# Location of charging stations for electric vehicles

Rodrigo de Almeida Nascimento[1], Ricardo Poley Martins Ferreira[1]

[1]*Dept. of Mechanical Engineering, Federal University of Minas Gerais*
*Ave. Pres. Antônio Carlos, 6627 – Pampulha, 31270-901, Belo Horizonte/MG, Brazil*
rodrigopitangui@gmail.com, ricardopoley@gmail.com

**Abstract.** The establishment of alternative mobility technologies, such as electric vehicles (EVs), is an effective step forward in reducing restrictions on the use of carbon oxides and nitrogen oxides. However, EVs have other concerns related to the charging station infrastructure, such as insufficient quantity to meet demand, prolonged recharge time and the problem of defining the facilities of these facilities. This article studies the location of charging stations for electric vehicles by applying the median problem, in order to minimize the distance-customer-station according to the geographic service capacity. The methodology takes into account socioeconomic and demographic data, obtained and made available by research and statistical institutes in order to delimit, through these indicators, the set of demand centers and the candidate sites for the installation of charging stations. A case study is presented to investigate the problem of location and model choices.

**Keywords:** Problems locating facilities, charging station, electric vehicle

## 1 Introduction

As the auto industry progresses, some problems arise, the most serious of which include air pollution and land traffic congestion. In this sense, many automotive companies are committed to the development of electric vehicles (EVs), instead of just maintaining the production of conventional internal combustion cars, in order to reduce the emission of greenhouse gases and have a non-polluting energy system, reliable and sustainable. While electric vehicles are still expensive compared to conventional cars, users can benefit from lower maintenance and operating costs. With the popularization of EV, the charging stations, basic facilities to support the operation, gradually moved into a large-scale planning and construction process. For planners, achieving the rational elaboration of the charging station locations, ensuring the efficient operation of the EV charging station network, improving traffic, providing convenience for users to travel and improving the efficiency of charging stations, are the problems to be addressed. For Zhang et al. [1], the selection of EV charging station locations should take into account factors such as urban and electrical network planning. In addition, this process will further promote the development of urban logistics and, ultimately, the rapid growth of the metropolitan economy.

Problems like these can be modeled as a location problem, in which it is desired to establish places where facilities will be housed (factories, warehouses, hospitals, schools, etc.) to serve, in the best possible way, a spatially distributed set of demand points. Given its variety and practical importance, the problems of location have been studied by many researchers, with an extensive literature on the subject. According to Sun et al. [2] location theory was first introduced by Alfred Weber and later, Hakimi proposed the p-center location model and the p-median location model in 1964.

Considered as location-allocation classics, the p-median problem aims to determine the locations of p facilities (called medians) in a n-node network, in order to define the configuration in order to minimize the sum of the distances between each node. demand and the nearest median in a network connected by a finite number of paths. According to Garey and Johnson [3], these problems are recognized as NP - complete combinatorial optimization, since admissible solutions may require excessive computational times so that they can be considered, for example, in the context of decision making.

Several heuristic methods that explore a tree search have been developed for the problem of p-medians, but according to Hörner [4] one of the main methods cited in the literature for the problem of p-medians is the heuristic of Teitz and Bart [5], or Vertex Replacement method. This algorithm was presented by Michael B. Teitz and Polly Bart in the article entitled “Heuristic methods for estimating the generalized vertex median of a weighted graph”, in 1968. The algorithm starts from a viable initial solution and considers that all vertices are suitable candidates to be p-medians. By replacing these vertices, the algorithm determines whether the new configuration is better than the previous one, and consequently will use it as an initial solution in the next iteration.

The p-median problem is of great practical importance with many notable examples of studies applied to the location of public service networks such as those developed by Lorena and Pereira [6] in the location of telecommunication antennas, the one proposed by Pizzolato et al. [7] in the location of public schools, in the location of shopping centers presented by Rozental and Pizzolato [8], a study on the location of maternity hospitals proposed by Galvão et al. [9], among others. The problem that is the object of this work falls within this domain of studies applied to problems of interest to society, being reported by vast correlated material such as the works presented by Cavadas et al. [10], another by Sun et al. [2] and more recent by Zhang et al. [1].

This article proposes to study the location of charging stations for electric vehicles through the application of the p-median problem, solved by an optimization software package and also by Teitz Bart's Heuristics, in order to minimize the customer-station distance according to the geographic service capacity. In this sense, a methodology is proposed to define the most likely locations of demand centers considering demographic data provided by research institutes. The planner defines, according to its most convenient criteria, the candidate sites for the implementation of loading stations and the model selects from this set those p stations that meet the defined demand centers in the shortest possible distance. A case study is carried out to investigate the methodology and the choices of the proposed model.

