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A bi-objective, reliable single allocation p-hub maximal covering location problem: Mathematical formulation and solution approach

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ABSTRACT

In the last few years, the *p*-hub maximal covering problem (pHMCP) has been applied in a variety of applications, including the design of air transportation networks, distribution systems for perishable products, postal delivery networks, and tourism routing. In hub-based systems, disruptions at hubs or unavailability of routes significantly affect service level and result in excessive costs. To tackle these problems, selecting backup hubs for unavailable hubs and rerouting the related flows are often proposed. This paper develops a bi-objective reliable single allocation *p*-hub maximal covering problem (BRSApHMCP) considering two objectives: maximizing expected covered flows and minimizing congestion. After formulating an initial non-linear model, a linear model is presented; the NP-Completeness of the developed model is proved and a non-dominated sorting genetic algorithm (NSGA-II) is proposed to solve it. In order to show the superior performance of the proposed NSGA-II, a well-known evolutionary algorithm, the multi-objective particle swarm optimization (MOPSO), and the epsilon constraint methods are utilized and the results are analyzed and compared. The parameters of the proposed algorithms are calibrated using the Taguchi approach. Also, a case study and some parametric analyses are done. The results show that NSGA-II is able to find the better solutions in comparison with MOPSO and by opting this proactive strategy in the investigated case study, NSGA-II could recover up to 73% of lost flow in a well-balanced system.

1. Introduction

Hub location problems (HLPs) are used in systems that have many origins and destination nodes, where connecting all nodes in the networks is impossible or expensive. In such systems, flows consolidate at the hub nodes and it becomes possible to route all transportation through the hubs. Also, costs are reduced because of economic advantages scale for transportation flows between hub nodes. The aim of HLPs is to locate facilities in potential hub nodes in networks and allocate other nodes (non-hub) to these hubs. Farahani et al. (2013) considered various criteria, such as solution domain, objective function criterion, allocation type, etc. and classified HLPs into 13 most applicable categories; one the most important criteria discussed in (Farahani et al., 2013) is the objective function type that can divide HLPs into two groups, first group are cost-oriented and try to minimize total cost and include most of the classes but the second group are service-oriented and try to maximize service level and include two problems, *p*-hub center problem and the hub covering problem. The *p*-hub center problem minimizes the maximum distance/time/cost between hubs and their allocated nodes, and the *p*-hub covering location problem attempts to locate hub facilities in such a way that the origin–destination (O-D) pair of two non-hub nodes is covered by a pair of hub nodes. In fact, O-D pairs are covered only if the distance/time/cost of total or each connection link(s) between these nodes through their hubs is less than or equal to the pre-specified value or the reliability is more than or equal to pre-specified value. This class of problems can be further developed into two other HLPs, namely the hub set covering location problem and the *p*-hub maximal covering location problem (pHMCP). Hub set covering problems minimize the number of hubs (or in other words, minimize total hub locating costs) while satisfying service requirements for all O–D pairs; pHMCP maximizes the covered flows in O–D pairs using a pre-determined number of hubs. Although the problems with economic objectives are applicable, sometimes their solutions can lead to unsatisfactory results in terms of service levels; therefore, for some sectors, better service may be preferable to lower

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costs (Ernst et al., 2009). PHMCP can be applied in a wide range of applications, including the design of air transportation networks, distribution systems for perishable products, postal delivery networks, and tourism routing.

Most studies in the HLP field assume that hub facilities are always available. In practice, however, one or more of the facilities or routes linking nodes might become unavailable from time to time. The main disruptive events that generally affect the applicable are in pHMCP include severe weather (dense fog, heavy rain or snow, hurricanes, and tornadoes), unpredictable catastrophic failures of network facilities, natural disasters (earthquakes, tidal waves, and volcanos), traffic jams caused by accidents, and terrorist attacks. In some cases, these events can be interrelated and occur simultaneously (Janić, 2015).

Disruptions at hubs may significantly affect service levels and result in excessive systematic costs; below are two examples of disruption in air transport hub-based systems and their consequential financial losses:

- On 13 April 2010, Eyjafjallajokull volcano in Iceland erupted, and a cloud of smoke and ash spread over most of the countries in the EU. This led to the closing of the airspace between 14 and 24 April and cancellation of about two-thirds of European flights and about 180 transatlantic flights in a single day. The International Air Transport Association reported that as a result of this disaster, the air transport system incurred losses of about US $1.7 billion (BBC, 2010; Gertisser, 2010; Gudmundsson et al., 2010).
- On 10 August 2006, a terrorist attempt to steal an airplane traveling from the UK to the US was detected and prevented. However, the consequent immediate closing of the UK airspace led to the cancellation of about 2300 flights and delays of up to 7 days in other flights. Financial losses were estimated at more than EUR 50 million (AEA, 2006).

