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The gateway hub location problem

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ABSTRACT

We introduce the Gateway Hub Location Problem (GHLP) to design global air transportation systems. Relying on a three-level hub network structure and on having nodes located in different geographic regions, the GHLP consists of locating international gateways and domestic hubs, activating arcs to induce a connected gateway and hub network, and routing flows within the network at minimum cost. Most previous studies focus on a typical hub-and-spoke network, in which local and global flows are not differentiated. Here to better represent a world wide air transportation system, global flows can only leave or enter a given geographic region by means of a gateway, while local flows can only use hubs within their respective region. As routing local or global flows involved different agents, this study presents a mixed integer programming formulation that exploits these differences to model both the local and global flows. Due to the formulation's characteristics, two algorithm variants based on Benders decomposition method are devised to solve the problem. A new repair procedure produces optimality Benders cuts whenever feasibility Benders cuts would rather be expected. While the monolithic version failed to solve medium size instances, our algorithms solved lager ones in reasonable time.

1. Introduction

By the year 2034, global air traffic is expected to double reaching over seven billion passengers annually transported (IATA, 2015), being Africa, Middle East, Asian and Latin America the geographic areas with the largest percentage growths till then. This rapid demand growth is pressuring airlines and air transport management agencies to extend and expand the existent networks to accommodate new markets, new players, new infra-structures, and new flight connections to serve both increasing domestic (local) and international (global) passenger flows.

Modeling and understanding these local and global passenger flows are generally done separately in the literature (Preis et al., 2013; Mao et al., 2015), or are usually considered to be non differentiable when designing networks for many-to-many air transportation systems with a hub-and-spoke structure (Campbell et al., 2002; Alumur and Kara, 2008; Campbell and O'Kelly, 2012; Farahani et al., 2013). However, there are some differences between domestic and international passengers that might justify differentiating them.

From the perspective of service quality, reliability was ranked by international passengers as the most important dimension, whereas domestic passengers value more assurance dimension (Arslan et al., 2011). According to the Resource Manual for Airport In-Terminal Concessions (2011), international passengers, on average, arrive at the airport earlier and spend more time in terminals. Thereby, their needs for food, reading materials, travel accessories and other amenities are larger than domestic passengers' needs. They also tend to be more sophisticated with higher average incomes. This represents a higher potential revenue for international airports, which usually have a better infrastructure for shopping, eating and even resting when contrasting to domestic airports. In this way, even though they might share some resources, and affect each other's routing design decisions, when designing air passenger networks, local and global flows are required to be routed through different facility types over the network.

Local flows are routed via domestic hubs (hubs), while global flows go through international gateways (gateways) to leave from or to enter into a different geographic region. Hubs allow passengers to change connections and airplanes along their routes, whereas gateways are critical for connecting wide regions, such as continents, and for performing customs, immigration and security checks. Since a global passenger flow may be routed via some hubs before going through some

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gateways to reach its destination, or vice versa, a global flow may share then some inter-hub connections with other local flows, showing thus how both flow types are intertwined.

To articulate both local and global flows, three connection levels are needed: international gateway level with inter-gateway connections, domestic hub level with inter-hub connections, and spoke level with regional airports linked to hubs or gateways. Inter-hub connections are usually done by large carriers, while inter-gateway connections are performed by even larger, long-range airplanes. Further regional airports are usually linked to hubs or gateways by middle to small size planes. This three level setting can be seen as a three-tier hierarchical hub-and-spoke network structure.

Hub-and-spoke systems are commonly used in many-to-many transport applications to lower transportation costs by exploiting scale economies whenever large carriers can be used to carry consolidated flows over the network (O'Kelly, 1987; Jr, 2012). A typical hub-and-spoke network uses two connection levels instead of three: hub level with inter-hub connections, and spoke level with flow exchanging nodes (regional airports) linked to hubs. Scale economies are usually achieved on the hub level by bulk transportation on inter-hub connections. A myriad of applications and topologies have been modeled as hub-and-spoke networks as can be seen in Campbell et al. (2002); Alumur and Kara (2008); Campbell and O'Kelly (2012); Farahani et al. (2013).

In the past 20 years the global airline industry has undergone major changes. The notion of international airlines collaborating for creating cost and revenue synergies through the formation of strategic alliances (such as Star Alliance, Oneworld and Skyteam) has been gained credibility (Schosser and Wittmer, 2015). Thereby, design air network from a global perspective becomes necessary. However, only in the last decade, the idea of differentiating local from global flows has attracted some attention from the research community (Adler and Smilowitz, 2007; Sasaki et al., 2009; Yaman, 2009; Catanzaro et al., 2011).

