

OPTIMIZING ALLOCATION OF SCOOTER BATTERY SWAPPING FACILITY IN MINNEAPOLIS

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ABSTRACT. Better battery swapping station (BSS) allocation helps improve operation and management of scooter sharing. Demand fulfilling and capacity constraint jointly determine the optimal location for BSS, and this consideration results in nonlinear constraints. To minimize the total cost, this project develops a modified facility location model based on optimization programming. The optimization model is demonstrated on a case study in Minneapolis including 2826 streets and 20 neighborhoods. The results reveal that performance of the model is different from clustering, and provide strong evidence to its feasibility.

Keywords: Dockless E-scooter; Battery Swapping Station; Optimization

1 Introduction

In recent years, with the rise of green transportation and sharing economy, e-scooters have appeared in all States of the United States. As a product of the joint development of Internet and sharing economy, e-scooter provides people with more economic and environmental protection travel options with its advantages of environmental protection, flexibility and convenience, and has been favored by urban residents(Bai and Jiao (2020)). Compared with traditional bicycles, e-scooter has better electric drive, more flexible road choice and longer mileage(Lee and Lin (2015)). Fig. 1 shows the Lyft (Figure (a) on the left) and Lime (Figure (b) on the right) dockless electric scooters (e-scooter from here on out) parked on streets.

With the increasing use of e-scooters, managing and running scooters has become the primary problem of various companies. Because of the randomly parking of dockless scooters, managing and operating scooters become more and more complicated. However, research in user pattern based on historical data provide a new clue for the companies. In the context of increasingly severe congestion and advocating healthy travel, the demand for short-distance daily travel with the scooter as the travel mode in US has increased significantly. Minneapolis has a smaller population, but it has a higher per capita travel frequency and riding duration. The negative binomial regression model and GIS hotspot spatial analysis in the article show that most of the higher scooter use occurs in the densely populated central urban area and university campuses, and the diversity of land use is a positive proportion of e-scooter ridership (Bai and Jiao (2020))

Based on the previous research, we proposed a new method to optimize the Battery Swapping Station allocation and the number of batteries they should provide. The main work in this project includes:

- Optimize the location for each BSS by optimization and clustering
- Visualize the optimal allocation on map
- Verify the performance improvement of the model by comparing the total cost



(a) Lyft scooter



(b) Lime scooter

Figure 1: Scooters in Minneapolis

2 Methods and Data

2.1 Clustering

Clustering aims to discover latent knowledge from data. It is an unsupervised learning method, it is used in many fields such as data mining, pattern recognition, healthcare, document clustering, big data, image processing, bioinformatics, social networks, and outlier detection, and so on. Clustering is an unsupervised classification since there is no training dataset or predefined labels.

k-means, as one of the clustering methods, is a very good way to vector classification, which aims to partition n observations into k class. Typically, the k-means method randomly choose the center of each cluster and then for each single point, calculate the Euclidean distance between the point and each center. Then the point belongs to the cluster who has shortest distance. As talked for a very long time, the k-means clustering is a NP-hard problem, which means we cannot get the results in a polynomial time. In other words, the k-means method can be thought as an optimization problem to minimize the squared errors.

2.2 Modified Facility Location Problem

The facility location problem (FLP) is an optimization problem that appears in many disciplines and whose methods of solution can be applied to a vast range of initial problems. The traditional FLP is based on linear program with objective function to minimum the total cost, when fulfilling all the demand. The modified facility location problem we build in the project includes more constraints and specifically divide the cost into fixed cost and variable cost. Moreover, the constraints of our model are nonlinear inequality instead of linear function, which is more close to the operation of battery swap in Minneapolis.

