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The design of capacitated intermodal hub networks with different vehicle types

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ABSTRACT

In this study, we allow using alternative transportation modes and different types of vehicles in the hub networks to be designed. The aim of the problem is to determine the locations and capacities of hubs, which transportation modes to serve at hubs, allocation of non-hub nodes to hubs, and the number of vehicles of each type to operate on the hub network to route the demand between origin-destination pairs with minimum total cost. Total cost includes fixed costs of establishing hubs with different capacities, purchasing and operational costs of vehicles, transportation costs, and material handling costs. A mixed-integer programming model is developed and a variable neighborhood search algorithm is proposed for the solution of this problem. The heuristic algorithm is tested on instances from the Turkish network and CAB data set. Extensive computational analyzes are conducted in order to observe the effects of changes in various problem parameters on the resulting hub networks.

1. Introduction

In today's competitive environment, most firms use alternative transportation modes and different types of vehicles within their hub networks. The main reason for using different vehicle types in hub networks is to achieve economies of scale and decrease unit transportation costs by employing vehicles with larger capacities. In this study, we focus on minimizing total cost to efficiently locate hub facilities and design intermodal hub networks.

The motivation of this study arises from the operational characteristics of small parcel delivery networks. Such networks operate on a hub-and-spoke network structure. Hubs are crossdock terminals consolidating flow in which the main operations are unloading, sorting, and loading. Spokes or demand nodes, on the other hand, are typically branch offices. In real-life parcel delivery networks, each branch office is customarily allocated to a single hub mainly due to ease of management. Allocation connections carry low volume traffic and distances are relatively short; therefore, only ground transportation is employed on these connections. Moreover, usually a single vehicle type is used to transfer the flow between branch offices and hubs. Customarily, the flow is collected from hubs in the mornings and delivered to hubs at the end of a day. During the day, the vehicles on these allocation connections are used to deliver and pick-up parcels from customers. Alternative modes of transportation and different types of vehicles with larger capacities are used, on the other hand, while transporting flow

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between hub facilities. Each firm operates with its own fleet. Additional vehicles can be rented especially to address peak demand periods.

Operations in small parcel delivery are planned daily and the amount of flow to be transported refers to daily demand. The capacities of hubs in parcel delivery networks are usually expressed in terms of the total number of vehicles of each type that can be handled within a day. For example, the number of docks limits the number of trucks that can be loaded and unloaded at a hub during a day. Similarly, the number of airplanes that can be handled within a day is limited.

Various costs are involved in building and operating this hub network including the costs of establishing hubs with different capacities, purchasing, operational and transportation costs of vehicles. In addition, there is material handling costs associated with unloading, sorting, and loading operations at hubs. Material handling cost is dependent on the mode of transportation. For example, the cost of loading and unloading an airplane is different than the cost of loading and unloading a truck. In addition, material handling cost may also depend on the location of a hub as some components of cost, such as minimum wage and electricity rates, can vary from location to location.

In this paper, we model and solve the intermodal hub network design problem with the specifications described above. We develop a mixed-integer programming formulation and a variable neighborhood search heuristic. We solve the model and test the algorithm on instances from the Turkish network and CAB data set (Beasley, 1990).

Hub location problems deal with choosing the sites of hub facilities and allocating demand nodes to hubs so as to effectively route the traffic between origin-destination pairs. The reader may refer to Alumur and Kara (2008); Campbell and O'Kelly (2012); Farahani et al. (2013), and Contreras (2015) for an overview of hub location studies in the literature.

In this study, in addition to the hub location and allocation decisions, we also consider decisions regarding the design of the inter-hub network; that is, we do not assume a fully interconnected hub network. Examples of hub location studies which incorporate decisions on inter-hub network design include Nickel et al. (2001); Campbell et al. (2005); Yoon and Current (2008); Alumur et al. (2009); Contreras et al. (2010); Martins de Sa et al. (2015); and Alumur et al. (2015). In all of these studies, only one transportation mode is allowed within the hub network to be designed.

The choice for mode of transportation within a hub network is initially discussed by O'Kelly and Lao (1991). Different hub location models are used in the literature to determine locations of hubs in intermodal transportation networks. Examples of such studies are Racunica and Wynter (2005) using an uncapacitated multiple allocation hub location model, Limbourg and Jourquin (2009) and Ishfaq and Sox (2011) both using a p-hub median model. In these studies, inter-hub network is assumed to be complete with a direct link between every hub pair.

The most relevant studies to our problem are the ones jointly considering the location of hubs and the design of intermodal hub networks. Meng and Wang (2011) proposed a hybrid genetic algorithm to solve the intermodal hub network design problem for multi-type container transportation with multiple stakeholders including the network planner, carriers, hub operators, and intermodal operators. In our problem, we have a single stakeholder and we solve a single company's hub network design problem.

Alumur et al. (2012a) developed a mixed-integer programing formulation for multimodal hub location and hub network design problem with different service options. In this study, only one type of service and one transportation mode is allowed between each pair of hubs. In a subsequent study, Alumur et al. (2012b) modeled and solved a hub location problem designing a hierarchical intermodal network while ensuring time-definite deliveries. In the current study, we do not impose any specific hub network structure or delivery time restrictions.

Most studies on hub location allow using a single transportation mode and a single vehicle type on the hub network to be designed. The studies considering the design of intermodal hub networks, on the other hand, do not model the possibility of employing different types of vehicles with different capacities. To the best of the authors' knowledge, there are not any hub location studies in the literature determining the optimal number of different types of vehicles to operate on an intermodal hub network. Choice for mode of transportation and number of vehicles to be handled at hubs affects both hub location and capacity decisions. Hence, such decisions should be considered simultaneously in designing hub networks.

A related field to our study is service network design. Service network design is concerned with tactical operations and decisions like selection and scheduling of services, specification of terminal operations, and routing of freight using already existing hub facilities. Interested reader may refer to Crainic (2000) and Wieberneit (2008) for reviews in this area. In this study, we focus on the strategic decisions and do not address any tactical decisions such as the frequency or scheduling of the vehicles.

In most hub location studies, economies of scale is modeled by using a constant discount factor (usually referred as α) to reflect the discounted cost of flow between hubs. However, as pointed out by many studies in the literature (e.g., O'Kelly and Bryan (1998), Kimms (2007), and Campbell (2013)) using flow-independent discounts between hubs results in a misapplication of economies of scale. O'Kelly and Bryan (1998) and Bryan (1998) suggested using a nonlinear concave cost function to correctly model economies of scale. Camargo et al. (2009) proposed a stronger formulation and a Benders decomposition algorithm for the function introduced in O'Kelly and Bryan (1998). Podnar et al. (2002) used a threshold-based discounting on links. Campbell et al. (2005) introduced hub arc location models where the models locate hub arcs with reduced unit flow costs rather than locating hub facilities. O'Kelly et al. (2015) added fixed costs for arcs to better model transportation operations. By the use of fixed costs, the unit cost per flow on an arc decreases as more flow is routed on that arc.

Kimms (2007) suggested alternative formulations to model flow-dependent economies of scale in hub networks. Alternatives were introduced using the classical single allocation hub location problem with fixed costs and the effects were