Transportation Research Part B 115 (2018) 126–142

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Shipment scheduling in hub location problems

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A R T I C L E I N F O

Article history:
Received 30 May 2017
Revised 15 May 2018
Accepted 3 July 2018

Keywords:
Hub location
Shipment scheduling
Economies of scale
Holding costs

A B S T R A C T

In this paper, we incorporate shipment scheduling decisions into hub location problems. Our aim is to determine the optimal locations of hubs, hub network structure, and the number of dispatches to operate on the hub network as well as the time period of dispatching each vehicle from a hub. We develop three mixed-integer programming models for different versions of this problem, depending on whether holding costs are incorporated and whether the vehicles are of different types. We investigate the impact of shipment scheduling decisions and holding costs on hub network configurations, routing decisions, and total cost of the network. We solve the models on instances from a new dataset with real data.

1. Introduction

Hub facilities provide switching, sorting or connecting and consolidation/break-bulk functions (O'Kelly and Bryan, 1998). Hub location models are widely used for many applications such as air transportation, ground freight transportation, postal, and parcel delivery. They provide an optimal structure for the hub network and routing decisions with minimum total costs.

Operational characteristics of parcel delivery companies stimulate the primary motivation of this study. Parcel delivery networks use a hub-and-spoke network structure where branch offices are typically referred to as origins/destinations or spoke nodes. Parcels are routed from the originating branch office through at least one hub, known as an operation center, to the consignee branch office. Every branch office is allocated to a single operation center. This is referred to as *single allocation* in the literature. Parcels dropped at branch offices customarily travel relatively short distances to arrive at the origin's operation center. They are consolidated with other parcels, loaded onto vehicles with large capacities, and destined toward consignees' operation centers. Each parcel delivery company ordinarily uses its own private fleet of vehicles to serve the inter-hub links.

Growing competition leads delivery companies, such as FedEx, UPS, and DHL, to provide express services such as same-day or next-day delivery. Such services are offered in response to urgent freight and just-in-time production schedules in which cost efficiency is also important. Parcel delivery networks adopt a hub-and-spoke network structure to reduce transportation costs. They take advantage of economies of scale through consolidation of freight shipments at hub facilities. To do so, delivery companies need to schedule the shipments in between hubs. Individual shipments might be held at hub facilities to dispatch a consolidated load at a later time. In this way, by efficiently scheduling the shipments, economies of scale can be exploited. Introducing shipment scheduling into hub location problems is essential to efficiently design hub networks, as consolidation decisions may have an effect on the optimal hub locations. Nevertheless, this issue has not been addressed in the literature to date.

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https://doi.org/10.1016/j.trb.2018.07.003

The work of O'Kelly (1986a,b) pioneered the research on hub location problems. The publication of the seminal paper by O'Kelly (1987), who proposed the first mathematical formulation for a general p-hub median problem, has triggered several papers that addressed hub location problems with a fixed or variable number of hubs (see e.g., Campbell, 1996; Skorin-Kapov et al., 1996; Ernst and Krishnamoorthy, 1999; Ebery, 2001; Marín et al., 2006; Puerto et al., 2016). The p-hub median problem aims at serving the origin-destination (O-D) demands through a predetermined number of hub facilities (p) with minimum total transportation cost. The p-hub median models ignore the fixed costs of opening hub facilities. O'Kelly (1992) introduced the single allocation hub location problem with fixed costs, where the number of hubs is a decision variable. He formulated the problem as a quadratic integer program and proposed a two-step procedure to find a good upper and a tight lower bound. The reader may refer to surveys on hub location problems (e.g., Campbell et al., 2002; Alumur and Kara, 2008; Farahani et al., 2013; Contreras, 2015) for detailed reviews of the literature.

When it comes to economies of scale, most hub location models in the literature apply a constant discount factor α, where $0 \leq \alpha < 1$, to the unit transportation costs between hubs. However, modeling economies of scale by a discount factor α which is independent of flows is challenged by Kimms (2006). Some studies attempted to resolve this drawback by modeling economies of scale with flow-dependent costs, or arc type-dependent fixed costs. Examples of such publications are O'Kelly and Bryan (1998), Kimms (2006), Chen et al. (2014), and O'Kelly et al. (2015).

