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The design of a reliable and robust hierarchical health service network using an accelerated Benders decomposition algorithm

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ABSTRACT

This paper proposes a novel reliable hierarchical location-allocation model addressing a real-world health service network design problem. The model considers several key issues regarding health service network designs such as hierarchical structure of networks characterised by a two-level multi-flow hierarchy with service referral, uncertainty associated with demand, service and geographical accessibility, prioritizing patients based on their urgency and adopting different service strategies to serve them, service quality reflected in the patients' expected waiting time by considering the priority queuing system, and risk of unexpected disruptive events. To deal with different sources of uncertainty in the concerned problem, a robust scenario-based stochastic programming approach is employed. To solve the proposed model, a Benders decomposition algorithm enhanced by several accelerating methods is developed. A practical case study is presented to illustrate the applicability of the proposed model as well as the effectiveness of the designed solution procedure.

1. Introduction

A facility location problem involves several strategic decisions such as determining the number and location of new facilities in some given geographical areas, allocating demand nodes to the located facilities, and designing a transportation network such that the main objectives of system designers may be served. These objectives include minimization of total travel time, physical distance, operational and transportation costs or maximization of the market capture and reliability. To address these decisions, various modeling and algorithmic frameworks covering both continuous and discrete spaces have been proposed. The main application of facility location problems includes many practical contexts such as supply chain planning, transportation infrastructures, and public service systems. Exhaustive reviews in this area can be found in Revelle and Eiselt (2005) and Revelle, Eiselt, and Daskin (2008).

When making facility location and allocation decisions, different sources of uncertainty must be taken into account. As stated by Shen, Zhan, and Zhang (2011), the uncertainty can be classified into three categories: (1) provider-side uncertainty, (2) receiver-side uncertainty, and (3) in-between uncertainty. The first is related to the uncertainty in facility capacity and the reliability of facilities, the second includes the randomness within the demands, and the third corresponds to uncertain travel time, transportation cost, etc. The second and the third categories of uncertainty are investigated in a large body of facility location literature. The relevant works addressing these two categories assume that the topology of provider-side network cannot be changed due to uncertainty (Shen et al., 2011); however, it may be affected by unexpected future events during the operational process. Uncertain events may originate from different sources including natural disasters, equipment breakdowns, terrorist attacks, labor strikes, changes in ownership, etc. In the case of disruptions, it is impossible to immediately change the network substructure to serve the demands. Often, in order to achieve system reliability, mitigation or recourse operation is implemented in such a way as to reassign the demand nodes to other operational facilities much farther than their regularly assigned facilities (Aydin & Murat, 2013; Snyder & Daskin, 2005).

To deal with uncertainty, different approaches such as stochastic programming and robust optimization have been utilized in the literature. Stochastic programming is an efficient tool when there are enough historical data for the uncertain parameters such that their probability distributions can be obtained. Robust

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optimization is another suitable alternative that provides solutions to handle the uncertainty of parameters in optimization problems that can immunize the optimal solution from all possible realizations of parameter values within a deterministic uncertainty set (Pishvaee, Rabbani, & Torabi, 2011). Notably, there are three well-known approaches in the robust optimization area including robust scenario-based stochastic programming (see Mulvey, Vanderbei, & Zenios, 1995), robust convex programming (see Ben-Tal & Nemirovski, 1998; Ben-Tal & Nemirovski, 2000), and robust fuzzy programming (see Pishvaee & Fazli Khalaf, 2016; Pishvaee, Razmi, & Torabi, 2012).

Health service network is one of the most important public service provisions in urban and rural areas which is strongly affected by facility location and allocation decisions. There are several critical issues that must be considered in the planning of health service networks such as geographical accessibility, transportation network, service capacity, hierarchical structure of health system, service quality and different types of cost such as investment, transportation and operational costs. Since most of these issues have a long or mid-term effect on the health service network, it is important to investigate their relevant uncertainties which appear during planning and operating processes in order to obtain an efficient network design.

Health service networks are particularly vulnerable to disruptions during which the overall system efficiency and responsiveness might significantly be deteriorated. Following the disruptions, most of the regular services like accepting patients and scheduling surgical procedures cannot be served. Consequently, to obtain a reliable configuration of health service networks, it is crucial to consider the reliability aspects of provider-side uncertainty in the design.

