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Discrete Optimization

An implicit enumeration algorithm for the hub interdiction median problem with fortification

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ABSTRACT

Hubs are intermediate facilities that play a pivotal role in efficient functioning of transportation and telecommunication systems. Like any other service infrastructure, hub facilities can be subject to natural or man-made disruptions after installation. In this paper, we address the problem of optimally allocating protective resources among a set of p existing hub facilities in such a manner that the damage inflicted by an intentional strike against the service system is minimized. Casting the problem as a Stackelberg game, the leader (i.e., the network protector or defender) fortifies q of the p operating hubs in order to minimize the impact of the upcoming strike, whereas the follower (i.e., the attacker) tries to identify and interdict r of the $p-q$ unprotected hubs that their loss would diminish the network performance the most. A bilevel programming formulation is presented to model the problem and using a min-max approach the model is reduced to a single level mixed integer programming (MIP) model. Furthermore, an efficient exact solution algorithm based on implicit enumeration is proposed for solving the problem. Extensive computational experiments show the capability of the proposed algorithm to obtain the optimal solutions in short computational times. Some managerial insights are also derived based on the obtained numerical results.

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1. Introduction

Hubs are intermediate facilities that play a pivotal role in efficient functioning of transportation and telecommunication systems. The underlying network in such systems is called a hub-and-spoke (or simply, hub) network. The main advantages of hub networks over the traditional point to point networks is that in the latter, the flows are routed through a smaller number of the network links that makes it possible to exploit the economies of scale via efficient use of transportation resources (especially on the inter-hub connections). The *Hub Location Problem* (HLP) deals with locating hub facilities and assigning demand nodes to hubs in order to route the traffic between origin-destination (O/D) pairs in the most favorable way. There are two basic types of hub networks called single allocation and multiple allocation hub networks. In a single allocation network, all the incoming and outgoing traffic to/from every demand node is routed through a single hub, whereas in a multiple allocation network, which is the underlying network in this paper, each demand node can receive and send flow through more than one hub.

Hub networks, like any other logistics system, are usually susceptible to natural or intentional disruptions and hence protection plans are needed to prevent or mitigate the harmful effects of such disruptions. In this regard, the facility planners should identify the critical system components and plan to harden them as a necessary measure to enhance their security and reliability. Identification of critical system components is an ongoing research agenda for many organizations. One of the important tools in this regard is the interdiction models. In these models, the network planner tries to find the most harmful disruption plans (on behalf of an interdictor or the nature) that inflict the largest possible losses to the system's performance using a limited amount of disruptive resources available. Lei (2013) introduced the *Hub Interdiction Median Problem* (HIMP), which can be used to identify the critical hub facilities in a hub network. Having identified the critical system components, the planners then look for the most effective ways of hardening these components via allocating a limited amount of protective resources among them.

In this work, the *Hub Interdiction Median Problem with Fortification* (HIMPF) is considered where an existing hub network consisting of p hub facilities needs to be protected against a possible

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worst case disruption made by an external attacker. It is assumed that both the interdiction and fortification resources are limited. To this end, at most q of the existing p hub facilities can be protected and at most r of the $p-q$ non-fortified hubs can be interdicted. The attacker's objective is to identify the set of critical hubs and hit r of them aiming to reduce the system's efficiency (increase the total transportation cost) as much as possible. The defender, on the other hand, decides on how to allocate the protective resources among the operating hubs so that the damage inflicted by the intentional strike is minimized. It is assumed that when an unprotected hub facility is interdicted, it becomes completely inoperable (complete interdiction) in which case the O/D flows must be routed via more distant hub facilities which in turn results in increased service cost. The problem is casted as leader-follower Stackelberg game where the network protector (defender) who makes the initial decisions is called the *leader* and the interdictor (attacker) who reacts by hitting the unprotected hubs is called the *follower*. A bilevel mixed integer programming (MIP) formulation is proposed for the problem and employing a min-max approach via considering all possible interdiction patterns, the bilevel model is reformulated as a single level MIP model. To solve the proposed model, an efficient exact solution algorithm based on implicit enumeration (IE) is developed. Extensive computational experiments are conducted to evaluate the efficiency of the proposed IE algorithm using three well-known data sets from the literature of the HLP.

The remainder of this paper is organized as follows. In the next section, a review of the literature related to our problem is presented. The proposed mathematical formulations are presented in Section 3. In Section 4, we describe the developed solution procedure including its components tailored for solving the lower and upper level problems. Numerical results obtained by solving the problem based on three well-known data sets from the literature of the HLP are presented in Section 5. Finally, Section 6 concludes the paper and gives some directions for future works.

