Senior Project

2D Weighted Voronoi Diagram Application on Service Scope Delimitation of Power Plants in the U.S.

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Submitted in Partial Fulfillment of the Requirements of the BA in Computer Science

Bryn Mawr College

Spring 2021

Abstract The paper will present an application of Voronoi diagram on improving power distribution efficiency in the U.S. by delimiting geographically service scope for each power plant by constructing a weighted 2D Voronoi diagram considering factors such as the capacity of the power plants (the maximum electric output a power plant can produce). The service scope of a power plant is defined as the region where the power plant will be the main the power source for all demand points (residential site, industrial site, etc.) within the scope. Delimiting an appropriate servoce scope of each power plant is crucial for energy efficiency, because the longer the distance of transmission, the higher the energy loss would be. In the end, a Voronoi diagram will be constructed and visualized with the service scope of each power plant delineated.

Acknowledgments

Here, you can thank whoever you wish to thank.

Contents

1 Introduction

Electricity distribution and transmission efficiency has been a crucial consideration when constructing the electricity delivery system. A main factor that contributes to the inefficiency is the energy loss during long distance transmission (Martin, 2019, p.10). In the United States, modern electricity transmission systems have driven toward larger scale and more centralized electricity generation utilities, in contrast to local, small electric utilities that were dominant before the early 20th century (United States Environmental Protection Agency [U.S. EPA], n.d.). That is, the electricity that flows to the consumer usually generates from a distant power station and travels along the long transmission lines across cities, even states (U.S. EPA, n.d.). Although the centralized layout has increased supply reliability, the drawback is also salient – the transmission cost could be up to 30% more than the distributed layout (**p.10**)central-distributed. The "line loss" contributes to the main energy loss, which is caused by the resistance when the electricity flows through the cable, and the loss increases proportionally with the transmission distance, which can be up to $10\% - 20\%$ of the total electricity transmitting ("Energy Efficiency", n.d.).

Therefore, an ideal electricity distribution model should allocate each demand point to the nearest power generator possible without exceeding each generator's maximum energy output, the capacity of the generator. To construct such a distribution model, a 2D weighted Voronoi diagram is applied to a dataset of over 8000 power plants in the United States, including each of their location and capacity. By Voronoi diagram's nature of capturing proximity, the territory is partitioned into regions such that all demand points within the same region are closer to a power plant than to any other power plants. We define such a region as the optimal service scope of a power plant. By determining the optimal service scope of each power plant, the loss caused by long distance transmission can be reduced by having each power plant be the main power provider of each demand point in its optimal service scope. We will further introduce Voronoi diagram's properties and applications in the following section.

2 Background

The traditional Voronoi diagram is a partition of plane based on a set of homogeneous points. Those points are referred to as "sites" or "generators". Each site has one corresponding region called "cell". The cells are mutually exclusive and divide up the plane. All the points in a cell are closer to the corresponding site than to any other site. The points that are equidistant from two sites form a Voronoi edge, and the points that are equidistant from more than two sites are Voronoi vertices. The definition of the diagram is given as follows (Devadoss & O'Rourke, 2011) :

> The *Voronoi region* $\text{Vor}(p)$ of a site p in set S is:
>
> $$\text{Vor}(p) = \{x \in \mathbb{R}^2 \mid \|x - p\| \leq \|x - q\| \text{ for all sites } q \in S\}$$
>
> where $\|x-q\|$ denotes the Euclidean distance between points x and q in the plane. Thus, the Voronoi diagram is represented by the set $\text{Vor}(S) = \{\text{Vor}(p) \mid \text{for all } p \in S\}$. (p. 99)

With the resemblance to natural partition and structures, Voronoi diagram has extensive application in a variety of disciplines including archaeology, meteorology, biology, epidemiology, etc. In archaeology, voronoi diagrams are often used to define the domain of influence of neolithic clans or hillforts (Okabe et al., 2009, p.133). In biology, voronoi tessellation helps to model the 3D bone microstructure (Li et al., 2012), contributing to the measurement of physical constraints of body tissues. In meteorology, Voronoi diagrams, referred as Thiessen polygon (Schumann, 1998), are used to compute average areal rainfall of a catchment from discrete data collected by rain gauges. In epidemiology, a famous application is the 1854 London Broad Street cholera outbreak(UCLA Dept. of Epidemiology, n.d.). A Voronoi diagram is constructed to accurately delineate the region where the most deaths clustered and successfully identified the source of infection. (UCLA Dept. of Epidemiology, n.d.).

