Facility Location Optimization in Charging Infrastructures for Fleet-Operated Electric Vehicles

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Abstract
A change from combustion engines to electric drivetrains may offer a vision to allow for CO_2-neutral growth *in vehicle fleets at public and private sectors. Charging infrastructures that are both cost-effective and in line with the demand will play the key role in a successful change. This paper outlines a process for cost-optimized facility location planning of charging devices for fleet-operated vehicles and introduces a prototypical platform that can be used in real scenarios. First, a mathematical optimization model is developed which is then integrated into the Esri ArcGIS Geoinformation System. Both the process and the add-in are finally tested in a scenario of a major airport facing a change to electrical vehicles for parts of its ground services. This work illustrates, that methods from operations research combined with current technology of geoinformation systems give a valuable asset to the planning of charging infrastructures.*

1. Introduction

Climate change and increasing scarcity of mineral fuels are the major challenges for the future of mobility. Limiting the emissions of gases harmful to the climate without giving up profitable growth is a goal often heard of. The conversion of fleet vehicles to electric drives will help to accomplish this goal. Today, we are facing the following challenges:

- Battery powered electric vehicles have a significantly shorter range.
- The charging operations for battery-powered electric vehicles take considerably longer. The charging infrastructure needs to be developed. This causes high costs.
- In general, supply goals and tour plans that are well established, have to be maintained.

The procedure presented below for cost-optimized location planning of charging stations while respecting existing supply targets is suitable for use in real world scenarios. A newly developed ArcGIS extension component for site location optimization makes it easy to experiment with different technical and economic constraints such as charge time requirements, battery capacity and the costs of charging stations.

2. Problem Definition

The costs for the installation of charging stations are substantial, therefore charging stations are to be seen as a scarce commodity. A careful selection of sites is essential.

The basic motivation is: ***The conversion to electric drive systems shall trigger as few changes possible to the existing plans and established procedures in a fleet of vehicles. Detours to charging stations and waiting times for loading operations are thus virtually intolerable.***

One approach to achieve this goal is recharging whenever possible *while* performing the orders. This raises the following core question: ***At which places which number of charging stations is the minimum required to maintain the supply of a given demand structure at a minimum overall cost?***

Figure 1 outlines a solution representation to this issue in an exemplary form, the individual elements of the problem context and the solution itself are described below. The *demand points* (A, B, C, D, E) are at particular *nodes in* a road network and are visited by *vehicles* to carry out *orders*, e.g. delivery of goods or performance of a service. *Depots* are special demand points where *tours* begin and end (here: demand Point A).

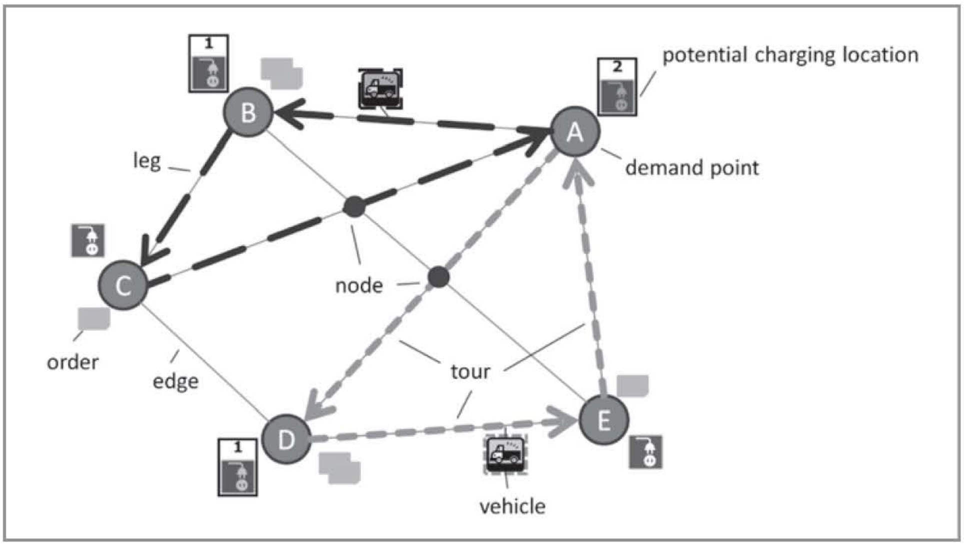

Figure 1: Schematic representation of solution results

The first step in the search for a solution assigns orders to the vehicles that successively visit the demand points in the form of *tours* (A-D-E-A, A-B-C-A). The set of orders is distributed to the available vehicles, so that the total travel time or the total distance is minimized. There can be additional weights taken into consideration, such as cost per unit of time or cost per kilometer driven The route between two points of a tour is a *leg*. This first step is often covered by well-established tour plans. The second part of the problem solving determines, at which demand points how many charging stations are required to adequately provide the vehicles with energy to run the tours without detours. In the illustrated exemplary result, the demand points A, B and D are equipped with charging stations, for C and E there are no stations required. The selection of the demand points to be equipped with charging stations and the necessary numbers of stations are determined according to the following optimization goal: ***Minimize the total cost as the overall aggregate of the number of required charging stations multiplied by the cost per station.***