Adler and Smilowitz (2007) analyze global alliances and mergers in an airline industry under competition. They present a game-theoretic competitive merger framework that allows airlines to choose partners with their installed gateways, inter-gateway connections, and regional networks so that mergers can be proposed and profits maximized. Selection is based on cost and revenue analyses by considering information of a given airlines and its competitors. Local and global flows are differentiated, but treated separately on a two stage approach. First hubs are installed to route local flows, then, assuming that global flows are temporarily aggregated at each installed hub, rather than in their original locations, one gateway per region is selected within these installed hubs. As the trace of each demand flow exchange can only be performed after the network is designed, transportation costs are poorly underestimated, questioning thus the quality of the achieved network configurations.

Disregarding the many-to-many nature of the local and global flows, Sasaki et al. (2009) develop a gateway and hub location model based on a two level p-median facility location problem. From a candidate set, a fixed number of gateways and hubs are selected so that each regional airport is served by a hub, and each installed hub is linked to a gateway at minimum allocation cost. By not considering flow demands happening between pairs of origin-destination nodes, the problem's complexity is greatly reduced at the expense of having ill-formed air networks.

Yaman (2009) does not distinguish between local and global flows, he considers the design of a hierarchical hub and spoke network which consists of locating a fixed number of gateways and hubs, such that regional airports and hubs are single allocated to hubs and gateways, respectively, to form a star sub-network for each gateway. The simpler strict formulation imposes gateways to be fully interconnected, and prevent hubs to directly interact with each other. Given the single allocation policy, undesirable long distances are perceived by the demand flows in the attained solutions. Further, a fully interconnected gateway hub is not always possible to be assumed in an air network design, since airlines tend to avoid flying for long ranges over water without communication, or over conflict zones.

Finally, Catanzaro et al. (2011) investigate a particular variant of a hub location problem which partitions a given network into sub-networks, and locates at most a fixed number of gateways, but with at least one gateway in each sub-network. Sub-networks are supposed to have at least (at most) a minimum (maximum) number of nodes to exist. The problem's objective is to split the network into regions and then route flows at minimum transportation cost. A flow can only enter or leave a sub-network through an installed gateway, and once it leaves a sub-network, it can only be routed through gateways until it reaches its destination sub-network, when then it can use the available hubs and local links. Hubs and all network connections are assumed to be given beforehand, i.e. costs incurred from installing hubs, gateways, and inter-hub and inter-gateway connections are not considered.

Until now, the literature has acknowledged the importance of differentiating local from global flows, but, as aforementioned, has made assumption compromises that resulted into over-simplified problems or models. Here a more explicit formulation that incorporates local and global flows is proposed for the air transportation network design. Hubs, gateways, and inter-hub and inter-gateway connections are decided so that the induced network can route local and global flows at minimal transportation and installation costs. Different scale economies are granted for installed inter-hub and inter-gateway connections to mimic lower transportation costs due to consolidated flows. Regional airports can be linked to any installed hub or gateway within its region and within aircraft range, i.e. local airports can be multiple allocated to hubs and gateways. This provides greater flexibility to route flows at the expense of demanding a more elaborated model. Further fixed costs for establishing hubs, gateways, and inter-hub and inter-gateway connections are assumed to be known, and continental and country divisions are adopted as natural regions.

Because our aim is to consider the design of air network from a global perspective, we made some simplifications for now. The current study ignored, for example: airline competition, passengers behavior and choice of routes, congestion transshipment airports, the effects of frequency on service quality and schedule delay. These issues have been well studied in the literature (Hansen, 1990; Hong and Harker, 1992; Hsu and Wen, 2003; Adler, 2005).

The addressed air transportation network design is modeled as a multi-commodity flow based hub and spoke system, given rise to a gateway hub location problem or a three-level hub location problem. Given its large scale multi-commodity nature and its induced decomposable matrix structure, the devised formulation is solved by two specialized Benders decomposition algorithms (Benders, 1962) which incorporate two features that greatly speed up the method: a repair procedure which allows to generate Benders optimality cuts from unbounded dual subproblems, and a tailored dual subproblem solution algorithm which calculates the optimal dual values to produce Benders optimality cuts without relying on a Simplex solver. In order to evaluate and assess the efficiency and limitations of the devised Benders algorithms, computational experiments were performed and compared with a general purpose solver (IBM CPLEX) on solving the proposed formulation. Both algorithms clearly out-performed the general purpose solver when solving large instance sizes.

To be clear from the outset, the focus here is not on reproducing the current air network, rather, we wish to use network design tools that contribute to improve air transport systems. The proposed model of how things should be can be used to contrast to actual systems. We believe that this analysis is needed and should be of concern. There are many broad participants interested in the efficiency of the world's aviation system as World Bank, FAA (Federal Aviation Administration), Eurocontrol, mainframe manufacturers (Boeing, Airbus, Embraer) and probably many others. The rational planning of the air network has implications consistent with the strategic objectives of ICAO