Omega 52 (2015) 53–64

Contents lists available at ScienceDirect

Omega

journal homepage: www.elsevier.com/locate/omega

Multi-objective optimization in partitioning the healthcare system of Parana State in Brazil ☆

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ARTICLE INFO

Article history:
Received 26 February 2014
Accepted 18 October 2014
This manuscript was processed by Associate Editor Yeh.
Available online 28 October 2014

Keywords:
Health service
Healthcare system
Graph partitioning
Multi-objective optimization
Genetic algorithm

ABSTRACT

Motivated by a proposal of the local authority for improving the existing healthcare system in the Parana State in Brazil, this article presents an optimization-based model for developing a better system for patients by aggregating various health services offered in the municipalities of Parana into some microregions. The problem is formulated as a multi-objective partitioning of the nodes of an undirected graph (or network) with the municipalities as the nodes and the roads connecting them as the edges of the graph. Maximizing the population homogeneity in the microregions, maximizing the variety of medical procedures offered in the microregions, and minimizing the inter-microregion distances to be traveled by patients are considered as three objective functions of the problem. An integer-coded multi-objective genetic algorithm is adopted as the optimization tool, which yields a significant improvement to the existing healthcare system map of the Parana State. The results obtained may have a strong impact on the healthcare system management in Parana. The model proposed here could be a useful tool to aid the decision-making in health management, as well as for better organization of any healthcare system, including those of other Brazilian States.

1. Introduction

One of the challenges in logistics is to provide need-basis products or services. A bottom line task in logistic handling is to structure systems or distribution configurations so that markets away from production sources can be served in an optimized way or services can be provided in possible shorter time [2]. The healthcare system of Parana State in Southern Brazil is studied here in that direction.

The Parana State, which is divided into 399 municipalities, has a population close to 11 million inhabitants. In the case of health services in Parana, funds are transferred from the Federal and State authorities to local units based upon the population size and variety of health procedures expected to be performed. There is a proposal for decentralization of the healthcare services in Parana by aggregating its municipalities into smaller groups, known as microregions, where the majority of health procedures can be provided so as to reduce the number of inter-microregion trips and the distances to be traveled by patients [7]. Motivated by the proposal, the present optimization-based computational work is carried out. For this purpose, Parana State is first transformed into an undirected graph/network with its municipalities as the elementary units (nodes) and connecting roads of the municipalities as the edges of the network. The network is then partitioned into some non-empty zones, each zone representing a microregion, so as to optimize three objectives subject to five constraints. The first objective is to maximize the homogeneity of population in the microregions, which would ease the distribution of facilities and funds. The second objective is to maximize the variety of medical procedures offered within a microregion so that precious time and money can be saved by reducing the need to send patients from one microregion to another. The third objective is to minimize the distances to be traveled by patients on going from one microregion to another. In regard of constraints satisfaction during the partitioning process, the integrity of the municipalities is maintained by avoiding the inclusion of the same municipality in multiple

☆ This manuscript was processed by Associate Editor Yeh.

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http://dx.doi.org/10.1016/j.omega.2014.10.005
0305-0483/

microregions, and the contiguity of the microregions is maintained by forming a microregion with inter-connected municipalities only. Care is also taken to avoid the complete embedding (surrounding) of a microregion by another. Finally, the municipalities are aggregated (partitioned) into a number of microregions within a predefined range, and the number of municipalities to be included in each microregion is also maintained within another given range. A customized version of the integer-coded multi-objective genetic algorithm, proposed by Datta et al. [12,15], is employed as the optimization tool for the problem. In the experimental part, the best compromised scenario is presented by comparing the results of the genetic algorithm with the existing healthcare system map partitioning the 399 municipalities of Parana into 83 microregions.

It is to be emphasized that the main scientific contribution in this article is related to the modeling aspect of the problem, in particular the design of the three objective functions taking into account the real need in Parana and considering the proposal of the local authority for improving the existing healthcare system in the State. It seems to be very significant in the context of the graph partitioning problem in general, and the territory districting problem in particular. To the best knowledge of the authors after surveying the specialized literature, it is the very first attempt for developing such a model for this problem. Additionally, the application of the multi-objective optimization approach to the healthcare system partitioning, in which way it is done here, is also new. Surveying the specialized literature (as reported in Section 2), only two works, conducted by Datta et al. [13] and Benzarti et al. [4], could be obtained where healthcare systems were partitioned as a multi-objective optimization problem, but with very different approaches.

The rest of the article is organized as follows. The relevant works dealing with territory partitioning are reviewed in Section 2. The present healthcare system in Parana State is highlighted in Section 3, followed by Section 4 giving the present problem formulation and Section 5 describing the methodology used in this work. Section 6 presents the results and managerial implications. Finally, the article is concluded in Section 7.

