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Integrated redistricting, location-allocation and service sharing with intra-district service transfer to reduce demand overload and its disparity

Jeonghan Ko [a,b,1], Ehsan Nazarian [c], Yunwoo Nam [d,*], Yin Guo [e]

[a] Industrial and Operations Engineering, The University of Michigan, Ann Arbor, MI 48109, USA
[b] Industrial Engineering, Ajou University, Republic of Korea
[c] Global Business Processes, Walmart Home Office, Bentonville, AR 72716, USA
[d] Community and Regional Planning, University of Nebraska-Lincoln, Lincoln, NE 68588, USA
[e] Electrical Engineering & Computer Science, Case Western Reserve University, Cleveland, OH 44106, USA

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ABSTRACT

Service demand overload has been one of the main concerns in district-based service planning, because it strongly affects service quality. Moreover, the overload problem usually involves overload disparity among districts. The disparity often results from outdated district boundaries not reflecting up-to-date spatial demand distributions. A lack of systematic methodologies, however, has hindered solving such overload and disparity problems despite the increasing availability of information on spatial service demand and supply. This paper presents a novel mathematical programming model to address the service demand overload problem by reorganizing services in multiple spatial scales. The mathematical program optimizes simultaneously (1) redistricting service areas, (2) allocating multiple service resources into service-providing units in each district, and (3) sharing services between service-providing units within a district. Information on geographically distributed units is used as the spatial data of the model. This new model integrates districting and location-allocation problems as a combined problem. A heuristic solution approach is also presented to solve large problem instances. As a case study, a judicial service overload problem is examined for a state court system in the United States. This new integrated approach enables efficient utilization of the geographically distributed service capacity. In addition, these new features of the model allow for better utilization of spatial information for practical service planning.

1. Introduction

Spatial disparity in service demand overload (or capacity shortage) is a serious problem. Demand overload in service providers strongly affects the quality of service, a critical issue in service planning. However, many services, public or private, suffer from insufficient capacity because of problems such as downsizing and economic downturn. In some cases, overload is intentionally designed to avoid possible overcapacity and save costs. Furthermore, the service capacity often cannot be easily increased in the short-term.

Although service providers may have sufficient overall capacity to meet the total demand, spatially uneven overload and (consequently) uneven service accessibility usually exist. Such examples include more judicial filings than available judges in some regional courts (The National Center for State Courts) and physician shortages in rural and impoverished urban areas (Burkey, Bhadury, & Eiselt, 2012; US Department of Health and Human Services — Council on Graduate Medical Education, 2000; US General Accounting Office, 1995). This disparity often results from demographic or social changes. In some district-based service systems such as public services in less populated areas or judicial services, this spatial inequality is not easy to address without redistricting or capacity adjustment. This is because in these services, little boundary permeability often exists or service users cannot easily find alternative service providers.

One of the reasons for such spatial inequality is the lack of proper planning tools for decision makers to evaluate public service accessibility, adjust district boundaries, and set utilization levels in a cohesive manner. As pointed out in some research review papers and many geographical information systems (GIS)-related service research, the interrelationships among spatial service demand, utilization, and service outcomes are often neglected (Higgs, 2004; Mclafferty, 2003). The lack of integrated approaches to these inherently interwoven problems has hindered better service planning. Furthermore, despite the increasingly available diverse

* Corresponding author.
E-mail addresses: jeonghan@umich.edu, jko@ajou.ac.kr (J. Ko), ehsan.nazarian@huskers.unl.edu (E. Nazarian), ynam2@unl.edu (Y. Nam), yxg280@case.edu (Y. Guo).
[1] Mailing address: Ajou University, Industrial Engineering, 206, World cup-ro, Yeongtong-gu, Suwon-si, Gyeonggi-do 16499, Republic of Korea.

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spatial information such as geographical service demand and supply data, the existing models in the literature lag in using such information.

To overcome this problem, this study *integrates* three characteristics in organizing service providers: *spatial redistricting*, *multiple service capacity allocation*, and *intra-district service transfer*. Spatial redistricting is the reorganization of spatial units into geographical groups, called districts or regions. The spatial districting is of critical importance to the accessibility of potential service customers, because districting specifies the responsibility areas of each service-provider unit and the demand level for each provider. Location-allocation decisions of service capacity levels determine the level of supply at each service-providing unit or determine the location of such service-providing units. Intra-district service transfer is how the service capacity (supply) within each district is shared by transferring extra services in some service-providing units to overloaded ones. Thus, in addition to balancing workload between districts, the workload of facilities within each district is also balanced.

This intra-district service transfer is a new concept proposed in this paper, and it is critical for minimizing utilization disparity among service-providing units and maximizing the efficient utilization of service capacities. To the best knowledge of the authors, the majority of the existing literature on redistricting has focused on workload balance only on the district level. In addition, this study pursues the minimization of work overload in each district, whereas the majority of previous redistricting studies have sought balances among districts. Only some previous studies have solved problems on the balanced demand or workforce distribution in each district.

