le \lambda u_{kh} \qquad k\in\mathcal{K}, h\in\mathcal{H} \tag{3}$$

$$l_{k0} = \gamma_k \qquad k\in\mathcal{K} \tag{4}$$

$$\sum_{k\in\mathcal{K}} l_{kH} \ge \sum_{k\in\mathcal{K}} l_{k0} \tag{5}$$

$$l_{kh} = l_{kh-1} + a_{kh} - \sum_{t\in\mathcal{T}} c_{th}\delta_{th}x_{kt} \qquad k\in\mathcal{K}, h\in\mathcal{H} \tag{6}$$

$$l_{kh} \le Q_e \qquad k\in\mathcal{K}, h\in\mathcal{H} \tag{7}$$

$$\sum_{k\in\mathcal{K}} (1-u_{kh}) \le V \qquad h\in\mathcal{H} \tag{8}$$

$$u_{kh} + \sum_{t\in\mathcal{T}} \delta_{th}x_{kt} \le 1 \qquad k\in\mathcal{K}, h\in\mathcal{H} \tag{9}$$

$$\sum_{t\in\mathcal{T}} \epsilon_{it} \sum_{k\in\mathcal{K}} x_{kt} \ge 1 \qquad i\in\mathcal{R} \tag{10}$$

$$b_h, s_h \ge 0 \qquad h\in\mathcal{H} \tag{11}$$

$$a_{kh} \ge 0 \qquad k\in\mathcal{K}, h\in\mathcal{H} \tag{12}$$

$$l_{kh} \ge 0 \qquad k\in\mathcal{K}, h\in\mathcal{H}\cup\{0\} \tag{13}$$

$$u_{kh} \in \{0,1\} \qquad k\in\mathcal{K}, h\in\mathcal{H} \tag{14}$$

$$x_{kt} \in \{0,1\} \qquad k\in\mathcal{K}, t\in\mathcal{T} \tag{15}$$

Constraints (2) ensure that in each period, the energy produced is completely split among the batteries and the general network. Constraints (3) impose a limit on the amount of energy given to a battery in a period. Constraints (4) and (5) ensure that the average state of charge is the same at the beginning and at the end of the time horizon. Constraints (6) model the change in battery charge levels over time. Constraints (7) specify the upper bound for the battery charge levels. Constraints (8) set an upper bound on the number of active vehicles. Constraints (9) ensure that trips are done only by active vehicles. Constraints (10) ensure that each request belongs to at least one trip. Constraints (11)-(15) define the decision variables. Note that time and capacity constraints are taken into account when the trips are generated.

3 SOLUTION METHOD

Our problem can be seen as an integrated problem where both routing decisions and energy management decisions have to be made. Formulation (1)-(15) is an integrated model based on set $\mathcal{T}$ of trips. As formulation (1)-(15) suffers from the fact that the number of feasible trips is exponential, we propose a heuristic algorithm which is based on a heuristic generation of a subset of feasible trips. Specifically, the solution method can be divided into three phases:

1. generation of a subset $\mathcal{T}$ of trips
2. resolution of formulation (1)-(15) based on $\mathcal{T}$
3. repair procedure.

As for phase 1, we use a randomized construction heuristic. Let h_1 and h_2 denote the starting and ending period of a trip t, respectively. For every possible pair (h_1, h_2) we generate a pool of promising trips using a Greedy Randomized Adaptive Search Procedure (GRASP). Once we have set $\mathcal{T}$ we solve formulation (1)-(15) over set $\mathcal{T}$ (phase 2). Due to constraints (10) multiple trips that contain the same request may be selected and therefore a pair of nodes may be visited more than once. This could be needed in order to satisfy all requests, as we do not generate all possible trips. In such a case, solutions are repaired as follows (phase 3). If $\mathcal{T}_i$ is the subset of selected trips that all contain request i, we leave i in the trips that corresponds to the maximum saving of the distance travelled.

We tested our formulation on benchmark instances introduced in Li & Lim (2003) for the Pickup and Delivery Problem with Time Windows (PDPTW). We adapted the instances by generating data on energy production and consumption, as well as on selling and buying price for energy. Detailed results of the solutions will be presented during the conference.

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