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Design of a reliable hierarchical location-allocation model under disruptions for health service networks: A two-stage robust approach

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ABSTRACT

This study proposes a novel reliable hierarchical location-allocation model for health service network designs where facilities are subject to the risk of disruptions. To characterize the relationship between various levels of the concerned health network, a two-level multi-flow nested hierarchy with service referral is taken into account. The queuing system is considered in the model which handles uncertainty associated with demand as well as service. To ensure the service quality, a minimum limit reflected in the probability of patients' waiting time is defined. The proposed model is formulated based on a two-stage robust optimization approach in which decisions are defined in two stages such that a first-stage solution should be robust against the possible realizations of the disruption that can only be revealed in a second stage. A solution procedure based on Benders decomposition type algorithm is implemented to solve the model. To illustrate the applicability of the proposed model, a practical case study is presented. The results show that the proposed model can be applied as a flexible decision support tool for decision makers to adopt appropriate strategies and policies in designing a reliable and robust health service network.
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1. Introduction

Facility location and allocation decisions have gained growing importance in the success of health service networks since they involve strategic and operational policies with mid and long term effects. These decisions can ensure that the objectives of system designing, such as minimizing social costs or equivalently maximizing the benefits of the people, are served. They also provide a framework for investigating service accessibility problems, comparing the quality (in terms of efficiency) of previous location decisions, and generating alternative solutions either to suggest more efficient service systems or to improve the existing ones (Rahman & Smith, 2000).

Regarding facility location and allocation decisions as the fundamental elements in the planning of health service networks, different sources of uncertainty must be taken into account. Some critical input data such as demand is uncertain in the decision process. Furthermore, these decisions may be affected by the unexpected future events during the operational process. Although, most of the relevant works assume that a constructed healthcare facility will remain active forever, in practice there are many types of disruptive events which can make the facility unavailable from a time moment to another one. Disruptive events may originate from different reasons including natural disasters, equipment breakdowns, terrorist attacks, labor strikes, changes in ownership, etc. (Snyder & Daskin, 2005). Facility disruptions can significantly deteriorate the overall system efficiency and responsiveness. Recent examples of such disruptions include (1) the SARS outbreak in Toronto, Canada, in the summer of 2003 that quarantined many hospitals (Berman, Krass, & Menezes, 2007), (2) the massive power outage in 2003 that disabled major transportation systems in the Northeast (Li, Ouyang, & Peng, 2013), (3) the 2005 Hurricane Katrina that idled all production and transportation facilities in the Gulf Coast region (Aydin & Murat, 2013; Li, Ouyang, et al., 2013), and (4) the 2011 disastrous earthquake in Japan that halted the production in a broad spectrum of the country's industries, because of plant damage, transportation blockage or power outages (Peng, Snyder, Liu, & Lim, 2011). The aforementioned examples highlight the importance of the reliable network design to work properly in both normal and disruptive conditions.

In the occurrence of disruptions, the health service network may not be capable of serving most of the requests for regular services such as accepting patients, scheduling surgical procedures, etc. 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

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their regularly assigned facilities (Snyder & Daskin, 2005). Additionally, demands of health service networks may significantly increase according to the disruption types and the system may need to deal with a demand pattern which is totally different from that in the normal disruption-free situation (An, Zeng, Zhang, & Zhao, 2014; Ergun, Karakus, Keskinocak, Swann, & Villarreal, 2010). Generally, changes in demographic, socio-economic, or metrological factors are expected to cause significant changes in the structure of demands from the moment that the information is gathered until the moment in which the solution has to be implemented, as pointed out by Alvarez-Miranda, Fernandez, and Ljubic (2015). Consequently, to obtain a more reliable configuration of the health service network, it is crucial to consider future changes in a demand pattern due to the aforementioned factors.