Moreover, various generalizations and extensions have been developed to resolve more complex problems or better adapt to real-world situations (Okabe et al., 2009). For example, the high-order Voronoi Diagram(or k-order Voronoi Diagram) has more than 1 points that constitute of a generator(Okabe et al., 2009). The k-order Voronoi Diagram has been applied to facility location problems in terms of determining the critical k nearest facilities(Okabe et al., 2009, p.150). Another important generalization is the weighted Voronoi diagram. The ordinary Voronoi diagram assumes that sites are homogeneous. The weighted Voronoi diagram takes the variation in the properties and attributes of sites into account, which could be more suitable for practical applications (Feng & Murray, 2018) such as economic markets modeling, delivery system design, functional territories for facilities, etc.(Okabe et al., 2009, p.133).

3 Related Work

Voronoi diagram has been extensively applied to solving spatial coverage problems, especially in facility layout design, including optimizing service area delimitation of facilities. As discussed in the previous section, the ordinary Voronoi diagram relies on the assumption of a continuous and homogeneous space, but in reality, homogeneity and evenness hardly exist. Therefore, directly applying the traditional Voronoi diagram to actual situations can largely affect modeling inaccuracy and lead to functional inefficiency (Feng & Murray, 2018). Thus, numerous studies have added extensions to the traditional method to deal with spatial variability when solving coverage problems.

For example, introducing weights can compensate for the uneven attributes of the facilities to better fit the actual conditions. A study on determining ecosystem service scope (Zhang et al., 2018) compares the accuracy of traditional Voronoi diagram with the weighted Voronoi Diagram. Since ecosystem service value is a crucial indicator of the strength of ecosystem and which varies from region to region, the weighted diagram incorporates ecosystem service value and results in a more scientific service area delineation than the traditional approach does. The weighted Voronoi diagram has also been applied in a study of modeling water distribution networks (Guth & Klingel, 2012). The objective is to assign water demand points to the closest water sources. Being Aware of the geographical unevenness, a weighted Voronoi diagram is constructed with an additive constant on obstacles and boundaries that could not be passed by distribution pipes.

Moreover, the weighted Voronoi diagram has also been combined with other improvements to better adapt to the real-world circumstances. For example, a study in delimiting the service area of fire emergency stations has the fire risk index as the weight incorporated into distance calculation. In addition, the Voronoi diagram has been applied on block-like street network structure rather than on a homogeneous space to mimic the actual rescue routes(Yu et al., 2020). Another study on drone delivery of EMS from hospitals compares the traditional Voronoi diagram applying on homogeneous sites with the weighted Voronoi diagram applying on heterogeneous sites accounting to factors such as wind magnitude and obstacles. As a result, critical amount of response time, which is the most important measurement for delivery efficiency, could be saved by using the heterogeneous Voronoi diagram when determining the hospital assignment (Feng & Murray, 2018).

Thus, from the few studies discussed above, we see that Voronoi Diagram has been widely applied to determine optimal service scope, and introducing weight can compensate for spatial unevenness and produce more scientific results.

In this paper, we are going to apply a weighted Voronoi diagram on delineating the service scope of power plants in the United States in order to minimize the energy loss in transmission. The weight is introduced to reflect the variation in power plant capacity. Though we have not found any direct Voronoi diagram application on service scope delimitation for power plants, there is a relevant study on applying weighted Voronoi diagram to determining new substation sites, substation capacity and service scope to minimize the overall annual cost (Fan et al., 2009). The weight has been used to reflect the unevenness in load distribution and capacity. The major differences between our study and theirs are listed as follows:

1. In our study, the object is power plants which generate electricity, whereas their object is substations which distribute electricity.
2. Our study determines the service scope of located power plants, whereas they determines the location of new substations and their capacities.
3. Our objective is to reduce energy loss in transmission, and theirs is to reduce the overall substation operation cost.

