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Efficient Benders decomposition algorithms for the robust multiple allocation incomplete hub location problem with service time requirements

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ABSTRACT

Many transportation systems for routing flows between several origin-destination pairs of demand nodes have been widely designed as hub-and-spoke networks. To improve the provided service level of these networks, service time requirements are here considered during modeling, giving rise to a multiple allocation incomplete hub location problem with service time requirements. The problem consists of designing a hub and spoke network by locating hubs, establishing inter-hub arcs, and routing origin-destination demand flows at minimal cost while meeting some service time requirements. As travel times are usually uncertain for most real cases, the problem is approached via a binary linear programming robust optimization model, which is solved by two specialized Benders decomposition algorithms. The devised Benders decomposition framework outperforms a general purpose optimization solver on solving benchmark instances of the hub location literature. The achieved results also show how the probability of violating the travel time requirements decreases with the prescribed protection level, at the expense of the higher costs of the optimal solution for the robust optimization model.

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1. Introduction

The design of efficient transportation systems for routing flow demands in highly interconnected environments, where goods, people or information have to move back and forth through the network, is a challenging task. Decision planners have to select the most appropriate network topology that matches technological specifications, capacity requirements to serve users, and owners' expectations. One of the available network topologies which has been widely employed for many-to-many flow exchanging nodes is the hub-and-spoke network, or simply, hub networks.

In these networks, the exchange of flows between several origin-destination nodes are consolidated at intermediate facilities (known as hubs) and routed through hub arcs and spoke connections (links between hubs and non-hub nodes). Only hubs are here assumed to act as transshipment nodes. Flow consolidation at the hubs encourages the use of larger, more efficient transportation modes on hub arcs. Consequently, scale economies can be achieved for transportation costs or travel times.

Their simpler underlying structure with fewer connections when compared with fully interconnected networks, together with the scale economies exploitation are two compelling features that partially explain the widespread use of hub and spoke networks in many applications, such as in public transportation systems (Gelareh, 2008; Nickel, Schobel, & Sonneborn, 2001; Martins de Sá, Contreras, Cordeau, Saraiva de Camargo, & de Miranda, 2015a), in cargo (Alumur, Kara, & Karasan, 2012a; Calık, Alumur, Kara, & Karasan, 2009; Kara & Tansel, 2001) and air transportation networks (Bryan & O'Kelly, 1999), in postal service (Ernst & Krishnamoorthy, 1996, 1998), and in telecommunication systems (Klincewicz, 1998).

Generally speaking, hub location problems consist of selecting some nodes to become hubs, establishing hub arcs and allocating non-nub nodes to hubs, such that a given objective is optimized and some requirements are satisfied. Non-hub nodes can directly interact with only one hub of the network (single allocation) or with various (multiple allocation). Moreover, if all hub nodes are fully interconnected by hub arcs, the hub network is called complete, otherwise incomplete.

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Some examples of objectives and requirements addressed in the hub location literature are: the minimization of the total transportation costs assuming a given number of hubs to be located (O'Kelly, 1986), the minimization of the total cost of establishing hubs and transportation costs considering a fully interconnected network among hubs (O'Kelly, 1992), the minimization of the maximum travel time (Campbell, 1994), the minimization of the total cost of establishing hubs satisfying some time requirements (Campbell, 1994; Ernst, Jiang, Krishnamoorthy, Baatar et al., 2005; Kara & Tansel, 2003), and the minimization of the average transportation time considering a budget constraint for locating the hubs and hub arcs (Martins de Sá et al., 2015a; Martins de Sá, Contreras, Cordeau et al., 2015b). For further problem variants and assumptions, please refer to the surveys of Alumur and Kara (2008), Campbell and O'Kelly (2012) and Farahani, Hekmatfar, Arabani, and Nikbakhsh (2013).

Here a minimal total cost multiple allocation incomplete hub location problem with service time requirements (MAIHLPTR) is addressed. The problem consists of designing an incomplete hub-level network such that the total costs for locating hubs, establishing hub arcs and routing all origin-destination flow demands are minimized, and some service time requirements are satisfied. Considering transportation services, the service time requirement addressed here is to ensure that the total travel time for routing any origin-destination demand is lower than a given travel-time limit. This kind of service time requirement can arise in postal services in which the delivery time cannot exceed a predefined amount of time. An example is the next-day delivery services which promise to deliver the parcels in the next day, i.e. to delivery in less than 24 h, or less than 48 h. Observe that we can consider the same time limit for any origin and destination demand, as in next-day delivery services, or different time limits for the different origin and destination pairs, as, for instance, in some freight services that define the delivery times according to the origin and destination regions.