In this paper, we strictly consider the case of "private carriage" where freight is moved in vehicles that are owned or leased (i.e. controlled) by the parcel delivery company. To this end, we consider two costs to correctly model economies of scale: i) fixed cost of dispatching a vehicle and ii) vehicle operational cost that varies with distance. This cost model together with the vehicle capacities can help overcome the weakness of using a constant flow-independent discount factor. Since benefiting from economies of scale requires freight to be consolidated at hub facilities, we also introduce the dimension of time into our hub location problem.

Research on dynamic hub location problems began with the pioneering work of Campbell (1990). He proposed a continuous-approximation model to locate/relocate freight carrier terminals in response to increasing demand. The shipment origins and destinations are randomly dispersed over a fixed service region. The model aimed to keep low-cost terminal configurations through the trade-off between transportation costs, location and relocation costs of the terminals. He examined the performance of myopic strategies, which are based on current demands and terminal locations. The results showed that a myopic strategy is nearly optimal when relocation is not expensive, and provides lower and upper bounds on the transportation cost for the optimal strategy.

Contreras et al. (2011) analyzed a dynamic (multi-period) uncapacitated multiple allocation hub location problem over a finite discrete time planning horizon. For given sets of commodities in each time period, all single-period demand of a particular commodity is fully routed through a distinct set of hubs toward the destinations. They developed a branch-and-bound (BB) algorithm that yielded optimal solutions for a set of benchmark instances with up to 100 nodes and 10 time periods. A Lagrangian relaxation approach is employed to provide tight lower and upper bounds at each node of the BB tree. To reduce the number of nodes of the tree, they used an effective partial enumeration phase to explore the solution space.

Classical hub location models primarily address long-term strategic location and allocation decisions. Gelareh et al. (2015) illustrated certain applications such as maritime and land transport dealing with seasonal decisions. Since hub facilities are leased, the locations of the hubs can change when the current contracts conclude. They developed a mathematical model for a multi-period uncapacitated multiple allocation hub location problem with a budget constraint. The mixed-integer linear model is solved by CPLEX for small-sized instances. They proposed a meta-heuristic and a Bender's decomposition algorithm to solve large scale instances.

Alumur et al. (2016) studied other multi-period versions of hub location problems. Taking construction time into consideration, they presumed that the hub network is progressively constructed over time and its operating capacity may increase, gradually. They proposed mixed-integer linear programming formulations for multi-period modular-capacitated hub location problems for both single and multiple allocation versions. Reducing hubs' capacities and closing existing hubs are not allowed. Operating inter-hub links incurs fixed costs and might change over time, even if the set of hubs remains the same. They improved the models through several sets of valid inequalities. Using CPLEX software, they solved the models for moderately-sized instances. They developed a measure for the value of the multi-period solution. Computational tests revealed the importance of integrating the time dimension into hub location problems.

Analogous to multi-period hub location models, in this study we assume that the planning horizon is discretized into a set of time periods. However, as the planning horizon is assumed to be short (e.g., a couple of days), the resulting structure of the hub network remains steady over all time periods. Moreover, it is assumed that all parcels are delivered to hub facilities (consignees' operation centers) by the end of the planning horizon. To take advantage of economies of scale through shipment scheduling, parcels might be held at hub facilities for one or more time periods. Hence, as opposed to the static hub location models, flows on inter-hub links might change over different time periods.

Another relevant subject area might be the service network design problem (SNDP). SNDP addresses operational and tactical decisions associated with vehicle routes, service schedules, consolidation, repositioning of empty vehicles, and vehicle stops as well as waiting times using preexisting terminals. An interested reader may refer to Crainic (2000) and Wieberneit (2008) for thorough reviews of this area. Unlike the service network design problem, our study also incorporates decisions on locations of the hub facilities.

The literature on scheduling in hub location problems is scarce. Yaman et al. (2012) proposed release-time scheduling and hub location problems for next-day delivery. They investigated a single allocation p-hub median problem under release-time