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Delimiting service area using adaptive crystal-growth Voronoi diagrams based on weighted planes: A case study in Haizhu District of Guangzhou in China

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ABSTRACT

Most existing methods for service area delimitation are sensitive to the modifiable areal unit problem (MAUP) since the census data used to account for the socioeconomic context are tied to discrete census tracts. This paper presents an innovative Voronoi diagrams method – adaptive crystal-growth Voronoi diagrams based on weighted planes – to address this issue. The method uses weighted raster planes to represent continuous socioeconomic attributes. It adaptively adjusts the crystal-growth speed based on real-time results of the weight of each grown area. A case study of service area delimitation for 34 middle schools in Haizhu District of Guangzhou, China is used to demonstrate its value. The results indicate that the adaptive crystal-growth Voronoi diagrams produced superior results on addressing the socioeconomic context when compared to four other methods for delimiting service areas of public facilities. Furthermore, the method mitigates the MAUP since it is based on estimated continuous socioeconomic weighted planes and no arbitrary areal units are used. It is a superior tool for delimiting service areas of public facilities which are highly dependent on the distribution of socioeconomic attributes (e.g., fire stations, ambulance dispatching sites, waste recycling centres, and many others) and it is also applicable to many other fields of spatial optimization.

Introduction

Spatial partitioning is the process of dividing a geographic area into a finite number of non-overlapping subareas (e.g., school or electoral districts) according to a set of specific criteria or constraints, which may be the spatial attributes of or relationships among various physical or human geographic factors. There has been considerable interest in spatial partitioning in geography, planning, and related fields because spatial partitioning methods can be applied to address a wide variety of issues (Moreno-Regidor, García López de Lacalle, & Manso-Callejo, 2012). The earliest discussion about spatial partitioning was by Garrison (1959). Most notable among subsequent works, Yeates (1963) presents a method for partitioning service areas of schools based on transport cost, and Morrill (1973) examines the redistricting of political-electoral districts in the U.S. More recently, spatial partitioning is widely used in the regionalization of space and/or administrative organization (Tong & Murray, 2012), as evidenced by the literature on delimiting political districts (Barkan, Densham, & Rushton, 2006; Hess, Weaver, Siegfeldt, Whelan, & Zitlau, 1965; Horn, 1995; Macmillan & Pierce, 1994; Openshaw & Rao, 1995; Ricca, Scozzari, & Simeone, 2008; Williams, 1995), socioeconomic districting (Alvanides, Openshaw, & Rees, 2002; Openshaw & Alvanides, 2001), and unit clustering (Duque, Church, & Meddleton 2011), among others.

Delimiting service area is one of the most important topics in spatial partitioning, as every individual needs various services provided by facilities at particular locations (such as schools, firefighting stations, hospitals, shopping malls, and police stations) in their everyday life. Geographic distributions of these service facilities and delineation of their service areas often need to take into account the geographic distribution of the clients they serve. Representative examples in the literature that focus on delimitating service area of public facilities include market area districting (Fleischmann & Paraschis, 1988; Hess & Samuels, 1971; Marlin, 1981; Ríos-Mercado & Fernández, 2009; Shanker, Turner, &

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Zoltners, 1975; Sinha & Zoltners, 2001), police districts demarcation (D'Amico, Wang, Batta, & Rump, 2002; Hojati, 1996), and electrical power station service area districting (Bergey, Ragsdale, & Hoskote, 2003; Tiede & Strobl, 2006).

Many models have been developed to deal with various spatial partitioning and service area delineation problems (e.g., Garfinkel & Nemhauser, 1970; Mehrotra, Johnson, & Nemhauser, 1998; Yeates, 1963). These models are based largely on two basic strategies of spatial optimization: exact and heuristic methods (Tong & Murray, 2012). Exact methods include enumeration, linear programming, and integer programming with branch and bound. These are the earliest mathematical models for spatial partitioning. They are based on straightforward methods to find the best solution by evaluating and comparing all the potential possibilities. In most cases, a two-dimensional landscape with a set of N discrete areal units is aggregated to M regions based on both spatial constraints and thematic criteria expressed in the form of mathematical formulas (Williams, 2002). Linear programming is an important method for spatial partitioning, and a number of models have been developed (e.g., Ríos-Mercado & Fernández, 2009; Shirabe, 2005; Williams, 2002; Zoltners & Sinha, 1983). However, exact methods face a significant limitation: it is computationally difficult to solve large problems using exact methods since the number of possible solutions is very large even as finite solutions are possible (Shirabe, 2005). For instance, Horn's (1990) branch-and-bound algorithm took several days of computation to solve a spatial partitioning problem with 139 zones. Although time-consuming computation is acceptable in some cases, not all spatial partitioning objectives or constraints could be expressed in terms of mathematical formulas or linear functions for solving spatial partitioning problems.

