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Urban charging station location model based on multi-objective programming

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Abstract. As an efficient way to ease Range Anxiety, the rational location of charging stations is of great importance to promote the migration towards electric vehicles. In this paper, we mainly study urban charging station location problem and propose Urban Charging Station Planning Model whose goal is to minimize the construction costs of service facilities and minimize service costs while satisfying all the charging needs. Then we take Seoul as an example to detect our model and analyze the experimental results. Later, we use sensitivity analysis to expand the proposed model, trying to explore the impact of new technology such as battery capacity on the model and obtain some conclusions with a reference value. Finally, we directionally discuss the problem of charging station construction timeline, location problem between cities and the specific distribution within each region and these will be further completed in the future.

1. Introduction

Electric vehicles (EVs) hold a lot of potential for helping improve people’s quality of life and create a more sustainable future. However, as EVs are in the early stage of development, charging facility construction is backward. Range Anxiety, the problem people worry about, severely hinders the promotion and popularization of EVs, so having a reasonable charging station location plan is of great importance.

Weber is the first one to propose location theory in 1909 called Weber problem [1]. In 1971, Toregas [2] proposed the Set Covering Location Model (SCLM). Soon after, Church [3] proposed the Maximum Covering Location Model (MCLM) in 1974. Later, Current [4] proposed a multi-objective location problem called Maximum Covering and Shortest Path Problem (MCSPP) in 1985. The later scholars generally conduct in-depth studies based on these typical problems, for example, reference [5] proposed a model aiming at minimize the sum of the total cost of charging stations (including investment costs, operation and maintenance costs) and network loss costs. Reference [6] proposed a model aiming at maximize operating revenue from charging stations and use the particle swarm algorithm to prove the feasibility of the model.

The existing charging station location model has considered the construction cost and operating revenue of the charging station in a comprehensive manner, but it does not consider the cost of the
user’s cost systematically, such as the time spend on charging which will be further considered in this paper.

There are two kinds of general EVs charging facilities, destination stations and supercharging stations. The service occasions for supercharging stations are divided into two types, one is applied to roads between cities, such as highways, the other one is to meet the daily needs of people in urban areas together with destination stations. In this paper, we mainly study the latter, we take SCLM and MCSPP into account and propose a new multi-objective Urban Charging Station Planning Model whose goal is to minimize the construction costs of service facilities and minimize service costs while satisfying all the charging needs. Then, we experiment with Seoul and make some simplification, after that we use the Urban Charging Station Planning Model to determine the regional distribution of charging stations when it comes to all-electric.

2. Notation

| Decision variables | Explanation |
|--------------------|-------------|
| $z_j$              | Decision variable, if build a charging station at node $j$, $z_j = 1$, otherwise $z_j = 0$. |
| $Q_{ij}$           | Decision variable, if charging needs in $i$ is satisfied at node $j$, $Q_{ij} = 1$, otherwise $Q_{ij} = 0$. |
| $n_{jc}^j$         | Number of superchargers built at node $j$, if a charging station built at node $j$. |
| $n_{dc}^j$         | Number of destination-chargers built at node $j$, if a charging station built at node $j$. |

| Parameters         | Explanation |
|--------------------|-------------|
| $A_j$              | Cost of building charging stations at node $j$. |
| $B_{ij}$           | The total time spent in node $j$ is met by the charge demand of area $i$. |
| $n$                | Number of areas with charge demands. |
| $m$                | Number of candidate charging stations. |
| $c_{sc}$           | Cost of building a supercharger. |
| $c_{dc}$           | Cost of building a destination-charger. |
| $n_{i}^{pv}$       | Total number of EVs that have charging needs at area $i$. |
| $d_{ij}$           | Distance between area $i$ and station $j$. |
| $\bar{v}$          | Average driving speed of EVs in the city. |
| $k_{jc}^j$         | Percentage of charging services provided by superchargers at node $j$. |
| $k_{dc}^j$         | Percentage of charging services provided by destination-chargers at node $j$. |
| $\tau_{sc}$        | The time a supercharger takes to charge an EV. |
| $\tau_{dc}$        | The time a destination-charger takes to charge an EV. |
| $p_{sc}$           | Number of EVs a supercharger can charge in one day. |
| $p_{dc}$           | Number of EVs a destination-charger can charge in one day. |
| $n_{i}^{p}$        | Population of area $i$. |
| $d_{day}$          | Average daily distance of EVs. |
| $d_{full}$         | The distance that an EV can travel with a full charge |
| $\rho$             | Current ratio of Korean vehicles to the population. |
| $\beta$            | Proportion of charging needs met by home chargers. |
3. Assumption
To simplify our problems, we make the following basic assumptions, each of which is properly justified

- Charging demand in one area can only be satisfied at one candidate charging station.
- Assuming that after the city is all-electric, the population, Car ownership per capita, and charging speed are consistent with current data.
- Assume EV battery consumption only related to the distance travelled, unrelated to other factors.