Generally, health service networks are required to meet variable and random demands. However, the demand will be sometimes so heavy that the system may not be able to satisfy all the simultaneous requests for service due to the limited capacity. Such a system is called to be *congested*. In congested situations, patients may afford waiting until the facility becomes free to serve them whereas, in some other cases such as maternity homes, it is not possible to wait (Boffey, Galvao, & Espejo, 2007; Zarrinpoor & Seifbarghy, 2011). Indeed, in disruptive conditions, a higher level of congestion in health service networks is expected. The queuing theory is an efficient approach to cope with congested situations in a health service network design. It can also provide greater realism by incorporating two sources of uncertainty associated with demand and service (*e.g.* the exact timing of demand and the time it takes to serve individual demands at service facilities) (Castillo, Ingolfsson, & Sim, 2009).

As another considerable view, most health service networks are hierarchically structured. There is often a linkage between the facilities at different levels which makes it impossible to determine the location of each level separately. Therefore, an effective coordination of services provided at different levels requires integration in the spatial organization of facilities (Marianov & Serra, 2001; Sahin & Süral, 2007). In order to achieve a more practical health service network design, the hierarchical relationships among different facility types and the flow of services in the hierarchy must be taken into consideration.

Geographical accessibility is one of the fundamental elements for the success of health service networks that can significantly affect a transportation network design. Although improving geographical accessibility may require establishing hospitals in candidate locations with a small population, higher inefficiencies and costs will be incurred due to the lack of surrounding public infrastructures and human resources (Mestre, Oliveira, & Barbosa-Póvoa, 2015; Moore & ReVelle, 1982; Rahman & Smith, 1999). Therefore, the minimum population required for opening a facility, geographical accessibility, and corresponding costs must concurrently be taken into account for designing health service networks.

With regard to the above-mentioned points, the present research proposes a novel hierarchical location-allocation model addressing a real-world health service network application. Risks of unexpected disruptive events are taken into account by considering a set of disruption scenarios each associated with a given probability. The relationships among various levels of the concerned health network are characterized by a two-level multi-flow hierarchy with a service referral. Patients are prioritized based on their urgency, and different service strategies are adopted to serve them accordingly. The uncertainty associated with demand as well as service is considered in the model within the priority queuing system. Moreover, the geographical accessibility of a health service network is considered in terms of the proximity of the facility to potential patients, and its value depends on the realized disruption scenario. To ensure the service quality, a maximum limit reflected in the patients' expected waiting time in queues is defined. The minimum population required to open a facility is also taken into consideration, which ensures the health service facilities are constructed in locations with sufficient surrounding public infrastructures, human resources and demand. We formulate the problem as a robust scenario-based stochastic programming model to deal with different categories of uncertainty including provider-side, receiver-side and in-between. To solve the proposed model, a Benders decomposition algorithm enhanced by several accelerating methods is proposed. A practical case study and several generated instances are presented to illustrate the applicability of the developed model as well as the effectiveness of the designed solution procedure.

The rest of this paper is organized as follows. The next section reviews the related literature. Section 3 defines in detail the concerned problem. Section 4 presents a mathematical model. In Section 5, an accelerated Benders decomposition algorithm is developed to solve the model. Section 6 describes a real-world case study as well as several generated instances to illustrate the applicability of the proposed model. Section 7 ends with some conclusions and possible directions for future research.

2. Literature review

In this section, the relevant literature is reviewed in two separate but complementary research streams in the context of health service network, and then the main contributions of this research are presented.

2.1. Facility location problem for health service networks

Facility location problems have gained growing importance in the success of health service networks because they can ensure that the objectives of system designing such as minimizing social costs or equally maximizing the benefits of people, are served. They also provide a framework for investigating service accessibility problems, comparing the quality of previous location decisions, and generating alternative solutions either to suggest more efficient service systems or to improve the existing ones (Rahman & Smith, 2000). Basic applications of facility location problems in the context of a health service network include geographical considerations in healthcare planning (Harper, Shahani, Gallagher, & Bowie, 2005), locating ambulances (Schmid & Doerner, 2010), trauma care resources (Branas, MacKenzie, & ReVelle, 2000), organ transplant services (Bruni, Conforti, Sicilia, & Trotta, 2006; Zahiri, Tavakkoli-Moghaddam, Mohammadi, & Jula, 2014), locating blood banks (Jabbarzadeh, Fahimnia, & Seuring, 2014; Jacobs, Silan, & Clemson, 1996), emergency medical service designs (Beraldi & Bruni, 2009), and preventive healthcare facility network designs (Zhang, Berman, & Verter, 2009).