Most of the models proposed in relevant works (see Section 2) are based on the explicit probabilistic information about disruptive events. Although several researches rely on scenario-based stochastic programming (SP) techniques, the quality of their solutions only provides probabilistic guarantees to the system reliability. To obtain a reasonably high guarantee requires a large number of scenarios, which results in large-sized, computationally challenging problems (Bertsimas, Litvinov, Sun, Zhao, & Zheng, 2013). As a suitable alternative, robust optimization (RO) theory provides solutions to handle the uncertainty of parameters in optimization problems that can immunize the optimal solution from all possible realizations of the parameter values within a deterministic uncertainty set (Pishvaee, Rabbani, & Torabi, 2011). Regarding the decision-making context, RO can be classified into two major categories: (1) first-stage RO and (2) two-stage RO (and the more general multi-stage RO). The former is used where the decision-maker has to select a solution before knowing the real value of uncertain parameters; and the latter is applied to model decision making after the first-stage decisions are made and the uncertainty is revealed. Indeed, two-stage RO was inspired from two-stage SP in which, based on the probability distributions of uncertain parameters, "*here-and-now*" decisions are made before the discloser of uncertainty using an expected value of all possible recourse decisions and "*wait-and-see*" decisions are made after the uncertainty has been revealed (Gabrel, Lacroix, Murat, & Remli, 2014). Compared to two-stage SP, two-stage RO models are more practical since they do not require assumptions about the hard-to-obtain probability distribution of the uncertain parameters (Bertsimas et al., 2013).

As another considerable view, health service networks encounter variable and random demands. Although the system may be able to meet the average demand, the demand will be sometimes so heavy that the system is not capable of serving all simultaneous requests for service. Such a system is called to be *congested*. When the systems are congested, the patients may afford to wait 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). Precisely, in disruptive conditions, we might expect a higher level of congestion in health service networks. Compared with disruptions, which are less likely to be characterized by accurate probabilistic information (An et al., 2014; Peng et al., 2011), there are several alternatives for addressing problems with uncertainty in service demands, depending on their nature. Queuing location models have been used to model situations where the goal is to optimize the system performance. They can also provide greater realism by incorporating two sources of uncertainty associated with demand and service (e.g. the exact timing of demands and the time it takes to serve individual demands at service facilities) (Castillo, Ingolfsson, & Sim, 2009). Moreover, the quality of a health service network can be expressed in terms of the expected or the worst-case waiting times or queue length for a specific service (Burkey, Bhadury, & Eiselt, 2012; Zhang, Berman, & Verter, 2009). Therefore, addressing congestion is relevant to assist health service network planning.

In a different context, most health service networks are hierarchically structured. Since a hierarchical network consists of different types of interacting facilities, there is often a linkage between the facilities at different levels which makes it impossible to determine the location of each level separately (Marianov & Serra, 2001). As the related literature shows, location-allocation models in the context of health service networks have been mostly studied for single-level systems, and hierarchical location-allocation models have gained less attention. Moreover, there is no research in the literature that applied different relevant aspects of configuration of a health service network such as queuing framework that addresses the uncertainty associated with demand and service, probabilistic capacity constraint that reflects the dynamic nature of congestion, risk of disruptions that arises from varied sources, and future changes in demand patterns.

With regard to the enumerated matters, this paper aims to propose a novel reliable hierarchical location-allocation problem for the design of health service networks. We consider several key issues in the proposed model, which assist in the management and the design of health service networks, such as the hierarchical structure of networks, risks of unexpected disruptive events, uncertainty associated with demand and service within the queuing framework, and impacts of demand changes due to a number of reasons such as changes in demographic, socio-economic, or metrological factors. We formulate the problem as a two-stage RO model to find a robust first-stage solution that minimizes both the first-stage cost and the worst-case second-stage cost among all the possible realizations of the disruption that can only be revealed in a second stage. To solve the proposed model, a Benders decomposition type algorithm is developed. A practical case study is also presented to illustrate the applicability of the proposed 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 and Section 4 formulates two-stage robust hierarchical location-allocation model. Section 5 presents the solution procedure and a real life case study to illustrate the applicability of the proposed model is examined in Section 6. Section 7 ends with some conclusions and possible directions for future research.

2. Literature review

In this section, we review the relevant literature in three separate but complementary research streams in the context of health service networks, including hierarchical location-allocation model for health service networks, facility location for congested systems and facility location under disruptions.

2.1. Hierarchical location-allocation model for health service networks

Location-allocation models deal with finding the location of new facilities in some given geographical areas and the allocation of demand nodes to the located facilities. Depending on the system nature, location-allocation models can include single-level or hierarchical networks. Numerous researches have been developed for facility location-allocation problems in the literature. The goal here is not to review all related works in the facility location literature; rather, we direct the reader to exhaustive reviews in this area provided by ReVelle and Eiselt (2005) and Revelle, Eiselt, and Daskin (2008). Basic applications of location-allocation models in the context of a health service network include geographical considerations in healthcare planning (Harper, Shahani, Gallagher, &

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