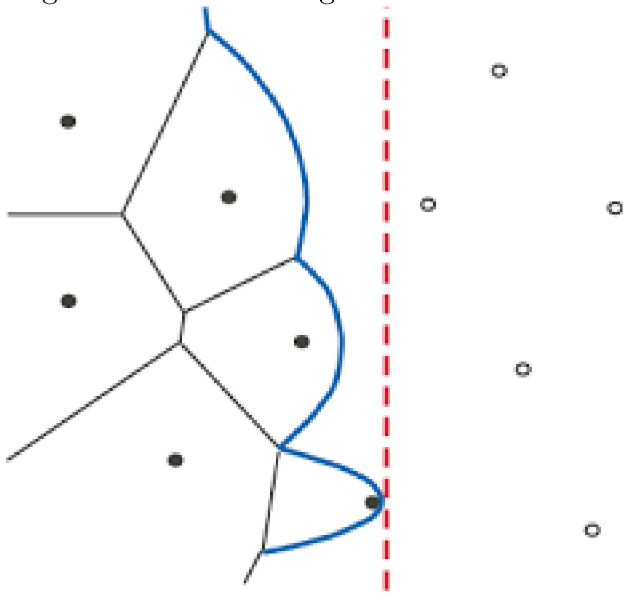
Therefore, our study is relatively pioneering in reducing the electricity loss in transmission by delimiting service scope for power plants.

4 Methodology

In this section we will discuss the Voronoi diagram construction methods. Our goal is to determine each power plant's optimal service scope by partitioning the territory of the United States based on the locations of the power plants. We define the Voronoi sites as the locations of the power plants. The corresponding Voronoi cell of each site as the result of partition is the optimal service scope of that power plant that we aim to delimit.

There are various approaches for constructing the diagram, including the incremental approach, the divide-and-conquer approach and Fortune's algorithm (the sweep line algorithm). The incremental approach proposed by Peter Green and Robin Sibson in 1977 constructs the diagram by including one site a time to the current diagram and form a new cell, until all sites are included. The time-complexity is $O(n^2)$ (Devadoss & O'Rourke, 2011, pp.105 - 106). The divide-and-conquer approach recursively divides the plane into two halves and construct the diagram for each half, and then combines the two diagrams together. The time complexity is $O(nlogn)$, which is more efficient but the combination step "is complex

Figure 1: Fortune's Algorithm Visualization



and hard to implement"(Fortune, 1986). We adapt Fortune's sweep line algorithm for our study, which has the same time complexity as the divide-and-conquer approach but has a less complicated implementation. The algorithm maintains a horizontal line sweeping from top of the plane to the bottom, which is defined as "sweep line". The sweep line and the sites that the line swept through co-determine a series of parabolas, where each parabola consists of equidistant points from a site and the sweep line that changes as the line moves downward. The union of the parabolas forms the "beach line". The breakpoints of the beach line, which are the intersections of parabolas, trace out the Voronoi edges. The disappearance of an parabola generates a Voronoi vertex. When the sweeping ends, the Voronoi diagram is produced(Fortune, 1986).

5 Data Description and Preprocessing

The data used for the application is obtained from a comprehensive, open source database of the power plants all over the world. The database is developed by World Resources Institute (WRI) in partnership with Google Earth Outreach and multiple authoritative organizations and it mainly draws upon trusted sources such as national governments and other official sources, integrated with a small portion of crowdsourced data such as satellite images for accuracy improvement (Byers et al., 2018). More importantly, among all current existing databases on this topic, it's the only one "truly comprehensive and fully accessible"(Byers et al., 2018) with all sources traceable to publicly available webpages, and is still under maintenance. The dataset in CSV form can be accessed at https://www.kaggle.com/eshaan90/global-power-plant-database. We adapt the latest official release, the release of 2018.

The dataset contains over 28,500 power plants in 164 countries, representing about 80% of the world's capacity(Byers et al., 2018). The set of attributes of power plants covers identification information (name and unique identifier), geographic information (country, longitude and latitude in WGS84 standard), electricity generation data (generation capacity in megawatts, actual generation for each year from 2013 to 2016, estimated annual electricity generation), and other information including owner of the plant, year of operation, attribution of data sources.

We leverage Python pandas library for exploratory data analysis and wrangling. Since our study object is the power plants within the United States, we only keep the dataset entries that are within the U.S. The processed dataset has 8119 instances with 5 attributes: ID, name, longitude, latitude and capacity. Through the data profiling, there are no missing data, and have reasonable range of numbers. The electrical generation capacity ranges from 1 to 6800 megawatts, the longitude ranges from -171.71 to 144.90, the latitude ranges from 13.30-71.29. All figures are within reasonable ranges.

6 Results and Analysis

7 Future Work

8 Summary

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Appendix