2. Literature review

The most widely studied variant of the HLP is the p-hub median problem which involves the optimal location of a set of p hub facilities that provide service to a set of O/D demand pairs in such a manner that the total transportation cost (or weighted distance) of serving the demands is minimized. Research on the HLP was formally inaugurated by O'Kelly (1986). He proposed the first mathematical formulation for the uncapacitated single allocation p-hub median problem (USApHMP) as a quadratic programming model (O'Kelly, 1987). In case of uncapacitated multiple allocation p-hub median problem (UMApHMP), the first mathematical model was introduced by Campbell (1992). Linear integer programming formulations for single and multiple allocation p-hub median problem were presented in Campbell (1994). Skorin-Kapov, Skorin-Kapov, and O'Kelly (1996) proposed MIP formulations for both the USApHMP and UMApHMP with tight linear programming relaxation bounds. Ernst and Krishnamoorthy (1996) presented a smaller formulations for the USApHMP with three-index variables that track flows by origin on each arc. Based on the same idea, they proposed another flow based formulation for the UMApHMP in Ernst and Krishnamoorthy (1998). Kara (1999) proved that the p-hub median problem belongs to the class of NP-hard problems. For more details on the HLP and recent advances in this field, the interested readers are referred to surveys (Alumur & Kara, 2008; Campbell & O'Kelly, 2012; Contreras, 2015; Farahani, Hekmatfar, Arabani, & Nikbakhsh, 2013), and the references therein.

Proper functioning of hub facilities play a crucial role in the success and efficiency of hub-and-spoke networks. In the classical hub location models, it is assumed that the hub facilities and connecting linkages will operate as designed during the whole system life. However, the network components are subject to various random or deliberate disruptions in real-world situations which can substantially affect the system's performance. Addressing the reliability issues in the design of hub networks is a burgeoning research area in the field of the HLP. To date, a limited number of papers have been published which consider the reliability issues and the effect of disruptions in the design of hub networks. Kim and O'Kelly (2009) presented a reliable p-hub location problem for telecommunication networks aiming to maximize the network's performance in terms of reliability. They defined the reliability of each O/D path as the probability that the path will not fail calculated based on the failure probabilities of individual links along the relevant path. Later, Kim (2012) extended the work in Kim and O'Kelly (2009) by considering the rerouting of flows after link or node failures happen. An, Zhang, and Zeng (2015) proposed a set of reliable hub network design models, where the selection of backup hubs and alternative routes were taken into consideration to proactively handle hub disruptions. They developed Lagrangian relaxation and branch-and-bound algorithms to solve these nonlinear mixed integer formulations for reliable network design problems. Sadeghi, Jolai, Tavakkoli-Moghaddam, and Rahimi (2015) considered the reliable HLP using a new stochastic approach. Their aim was to minimize the total transportation cost and obtain maximum flows that the network can carry, where the link capacities were subject to stochastic degradations, as in a form of daily traffic, earthquake, flood, etc. They developed a metaheuristic procedure based on the Differential Evolution (DE) algorithm to solve the problem. Mohammadi, Tavakkoli-Moghaddam, Siadat, and Dantan (2016) addressed a reliable hub network design problem considering complete and partial disruption at hubs and proposed a new MIP model to minimize the total sum of the nominal and expected failure costs. To solve the problem, they presented a hybrid metaheuristic procedure based on Genetic Algorithm (GA) and Imperialist Competitive Algorithm (ICA). In another work, Tran, O'Hanley, and Scaparra (2016) investigated the reliable design of hub networks and presented a mixed integer nonlinear programming model for optimally locating p uncapacitated hubs, each of which could fail with a site-specific probability. Their objective was to determine the location and assignment decisions in such a way that the expected demand weighted travel cost plus a failure penalty cost was minimized. They linearized their model using a specialized flow network called a probability lattice to evaluate compound probability terms and solved it using a Tabu Search (TS) algorithm for large problem instances.

Azizi, Chauhan, Salhi, and Vidyarthi (2016) proposed a new mathematical model for the hub network design under the risk of hub disruptions. Their model aimed at minimizing the weighted sum of transportation cost in regular situation and the expected transportation cost following a hub failure. More recently, Chaharsooghi, Momayezi, and Ghaffarinasab (2017) addressed a reliable uncapacitated multiple allocation HLP under random hub disruptions. They assumed that every open hub facility can fail during its service life in which case either the flows are routed via more distant hubs or some flows are not served by paying a penalty cost. The problem was as a two-stage stochastic program and an Adaptive Large Neighborhood Search (ALNS) metaheuristic was proposed for solving it.

The study of intentional disruptions on the hub networks is even more scarce in the literature of the HLP and so far, only few papers have been published on this subject. Lei (2013) introduced the hub interdiction median problem (HIMP) for identifying the set of critical facilities in a hub network. The proposed model was solved using a commercial software on a test data of 40 nodes and valuable insights on the problem was derived. The author also proposed two bilevel formulations called the hub median protection

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