3. Implementation and Integration of the Solution

The literature study on the context described above shows, that certain methods from Operations Research (OR) and a number of technology elements found in current geographic information systems have a great value in developing a method and implementing a prototype for location optimization of charging facilities (Böhm, 2012). The vehicle routing problem (VRP) is suitable for the first part of the solution search – planning the tours of the vehicles (Dantzig and Ramser, 1959). VRPs can be set up and solved by current geographic information systems, such as Esri ArcGIS Network Analyst. The optimization models known as *facility location problems* mostly handle problems where the demand to be covered is assumed stationary (Hakimi, 1964 and 1965, Church and Velle, 1974 and Toregas et al., 1971). When selecting locations for charging equipment, the demand to be considered emerges at vehicles in motion - the energy consumed for the movement itself must be refilled. The so-called *flow-based demand models* cover such motion-based scenarios (Zeng, 2007, Hodgson, 1990, Kuby and Kuby, 2007 and Kim, 2010). In current GIS software products, there are no solvers available for this kind of problems. So, based on some ideas from the article *"Locating Flow Recharging Stations at Tourist Destinations to Serve Recreational Travelers"* (Wang, 2011), a new optimization model called *LFRS* was developed and integrated as an add-in for the Esri ArcGIS software. The Esri ArcGIS geographic information system provides the basic functions, such as spatial data management, visualization, a VRP solver for the first problem step (tour planning) and further analysis capabilities. The model **LFRS** refers to the following sets:

- N Nodes (demand points), potential sites for charging stations
- M Vehicles
- S Sequences (tours), ordered sequence of node visits by vehicles

The model **parameters** are:

- c_i Costs of setting up a charging station at node i
- u_i Maximum number of stations that can be installed at node i
- $d_{i,j}$ Distance between node i and node j (in km)
- $\delta_{i,m,s}$ If node i is visited by vehicle m at sequence element (leg) s : $\delta_{i,m,s} = 1$, otherwise $\delta_{i,m,s} = 0$
- $t_{i,m,s}$ Time to carry out order in node i by vehicle m at sequence element (leg) s , potential charging time (in min)
- α Initial range at tour start (in km)
- β Charging rate in km/min, range gain per unit of time
- γ Battery capacity (maximum range in km when fully charged)

The following **decision variables** are used in LFRS:

- X_i If node i is equipped with charging stations: $|X_i|$ = number of stations in node i, otherwise $X_i = 0$
- $Y_{i,m,s}$ If vehicle m is charged at node i at sequence element (leg) s: $Y_{i,m,s} = 1$, otherwise $Y_{i,m,s} = 0$
- $I_{i,m,s}$ Coefficient for unused charging time at node i for vehicle m at sequence element (leg) s (in km)
- $r_{i,m,s}$ Range gain by charging at node i for vehicle m at sequence element (leg) s (in km)
- $b_{i,m,s}$ Range remaining at node i for vehicle m at sequence element (leg) s (in km)

The **objective function** of LFRS is:

$$Minimize \sum_{i \in N} c_i X_i \qquad \text{Equation 1}$$

The following **restrictions** apply:

$$b_{i,m,s} = \sum_{j \in N} \left(\left(b_{j,m,s-1} + r_{j,m,s-1} - d_{ji} \right) \times \delta_{i,m,s} \times \delta_{j,m,s-1} \right)$$

$$\forall i \in N, \forall m \in M, \forall s \in S, \qquad \text{Equation 2}$$

$$r_{i,m,s} = Y_{i,m,s} \times t_{i,m,s} \times \beta - I_{i,m,s} \qquad \forall i \in N, \forall m \in M, \forall s \in S, \qquad \text{Equation 3}$$

$$r_{i,m,s} \leq \gamma - b_{i,m,s} \qquad \forall i \in N, \forall m \in M, \forall s \in S, \qquad \text{Equation 4}$$

$$\sum_{m \in M} max_{s \in S} \{Y_{i,m,s}\} \leq X_i \qquad \forall i \in N, \qquad \text{Equation5}$$

$$X_i \leq u_i \qquad \forall i \in N, \qquad \text{Equation 6}$$

$$Y_{i,m,s} \in \{0,1\} \qquad \forall i \in N, \forall m \in M, \forall s \in S, \qquad \text{Equation 7}$$

$$X_i, I_{i,m,s}, b_{i,m,s}, r_{i,m,s} \geq 0 \qquad \forall i \in N, \forall m \in M, \forall s \in S \qquad \text{Equation 8}$$