2. Literature review

Under the broad name of the territorial districting or network partitioning problem, numerous mathematical programming models have been proposed for grouping smaller territorial units into larger ones with applications to different fields. Although the deterministic mixed-integer linear programming (MILP) is the most appropriate approach for handling such models, its inadequacy for working with large-size real-world situations has led to the development of different heuristics and metaheuristics for the territorial partitioning problem [3]. However, such metaheuristics are generally real-valued and their direct application to the integer variables of a problem is likely to generate infeasible solutions, whose steering to the feasible region becomes a challenging task (*see*, e.g., [14]). Hence, many problem-specific versions of different metaheuristics are being proposed for generating feasible solutions directly. Such approaches reported in the specialized literature in the last decade are reviewed here in detail in chronological order (and also summarized in Table 1).

D'Amico et al. [9] applied a single-objective simulated annealing (SA) to the police management problem in Buffalo City, USA, in which the aim was to obtain an optimum police district map that minimizes the disparity between the extreme workloads of the police officers in the process of determining the number of patrol cars on duty at various time periods of a day. As a major merit, their proposed map helped to alleviate an annoying dispatching quirk that appeared in the practicing configuration. Muyldermans et al. [25] studied salt spreading in the province of Antwerp, Belgium, through a multi-objective heuristic search procedure, in which the road network was partitioned in order to minimize both the traveling distance and number of trucks required in the operation. Applying a multi-objective genetic algorithm (GA) to partition the power grid of the Republic of Ghana into economically viable districts (distribution companies), Bergey et al. [5] identified some fundamental characteristics required to correctly model and solve an electrical power districting problem. A tabu search (TS) approach coupled with an adaptive memory heuristic was proposed by Bozkaya et al. [6] with the application to the electoral districting problem of the city of Edmonton, Canada. Galvão et al. [19] presented a multiplicatively-weighted Voronoi diagram for treating the parcel delivery in the city of São Paulo, Brazil, as a logistics districting problem, which resulted in more balanced time/capacity utilization compared with other approaches. A benchmark transportation delivery planning system is studied by Haugland et al. [20] in two stages using TS and a multi-start metaheuristic, in which the districting decision is made in the first stage and then the vehicle routing problem is solved for each district in the second stage. Combining a local search with a multi-objective GA, Tavares-Pereira et al. [32] analyzed the public transportation system of the Paris region in order to suggest a reform to its pricing system. A spatial-GIS based multi-objective GA is investigated by Datta et al. [14] for the problem of land-use management in Baixo Alentejo, Portugal, with the objectives of both natural balance of the environment and financial profit. Targeting population equality, compactness and administrative conformity, Ricca and Simeone [28] studied descent, TS, SA and old bachelor acceptance algorithm in a comparative way on the multi-objective electoral districting problem in the Italian regions. Ricca et al. [27] investigated the potentiality of weighted Voronoi diagrams (WVR) in locating the Italian electoral centers with the objectives of population equality and compactness. With transportation and logistics applications in an urban distribution service in a part of the city of São Paulo, Brazil, Novaes et al. [26] also investigated Voronoi diagrams, but in association with continuous approximation models, for solving the location-districting problem by minimizing total daily delivery costs and balancing the distribution effort among vehicles. Salazar-Aguilar et al. [30] applied the ϵ-constraint method for handling the beverage distribution in the city of Monterrey, Mexico, as a multi-objective problem with respect to the number of customers and sales volume. Shirabe [31] applied a single-objective map algebra based heuristic for solving MILP models of several illustrative instances of the well-known school bus problem. Contreras et al. [8] presented two MILP formulations, as the generalization of the classical p-center problem, for the location of facilities and the design of its underlying network so as to minimize the maximum customer-facility travel time. A model for locating emergency medical services by incorporating survival functions for capturing multiple-classes of heterogeneous patients was proposed by Knight et al. [21] for maximizing the overall expected survival probability of multiple-classes of patients, which was solved for the ambulance service in Wales using an approximation approach. An integer-coded multi-objective GA was proposed by Datta et al. [15] to deal with the census tracts in the Census Metropolitan area of London, Ontario, Canada, by aggregating the census units so as to obtain a higher level of compactness and population/area uniformity. A customized version of this integer-coded multi-objective GA was proposed by Datta et al. [13] for presenting an optimal administrative healthcare geography for East England with five objectives of geographical compactness, co-extensiveness with current local authorities, size homogeneity, age homogeneity and economic homogeneity. Lin et al. [23] proposed a framework for multi-objective simulation optimization that combines GA with data envelopment analysis, which was applied to determine the optimal resource levels in surgical services. Benzarti et al. [4] studied the home healthcare as a mixed-integer programming districting problem under four objectives of indivisibility of basic units, compactness, workload balance between