3 Battery Swapping Station(BSS) Allocation Model

3.1 List of Symbols

Table 1: Notations and Explanation

| Notations | Type | Explanation |
|------------|----------|--|
| FC_i | constant | Fixed cost for building a BSS at i |
| VC_{ij} | constant | Variable cost when station i is responsible for region j |
| HC | constant | Holding cost for each battery |
| DIS_{ij} | constant | Distance between i and j |
| URC_i | constant | Unit rental cost |
| UTC | constant | Unit travel cost |

| | | |
|----------|-----------------|---|
| ASF | constant | Average Square Foot of BSS |
| AE | constant | Average Electricity usage per mile |
| CAP | constant | Capacity of battery reserve in each BSS |
| K | constant | Battery usage coefficient |
| d_j | constant | Battery demand at area j |
| x_{ij} | variable | fraction of the demand at j that is serviced by the facility at i |
| y_i | binary variable | equal 1 if build BSS at i , 0 otherwise |
| z_i | variable | Number of batteries BSS i reserve |
| TC | dependent var | Total Cost |

3.2 Mathematical Model

$$\min TC = \sum_{i=1}^n FC_i y_i + \sum_{i=1}^n \sum_{j=1}^n VC_{ij} x_{ij} d_j + \sum_{i=1}^n HC y_i z_i \quad (1)$$

$$\text{s.t. } FC_i = URC_i * ASF, \quad \forall i \in V \quad (2)$$

$$VC_{ij} = DIS_{ij} * UTC, \quad \forall i, j \in V \quad (3)$$

$$z_i = K * \sum_{j=1}^n x_{ij} d_j, \quad \forall i \in V \quad (4)$$

$$\sum_{i=1}^n x_{ij} = 1, \quad \forall j \in V \quad (5)$$

$$(1 - y_i) z_i = 0, \quad \forall i \in V \quad (6)$$

$$z_i \leq CAP, \quad \forall i \in V \quad (7)$$

$$x_{ij} \leq y_i \quad \forall i, j \in V \quad (8)$$

$$0 \leq x_{ij} \leq 1, \quad \forall i, j \in V \quad (9)$$

$$y_i \in \{0, 1\}, \quad \forall i \in V \quad (10)$$

Here, i is the index for Battery Swap Station, j is the index for streets. The Eq (1) is the objective function, TC consists of the fixed cost, variable cost and holding cost. Specifically, in Eq (2), fixed cost refers to the product of unit rental cost and the average BSS area(Lin et al. (2021)). In Eq (3), variable cost is calculated by distance between BSS i and street j times unit travel cost. After this, the reserved battery number z_i is determined through the demand of it's area of responsibility Eq (4). Eq (5) shows that all the demand should be fulfilled by one or several BSS. To make sure only reserve battery in the BSS chosen to built, Eq (6) set up an nonlinear feasible region. As given in Eq (7), Eq (9), they are the upper bounds and lower bounds of independent variables(Lin et al. (2022)).

4 Case Study

4.1 Scooter in Minneapolis

The first scooters were deployed in Minneapolis and neighboring St. Paul on the morning of July 10th, 2018 by the company Bird Rides, Inc. The arrival of the scooters was unexpected and both cities rushed to put policies in place around their usage. The Minneapolis City Council approved a resolution on July 24th developing a pilot licensing program for shared scooter operators within the city. The pilot program ran for 144 days. The pilot program set the maximum number of scooters at 200 for the first two months of the program, after which it could be increased to 400 until the program ended on November 30th, 2018 (Calabrese et al. (2019)). The University of Minnesota held a concurrent pilot program with 200 scooters. The pilot program in Minneapolis also required operators to pay a fee of \$20 per scooter and to share usage data with the city. The requirement that scooter operators share usage data with cities gave rise to the public dataset that this research is built on. However, the topic is subject to contentious debate in the industry.

4.2 Scooter Usage Analysis

The usage of dockless scooters, which describes the context and circumstances in which the scooters are used, is important to understand if the scooters are to become a part of the transportation fabric of the City of Minneapolis.