The other basic strategies are heuristic methods, including location-allocation method, simulated annealing, tabu search, and genetic algorithms. Heuristic methods are hill-climbing procedures that explore the solution space and progressively generating good or near-optimal solutions (Horn, 1995). The heuristic model first developed for spatial partitioning is pioneered by Hess et al. (1965). In the study, a location-allocation method is developed to draw nonpartisan constitutional political districts. The general planning problem and mission of the location-allocation model can be stated as "Locate a multiple number of facilities and allocate the demand served by these facilities so that the system service is as efficient as possible" (Church & Murray, 2009), and location-allocation model is also known as the p-median problem (PMP) which was originally described by Hakimi (1964, 1965). Unfortunately, location-allocation solutions are based on aggregate estimates of demand, so it is subject to errors because of a loss of locational information during aggregation (Goodchild, 1979). Furthermore, p-median problem cannot deal with large problem when applied in practice. Even though heuristic solutions have been developed to deal with the shortcoming of PMP and good heuristic designs are likely to perform well in terms of efficiency and quality of the solution (Rushton, 1984; Rushton & Kohler, 1973; Teitz & Bart, 1968), there is no guarantee that they will find the optimal solution (Massam, 1975, 1980) and the solution can only be characterized as a local optima (Hillsman & Rushton, 1975). Pearce (2000) improved the location-allocation model and applied it for defining school catchment areas and establishing the link between census data and school performance. In addition, simulated annealing and tabu search are widely applied in the field of spatial partitioning (Aerts & Heuvelink, 2002; Bozkaya, Erkut, & Laporte, 2003; D'Amico et al., 2002; Macmillan, 2001; Openshaw & Rao, 1995). More recently, the development of heuristic models made them more efficient for solving spatial partitioning problems (Bação, Lobo, & Painho, 2005; Bergey et al., 2003). Of note is the recent application of genetic algorithm by Fraley, Jankowska, and Jankowski (2010) that improves overall heuristic performance in drawing neighbourhood boundaries. However, heuristic models for solving spatial partitioning problems lack capacities in validating the solutions or assessing their quality.

In light of these limitations, there is a critical need to develop alternative methods or models, such as Voronoi diagrams, for spatial partitioning (Moreno-Regidor et al., 2012). Voronoi diagram, named after Georgy Voronoi who defined the Voronoi diagram and general n-dimensional Voronoi diagram (Voronoï, 1908), is a method for dividing space into a number of areas or regions based on a set of seed points specified beforehand. Each seed point has a corresponding region that contains all points closer to that seed than to others. Voronoi diagrams are widely used in the fields of geography and planning. Many researchers use Voronoi diagrams to deal with human geographic problems, especially in spatial optimization and spatial partitioning (Boots & South, 1997; Boyle & Dunn, 1991; Okabe, Boots, Sugihara, & Chiu, 2009; Okabe & Suzuki, 1997). To address the complexity of real-world geographic problems and to simulate reality more closely, weighted Voronoi diagrams have been developed in addition to ordinary Voronoi diagrams (Moreno-Regidor et al., 2012). Among all the applications of weighted Voronoi diagrams, Mu (2004) classified them into four periods: early prototypes (1800s–1940s), applications in market and urban analysis (1950s–1970s), parallel developments in computational geometry and GIS (1980s–1990s) and from algorithm to implementation (1990s and beyond). The typical examples include the application of Voronoi diagrams in public facilities optimization (Okabe & Suzuki, 1997; Zhang & Zhou, 2004; Zhu, Yan, & Li, 2008), in urban planning and zone design (Boots, 1975; Boots & South, 1997; Huff & Lutz, 1979), in delimitating service area according to socioeconomic context (Masouleh, 2006; Mu, 2004; Mu & Wang, 2006; Ricca et al., 2008). More recently Moreno-Regidor et al. (2012) proposed a discrete version of the adaptive additively weighted Voronoi diagrams for partitioning a two-dimensional space into zones of specific sizes.

In much previous research on service area delimitation, spatial constraints and thematic criteria used for performing spatial partition are largely based on census data. Pearce (2000) discussed and compared three techniques for establishing the link among school location, the performance of school, and areal census data. Census data, including those about socioeconomic context, are tied to discrete areal units (census tracts) and therefore are zone-based. In reality, however, socioeconomic context is continuous in geographic space. Although techniques like areal interpolation (e.g., pycnophylactic interpolation) or dasymetric modelling could help approximate the continuous distribution of context when using discrete zone-based census data, they can only provide rough estimations of the spatially continuous context. The major challenge is how to represent the continuous social and economic context (thematic criteria) more accurately when using zoned-based census data for delimiting service area. In addition, all previous studies face a fundamental methodological problem: the modifiable areal unit problem (MAUP). The MAUP has long been recognized (Openshaw, 1983) and is due to the use of arbitrary areal divisions or zones such as census tracts. In previous service area delimitation models, the results of analysis might have been affected by the areal units or spatial scale used, and the partition results might vary between different zonal or areal schemes.

In this paper we propose an adaptive crystal-growth Voronoi method to improve the representation of spatially continuous socioeconomic context in service area delimitation. The method provides a means for achieving both zone compactness (travel time based on road network and natural barrier of water) and consideration of the socioeconomic context when delimiting service area of public facilities. Different from previous research, social or