Time-based service level considerations were first introduced by Campbell (1994) on a hub covering problem. Hubs are installed at minimal total cost to form a fully interconnected hub-level network such that a coverage bounding pattern for the total travel cost is satisfied. In general, costs are associated to travel times in hub covering problems. The present paper extends these concepts to a more general variant that assumes a partially interconnected or incomplete hub-level network.

Incomplete hub networks are commonly found in cargo, and in high capacity public transportation systems (e.g. a metro system) (Alumur, Kara, & Karasan, 2009). In these systems, fully interconnecting all hubs is cost prohibitive or technically infeasible (Gelareh, 2008; Nickel et al., 2001). Hence a topology with fewer inter-hub arcs is more appropriate. Further imposing a travel time limit for incomplete hub network has its perks to many applications. In the transportation of perishable commodities (Campbell, 1994), it prevents the decay of the transported goods, while it improves the attractiveness of the overall system by avoiding undesirable long trip times for a public transportation network. Imposing time-definite deliveries can even increase market competitiveness for some cargo applications (Alumur et al., 2012a).

When considering time service levels, most hub location problems consider travel times to be known beforehand during design. Unfortunately, by disregarding data uncertainty, the resulting networks may disrespect time requirements in practice. One way of properly handling data uncertainty is by using a robust optimization approach. This technique has been recently applied to some hub location problems to address uncertainty on: demands (Ghaffari-Nasab, Ghazanfari, & Teimoury, 2015; Huang & Qingyun, 2009; Makui, Rostami, Jahani, & Nikui, 2012; Meraklı & Yaman, 2016; Shahabi & Unnikrishnan, 2014), hub processing times (Makui et al., 2012), hub arc fixed costs (Alumur, Nickel, & Saldanha-da Gama, 2012b; Boukani, Moghaddam, & Pishvaee, 2014), hub capacities (Boukani et al., 2014), demands and fixed setup costs (Martins de Sá, Morabito, & de Camargo, 2018), and demands and transportation costs (Zetina, Contreras, Cordeau, & Nikbakhsh, 2017). Uncertainties on hub location problems have also been addressed by stochastic optimization approaches. Contreras, Cordeau, and Laporte (2011b) propose a stochastic model to deal with uncertainty on demands and transportation costs, while Ahmadi, Karimi, Davoudpour, and Hosseinijou (2014) formulated a two-stage stochastic model with demand uncertainty. Here Bertsimas and Sim (2003)'s technique is deployed to handle the travel time uncertainties of the MAIHLPTR, yielding a robust optimization model named RMAIHLPTR. To the best of our knowledge, this is the first work to address travel time uncertainties to design multiple allocation incomplete hub networks by a robust optimization approach.

The main contributions of this paper are: *(i)* To introduce two robust optimization models capable of producing a set of solutions with different protection levels against uncertainties for the travel times. Monte Carlo simulations were performed to assess these solutions regarding the violation probability associated with different protection levels, and to compare them with the solutions obtained for the deterministic (nominal) problem. *(ii)* To present four specialized Benders decomposition frameworks to solve the proposed robust optimization problems. Benders decomposition method is an exact partitioning procedure that has been successfully applied to solve large scale incomplete hub location problems due to their decomposable structure (Gelareh, 2008; Martins de Sá et al., 2015a; Martins de Sá et al., 2018). The method's suitability when facing the decomposable structure is explained in Section 4. Since designing hub networks is a strategic decision that involves high risks and financial investments, it is important to have effective computational tools to find optimal solutions. Computational results on solving benchmark instances for hub location problems with up to 50 nodes show the algorithms' efficiency when compared with a general purpose optimization solver.

The remainder of this paper is organized as follows. Section 2 presents notation and definitions and an integer program for the deterministic version of the problem, while Section 3 describes the adopted robust optimization strategy. The devised Benders decomposition algorithms and the attained computational results are shown in Section Sections 4 and 5, respectively. Section 6 concludes this work with the final remarks and highlights potential future research.

2. Notation and definitions

Before introducing a formulation for the RMAIHLPTR, a model for its deterministic counterpart is presented. The MAIHLPTR consists of selecting nodes from a set of candidate nodes to become hubs, and establishing hub arcs and spoke links (connections between non-hub nodes and hubs) to form a network having minimal total cost, but capable of routing each origin-destination demand of flow exchanging nodes within a given time requirement. Fixed setup costs for locating hubs and establishing hub arcs, and transportation routing costs compose the total cost. To design the network, some assumptions are made: (*i*) direct connections between non-hub nodes are not allowed, i.e. all demand flows are routed through a hub level network; (*ii*) the hub level network is connected; (*iii*) multiple allocation is accepted, i.e. a non-hub node can be allocated to more than one hub; (*iv*) network arcs are set to operate in both directions, but traversing times and unitary transportation costs rely on the direction of the flow being routed; and, (*v*) finally, hub arcs have lower traversing times and unitary transportation costs than spoke links for the same pair of nodes because

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