4. Model
Our model is shown below:

\[ \text{min } C = \sum_{j=0}^{m} z_j A_j + \lambda \sum_{i=0}^{n} \sum_{j=0}^{m} Q_{ij} B_{ij} \]  

s.t.

\[ z_j \in \{0, 1\} \]  

\[ Q_{ij} \in \{0, 1\} \]  

\[ z_j \geq Q_{ij} \]  

\[ n_j^{sc}, n_j^{dc} \in R \]  

\[ z_j \left( P_{sc} n_j^{sc} + P_{dc} n_j^{dc} \right) \geq \sum_{i=0}^{n} Q_{ij} n_i^{ev} \]  

\[ \sum_{j=0}^{m} Q_{ij} = 1 \]  

where

\[ A_j = c^{sc} n_j^{sc} + c^{dc} n_j^{dc} \]  

\[ B_{ij} = n_i^{ev} \left( \frac{d_{ij}}{b} + k_j^{sc} T^{sc} + k_j^{dc} T^{dc} \right) \]  

The meaning of each variable can refer to notation.

Formula (8) is the first goal we try to optimize which is the charging station construction costs within the city.

In fact, the construction cost of the charging station is only one of the factors that need to be considered in the construction of a charging station in reality. The convenience of the location of the charging station and the service capacity also have a great influence on the construction of the charging station. Considering charging needs to be met will go through two processes. One is the time needed to reach the charging station and the other is the time at the charging station waiting for the charging to complete. So, in formula (9) we let the service demand be allocated to superchargers and destination-chargers in the actual proportion. And introduce two variables \( T^{sc} \) and \( T^{dc} \) to represent the time user spend in charging. After that, we take formula (9) as our second objective equation we optimized.

Formula (4) is a logical constraint that if the demand for area \( i \) is to meet at node \( j \), then node \( j \) must build a charging station.

The meaning of the formula (6) is the available charging capacity of station \( j \) must meet the charging needs of this station. Note that formula (6) is a nonlinear constraint, which makes Urban Charging Station Location Model a nonlinear programming model.

On the formula (7), we assume that all EVs in area \( i \) can only charge at one charging station.

Since the Urban Charging Station Location Model is a nonlinear integer programming model, we use LINGO 17.0 which is an optimization modelling software for linear, nonlinear, and integer programming to solve.
5. Experiment

5.1. Parameter setting

5.1.1. City selection. There are many reasons to choose Seoul as the planned city, the main reason is that the area of South Korea is small, and it has a low Gini coefficient as well as a high proportion of urban population. Because of that, some South Korean statistics can be directly applied to Seoul, reducing the time to collect and process data during the experiment.

5.1.2. Data sources. Our data for various districts of Seoul comes from Wikipedia [7]. To calculate the number of vehicles in each district, we inquire about the list of countries by the number of road motor vehicles per 1,000 inhabitants [8], and in South Korea, every 2.3 people have a car. According to the research of Smart et al [9], we obtain the average daily distance of EVs is 65 km. we set the average driving speed of the EVs to 40 km/h.

According to the research of Fitzgerald and Nelder [10], we set $c_{sc} = 50000$, $c_{dc} = 600$. In reality, $d_{ij}$ can be measured according to the actual situation, but in the experiment, due to the lack of data and for the purpose of simplifying the experiment, we take the straight distance between area $i$ and station $j$ as the value of $d_{ij}$.

Based on the existing data analysis, we set $k_{ij}^{sc} = 20\%$ and $k_{ij}^{dc} = 80\%$. And we take the Tesla chargers as standard, set $T_{sc} = 0.5$, $T_{dc} = 6$. Assuming that the daily service time of the supercharger is 14 hours and the destination-charger is 24 hours, so that we set $p_{sc} = 28$, $p_{dc} = 4$.

We use formula (10) to calculate $n_{i}^{ev}$ in experiment.

$$n_{i}^{ev} = \frac{n_{i}^{p} \rho d_{day} (1 - \beta)}{d_{full}}$$

The meaning of each variable can refer to notation.