The optimization goal – minimizing costs – is expressed by (Equation 1). Restriction (Equation 2) describes the calculation of the remaining range when reaching node *i* while restriction (Equation 3) depicts the range gain by charging at node *i*. The decision variable *I* expresses the part of possible range gain which is not used, because a vehicle may leave the node before completing the charge to full extent. Restriction (Equation 4) limits the range gain to the maximum range of the battery. Restriction (Equation 5) assures that there is a sufficient number of charging stations for the necessary charging processes. The number of necessary charging stations at a demand point is the number of different vehicles that need to charge at the node during the period of time in question.

The equations (Equation 6) to (Equation 8) restrict the decision variables to reasonable values, for example non-negative residual ranges for each vehicle at any node it is visiting.

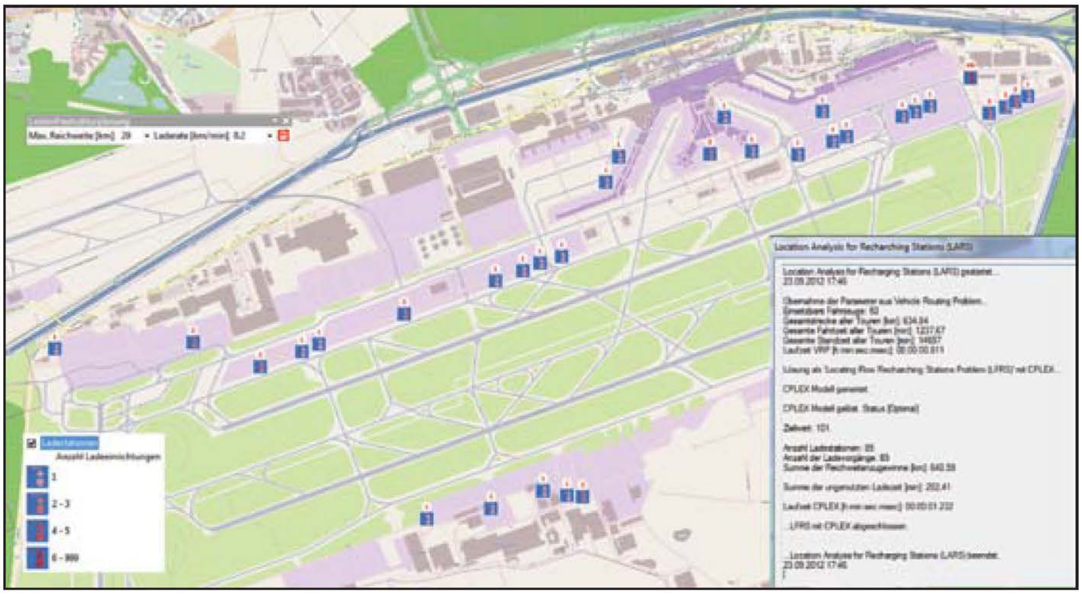

Figure 2: Solution for 0.2 km / min loading rate, 20 km maximum range

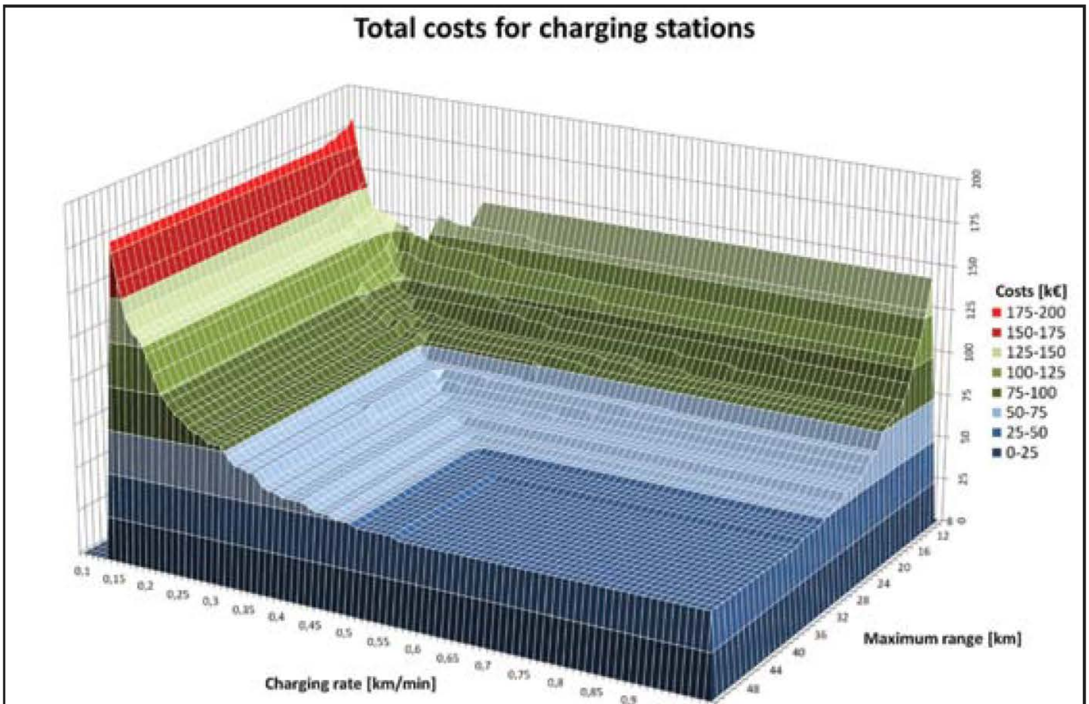

Figure 3: Cost chart for charging stations

4. Application in a Major Airport Scenario

The optimization model LFRS was implemented as an add-in to the Esri ArcGIS system and tested in a fictional scenario at the main airport in Frankfurt, Germany. The scenario considers dispenser vehicles that are used for refueling aircrafts from an underground tank system. This part of the ground fleet services is planned to be converted to electric drivetrains. The necessary spatial data for the road and trail network are extracted from *OpenStreetMap* (OSM, 2012) and converted into an Esri ArcGIS Network dataset with edges, nodes, barriers and turns. There are 123 demand points located at the parking positions of the aircrafts at terminal gates, at positions in apron, in air cargo and workshop areas. The refueling of the aircrafts happens at the demand points. The time during refueling is used as a potential charging time for the dispenser vehicles. Each demand point is stored as a part of the road network, along with the maximum number of charging stations and the cost for setting up a charging station as attributes. The scenario is based on more than 30 refueling operations per hour, which is above the profile of 1250 aircraft movements per day on average reported by Fraport AG (Fraport, 2012). A shift of 9 hours with 300 individual refueling orders is simulated. The shift includes a setup time in the depot, which can be used for initial charging. After storing demand points, vehicles and orders as elements of a network dataset into a Geodatabase, a vehicle routing problem (VRP) must be set up and solved This step assigns orders to vehicles and