## 2 Model formulation

Facility location problems refer to the decision of where to place installations or service stations geographically such that, in their operation, some measure of useful interest is maximized, satisfying restrictions imposed mainly related to demand.

When using the facility location problem in defining the best locations for the installation of gas stations for electric vehicles, the objective can be to minimize costs while looking for a location that seeks to maximize the benefits offered to society and in this case, the biggest concern is with the average user-installation distance.

The usual model for facility location studies is the p-median model. This model is appropriate for urban and densely populated areas; it assumes that the customer prefers the charging station closest to their current location, thereby minimizing the customer-charging station distance.

The use of the p-median model can be seen as the problem of taking a certain number of vertices and grouping them in $p$ sets, around a median vertex, where there should be an EV charging station. This process produces $p$ microregions of geographic service to the respective users. This criterion corresponds to the intuitive idea that the customer will choose the station closest to their location. Experience suggests that this hypothesis is true when charging stations have equal attractiveness and will be less realistic when the stations are heterogeneous, both with regard to the quality of service provision, supply prices and other attractions made available to the user during the recharge time. The following simplifications were also considered: assumption of a single type of electric vehicle with similar characteristics and driving range, sufficient electrical power at any of the candidate points for charging stations to meet demand and fixed and equal supply costs for all e any season.

The p-median model corresponds to the following binary linear programming model:

Minimize:

$$\sum_{i \in I} \sum_{j \in J} \alpha_i d_{ij} x_{ij}. \tag{1}$$

Subject to:

$$\sum_{i \in I} x_{ij} = 1; \forall j \in J. \tag{2}$$

$$\sum_{i \in I} y_i = p. \tag{3}$$

$$x_{ij} \leq y_i ; \forall i \in I, \forall j \in J. \quad (4)$$

$$x_{ij} \in B^{|I||J|}; y_i \in B^{|I|}. \quad (5)$$

Where the model's notations are presented below.
Sets:
$I$ is the set of candidate sites for charging stations (facilities), $i \in I$;
$J$ is the set of demand centers (customers), $j \in J$.
Parameters:
$d_{ij}$ is the distance, traveled by the vehicle, from a demand center $j$ to the charging station $i$;
$\alpha_i$ is the cost factor for implementing station $i$;
$p$ is the number of stations, or medians, to be located.
Decision variables:
$y_i$ is a decision variable that if candidate station $i$ is selected, then $y_i = 1$, otherwise $y_i = 0$;
$x_{ij}$ is the allocation of the facility, where $x_{ij} = 1$ if the vertex $j$ is a median, otherwise $x_{ij} = 0$.

The objective function, eq. (1), minimizes the distance of each user $j$ to the location of the chosen candidate station $i$. The restriction of eq. (2) states that every customer must carry out the loading in only one station and eq. (4) guarantees that it will only direct customers to any selected station. Equation (3) establishes the number of stations $p$ to be selected and eq. (5) indicates the conditions of completeness.

In the next section, a methodology for selecting sets of demand centers ($J$) will be proposed, taking into account socioeconomic and demographic data. A case study in the Brazilian city of Belo Horizonte, capital of the State of Minas Gerais, is presented to evaluate the model's choices.

# 3 Methodology for selecting demand centers

For a proper study of the location of facilities/service stations that aim to meet the immediate demands of vehicles, it is reasonable to take into consideration the areas, within the analyzed territory, where these vehicles normally circulate. However, unless there is a global positioning system for the entire population to be analyzed through which it is possible to obtain data with the geographic information necessary for such an application, it is necessary to use alternative ways of correlating demographic data provided by research institutes. research in such a way that information relevant to the model can be extracted.

Thus, to facilitate analytical studies, the proposed simplification is to use the proportion of the fleet of circulating vehicles in relation to the total population of the place where the study is intended, in such a way that it is possible to use socio-economic demographic indicators of censuses carried out and made available by research and statistical institutes containing detailed information about that population group.

These data are usually separated by census tracts, a spatial configuration with a number of houses defined by the institutes, in such a way that the designated professional is able to collect the information from the Demographic Census. Thus, the most frequent proposed simplification consists of discretizing the population according to the census sectors, concentrating the information on the centroids of the areas defined by each of them, the so-called demand center. This discretization of the demographic space enables studies called discrete location problems.

In this study, the socioeconomic indicators of the census sectors will be correlated in order to propose, within the geographic space analyzed, the favorable locations for demand centers, thus forming the set $J$.