For the new approaches, this study develops a novel mathematical model that simultaneously considers redistricting, multiple location-allocation and capacity sharing for district-based service planning. The mathematical model is developed as a mixed-integer program (MIP). An effective heuristic solution method is also developed to calculate large-size problems. Information on geographically distributed units, such as service demand, location, supply, and cost are used as spatial data for the model. A judicial boundary problem in a US state is presented as a case study.

The contributions of this study are summarized as follows. First, this paper presents a new integrated model of districting and multiple location-allocation problems. Many previous studies have focused on either districting or allocation. In this paper, the district generation (i.e., clustering of spatial units into districts of aggregated service locations and demand units) and multi-facility location-allocation (i.e., setting service supply levels of multiple service units in each district) are determined simultaneously. In other words, this paper extends the districting problem, also called *p*-regions or zonation problems (Duque, Church, & Middleton, 2011), to a problem of *p*-capacitated-regions with multiple location-allocation. Thus, this paper deals with a multi-scale spatial problem.

Second, this paper presents a new mathematical model for capacity sharing combined with districting and location-allocation decisions by allowing the transfer of extra services in some service units to other service units with excessive demands. Most previous studies on service location problems have focused on opening or closing of service units depending on the service demand but have not utilized sharing service capacities among these facilities. This new integrated service transfer, however, is not simple to model. For instance, service transfer should not occur between extra-service facilities or between overloaded facilities, and a portion of transferred service may be used or lost during the transfer. Furthermore, the service transfer and districting of each unit are interwoven decisions. One of the innovative features of this study is to develop mathematical models that can consider the detailed conditions of such complex service transfer.

Third, the new approaches and model in this study help optimize district-based service planning and will help advance scientific knowledge in related research fields. Moreover, the integrated approach enhances the use of spatial demand and supply information to a more sophisticated level.

In addition, to the best knowledge of the authors, this study is the first attempt to address judicial redistricting, and actual judicial workload was analyzed and used for the case study.

The rest of this paper is organized as follows. Section 2 reviews the related literature. Section 3 describes the mathematical programming models in this study. Section 4 describes the solution method. Section 5 presents numerical examples and their results and discussion. Section 6 concludes.

2. Literature review

Location and redistricting problems can be categorized based on underlying assumptions, as summarized in some review papers. The health care location problem models were categorized into accessibility, adaptability, and availability models, and relevant formulations and analysis for each category were presented (Daskin & Dean, 2005). This study summarized the location set covering and maximal covering models as well as P-median models. A comprehensive literature review was performed on the methods for facility location and layout planning problems and their relevant mathematical models (Domschke & Krispin, 1997). A unified framework was proposed for location problems based on facilities, customers, and locations (Scaparra & Scutella, 2001). The healthcare related location and redistricting research has extended to combine other issues in healthcare, including dispatching emergency services (Toro-Díaz, Mayorga, Chanta, & McLay, 2013), ambulance allocation (Knight, Harper, & Smith, 2012) and emergency response locations (Li, Zhao, Zhu, & Wyatt, 2011).

Facility location-allocation problems have been applied for a variety of services. The studies in these applications include electrical power redistricting and their physical special features for modeling (Bergey, Ragsdale, & Hoskote, 2003), sales territory planning with new models and solution methods such as a computational geometry based method (Kalcsics, Nickel, & Schröder, 2005; Salazar-Aguilar, Rios-Mercado, & Cabrera-Rios, 2009), liver allocation systems (Demirci, 2008; Kong, Schaefer, Hunsaker, & Roberts, 2008; Stahl, Kong, Shechter, Schaefer, & Roberts, 2005), organ transplantation (Bruni, Conforti, Sicilia, & Trotta, 2006), and environmental planning and supply chain management (Smith, Laporte, & Harper, 2009). Optimization models for emergency logistics were also analyzed and classified, including facility location, stock pre-positioning, and relief distribution (Caunhye, Nie, & Pokharel, 2012; Galindo & Batta, 2013). Recently, an electric car charging location problem has received attention due to the more penetration of electric cars to the market (Giménez-Gaydou, Ribeiro, Gutiérrez, & Antunes, accepted for publication; Jung, Chow, Jayakrishnan, & Park, 2014). A variety of covering problems were reviewed for models, solutions and their applications (Farahani, Asgari, Heidari, Hosseininia, & Goh, 2012).

Recently, a new set of MIP models, called a family of *p*-regions models, have been published for spatial aggregation (districting). The notable studies include Duque et al. (2011), Duque, Anselin, and Rey (2012), Kim, Chun, and Kim (2015), and Li, Church, and Goodchild (2014a), each of which has a little different approaches. The *p*-regions problem was defined as a generic model for aggregating a number of small areas to *p* number of regions with minimizing region heterogeneity (Duque et al., 2011). This study also provided three new MIP models and compared their computational complexity. Duque et al. (2012) proposed MIP models and heuristics solution methods for clustering spatial areas to the maximum number of homogeneous regions with certain criteria values above predefined thresholds. A flow-based regionalization problem was also modeled to determine *p* functional centers and contiguous regions where areal units interact with a center (Kim et al., 2015). Li et al. (2014a) defined a *p*-compact-regions problem to additionally consider region compactness, and proposed a new efficient heuristics method of several steps including a solution seed selection, region growth, randomized greedy selection, and area reassignment.