4.2.1 Total daily distance and duration

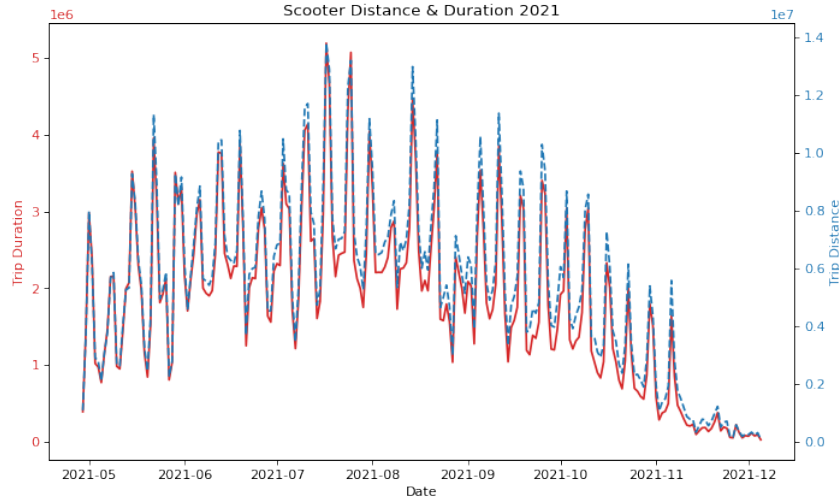


Figure 2: Total daily distance and duration

As shown in Figure 2, the daily usage depends on season and weather. The usage in 2021 goes up from May, reaching its peak in August and deeply falls down in November. Taking Covid-19 into consideration, Omicron blew up in December 2021, which means people's travel intentions heavily decrease.

4.2.2 Geographical distribution

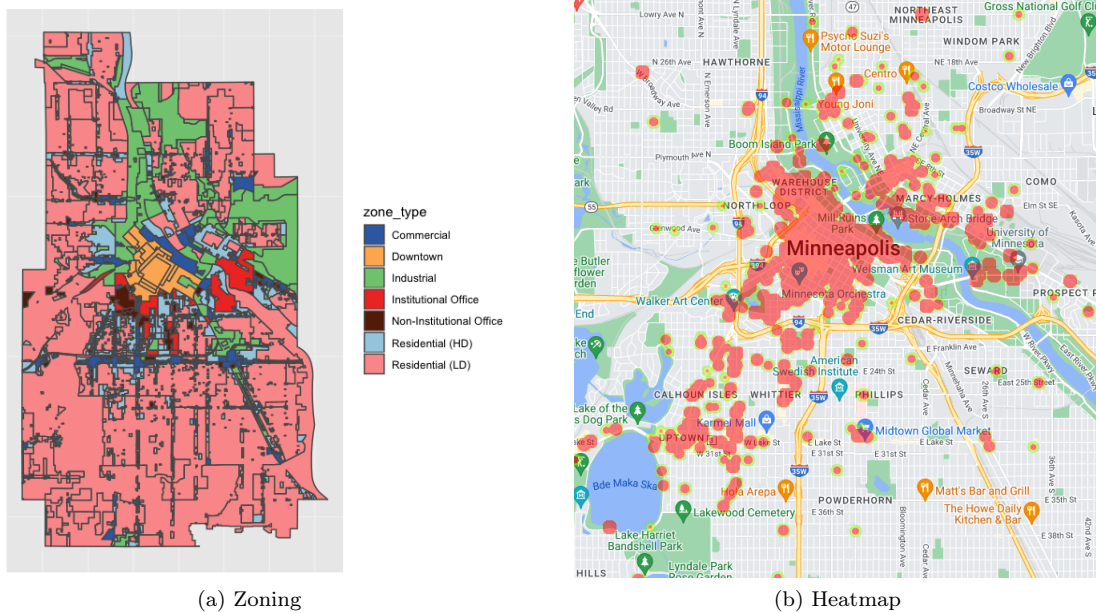


Figure 3: Zoning and Heatmap

The left picture shows zoning information in Minneapolis, and the right picture is the heatmap of scooter sharing trip. The majority of scooter rides begins in downtown Minneapolis, followed by 19% in residential areas, and 17% in commercial areas, including university campuses.

4.3 Clustering

Initial cluster center significantly affect the results of clustering. In this project, we randomly select k points from the data points as the initial cluster center. As for the number of clusters, typically, we use elbow method to test the weighted sum of distance between the point and cluster center and then determine the k value according to the curve. Given by Fig 4 left, the best number of clusters suppose to be 6. In clustering, we mainly use Lloyd's algorithm, which calculating the distance between each point and cluster center, then assign it to the nearest cluster, repeating the process until all the points are assigned to a cluster.

