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A game-based meta-heuristic for a fuzzy bi-objective reliable hub location problem

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ABSTRACT

Nowadays, offering fast and reliable delivery service has become a vital issue associated with all shipment delivery systems. Due to unpredictable variability in travel times, configuration of transportation systems plays a key role in ensuring of meeting the delivery service requirement. This paper tries to investigate the effect of delivery service requirement on the configuration of the transportation system through a hub-and-spoke network. The primary goal of this paper is to study a bi-objective single allocation p-hub center-median problem (BSpHCMP) by taking into account the uncertainty in flows, costs, times and hub operations. The proposed problem is modeled through a bi-objective mixed-integer non-linear programming (BMINLP) formulation that simultaneously locates p hubs, allocates spokes to the located hubs, and assigns different transportation mode to the hub-to-hub links. Then, a fuzzy-queuing approach is used to model the uncertainties in the network. Additionally, an efficient and powerful evolutionary algorithm based on game theory and invasive weed optimization algorithm was developed to solve the proposed BSpHCMP model and obtain near optimal Pareto solutions. Several experiments besides a real transportation case show the applicability of the proposed model as well as the superiority of the proposed solution approaches compared to NSGA-II and PAES algorithms.

1. Introduction

Hub location problems (HLPs) arise in systems with the need of transporting flows (e.g., goods or passengers) between origin–destination (OD) nodes (spokes). In such systems, a direct transportation of the flows between spokes is neither practical nor costly efficient. Therefore, one may use a specific network structure called hub-and-spoke network, wherein the hubs are intermediate facilities in these networks whose duties are consolidating the flows from the origins, transferring the flows between hubs, and distributing the flows to the destinations. Transferring the flows via the hub-to-hub links allow us to exploit transportation flow economies (Ernst et al., 2009). Spokes can be allocated to one or more hubs based on single or multiple allocation strategies. A common assumption is that the hubs are fully interconnected, while there is no connection between spokes. Therefore, all flows must pass at least one hub on their route.

In HLPs, the considered objectives are mainly median and center. The hub median problem is to locate a set of hubs and to allocate spokes to the located hubs with the objective of minimizing the total transportation cost. The hub median problems are applied to airline and telecommunication systems. A drawback of median design of a hub network is when maximum OD distances are excessively large. To overcome this weakness, hub center problems arise when the main objective is to minimize the maximum distance or cost between OD pairs. This objective is significantly important for the shipment delivery systems as well as delivery of perishable or time sensitive items (Campbell et al., 2007).

In shipment delivery systems, most customers are looking for companies that offer fast, cheap and reliable delivery service as well as guarantee that when deliveries will be made. However, these companies have to operate a huge volume of shipments each day (Sim et al., 2009). To operate a huge volume of deliveries between many pairs of OD nodes, companies need to design an efficient and reliable hub-and-spoke network not only to meet delivery requirements, but also to offer cheap deliveries (Grove and O'Kelly, 1986; Hall, 1989; Sim et al., 2009). Shipment delivery systems through hub-and-spoke topology benefit from economies of scales by transferring large volume of flows through hub-to-hub links that result in faster delivery as well as cheaper transportation. To this

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aim, the hub network should be designed respecting median and center objectives.

The considered hub location problem in this paper is called the bi-objective single allocation p-hub center-median problem (BSpHCMP), where the hubs and the connection links have infinite capacity. The aim is to locate p hubs and allocate the spokes to exactly one of the located hubs in such a way that the total transportation cost (i.e., median objective) besides maximum transportation time between any OD pair (i.e., center objective) is simultaneously minimized. After designing the hub network, a company may evaluate alternative transportation modes for those OD pairs that are not tightly limited by the time service requirement. For example, a single or a combination of slower but lower cost transportation modes may be used between some particular OD pairs while their delivery requirement is still met.

Different attributes of such problem, like size, responsibilities, services, and the nature of spoke allocation have made designing it quite complicated. Owning to the complexity and several components of the hub network, a little uncertainty may cause a huge disruption in the network, which imposes huge costs and hard-to-recover effects on the network (Cui et al., 2010). These uncertainties (natural disasters, terrorist attacks, unexpected work overloads, shortages, labor strikes, etc.) can affect not only costs, demands and transportation times, but also hub operations. That is, disruptions can occur and the hubs may become temporarily unavailable to provide service. In these situations, retrieving of the hubs yields extra costs and time in the network.

Hub's disruptions particularly affect the center objective, where the flows entering the hub must wait until the hub is retrieved then receive services. These waiting times at the hubs lead to higher delivery time and increase customer dissatisfaction. Since the flow entering a hub is uncertain, the queuing theory is needed to analyze the waiting time of the flows at the hubs. Therefore, the uncertainties of flows, costs, times and hub operations should be taken into account in network design phase (for uncertainties in network designs see Mohammadi et al., 2011a, 2011b, 2013, 2014a; Contreras et al., 2011; Ishfaq and Sox, 2012; Yang et al., 2013a, 2013b, 2014; Mousazadeh et al., 2015; Zahiri et al. 2014a; 2004b, 2015).