The set $I$ of candidates for the charging station can be chosen according to the criteria imposed by the planner himself. These criteria can be comprehensive, such as, for example, considering all the census sectors available in the Census data or restricting only to the set formed by the demand centers ($J = I$) or even using other criteria that are more appropriate. Regardless of the criterion used by the planner, the model proposes to select $p$ elements from set $I$ most favorable to the implementation of the charging station in such a way as to minimize the distance between these centers of demands (elements formed by set $J$).

### 3.1 Correlation of demographic indicators for selection of demand center

In the context of the study, two socioeconomic indicators are relevant in the analysis: average and quantitative income of people by census tracts. The first because, due to the relatively high costs of purchasing EVs, this asset is still limited to groups with a certain income range and the second because it is assumed that the greater the number of people in a given area, the greater the probability of circulation of vehicles in that area. In this way, a correlation between such indicators is proposed in order to determine, among the total set of available census sectors, which are the most appropriate that will compose the set of demand center.

Initially, it is necessary to establish *k* Income Ranges (in minimum wages) and thereby obtain the Average Income ($MI_k$) of each of the *k* Income Ranges based on the available Demographic Census data. Table 1 shows the income ranges considered in this study.

Table 1. Income Range for minimum wage

| Class (k) | Income Range in Minimum Wage | Mean Income for Range ($MI_k$) |
|---|---|---|
| 1 | $MW \geq 14.5$ | $MI_1$ |
| 2 | $8.5 \leq MW < 14.5$ | $MI_2$ |
| 3 | $5 \leq MW < 8.5$ | $MI_3$ |
| 4 | $MW < 5$ | $MI_4$ |

Then define the Income Factor ($IF_k$) of the Income Range (*k*) as the Average Income ($MI_k$) of *k* by the sum of the Average Income of all *k* income ranges, as shown in eq. (6) as follows:

$$IF_k = \frac{MI_k}{\sum MI_k}. \tag{6}$$

The population of each census sector *j* ($Psc_j$) is multiplied by its respective Income Factor ($IF_k$) corresponding to its Income Class *k*, thus establishing a population quantity for that census sector ($CP_j$) proportional to its average income, according to eq. (7):

$$CP_j = IF_k \times (Psc)_j. \tag{7}$$

It establishes a minimum value for *CPj* from which to accredit this census sector to compose the set of demand center *J*. This can be done in several ways. This study was done in such a way that it is possible to adjust by iteration the exact number of demand centers that will be considered. For this, the corresponding fraction *CPj* of each census sector *j* is multiplied by a single natural number *N*, according to eq. (8) as follows:

$$n_j = rouding\left(\frac{CP_j}{\sum CP_j} \times N\right). \tag{8}$$

The number $n_j$ obtained must be an integer. So if:

i. $n_j > 0$, the census sector *j* is a demand center, otherwise it is not;
ii. $n_j = \beta$, such that $\beta \in \mathbb{N}^*$, then this vertex is repeated $\beta$ times in the set *J*.

The sum of the $n_j$ found establishes the quantity of demand center of set *J*, so it is possible to adjust the number *N* until the number of elements of set *J* desired by the planner is obtained.

Defining set *J* by the methodology presented and set *I* by the criteria established by the planner, it is possible to obtain the matrix of distances between the elements of these sets and, in this way, solve the problem of p-medians. As these problems are considered as NP - complete, depending on the size of the input, the use of a heuristic can become important to arrive at an acceptable solution in times of admissible computational processing.

In his thesis, Hörner [4] implemented and compared heuristics applied to the problem of unqualified localization in order to evaluate their responses and the Teitz and Bart algorithm showed better solution quality. This algorithm consists of starting with an initial random solution with *p* elements and from there comparing the nodes that are outside the current solution one by one, replacing the nodes best placed in the objective function until finding the set that has the shortest distance between the user *j* to carrier station *i*.

For this case study, the model was solved by the IBM ILOG CPLEX Optimization Studio optimization software package and by Teitz Bart's heuristic.

### 3.2 Case study in the city of Belo Horizonte / MG

It considered the Brazilian Municipality of Belo Horizonte in the State of Minas Gerais to apply the methodology using data from the last census (2010) provided by IBGE (Brazilian Institute of Geography and Statistics). According to these data, Belo Horizonte had a population of 2.37 million inhabitants distributed in 3936 census tracts, 487 neighborhoods and 9 administrative regions.

