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Air express network design based on express path choices – Chinese case study

Shunan Yu [a, b], Zhongzhen Yang [a, b], Bin Yu [a, b, *]

[a] Collaborative Innovation Center for Transport Studies, Dalian Maritime University, Dalian, 116026, PR China
[b] Transportation Management College, Dalian Maritime University, Dalian, 116026, PR China

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ABSTRACT

Due to the shortage of cargo aircraft, Chinese express companies have to provide transportation services with a hybrid method that consists of "rented bellies and self-owned cargo aircraft". Because the bellies are rented from air passenger companies and because the cargo aircraft are owned by the express companies, it is important for the express companies to use their cargo aircraft as effectively as possible. This paper constructs a bi-level model to optimize the flight transportation network of an express company. The upper model designs the network and allocates the transportation capacity with the objective of minimizing the total transportation cost, and the lower model calculates the link flows in user equilibrium. Data from ShunFeng (SF) Express Company (China) are used to conduct the case study. Using the model outputs, the flows on links and at nodes are analyzed to illustrate the transportation and transshipment situations.

1. Introduction

Over the last twenty years, the air cargo industry in China has seen a rapid expansion. In particular, with the rapid expansion of e-commerce markets, the amount of cargo transported by such express companies has increased continuously. For example, the cargo transported by ShunFeng (SF) Express Company by air in 2014 reached 0.83 million tons, increasing 84.4% compared with 2011. However, Chinese air express companies typically only own a few cargo aircraft, and their capacity is far behind the increasing demand. For example, the SF Express Company, one of the largest such companies in China, has established a flight network covering 80% of the main cities; however, the company only has 15 cargo aircraft. Due to this shortage of cargo aircraft, Chinese air express companies have to rent the bellies of passenger aircraft from passenger airline companies and provide transportation services under the hybrid model of "bellies + cargo aircraft".

In China, direct passenger flights are currently operated between most main cities. Thus, the flight network of the bellies of passenger aircraft transportation mode presents a "point-to-point" configuration, and cargo aircraft are operated between mega-cities to maximize the loading ratio. In this case, the cargo in cargo aircraft contains cargo traveling directly from one mega city to another mega city and cargo transshipping from the bellies of passenger aircraft. Thus, cargo aircraft and belly transportation utilize a "hub-and-spoke" configuration. As the result, the Chinese air express transportation network is a mixture of "point-to-point" networks and "hub-and-spoke" networks. In this mixed network, due to short of cargo aircrafts, the rented bellies play the main role.

This study designs the structure of the mixed air cargo transport network, in which the bellies of passenger aircraft and cargo aircrafts are jointly used. Then we optimize the operation plans for transporting cargos between O-D pairs based on the mixed network. With the calculated results, we further analyze the paths of cargos and discuss the transshipments at some airports.

The remainder of this paper is organized as follows. Next section reviews the relevant literature. In section 3, the problem of this paper is described. Section 4 constructs a bi-level programming model to tackle the problem. In section 5, a genetic algorithm is developed to solve the upper model and the lower model is solved with the algorithm of Frank-Wolfe. Section 6 tests the constructed model with a case study. In section 7, this paper ends with some conclusions of the research.

* Corresponding author. Collaborative Innovation Center for Transport Studies, Dalian Maritime University, Dalian, 116026, PR China.
E-mail address: ybzhyb@163.com (B. Yu).

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2. Literature review

Some literature have studied the hub-and-spoke network. O'Kelly (1987) reported a new formulation of a general hub location model as a quadratic integer program and discussed a variety of alternative solution strategies. Gelareh and Nickel (2011) proposed a 4-index formulation for the uncapacitated multiple allocation hub location problem tailored for urban transport and liner shipping network design. Vasconcelos et al. (2011) proposed a new hub location model defined by the minimization of costs. Oktal and Ozger (2013) modeled constrained choices when establishing cargo hub and spoke networks. They developed a mixed integer linear programming model introducing additional constraints to the traditional model of un-capacitated multiple allocation hub location problem. An et al. (2015) proposed a set of reliable hub-and-spoke network design models, where the selection of backup hubs and alternative routes were taken into consideration to proactively handle hub disruptions. Damgacioglu et al. (2015) studied the un-capacitated single allocation planar hub location problem. In this problem, all flow between pairs of spokes went through hubs and the capacities of hubs were infinite, they could be located anywhere on the plane and were fully connected, and each spoke must be assigned to only one hub. Gelareh et al. (2015) proposed a mathematical model for a Multi-period uncapacitated multiple allocation hub location problem with budget constraint. However, these studies do not consider the problem of transport capacity, while in reality, the transport capacity is not always enough.