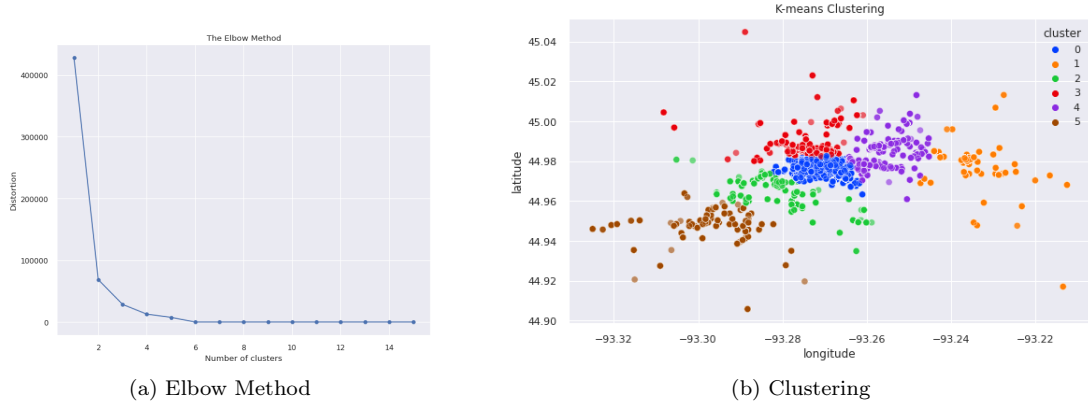


Figure 4: Elbow method and Clustering

By using k-means clustering, historical scooter sharing rides are divided into 6 group, and the number of each group are 54016, 30051, 26889, 20862, 11496, 6433 separately. Based on the results, we can come up with a BSS allocation plan, which is to build the BSS at the center of each cluster. However, this method only concerns about the geographical distribution of the e-scooter usage, ignoring the BSS capacity, fixed cost and variable cost and travel cost. So in next session, we will introduce a more advanced optimization model to determine the allocation of BSS, taking cost into consideration.

4.4 Optimization Model

The parameter setting for the case study are sated as follows. The Unit rental cost is obtained by zip code from Zillow and average squre foot is 2000 sf. The average electricity use is 0.1kwh/mile. Normally, the capacity for each BSS is 1000, because the cable can only charge about 50 battery at one time. The distance of each 2 street are calculated by Google Map Distance Matrix API, setting mode to driving. Assume travel cost to be \$0.9 per mile. Then plug all the information to the Gurobi, and generate the nonlinear programming.

To simplify the problem, we rezone the area by zip code. The nonlinear optimization model has 440 variables and 460 constraint. After inputting all the variables and constraints and setting objective function to minimize the total cost including fixed cost, variable cost and holding cost, use Gurobi 9.5.0 to solve the program. and get the results as shown in table 2.

Each set BSS is responsible for several regions in the neighborhood except for Minneapolis (zip code: 55430). However, after displaying all the spot on the map, we find that the e-scooter sharing happened in some rural places, far away from downtown. So the BSS in that area only take care of small part of workload to the whole battery swapping.

Table 2: Optimization Results

| Neighborhood | BSS Location | Zip code | Serve Region |
|--------------|--------------|----------|--|
| Lowry Hill | | 55405 | Lowry Hill, Calhoun Isles, Near North, Minneapolis |
| Phillips | | 55404 | Downtown West, Downtown East, University Of Mn, University |
| Beltrami | | 55413 | University Of Mn, North Loop, Beltrami, Audubon Park |
| King Field | | 55409 | King Field, Carag, Howe, Fulton, Powderhorn Park, Tangletown |
| Minneapolis | | 55430 | Minneapolis |

4.5 Results

Use Google Map API to visualize all the data as shown in Figure 5.

