Transportation Research Part E 118 (2018) 568–588

Contents lists available at ScienceDirect

Transportation Research Part E

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

# Joint design of fleet size, hub locations, and hub capacities for third-party logistics networks with road congestion constraints

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ARTICLE INFO

*Keywords:*
3PL system
Fleet size
Hub location
Hub capacity
Road congestion
Hub and spoke network

ABSTRACT

This paper describes third-party logistics (3PL) systems with consolidation hubs as a hub-and-spoke network. We propose a multiple assignment (MA) model for the joint design of the fleet size and the number, locations and capacities of hubs. The objective is to minimize the total costs, including congestion costs. We explicitly model the road congestion by formulating the route travel time as an increasing function of the number of trucks on the route. We consider two types of trucks to model economies of scale. Similar to a truck booking system, we control the node and road congestions by delaying some of the overfull demand at the origin nodes. We derive the asymptotic behavior as design variables increase and demonstrate how the 3PL system throughput is bounded by the bottleneck routes. When the existing road congestion on the bottleneck routes is heavy, excessively large fleets and hub capacities will worsen the traffic conditions and downgrade the system throughput. We develop a math-heuristic algorithm to solve our problem, which is decomposed into two subproblems. We prove that the two subproblems can be linearized. The numerical experiments reveal some interesting findings: (1) heavier congestion on an existing road network (without 3PL trucks) generates a design with higher requirements (a larger number of hubs, a larger hub capacity and a larger fleet size) and larger economies of scale; (2) neglecting the road congestion constraints optimistically estimates the system performance and generate a design with fewer hubs and a larger number of large trucks; and (3) decreasing the fixed costs of establishing hubs or the large truck-related costs can significantly increase the economies of scale and reduce the total number of trucks.

## 1. Introduction

Third-party logistics (3PL) is playing an increasingly important role in modern supply chain management (Marasco, 2008). This approach helps producing or selling companies to avoid the setup, management and operation costs of logistics, allowing companies to focus on their core businesses. A 3PL provider has more global networks as the total number of clients and larger delivery demand areas than the individual producing or selling companies, and is therefore able to achieve the commodity delivery more efficiently by taking advantage of economies of scale. Furthermore, it can make geographic distribution more flexible, and may offer various delivery services, such as picking, packing, sorting, labeling, cross-docking, distribution, and tracking in addition to the storage and transportation of commodities. In recent years, 3PL has been progressively developed around the world. The global 3PL market has

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https://doi.org/10.1016/j.tre.2018.09.002
Received 28 November 2017; Received in revised form 30 August 2018; Accepted 5 September 2018
1366-5545/ 

reached an estimate of $ 750 billion in 2014 (Armstrong and Grabowski, 2015). As of 2014, 80% of all Fortune 500 companies and 96% of the Fortune 100 used 3PL services (Menner, 2015).

The 3PL industry involves decision making by multiple stakeholders, i.e., logistic providers, public sectors and producing or selling companies as well as customers. The providers typically aim to expand the market share in the short run and minimize the overall logistics costs in the long run by meeting market demand. The major types of 3PL providers include: (1) standard 3PL provider (performing the most basic logistics such as picking, packing, warehousing, and distribution), (2) service developer (focusing on economies of scale and offering more value-added services such as cross-docking, tracking, and specific packaging), (3) customer adapter (taking over the company's existing logistics but not developing a new service), and (4) customer developer (involving high integration with the company in addition to taking over its logistics).

In this paper, we consider the most common 3PL operated by the second type of provider, e.g., DHL Express, FedEx Corporation, UPS Express and TNT Express. To benefit from economies of scale as much as possible, the 3PL providers try to set up consolidation hubs to collect, transfer and distribute the commodity flow. In the past thirty years, urban consolidation hubs have become more and more popular in city logistics (Verlinde et al., 2012). By the end of 2010, 114 urban consolidation hub projects were carried out in 17 countries (Allen et al., 2012). There are many benefits by doing so: (1) increasing truck capacity utilization, and (2) decreasing the number of truck trips. More importantly, it may solve the problem of last-mile logistics, which is usually the most costly part of the delivery process (Lewis et al., 2010; Wang et al., 2016). At the same time, its social and environmental benefits include: (1) relieving traffic congestion, particularly within the central business district, and (2) reducing the truck emissions. Hence, it is also greatly supported by the local governments (Zhou and Wang, 2013).