There are two main strategies for managing disaster situations: reactive (e.g., in air transportation networks: canceling, delaying, rescheduling, etc.); and proactive (e.g., in air transportation networks: investment in improving the reliability of existing facilities) (Janić, 2005). However, because the initial network is designed to work in perfect conditions, reactive strategies are often costly to implement and inefficient.

This study proposes a proactive strategy for designing a reliable system. PHMCP with single allocation will be discussed, where each node and each route between nodes has a specific and predetermined probability of unavailability. Each hub must have a backup hub, and when it is unavailable, all O-D pairs that are connected using this hub will be rerouted and connected to the designated backup hub.

Rerouting large amounts of flow and allocating them to a single hub can increase the pressure on the selected backup hub facility and reduce its service levels, which can lead to a decrease in customer satisfaction. Thus, rerouting flows from an unavailable hub node to its backup hub can compensate for lost flow, but it can also have an inappropriate effect in system performance. In this paper, besides the primary objective of maximizing the reliability of the system in covering the maximum flow, a secondary objective is balancing the flows passing through each hub.

Fig. 1 provides an example for the proposed problem, and it is based on the Iranian Aviation Dataset (IAD) which was introduced by Karimi and Bashiri (2011) and are listed in Table 1. This figure illustrates the airport locations for Iranian aviation among the 37 cities where there are active airports. Hub nodes are indicated with larger circles, and smaller nodes of the same color are allocated to the same hub. In normal situations, the flow from Rasht to Birjand should transit through Tehran and Sabzevar. If Tehran airport was unavailable due to a disaster, this flow would be rerouted through Khoramabad and Sabzevar to reach its destination (regular and alternative routes are indicated using solid and dashed lines, respectively).

To the best of authors' knowledge, there is no research on reliable pHMCP in the HLP literature. Because of the considerable financial losses of disruptions, developing a proactive strategy for service-oriented hub-based systems could be worthwhile. In this paper, first BRSApHMCP will be formulated, and then the linearized model will be proposed. Additionally, it was identified that the proposed model is an extension of pHMCP, and it is known to be an NP-hard problem (Kara and Tansel, 2003). Therefore, solving the proposed model, in general, is a challenging task.

The remainder of this paper is organized as follows. After reviewing the relevant literature in Section 2, the proposed model and its linearized form are explained in Section 3. The computational complexity of the proposed model is investigated, and the proposed solution approach is described in detail in Section 4. After introducing some evaluation indices and tuning the parameters, the computational results with statistical comparison and a case study are discussed in Section 5. Finally, the conclusions and suggestions for future research are presented in Section 6.

2. Literature review

Literature related to the reliable pHMCP can be divided into two areas. First, the studies of pHMCP are introduced; then the research on other aspects, including the strategies to tackle disasters, are discussed.

O'kelly (1986) proposed the first version of HLP model, and then Campbell (1994) classified HLPs and formulated the single allocation hub maximal covering problem (SAHMCP) by $O(n^4)$ where the allocation variable was four-dimensional. Marianov et al. (1999) presented an uncapacitated single allocation HLP in a competitive environment to maximize covered flows. Kara and Tansel (2003) improved SAHMCP model with $O(n^2)$ variables and constraints; they also proved that SAHMCP is NP-Hard, Weng et al. (2006) used genetic and simulated annealing algorithms to solve SAHMCP and verified the performance of their solution approaches by solving a case study from the air transport industry of China. The model proposed by Kara and Tansel (2003) was improved twice. First Wagner (2008) improved it and provided a new formulation and discussed multiple and single allocation problems, including non-increasing quantity-dependent transport time functions for transport links. Then Ernst et al. (2011) showed that the proposed model could be further tightened by lifting some of the constraints. Qu and Weng (2009) investigated the multiple allocation pHMCP and proposed a new formulation and a heuristic algorithm, the path relinking approach. They introduced a new dataset for hub airport locations of Chinese airfreight flows between 82 cities in 2002 and verified the performance of their heuristic algorithm by applying it to the introduced dataset and the AP[1] dataset. Karimi and Bashiri (2011) investigated the unstudied coverage types in pHMCP and proposed two heuristic procedures to handle those models. Setak and Karimi (2014) considered time covering under gradual decay function integrated with the single allocation strategy for hub covering location problem, and after formulating the model, they solved some instances of CAB and AP benchmarks using a tabu search algorithm. Peker and Kara (2015)extended the definition of coverage and introduced partial coverage in SAHMCP that changes with distance.

[1] Australian Post.

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