Finally, the primary goal of this paper is to address the BSpHCMP considering uncertainty in flows, costs, times and hub operations. We model the proposed problem through a bi-objective mixed-integer non-linear programming (BMINLP) formulation that simultaneously locates p hubs, allocates spokes to the located hubs, and assigns different transportation mode to the hub-to-hub links. The median objective minimizes the sum of total transportation cost and cost of locating hubs and assigning different transportation modes across the network. The center objective minimizes the maximum transportation time between each OD pair in the network.

One of the most challenging issues in HLPs is how to solve them, since they are known to be NP-hard (Alumur and Kara, 2008). Solving the proposed BSpHCMP, compared with its single-objective version, has not been so extensively studied in the literature, and so far a few papers have developed multi-objective evolutionary algorithms to deal with the multi-objective HLPs (e.g., Mohammadi et al., 2013, 2014a and references herein). These articles mainly lack for efficient and fail to propose powerful algorithms that are able to find near optimal solutions for a bi-objective HLP.

Accordingly, the second purpose of this paper is to propose an efficient and powerful evolutionary algorithm, based on game theory and invasive weed optimization algorithm (Mehrabian and Lucas, 2006) to solve the proposed BSpHCMP model and obtain near optimal Pareto solutions.

The rest of this paper is organized as follows. Section 2 reviews prior researches, first, in the area of center-median HLPs under uncertainty and, second, in domain of evolutionary algorithms to solve HLP models. Section 3 describes the modeling framework and presents the BMINLP formulation. Section 4 describes the solution approach and develops a meta-heuristic algorithm. Computational experiments with comprehensive sensitivity analyses are provided in Section 5. Finally, the conclusion is presented in Section 6.

2. Literature review

This section is organized in two sections. First, Section 2.1 provides a brief review of HLPs considering uncertainty and disruption in the hub network design. Next, some relevant papers developing meta-heuristic algorithms are reviewed in Section 2.2.

2.1. HLPs and uncertainty

Campbell (1994) proposed the first formulation for p-hub center problem (pHCP) as a quadratic programming model. Afterwards, several alternative linear formulations for the single allocation pHCP were proposed by Kara and Tansel (2000). Ernst et al. (2000) modeled both single and multiple allocation pHCP through a new mixed-integer linear programming formulation based on the concept of the radius of hubs. Kara and Tansel (2001) incorporated an operational-level constraint to the pHCP which flows departing from a hub cannot leave until all flows entering the hub have arrived. They called this problem as the latest arrival hub location problem.

Wagner (2004) explained that the solution of the min–max version of the latest arrival hub location problem is similar to the pHCP because the route that determines the longest path in the network is the one where the transient or waiting times at the hubs are zero. Yaman et al. (2007) presented a new version of the latest arrival hub location problem by considering stop overs and between the spoke and hubs. Campbell et al. (2007) studied the single and multiple allocation versions of the pHCP, and concluded that several special cases of the pHCP and latest arrival HLP can be solved in polynomial time.

For the first time, O'Kelly (1987) formulated a single allocation p-hub median problem (pHMP) as a quadratic integer program. However, this formulation resulted in a very difficult problem to be solved. Next, Campbell (1994) provided new formulation for the p-hub median problem as an integer program, but this formulation contained many variables and constraints. Yaman (2011) proposed three different formulations for the uncapacitated r-allocation pHMP. For more details on pHCP and pHMP formulations, interested readers are referred to Alumur and Kara (2008) and Campbell et al. (2002) and more recently Zanjirani Farahani et al. (2013) for surveys on HLPs.

To the best of our knowledge, a few papers have studied the pHCP and pHMP with uncertainty in flows, costs, and transportation time. Sim et al. (2009) introduced a stochastic pHCP (SpHCP) utilizing a chance-constraint method to model the minimum delivery service requirement by taking the variability in transportation times into account. Yang et al. (2013a) presented a new risk aversion pHCP with fuzzy travel times by adopting value-at-risk (VaR) criterion in the formulation of objective function. In order to solve and validate the model, they first turned the original VaR pHCP into its equivalent parametric mixed-integer programming problem, and then developed a hybrid algorithm by incorporating genetic algorithm and local search (GALS) to solve the parametric mixed-integer programming problem. Yang et al. (2013b) proposed a new pHCP with normal fuzzy travel time, in which the main goal is to maximize the credibility of fuzzy travel times not exceeding a predetermined acceptable efficient time point along all paths on a network. Due to complexity of the proposed model, they applied an approximation approach (AA) to