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Locating transit hubs in a multi-modal transportation network: A cluster-based optimization approach

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ABSTRACT

This paper develops a mathematical model with equilibrium constraints for integrated design of transit hub locations and link establishments in a multimodal network, grounded on the cluster-based framework to capture real-world geographical and administrative features as well as to improve the overall transit-oriented system performance. By explicitly capturing multimodal transfer activities and cost implications with virtual transfer nodes and arcs, this study models transit hub as a realistic transportation infrastructure rather than a single node in the network. A genetic-algorithm-based heuristic embedded with the Augmented Lagrangian Dual algorithm is developed to solve the problem to meta-optimality.

1. Introduction

In recent years, many major cities have been dedicated to developing and improving transit-oriented urban transport systems to relieve traffic congestion during the process of urbanization. As the key facilities in the entire transit and transportation system, transit hubs are designed to provide switching points for inter-modal flows to feature seamless connections. Therefore, well positioning and connecting hubs are critical to the effectiveness of intermodal transportation network. (Marwah et al., 2005; Yu et al., 2008, 2009, 2013; Resat and Turkay, 2015; Yang et al., 2016; Amirgholy et al., 2017).

Transit hub location planning is a branch of the general hub location problems. O'Kelly (1987) first formulated a quadratic single assignment model for interacting hub facilities from an operations research point of view. Campbell (1994) later formulated the *p*-hub median problem, which classified hub location problems into two major categories: the single allocation models and the multiple allocation models, depending on how non-hub nodes are connected to the hubs (O'Kelly et al., 1996; O'Kelly, 2010; Bryan and O'Kelly, 1999; Alumur and Kara, 2008). In the single-allocation model, each node is connected to a single hub (Campbell, 1994; O'Kelly et al., 1996; Ernst and Krishnamoorthy, 1996; Skorin-Kapov et al., 1996; Sohn and Park, 1997; Ebery, 2001; Kim et al., 2007; Alumur et al., 2009), and there is no sorting at the origin because all flows must travel to the same hub. In contrast, the multiple-assignment model allows each node to be connected to more than one hub, and thus sorting must take place at each origin that interacts with more than one hub (Campbell, 1992, 1994, 1996; Skorin-Kapov et al., 1996; Ernst and Krishnamoorthy, 1998; Boland et al., 2004). With the objective of minimizing the total travel cost, these two basic models require all services between the non-hub nodes to be hub-connected, known as a strict hubbing policy. To deal with more realistic characteristics of hub networks, researchers have explored various extensions (Klincewicz, 1998; Nickel et al., 2001), including a fixed cost added into the objective function so that the tradeoffs between travel costs and fixed costs are captured (O'Kelly, 1992; Campbell, 1994; Abdinnour-Helm and Venkataramanan, 1998; Ernst and Krishnamoorthy, 1999; Marin et al., 2005b), a capacity constraint incorporated in the model by limiting the flows entering a hub under its capacity (Ebery et al., 2000; Marin, 2005a; Rodriguez et al., 2007), the non-strict hubbing

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policy which allow every pair of spoke nodes to interact directly with each other (Aykin, 1994, 1995; Sung et al., 2001; Campbell et al., 2005a, 2005b; Yoon and Current, 2008), and other hub network topologies (Contreras et al., 2010).

The conventional hub location models are effective in capturing the impacts of hub locations on system performances, but neglect route choices of travelers in the multimodal network setting, which was addressed by application of multimodal traffic assignment. In review of literature on transit network design, Cipriani et al. (2012) proposed a procedure for dealing with bus network design problem with elastic demand, in which the performances of the transportation system are estimated with user equilibrium on both automobile and transit networks. Gallo et al. (2011) presented an optimization model to determine metro frequency considering the costs of all transportation systems (car, bus and rail) as well as the external costs to ensure solutions represent the actual objectives of the design. Zhang et al. (2014) investigated the auto network expansion scheme and the bus network design scheme in the multimodal network using an asymmetric multimodal user equilibrium problem to capture the congestion interaction among different modes. Mohaymany and Gholami (2010) designed a feeder network to cover demand areas with a medium or low-capacity transit system (e.g. feeder) that is connected to high-capacity mass transit (e.g. metro), and evaluate the total cost in multimodal network with two or more transit modes.