Elhedhli and Hu (2005) studied the hub-and-spoke network design problem with congestion, they proposed extends current models by taking congestion effects into account. However, in these studies, the congestion is only in hubs and not on the link.

Some literature take the capacity into consideration, for example, Lin et al. (2003) compared the economic effects of hub-and-spoke networks with center-to-center directs on the carrier's operations. They constructed an integer program model of hub-and-spoke network with center directs in the paths and evaluated the results against the Federal Express AsiaOne express network. Lin and Chen (2008) proposed a generalized hub-and-spoke network in a capacitated and directed network configuration that integrated the operations of three common hub-and-spoke networks: pure, stopover and center directs. Lin et al. (2012) studied the problem of hub-and-spoke network design considering economy of scale and constraints on the paths. They constructed a relative model and solved it by genetic algorithm using the path for encoding. Correia et al. (2011) considered an extension of the capacitated single-allocation hub location problem in which the capacity of the hubs was part of the decision making process and balancing requirements were imposed on the network. Sender and Clausen (2013) presented a capacitated multiple allocation hub location problem. They developed heuristic solution approaches based on local improvements.

Some literature studied the solving methods of hub and spoke network. Saberi and Mahmassani (2013) presented continuous approximation techniques for the airline hub location and optimal market problems, and illustrated the usefulness of continuous approximation modeling in airline operations and network design with example applications. Zheng et al. (2015) proposed a liner hub-and-spoke shipping network design problem by introducing the concept of a main port, as well as some container shipping constraints such as multi-type container shipment and transit time constraints. He et al. (2015) developed an improved MIP heuristic combining branch-and-bound, Lagrangian relaxation, and linear programming relaxation.

de Camargo et al. (2009) addressed the multiple allocation hub-and-spoke network design under hub congestion problem. They proposed a non-linear mixed integer programming formulation, modeling the congestion as a convex cost function. Karimi and Bashiri (2011) studied the hub covering problem with different coverage type over complete hub networks. Furthermore, hub set and maximal covering were expressed with single and multiple allocation strategies. Alumur et al. (2012a,b) addressed several aspects concerning hub location problems under uncertainty. Alumur et al. (2012a,b) approached the hub location problem from a network design perspective. In addition to the location and allocation decisions, they also studied the decision on how the hub networks with different possible transportation modes must be designed. Rahimi et al. (2016) present a new bi-objective model for a multi-modal hub location problem under uncertainty considering congestion in the hubs. Mahmutogullari and Kara (2016) proposed a competitive hub location problem where the market was assumed to be a duopoly.

These studies mainly focused on the network structure with the objective to determine the hub location (Yao et al., 2014a,b). When the network structure is determined, the cargos from origin to the destination mostly have only one path, thus it is not necessarily to study the path choice behaviors and transportation schemes. Meanwhile, in most of the literature, there is only one type of carriers, while the reality in China is that both passenger aircraft bellies and cargo aircrafts are used in the network. Especially, when the cargo aircrafts is self-owned and the bellies are rented, the operators need to simultaneously determine the cargo aircrafts' operation and the quantity of rented bellies, which makes the network design much more complicated.

Some studies discussed the price and revenue management of air cargo transportation. Alderighi et al. (2005) identified conditions under which asymmetric equilibria may exist when carriers compete in designing their network configurations in a game-theoretical framework. They assumed that carries offer all their capacity to the market so that the price a carrier receives only depends on market demand. However, in China, the belly capacity are not always rented out by passenger flight companies. Fu et al. (2011) examined the forms and effects of vertical relationships between airports and airlines with a focus on the North American and European aviation markets. Zhang et al. (2013) explored factors influencing the pricing behavior of full-service carriers in hub-to-hub markets. Saraswati and Hanaoka (2014) analyzed airport–airline cooperation where an airport offers to share a proportion of its commercial revenue with airlines in exchange for a fixed payment. Feng et al. (2015) proposed a tying mechanism for capacity allocation by integrating hot-selling routes and underutilized routes. They designed the tying mechanism for air cargo capacity allocation and derived the closed-form optimal solution. Chi and Baek (2012) examined the demand for airfreight in the US as a function of real income and the price of airfreight between 1996 and 2010.

3. Problem description

Chinese air express companies adopt the method of jointly using the self-owned cargo aircrafts and the rented bellies to transport express cargos, among which the rented bellies play the main role. The operation cost of the express companies mainly includes the bellies' rents and the costs covering holding and using the cargo aircrafts. As the total supply for air cargo transportation is no enough as a whole, Chinese passenger flight companies are not willing to rent all their owned bellies out for the whole year while the express companies want to rent a batch bellies in long term. For the demand varies seasonally, the passenger flight companies wish to hold some capacity to obtain more profits in the peak season. As a result, the long term unit rent of the bellies of passenger aircrafts

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