PROJECT PROPOSAL

for

A Lagrangian Relaxation Method for an Online Decentralized Assignment of Electric Vehicles to Charging Stations

Submitted
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CS 357 Optimization Algorithms and Techniques
by

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Overview

The road transport system's dominance by conventional vehicles and resulting pollution, with 73 of Europe's oil consumption for transportation and road transport contributing 25 of CO2 emissions, necessitates innovative solutions. Electric vehicles present an eco-friendly alternative, yet their adoption faces challenges such as charging station congestion due to limited infrastructure and extended charging times compared to refueling. This proposal aims to optimize electric vehicle charging through a comprehensive approach that involves route optimization, charging scheduling, and a reservation policy to address congestion.

Problem Statement

This project focuses on the critical problem of efficiently assigning electric vehicles to charging stations while minimizing their maximum completion time. The approach envisions a collaborative and decentralized interaction between electric vehicles and the charging infrastructure to effectively match supply and demand. To address this challenge, the assignment problem is formulated as a linear integer programming issue. A Lagrangian relaxation heuristic is introduced to solve this problem, enabling each electric vehicle to select an optimal charging station and route that minimizes its own completion time. The completion time of each electric vehicle is composed of several factors, including travel time (TT), waiting time (WT) at the station, and the actual charging time. The proposed Lagrangian relaxation heuristic demonstrates superior effectiveness compared to other local heuristic methods, ensuring a fair and efficient allocation of electric vehicles to charging stations. In light of these findings, the consideration of a reservation policy is also integrated to further enhance the overall efficiency of the system.

Symbols

e: electric vehicle
a: an edge of U between two nodes of the urban network
L_e: starting battery charge level of e
F_e: desired final battery charge level of e
λ_s: Lagrangian Multipliers
r_e: time e can start its path (release date)
w_e: estimate of waiting time in queue at s
$R_{e,s}$: unit rate of the charging stations to charge e
$t^p_{e,s}$: travel time of e to reach s, travelling along the path $p_{e,s}$
$c^p_{e,s}$: completion time of e at the charging station s, travelling along the path $p_{e,s}$
$\epsilon^p_{e,s}$: consumption of energy to travel from v_e position to Us, travelling along the path $p_{e,s}$
C_{max}: the maximum completion time among all the charging stations
C_s: the completion time of the charging station s

Problem Formulation

The system model for this problem involves an urban road network represented by a directed graph, with edges indicating streets and vertices as intersections. Completion time of EV depends on departure time, path travel time, station queue, and charging duration, with charging time influenced by various energy-related factors. This problem can be considered as an assignment problem where an EV has to decide the most optimal charging station. Hence, this can be modeled as a linear integer programming problem.
The decision variables are:

$$x_{e,s} = \begin{cases} 1, \text{ if the EV } e \text{ is charged by the station } s \\ 0, \text{ otherwise.} \end{cases}$$

$$C_{\max} = \max_{\mathrm{s}\in\mathrm{S}}\{\mathrm{C_s}\}$$

Constraints:

$$\begin{aligned}
&\textstyle\sum_{e=1}^{m} \tau_{e,s}^{p} x_{e,s} \le C_{\max} && s = 1, \ldots, n && \text{(3a)}\\
&\textstyle\sum_{s=1}^{n} x_{e,s} = 1, && e = 1, \ldots, m && \text{(3b)}\\
&\epsilon_{e,s}^{p} x_{e,s} \le L_e, && e = 1, \ldots, m && \text{(3c)}\\
&x_{e,s} \in \{0, 1\}, && e = 1, \ldots, m,\ s = 1, \ldots, n && \text{(3d)}\\
&C_{\max} \ge 0. && && \text{(3e)}
\end{aligned}$$

The completion time $C_{ep,s}$ of e traveling the path $p_{e,s}$ and recharging at station s is computed as follows:

$$C_{e,s}^{p} = \max\{r_e + t_{e,s}^{p}, w_s\} + \tau_{e,s}^{p}$$

The charging Time is computed as:

$$\tau_{e,s}^{p} = (F_e - L_e - \epsilon_{e,s}^{p} + a_{e,s}^{p})/R_{e,s}.$$

Methodology

1. **The Divide and Conquer Approach**
   A Lagrangian relaxation approach is proposed for the online decentralized assignment of electric vehicles to charging stations.
   The method involves three key steps:
   (a) Pre-processing routing phase to compute optimal paths.
   (b) Lagrangian relaxation for decentralized assignment to determine optimal EV-station matches.
   (c) An e-vehicle decision module allowing each EV to choose its optimal station and path for minimal completion time.

   This approach utilizes divide and conquer strategies in solving two subproblems within the Lagrangian relaxation step:
   (a) Inner subproblem assigning EVs to stations with existing waiting times, solved through a greedy algorithm.
   (b) Lagrangian relaxation for decentralized assignment to determine optimal EV-station matches. Outer subproblem updating station waiting times based on inner subproblem solutions, solved using gradient descent. Simulations confirm the method's effectiveness in efficiently assigning EVs to charging stations while minimizing completion time, demonstrating its potential for real-world application.

2. **Lagrangian Heuristic**
   Lagrangian relaxation decomposes centralized problems into manageable sub-problems, often utilized in heuristic methods for feasible solutions. This problem is modeled as a parallel job-shop scheduling problem, aiming to minimize maximum completion time and achieve load balancing among machines. The problem is NP-hard, and to address it, the set of constraints in (3a) is relaxed, leading to the formulation of the Lagrangian problem PR(lambda).

$$P_R(\lambda) = \min C_{\max} - \sum_{s=1}^{n} \lambda_s \left(C_{\max} - \sum_{e=1}^{n} \tau_{e,s}^{P} x_{e,s} \right) \Bigg\}$$

$$= \min \left(1 - \sum_{s=1}^{n} \lambda_s \right) C_{\max} + \sum_{s=1}^{n} \lambda_s \sum_{e=1}^{m} \tau_{e,s}^{P} x_{e,s}$$

$$\text{Subject to} \quad \begin{cases} \sum_{s=1}^{n} x_{e,s} = 1, \; e = 1, \ldots, m \\ c_{e,s}^{P} x_{e,s} \leq L_e, \quad e = 1, \ldots, m \\ x_{e,s} \in \{0, 1\} \quad e = 1, \ldots, m, \;\; s = 1, \ldots, n \\ C_{\max} \geq 0 \quad s = 1, \ldots, n \end{cases}$$

Goals

- Develop an efficient and decentralized assignment approach for electric vehicles to charging stations, minimizing completion time.
- Apply the Lagrangian relaxation heuristic to optimize EV-station assignments and enhance collaboration between electric vehicles and charging infrastructure.
- Evaluate the proposed method through simulations to demonstrate its effectiveness in assigning electric vehicles to charging stations while minimizing completion time.

Reference

L. Adacher, M.Flamini and F. Pascucci, "A Lagrangian Relaxation Method for an Online Decentralized Assignment of Electric Vehicles to Charging Stations," in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 53, no. 9, pp. 5568-5579, Sept. 2023, doi: 10.1109/TSMC.2023.3272828