An inventory routing problem in a city logistics context

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Introduction

Transport of goods is an essential factor for economic development in an urban area. With the rise of transportation problems for product deliveries in urban areas, the concept of city logistics is introduced. City logistics aims to optimally plan, manage, and control the vehicle movements within a logistical network in an urban area, considering integration and coordination among involved stakeholders (Neghabadi, Samuel, and Espinouse 2019). Since collaboration is a crucial element in city logistics (Crainic, Gendreau, and Jemai 2020, Lagorio, Pinto, and Golini 2016, Neghabadi, Samuel, and Espinouse 2019), innovative solutions for city logistics related to this element have been introduced over the years. Companies can, for example, collaborate to bundle freight flows in a two-or multi-echelon system using one or more intermediate consolidation points, such as urban consolidation centers (UCCs), city depots, micro hubs, etc.

Multi-echelon systems have been widely used in cities around the world. In most city centers, road space is limited and has to be shared with private and public passenger transport and parking facilities (Hemmelmayr, Cordeau, and Crainic 2012). Besides, heavy freight transportation in a city is a discomforting factor for citizens because it produces congestion, polluting emissions, and noise. As a result, city authorities usually want to reduce the number of large vehicles and only allow smaller vehicles in the city center. Although multi-echelon systems may help to achieve this, the additional costs of implementing a city hub (e.g., cost of the facility, additional handling) make it important to discuss the broader implications and potential cost reductions in other processes of the stakeholders involved.

Both in practice and academia, the main focus when implementing or studying multi-echelon systems is on the opportunity to consolidate transport flows, leading to more efficient and more environmentally friendly transportation activities. Another opportunity in such a system is to use the consolidation points as temporary storage facilities in a B2B setting, so that retailers can save costly storage space in the urban area. However, the study of inventory aspects in city logistics is relatively unexplored. Therefore, this work aims to study the opportunity of using UCCs as an intermediate storage point in an urban two-echelon distribution system. More specifically, our goal is to analyse to what extent the integration of inventory and routing decisions leads to additional operational benefits compared to a traditional setting in which the UCC is only used as a consolidation point.

The type of problem that integrates routing and inventory decisions is known as the Inventory Routing Problem (IRP). In the VRP, the main decision to make is the set of routes to travel in a single time period. In the IRP, three main decisions must be taken in a multi-period setting: when and how much to deliver to each customer and the routes to travel at each time period. Therefore, the IRP adds some complexity due to the integration of inventory and routing elements into a multi-period decision process, but it may lead to better overall decisions. While the IRP has been studied extensively, only a few studies consider inventory aspects along with the routing decisions in a city logistics context, with its specific characteristics. Examples of such characteristics include time windows, multiple vehicle trips per day, the use of heterogeneous vehicles, etc. In this work, we address this gap by modeling and solving an IRP in an urban context.

Problem Description

Our problem setting can be described as follows. We consider an urban two-echelon distribution system in which the network consists of a number of suppliers (outside the urban area), a single UCC, and multiple urban retailers. Retailers face a daily demand from their customers for multiple products over a predefined multi-period planning horizon. Each retailer orders the required products from the different suppliers (a single supplier per product type). Suppliers deliver their products to the UCC, after which they are consolidated and distributed to the retailers from the UCC using a heterogeneous fleet (e.g., bikes and vans). Retailers have a limited storage capacity, face a holding cost when storing products over the periods, and impose strict time windows on deliveries. Finally, holding costs at the UCC are assumed to be lower than at the retailers' locations, and bikes can make multiple trips per period.

To address our research question, two scenarios are considered and compared: a traditional one in which inventory and routing decisions are taken sequentially and an integrated one in which both decisions are taken simultaneously. In the first scenario, each retailer defines its orders based on a replenishment method over the multi-period planning horizon. Then, the suppliers deliver their products to the city hub on the requested days, and the city hub handles the delivery process of the products from all suppliers to the retailers. This involves solving a VRP with time windows, heterogeneous fleet and multiple trips on each day of the planning period. In the second scenario, the city hub simultaneously defines how many products of each type will be delivered to the retailers and the delivery routes, while ensuring sufficient inventory at the retailers. Therefore, the inventory and routing decisions are optimized simultaneously by the city hub. This results in a multi-period IRP with multiple products, time windows, a heterogeneous fleet and multiple trips.

Solution method

The inventory and routing decisions are made sequentially for the first scenario. In the inventory part, the retailers decide when and how many products to receive from the suppliers. To determine the delivery amount for each period, the retailers are assumed to use one of five different replenishment methods. For the first three replenishment methods, a periodic delivery method is used. In these methods, the delivery amount is the sum of the retailer's demands for n periods, with n being either 1, 2, or 3. The fourth replenishment method is an Order Up to policy (OU), in which the inventory level is raised to its maximum capacity whenever a retailer needs to be replenished. The last replenishment method applies the principle of Economic Order Quantity (EOQ). After determining the order quantity using one of the replenishment methods, a list of retailers that need to be visited and their order quantity for each period is generated. Then, for the routing part, a Large Neighbourhood Search (LNS) meta-heurstic algorithm is used to solve the route optimization problem. The best insertion heuristic is used to obtain an initial solution to the problem and to rebuild destroyed solutions. We use three types of removal mechanisms as the destroy operator: random removal, trip removal, and worst removal. In each iteration of the algorithm, one of these is selected randomly.

In scenario 2, the inventory and routing parts are optimized simultaneously. In addition to the delivery routes, the city hub must also define how many products to deliver to the retailers to have a minimum total cost. To solve this problem, we propose a matheuristic algorithm, based on the one proposed in Bertazzi et al. (2019) and extended for the multi-trip aspect in our problem. The matheuristic method consists of two phases: a route generation phase and an optimization phase. In the route generation phase, a large set of promising delivery routes is built. To this end, we run our LNS algorithm on the daily routing problems that result from applying the different replenishment policies considered in scenario 1 and store routes found during the search. Next, we enlarge the route pool by recombining trips into new delivery routes. For the optimization phase, we present a mixed integer linear programming model to simultaneously select routes from the route pool for every period and determine the delivery quantities to the retailers for each of these selected routes. The model minimizes the total routing and inventory cost, and is solved using CPLEX.

Computational Results

A numerical study is conducted to compare the two scenarios. Several problem characteristics are varied in this study, including the number of suppliers, the number of retailers, the holding cost, and the replenishment method applied by the retailers in scenario 1. Several values for each problem characteristic are considered, and each unique combination is tested. Artificial instances that correspond to each combination are generated and solved for both scenarios. With these computational experiments, we aim to see the impact of integrating inventory and routing decisions in a city logistics context. Preliminary results indicate that scenario 2 provides better solutions in terms of the total cost than scenario 1. Improvements of about up to 50% are found. In addition to the total cost, some performance measures related to the city perspective, such as the traveled distance, average vehicle loading degree, and the number of urban trips, are used for the evaluation process.

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