This study is motivated by the 3PL companies that deliver commodities to high-density shopping malls in Singapore. Currently, it is reported that around 4000 trucks make more than 20,000 daily delivery trips which takes up about 25% of the road space in Singapore (Chia, 2015). This has created a lot of traffic problems such as congestion and traffic safety issue (Wang et al., 2017). Therefore, Singapore government has urged the 3PL providers to set up urban consolidation hubs with the intention of reducing road congestion, air pollution and traffic accident.3PL networks with consolidation hubs are a typical hub-and-spoke network. A hub-and-spoke network contains a given set of nodes with corresponding commodities to send and/or receive. A subset of nodes is selected to consolidate and distribute the commodity flow; these nodes are hubs, and the non-hub nodes are spokes. Two basic assumptions are often considered for a hub-and-spoke network: (1) the hub network is a complete graph, which indicates that all hubs are directly connected, and (2) direct transfer is not possible between two spoke nodes (Alumur et al., 2012). This implies that the demand of each node is assigned to at least one hub and the demand of the hub node is assigned to itself. Fig. 1 illustrates a typical hub-and-spoke network. To design a hub-and-spoke network, decision makers have to decide the number, locations and capacities of hubs, as well as the fleet size.

Hub-and-spoke networks have been extensively employed in different logistics and transportation problems. Therefore, numerous studies explore the design of hub-and-spoke networks (refer to Zheng et al., 2015; Campbell and O'Kelly, 2012; Meng and Wang, 2011; Gelareh and Nickel, 2011; Takano and Arai, 2009; Cunha and Silva, 2007; Jeong et al., 2007). Problems with different features are addressed. According to the allocation patterns of the spokes to the hubs, single allocation (SA) and multiple allocation (MA) problems are proposed. In the SA problem, each spoke is connected to a single hub, whereas a spoke can send/receive flow to/from more than one hub in the MA problem. Research on SA and MA models include Abdinnour-Helm (1998),Labbé and Yaman (2004), Boland et al. (2004),Contreras et al. (2011a), An et al. (2015) and so on. We refer the reader to Alumur and Kara (2008),Campbell and O'Kelly (2012) and Zanjirani Farahani et al. (2013) for a thorough review of these problems. In this paper, we consider an MA problem.

In some cases, the number of hubs $p$ is pre-given when designing a hub-and-spoke network. For the $p$-hub median location problem in which the fixed costs of opening hubs is usually ignored, O'Kelly (1987) propose a quadratic programming approach to investigate the SA version by minimizing the transportation costs. Campbell (1994, 1996) propose linear integer programming

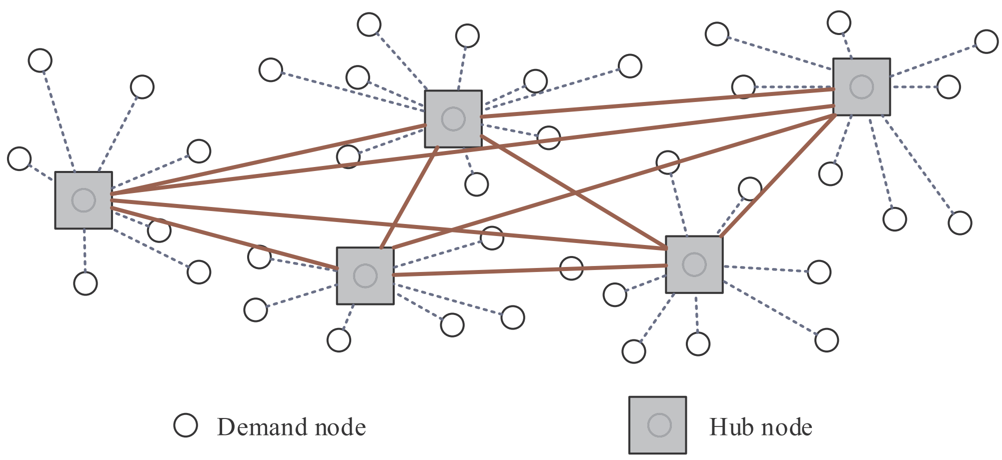


**Fig. 1.** A typical hub and spoke network.