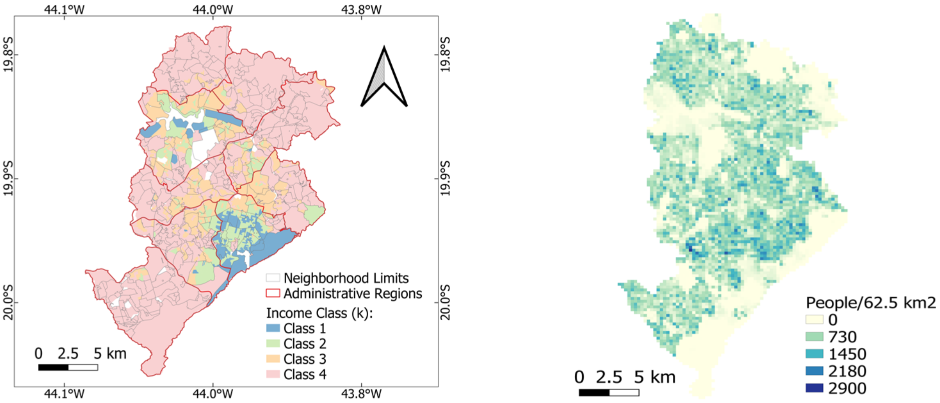


Figure 1 – a) Demographic distribution by income class b) Demographic density: number of people/62.5 km$^2$

Figure 1a represents the geographical distribution in the municipality of Belo Horizonte of the Income Range classification as established in Tab. 1 referring to the 2010 census data and Figure 1b shows the demographic density obtained from the Global Human Settlement Layer - GHSL for the year 2015 [11].

Applying the relations established in the previous section, the selection of demand centers is obtained according to the established quantity. A summary of the result is presented in Tab. 2 below.

Table 2. Consolidated results for selection of demand centers applied to the 2010 Census - Belo Horizonte

| (k) | Income Range in Minimum Wage | % Population | Mean Income ($MI_k$) | Income Factor ($IF_k$) | Number of Census Sectors | Number of Demand Centers | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 125 | 250 | 500 | 1000 | 2000 |
| 1 | $MW \geq 14.5$ | 4.40% | 19.66 | 0.49 | 172 | 103 | 141 | 188 | 293 | 452 |
| 2 | $8.5 \leq MW < 14.5$ | 8.90% | 11.1 | 0.28 | 354 | 21 | 104 | 230 | 331 | 505 |
| 3 | $5 \leq MW < 8.5$ | 14.60% | 6.44 | 0.16 | 586 | 1 | 5 | 81 | 343 | 499 |
| 4 | $MW < 5$ | 72.00% | 2.56 | 0.06 | 2824 | 0 | 0 | 1 | 33 | 544 |

The last column of the table shows how the demand centers are distributed according to the salary range established for different demand center quantities. This variation in the number of demand centers to be chosen indicates how popular the EV is being considered by the planner. That is, as the number of demand centers to be chosen increases, the EV is popular and the distribution is increasingly concentrated in layers with a salary range of up to 8.5 minimum wages where the largest percentage of the population is.

For this case study, the selection of 500 demand centers will be considered, in which the distribution is concentrated in the highest salary ranges precisely because of the costs still involved with the acquisition of this asset.

The selection of the set of locations favorable to the installation of charging stations, set *I*, is subject to the criteria established by the planner. Among the set formed, the model will choose the most favorable locations for installation. For this study, the following criteria were considered:

1) The 100 neighborhoods with the best average rents per home will be candidates for installation;

2) It is intended to install an installation in each chosen neighborhood.

With this it is possible to find the distances between the set $J$ of demand centers and the set $I$ of candidates to the charging station. In this case, the Distance Matrix API, an API (Application Programming Interface) of the Google Cloud Platform that provides the distance of the shortest real path between two informed coordinates, was used, thus establishing the real distance matrix.

He wants the model to choose the 20 most appropriate neighborhoods considering that it minimizes the distance to the user and has the lowest installation costs.

For a preliminary analysis, installation costs were disregarded, that is, $\alpha_i = 1$. In this case, the objective was to target customer service in such a way that the selection is made in order to reduce the distance between station and user.

In a second analysis, installation costs were inserted. In this study, these costs were restricted to the value of $m^2$ of real estate in each neighborhood considered in set I. With the difficulty in obtaining information related to the price of the average rental of commercial properties by neighborhood of Belo Horizonte, it considered the average price of the sale of residential properties per $m^2$ where there is a reasonable amount of information, for the purpose of this study, available in the Real Estate Market Research in Belo Horizonte: Construction and Commercialization [12]. A linear regression between the average income per home and the price of real estate sales per neighborhood was performed to obtain the values of neighborhoods that information was not available.

