The two-echelon distribution system considering the real-time transshipment capacity varying

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\textbf{A B S T R A C T}

As one of the most necessary infrastructures for two-echelon distribution with cross-docking systems, satellites enable transshipment and consolidation for cargo deliveries. Considering specially satellites’ real-time transshipment capacity (RTC) varying with transshipment and consolidation operations, we introduce the two-echelon distribution system considering the real-time transshipment capacity varying (called the 2E-DS-RTC). The 2E-DS-RTC adopts RTC constraints and time constraints to make routings of the two echelons interacting. Of each satellite, the RTC is constrained by the maximal transshipment capacity (MTC) and the occupied transshipment capacity. A mixed integer linear programming model for the 2E-DS-RTC is proposed. The savings-based algorithm followed by the variable neighborhood search phase is provided. The mathematical formulation and the two-stage heuristic are tested by using 20 randomly-generated small-scale instances and 99 realistic instances with up to 30 satellites and 900 customers. Some small-scale instances can be solved directly by CPLEX to find exact solutions. The computational results of realistic instances indicate that the heuristic can solve various scale instances of the 2E-DS-RTC such that the solution quality and the computation time are acceptable.

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1. Introduction

In city logistics two main transport strategies are identified: full truckload or less-than-truckload (Cattaruzza et al., 2017). Typical less-than-truckload examples include parcel delivery services, express services, supermarkets distribution, etc. Dense urban areas are characterized by a high concentration of commercial activities that are usually performed along with less-than-truckload cargo deliveries (Franceschetti et al., 2017). City distribution systems need to reduce the nuisances associated with cargo deliveries in dense urban areas while supporting commercial activities (Crainic et al., 2009). In recent years logistics enterprises have changed their distribution and inventory strategies for better adapting them to the growing delivery demand and legal restrictions on truck traffic in dense urban areas. The multi-echelon distribution system has emerged as a popular alternative to perform urban deliveries (Gonzalez-Feliu, 2012, 2013; Cuda et al., 2015). The most representative examples are seen in grocery distribution, parcel and postal distribution, etc.

Fundamentally, the multi-echelon distribution system implies to use different types of vehicles on different echelons, and to use satellites (i.e., intermediate platforms) to consolidate and transship cargoes. Such system allows enterprises to

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leverage economies of scale from larger shipments on upper echelons, and to comply with regulations that aim to reduce the environmental footprints of distribution operations on lower echelons of dense urban areas ( Merchán Dueñas, 2015 ). In multi-echelon distribution systems, two shipping strategies are predominant. In the multi-echelon distribution with warehousing system that includes factories, warehouses and the final destination of cargoes, cargo requests are made to warehouses. The warehouses command cargoes in large quantities to factories. The multi-echelon distribution with cross-docking system differs from the warehousing strategy. Cross-docking platforms don’t have the possibility to stock for a long time, but have the consent to cargo consolidation and transshipment ( Gonzalez-Feliu, 2010 ; Dondo et al., 2011 ).

Satellites are usually defined as the physical areas that enable transshipment and consolidation for cargo deliveries. A satellite usually operates on a small scale and consists of surface parking lots and weather protection spaces. In the paper, the two-echelon distribution with cross-docking system is configured for parcel delivery service. On the first echelon, trucks departing from the distribution center (DC) are used to serve satellites located at the surroundings of the district. On the second echelon, cargoes at satellites are reconsolidated and transferred to small and possibly less-polluting vehicles (e.g., electric tricycles) to reach customers ( Cuda et al., 2015 ; Cattaruzza et al., 2017 ). Such satellite concept is inspired in urban-distribution practices observed across many cities ( Merchán Dueñas, 2015 ). For example, a truck will reach a touristic or residential area early in the morning and park at one of the authorized locations. From the truck parking location, tricycles or motorcycles will complete the deliveries to residents or stores. On average, a tricycle or motorcycle will execute several delivery routes per day.

In the two-echelon distribution system, transshipment and consolidation operations require vehicles of different echelons being not independent of one another. A change in one 1st-echelon route may affect some 2nd-echelon routes, such phenomenon is called the interdependence. Drexl ( 2012 ) identified several types of synchronization to address the interdependence, one of which is the resource synchronization indicating that the total consumption of a specified resource by all vehicles must be less than or equal to a specified limit. Drexl ( 2012 ) stated that in most cases additional modeling and solution efforts are necessary to solve the routing problem with synchronization constraints. In the two-echelon city logistics system stated by Crainic et al. ( 2009 ) or the linehaul-delivery system stated by Li et al. ( 2016b ), satellites operate according to the vehicle synchronization. The 1st-echelon vehicles and the 2nd-echelon vehicles must meet at satellites at the appointed time. Cargos are moved as soon as possible from 1st-echelon vehicles to 2nd-echelon vehicles without intermediate storage. In many practices, parking lots and handling spaces are necessary for satellites, and satellites usually have limited temporary-storage capacities. Limited by minimal infrastructure requirements and low investments, satellites have the maximal transshipment capacity (MTC). To the best of our knowledge, the existing literature has not involved the transshipment capacity in formulating the two-echelon distribution system.

Considering satellites’ real-time transshipment capacity (RTC) varying with transshipment and consolidation operations, we address in the paper a variant called the two-echelon distribution system considering the real-time transshipment capacity varying (the 2E-DS-RTC). The RTC of a satellite varies along with the 1st-echelon vehicle arrivals and the 2nd-echelon vehicle departures. Supposing each satellite having own service area and assigned customers, the 2E-DS-RTC uses RTC constraints and two types of time constraints to make routings of the two echelons interacting. Classical time window constraints affect the route optimization for the second echelon. Synchronization constraints ensure that the arrivals of the 1st-echelon vehicles and the departures of the 2nd-echelon vehicles are coordinated at the same satellite, only if the transshipment and consolidation operations happen. Moreover, the RTC should be constrained by the MTC and the occupied transshipment capacity.

The paper examines a two-echelon distribution system variant of city distribution applicability that has not yet attracted adequate research interest. The contributions of the paper are: First, we introduce the 2E-DS-RTC that integrates RTC constraints, time window constraints, split delivery on the first echelon and vehicle’s multiple-route on the second echelon. A mixed integer linear programming model for the 2E-DS-RTC is put forward. Second, we provide a heuristic for the 2E-DS-RTC that incorporates a savings-based algorithm followed by a variable neighborhood search (VNS) phase. Third, the formulation and the heuristic are tested by solving 20 randomly-generated small-scale instances and 99 realistic instances. Some randomly-generated small-scale instances are solved directly by CPLEX. The heuristic can effectively solve various scale instances.

2. Literature review

Logistics enterprises have increased their competitiveness by adapting mathematical modeling techniques for optimizing vehicle routes. So far the majority of the optimization tools derives from methods for the vehicle routing problem (VRP). However, the VRP essentially refers to single-echelon systems. The optimization and modeling challenges in the two-echelon scheme are mainly related to the interactions arising between the two echelons, such as the synchronization and coordination of the fleets and terminal operations (Crainic and Sgalambrò, 2014). Although multi-echelon distribution systems are common in practice, in literatures they are usually decomposed into additions of single-echelon distribution cases ( Gonzalez-Feliu, 2013 ). Some literatures that deal with multi-echelon distribution optimization using global vehicle routing based approaches are found, especially in the last five years. There are two types of problems concerning multi-echelon distribution cost optimization: the N-echelon vehicle routing problem (NE-VRP) and the N-echelon location routing problem (NE-LRP). Most of the studies are related to two-echelon systems, i.e., N = 2.
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