calculates the tours representing the sequences of visits at demand points. In this process, as an optimization objective, the total travel time of all vehicles required to fulfill the orders, is minimized. The solution of the VRP then serves as input to the following determination of the optimal locations for the charging stations using the new LFRS optimization model. Figure 2 shows the toolbar of the new add-in in the top-left corner. A charging rate (“Laderate”) of 0.2 km / min and a maximum range (“Max. Reichweite”) of 20 km are selected. As a main result of the solution process, the distribution of the necessary charging stations is shown as a cartographic map. Some information on the solution process itself is shown in the text window. Figure 3finally visualizes a surface plot of an extensive series of measurements under variation of the two parameters charge rate and maximum range. The total costs for the necessary charging stations decrease monotonically with increasing charging rate and increasing maximum range The costs and the total number of charging stations reach a minimum plateau at a charging rate of 0.57 km / min and a maximum range of 35 km. At this point, no charging stations are required outside the depot, as all tours can be run without recharging required. Below a maximum range of 10 kilometers, there is no solution possible in this example, since the longest leg of all tours exceeds this limit. Similarly, a minimum charging rate is needed for solvability, since the initial load time must be sufficient to run the longest first leg of all tours.

5. Conclusions and Outlook

The results achieved in the major airport scenario demonstrate the feasibility of the GIS-based approach for cost-effective siting of charging devices. The geoinformation system software provides an effective environment for data storage and data management and for the visualization of results. Build-in features like solvers for network-related problems contribute significantly to the overall solution. Using the extensibility options of the GIS to develop and integrate a solver for a new optimization model suitable to the special problem context leads to a versatile working platform. The platform may be used in a variety of consulting situations, e.g. if a manufacturer of charging devices is asked to plan cost-effective charging infrastructures for his customers. Using this workbench in further scenarios will give an impetus for enhancements and new developments like additional parameters and even more sophisticated optimization models. The flexibility in setting the parameters charging rate and maximum range yet allows the investigation of alternative means of storing electricity, such as ultracapacitors.

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