$\beta$ is related to the population density of the city. Introducing $\beta$ allows the Urban Charging Station Planning Model to be applied to more cities. Seoul has a high population density, so only a few people have enough space to hold home chargers, then we set $\beta = 0$ as we suppose that there is no home chargers in Seoul. And we are here to use Tesla’s Model3 as standard, set $D_{full} = 500$ km. According to the maximum speed set by relevant laws of Seoul [11].

$\lambda$ in formula (1) plays the role of unit conversion and adjusts the quantitative relationship between formula (8) and formula (9). After some experiments, we think that $\lambda = 25$ is a reasonable value.

All parameter settings are shown in the table 1.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $n$       | 25    | $p_{sc}$  | 28    |
| $m$       | 38    | $p_{dc}$  | 4     |
| $c_{sc}$  | $50000$ | $d_{day}$ | 65 km |
| $c_{dc}$  | $600$ | $d_{full}$ | 500 km |
| $k_{ij}^{sc}$ | 20\%, j $\forall\{1, 2, \ldots, m\}$ | $\rho$ | $1/2.3$ |
| $k_{ij}^{dc}$ | 80\%, j $\forall\{1, 2, \ldots, m\}$ | $\beta$ | 0     |
| $T_{sc}$  | 0.5 hours | $\lambda$ | 25    |
| $T_{dc}$  | 6 hours | $\bar{v}$ | 40 km/h |
| $d_{ij}$  | Straight distance between area $i$ and station $j$ in reality | $n_{i}^{p}$ | Population of area $i$ according to [7] |

5.1.3. Problem simplification. Because the factors needed to be considered for the location of a charging station within a city are too complex, we have made some simplification.
Based on the actual data, we divide Seoul into 25 districts according to the administrative division, taking the centre of each district to represent it. After that, each district is further reduced to a node.

In the same way, we use the concept of candidate centres instead of charging stations in a certain area to determine the actual charging stations distribution in this areas by calculating whether the candidate centre should be constructed and the number of chargers to be built. We first select 25 districts centres as alternative centres, as shown in figure 1(a). Although the traffic in Seoul is complicated, the traffic flow is often concentrated in several important transportation hubs. So based on Seoul's traffic flow, we identify 13 candidate charging stations to meet the needs of vehicles on the road, as shown in figure 1(b). Combined with the above two types of charging stations, for Seoul, we identify a total of 38 candidate charging stations, as shown in figure 1(c).

![Figure 1](image)

**Figure 1.** The determination of candidate charging stations (a) Regional centre candidates (b) Road demand candidates (c) All candidate charging stations.

After calculating the scale and construction cost of all charging stations in the candidate charging centres, how to build a station around each charging centre depends on the terrain characteristics of the charging centres and other realities.

5.2. Result analysis

As we mention before, Urban Charging Station Planning Model is a nonlinear integer programming model, we use LINGO 17.0 to solve, LINGO 17.0 is designed for solving nonlinear integer programming models and other optimization models. Due to a large amount of computation is required, we only obtain the approximate solution of the model. The results show that a total of 23 candidate centres should be built, with 1976 superchargers and 55328 destination-chargers in total. In the actual establishment process, the destination-chargers can be distributed to the parking lot, shopping centre and entertainment centre in the certain area represented by candidate centres. Superchargers can be built near roads with low traffic flow to avoid traffic congestion. The final network of charging stations in Seoul is shown in figure 2(a).

To explain the feasibility of model results more intuitively, we compare the model results with the population density of Seoul. Observing figure 2(a) and figure 2(b), we can clearly see that there is a clear relationship between the number of charging stations and the population density which is consistent with our intuitive ideas. Besides, some of candidate centres have not been selected. According to the data analysis, the main reason for that is the non-selected candidate centres have a relatively smaller population in the region or a short distance from the other candidate centres that we chose to build which meets the goal of our model that minimize construction costs as well as minimize service costs.
Based on our experimental results above, we can assume that our model can solve the planning problem of charging stations in most cities with sufficient data, while in the case of insufficient data, taking our experimental results as an example, we can select the city roads or parking lot within a certain range of each candidate centre, and evenly distribute charging stations based on data such as traffic volume and parking rate.