The model was solved, for each of the two cases considered, by the IBM ILOG CPLEX Optimization Studio optimization software package and by Teitz Bart's heuristic. The optimal solution was obtained in both methods and the consolidated result is shown in Fig. 2 below.

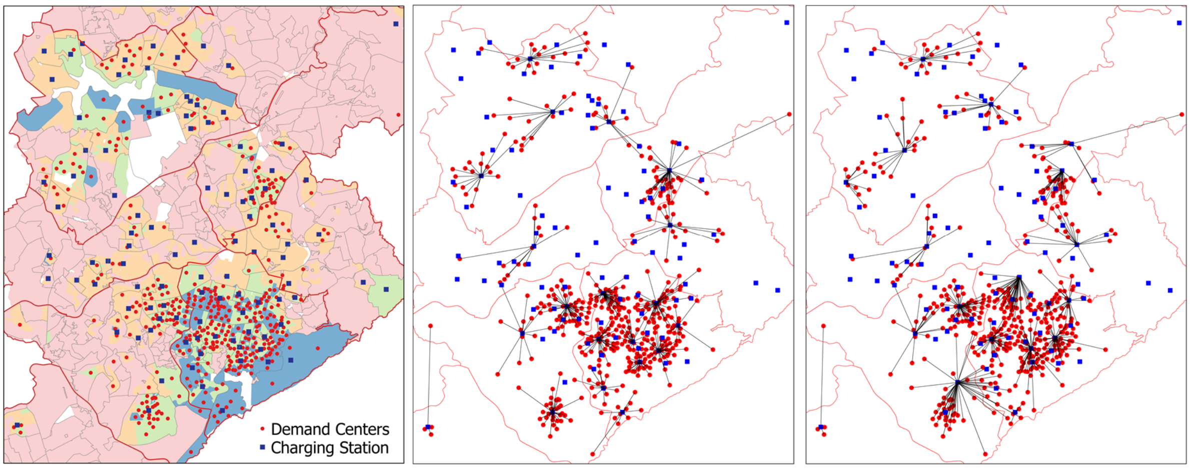


Figure 2 – a) Distribution of Sets I and J b) Result without installation cost c) Result with installation cost

Figure 2a shows the location of the 500 demand centers (red dots) selected by the proposed methodology as well as the 100 neighborhoods considered most favorable for the implementation of a charging station (blue squares). It can be seen from the figure that the demand centers are concentrated, according to Table 2, in regions with Income Class 1 and 2. Figure 2b and 2c show the selection of the 20 neighborhoods most favorable to the installation of a charging station of EV, whereas in Fig. 2b implementation costs were not considered and in Fig. 2c implementation costs related to real estate prices by neighborhood were considered. Despite the straight lines connecting directly between the demand centers and the charging station, the distances used by the model were the actual displacement between them.

It is not by chance that 40% of the neighborhoods selected for the implementation of the reference stations in the Central-South administrative region, where there is also the highest concentration of demand centers due to the predominance of income class 1 and 2.

It is important to note the changes caused by the costs of implementing the station that impacted 60% of the selected sites when considering these costs. Although the stations that suffered this geographical displacement are close to the location without considering the cost of the property, it was transferred to a neighborhood that has lower installation costs.

It is also observed that the system selected a neighborhood in the lower left corner of Fig. 2 to serve only 4 demand centers. In view of the planner's convenience, this installation may prove to be of no advantage.

In addition, the selected neighborhoods are referenced by the center of their area of expertise, however, the planner can define a location in that neighborhood best suited to the installation of the EV charging station.

## 4 Conclusions

The presented methodology is flexible to be changed, taking into account, for example, other factors and criteria more convenient to the planner when defining the candidate sites for the installation of recharge stations, or even changing the number of demand centers, restricting or expanding the selection of demand centers according to their considerations in such a way that it can better represent the reality that it intends to model. He will also be able to change the income ranges so that he can study in another configuration.

The costs of implementing the stations may also change in such a way as to portray the most important parameters for this purpose.

The results obtained are consistent with the relationships established and given the criteria previously established by the planners, they can assist in a preliminary approach to determine the regions favorable to the installation of charging stations. Factors such as limitation of the electricity distribution system, types of electric vehicles and chargers, locations that attract customers during recharging, among other factors, must be considered when defining the exact installation location.

The field of study in this area is broad and other considerations can be included in the model to enrich it, such as, for example, establishing the demand centers that take into account the residence-work-residence flow using, in addition to the census data, also geographic work/income data.

**Authorship statement.** The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

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