Multimodal hubs in those studies, however, are designated as nodes in the integrated transit (bus or metro) and road network, but not realistically considered as elements of transportation infrastructure due to neglect of multimodal transfer activities and cost implications. To this regard, Lo et al. (2003) proposed a State Augmented Multi-Modal (SAM) network with transfer arcs to model transfer congestion, in-vehicle crowdedness or discomfort, and road congestion for transit modes simultaneously. Employing the SAM network, Wan and Lo (2009) maximized the social welfare of transit network to determine the design scheme as well as the corresponding passenger flow and path utility, and the explicit transfer congestion effect was evaluated with a combined modal split and stochastic user equilibrium assignment problem in response to the design scheme. To represent transportation networks with transferring explicitly, Szeto and Jiang (2014) propose a bi-level transit network design problem minimizing the number of passenger transfers where the transit routes and frequency settings are determined simultaneously, and arcs of transfer, boarding, alighting, access and egress are considered explicitly. However, these studies focused on network design instead of transit hub location problems.

Previous studies also neglect the realistic geographical and administrative features on hub location planning, resulting in hubs usually located within most of the well-developed areas because of their concentrated demands. Cluster-based policy were introduced for a better planning of transit-oriented urban transport systems (Yu et al., 2008, 2009; Peker et al., 2016), in which Traffic Analysis Zones (TAZs) within the target network are grouped into clusters in advance based on their geographic and administrative features, and transit hubs are then distributed in each cluster, resulting in better transit service in newly developed areas and eventually improving the overall system performance. Regarding the determination of clustering rules, Marwah et al. (2005) developed a three-step procedure to select hubs and delineation of their influence areas. Yu et al. (2015) developed an aggregation-based clustering method to determine hub ports on the waterbus network. Peker et al. (2016) identified clusters of nodes using hub circles centered at important nodes and with a radius based on the proximity to other important nodes. However, review of literature indicates that limited efforts have been made to plan and locate transit hubs in the multimodal network incorporating cluster determination with explicitly captured travelers' route choice in response to traveling and transferring impedances. In addition, integrated design of inter-hub and intra-hub links to connect the located transit hubs was also neglected in previous studies.

This paper, proposed to deal with these critical issues, develops a mathematical model with equilibrium constraints for integrated design of transit hub locations and link connections in a multimodal network. The model formulation is designed to form network components into clusters, with a hub identified within each cluster, where a solution in this respect is called a cluster setting. A discrete hub location framework is used to capture real-world geographical and administrative features. Equilibrium assignment procedure is used for determining traffic flows on the road network under any deployment plan of candidate hub locations and link establishments. A genetic-algorithm-based heuristic embedded with the Augmented Lagrangian Dual algorithm (Yang and Huang, 2005) is developed to solve the problem to meta-optimality. A case study in Suzhou Industrial Park, China is conducted to assist local government in better planning the transit network, and sensitivity analysis on this case explores the impact of various budget levels and capacity settings on the results of proposed model.

2. System design

2.1. Design concept

This section explains the cluster-based design concept for locating transit hubs in a multimodal network (in Fig. 1). Four basic elements are defined as follows:

- TAZ nodes: The target study area for this study is divided into various Traffic Analysis Zones (TAZs). The origins and destinations of demand, as well as the hubs are assumed to be at the centroids of those TAZs, denoted as nodes.
- Clusters: This study employs a service zoning strategy that partitions all TAZ nodes into clusters based on their geographical and administrative features, because transit hubs usually serve as the centrally located service facilities to consolidate traffic flows on the inter-hub links. One of the main objectives of the model is to determine cluster settings (i.e. assignments of nodes to clusters), although for some purposes a pre-defined (or "fixed") clustering may be used (e.g. see Section 5.3).
- Links: The multimodal transportation network is represented by two sets of links, including:
  - Road links: provide a representation of individual, connected physical road links carrying motorized traffic (e.g., automobiles).