5.3. Sensitivity analysis on battery capacity
Technology is constantly innovating, and the most advantageous factor for the growth of EVs is the improvement of battery capacity and charging technology. For now, the biggest drawback of EVs relative to cars is their long charging time, which is also a major factor that limits people's purchase of EVs. In the long term, the increase in battery capacity will make the driving distance of EVs longer, resulting in a decrease in the density of the charging network. The work of Nykvist and Nilsson [12] shows that the price of batteries may drop below $150 per kWh by 2025 when EVs will begin to penetrate the market extensively. To accelerate the promotion of EVs, increasing the battery capacity to improve the endurance of EVs is a good way. Considering the Urban Charging Station Planning Model proposed in this paper, when the battery capacity increases $\gamma$ times, $D_{\text{full}}$ will also increase $\gamma$ times while charging demand will reduce $\gamma$ times. The details are shown in the formula (11).

$$n_{i}^{\text{ev}} = \frac{n_{i}^{p} \rho d^{\text{day}}(1 - \beta)}{\gamma d_{\text{full}}}$$

(11)

Sensitivity analysis of $\gamma$ is shown in figure 3:

Figure 3. Sensitivity Analysis of EVs battery capacity.
From figure 3, we can see that when the battery capacity is expanded to three times the current value, the target value of the Urban Charging Station Planning Model has significantly decreased. When the battery capacity is expanded to four times or more, the change effect to the target value is not obvious. This result can be used as a reference for battery developers.

6. Conclusions and future work
In this paper, we have proposed an Urban Charging Station Planning Model to solve the charging station location problem fully considers the construction costs of charging stations as well as service costs. We have obtained practical results through the experiment. In addition, we have expanded our model through the sensitivity analysis of the battery capacity and we found that when the battery capacity is three times the original, the increase in battery capacity will not have much impact on the cost of the station. This conclusion has certain reference value for relevant practitioners.

However, our model has some limitations:
- When we calculate the cost of the charging stations, we do not consider some more complicated factors, such as the operating costs of Charging station, the power supply network and so on.
- Due to the different peak periods of charging at various locations, we do not consider the queuing at peak times when calculating the cost of user experience.
- The specific construction sequence of each site is not given, but our model still provides a good reference for the actual construction plan.

In view of the deficiencies mentioned, the directions and priorities of our future work are as follows:
- We will further enrich our Urban Charging Station Location Model. When calculating the cost of charging stations, in addition to considering the pre-construction costs, we also need to consider the operating costs of the later period.
- We want to make a schedule for the construction of a charging station that corresponds to the all-electric progress. So we intend to modify the model proposed in this paper based on MCSSP (Maximum Covering and Shortest Path Problem) proposed by Current et al [4], and propose a new location model, and in this model, we will introduce a parameter $\alpha (\alpha \in \{0, 1\})$ which represents the process of charging station construction.

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References
[1] Wikipedia contributors 2018 Weber problem URL https://en.wikipedia.org/w/index.php?title=Weber\'s_problem&oldid=824803484
[2] Toregas C, Swain R, ReVelle C and Bergman L 1971 The location of emergency services Operations Research INFORMS 19 pp 1363-1373
[3] Church R and ReVelle C 1974 The maximal covering location problem Papers of the Regional Science Association Springer 32 pp 101-118
[4] Current J R, Re Velle C S and Cohon J L 1985 The maximum covering/shortest path problem: A multiobjective network design and routing formulation European Journal of Operational Research ScienceDirect 21 pp 189-199
[5] Liu Z, Wen F, Xue Y and Xin J 2012 Optimal siting and sizing of electric vehicle charging stations Dianli Xitong Zidonghua Automation of Electric Power Systems Automation of Electric Power Systems Press 36 pp 54-59
[6] Lingfeng K, Zifa L and Huan Z 2010 Modeling algorithm of charging station planning for regional electric vehicle Modern Electric Power 27 pp 44-48
[7] Wikipedia contributors 2018 Seoul URL https://en.wikipedia.org/w/index.php?title=Seoul\'s&oldid=834502539
[8] United nations world statistics pocketbook and statistical yearbook URL http://www.nationmaster.com/country-info/stats/Transport/Motor-vehicles

[9] Smart J, Powell W and Schey S 2013 Extended range electric vehicle driving and charging behavior observed early in the ev project SAE Technical Paper SAE Internationale

[10] Fitzgerald G and Nelder C 2017 From gas to grid building charging infrastructure to power electric vehicle demand URL https://www.rmi.org/wp-content/uploads/2017/10/RMI-From-Gas-To-Grid.pdf

[11] 2017 Speed limits reduced on most roads in seoul URL http://english.chosun.com/site/data/html_dir/2017/06/19/2017061901317.html

[12] Nykvist B and Nilsson M 2015 Rapidly falling costs of battery packs for electric vehicles nature climate change Nature Publishing Group 5 p 329