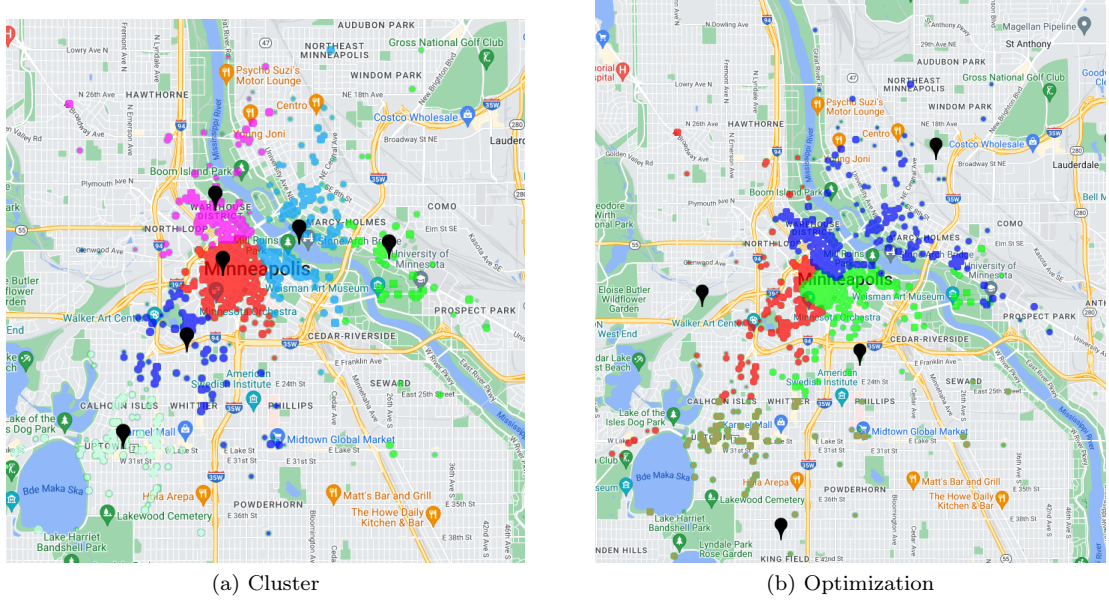
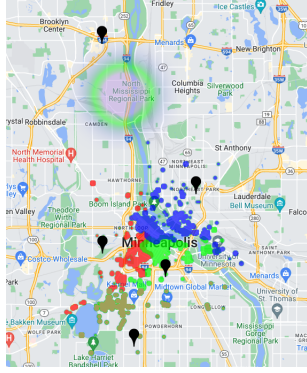


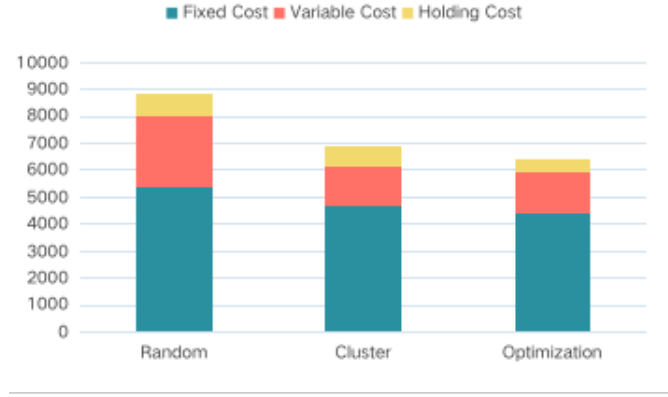
Figure 5: Cluster & Optimization

In the clustering, the allocation of BSS facility mostly locate at the center of each cluster, which means the BSS is very close to the busy area in the city. This is because in clustering, the only thing the Lloyd's algorithm cares is the shortest distance, ignoring the rental cost, and etc. When considering the rent difference among the regions, minimizing the total cost in optimization program, the locations of BSS are distributed at the rural area, balancing the travel cost and rental cost.

However, the optimization problem also has some cons, regarding some outliers. The optimal solution to the model is heavily affected by some usage outside downtown area. In Figure 6, there is a BSS especially built to fulfill the demand in the northeast area, while in clustering the result will not be influenced significantly.



(a) Outlier



(b) Cost Comparison

Figure 6: Outlier and Cost comparison

5 Conclusion

This work, which is motivated by the advent of the e-scooter popularity, aims to solve the battery swapping station location and optimize total cost considering geographical distance and rental difference. A modified facility location problem is proposed in our study which aims to minimize the total operation cost. Plus, a real case in Minneapolis using clustering and optimization method verify the feasibility of the model. The results shows that optimal solution based on our model is significantly effective and reduce the total cost up to 43% compared with randomly choose the location.

However, a limitation of our study is we simplify the city zoning by zip code, which is not precise enough to be used in reality. What's more, small part of usage in remote area influence the optimal result considerably, the sub-optimal solution ignoring the outliers may be more acceptable.

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