Urban deliveries using robots in a two-echeleon system

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1 Introduction

By leveraging new technologies (Autonomous Vehicles, Drones, etc.), many companies are developing new logistic systems that can change the competition landscape. We observed interest in freight distribution with robots has surged in the past five years, producing a number of studies and tests on new automated logistics and distribution tools. For example, UPS tested home delivery via truck and drone in Florida as a move towards a more automated delivery process. JD.com launched city delivery by autonomous vehicles in several Chinese universities and districts in Beijing. French start-up TwinswHeel is testing an unmanned delivery robot with the ability to climb a certain sidewalk height to complete last-mile delivery. Note that most small fully automated ground vehicles are electrically driven, which will help reduce local emissions in cities.

The contributions of this paper are as follows. We consider a new two-echelon urban delivery concept with time windows relying on autonomous vehicles. First level routes are operated by large vehicles (LVs) transporting delivery robots or small autonomous vehicles (SAV). First we introduce the problem and propose a mathematical formulation and a solution method. We propose a construction heuristic for the newly introduced problem, which is useful for quickly generating feasible initial solutions and providing a first upper bound. We then propose a multi-start hybrid metaheuristic approach based iterative local search and backtracking. The backtracking procedure is led to accurately connect the chosen SAV routes to the LV route. Furthermore, we analyze how LV/SAV speed combinations influence the objective value, : A sensitivity analysis for vehicle speed combinations reveals that increasing SAV speeds has only very limited effects on cost. We therefore recommend to keep SAV speeds rather low because of a more pedestrian friendly environment in practical implementations.

2 Problem Description

We consider a two-echelon urban delivery problem using SAVs for *2nd-level route* delivery. The LV carries the SAVs on the *1st-level route* and drops off and picks up them in the rendezvous nodes, while the SAV handles customer service on the *2nd-level route*. The research developed in this paper considers using the LV only for carrying SAVs, and so no direct shipping from LVs to customers is allowed. This setting is reasonable, since the SAV can only deliver parcels or other small commodities to pedestrianized areas such as campuses or residential clusters with current technologies. Also, our target customers are in these pedestrianized areas, where LVs are often banned. Hence, we assume the LV cannot serve customers directly.

Since campuses and residential clusters have multiple entrances and exits, the LV can drop off and pick up an SAV at different positions. In other words, the LV can move to other rendezvous nodes after making a drop-off operation without having to wait for its SAV to come back to the same rendezvous location. Besides, the SAV is not forced to return back to the rendezvous node it departed from, which means the *2nd-level route* is an open route.

Each pick-up or drop-off (rendezvous) node can only be visited at most once by the same vehicle. This setting is reasonable, as an LV can release all its associated SAVs immediately at a drop-off node and has no need to reach that node again. Likewise, an LV can arrive at a pick-up node when all its associated SAVs have arrived. Hence, a drop-off/pick-up node does not have to be visited twice by the same LV. Each customer node must be visited by just one SAV exactly once. In addition, customer nodes and depot have their time windows based on real demand in city logistics. Our model accommodates waiting at all locations without cost. Moreover, we allow an SAV to visit multiple customers during a dispatch rather than only visit one customer, since the maximum capacity for an SAV usually larger than that of a drone. The travel range of an LV is infinite. Nevertheless, the total travel distance of an SAV cannot exceed a predetermined value on the *2nd-level route*, as the SAV tends to be small-sized and thus equipped with limited fuel/battery capacity.

3 Solution Approach

This section introduces approximate solution methods for the LV-SAV problem. We first propose a construction heuristic to obtain a feasible solution quickly. The construction heuristic is applied to provide an upper bound during optimization of the primary objective of the MIP model, and also to generate multiple initial solutions for a hybrid metaheuristic approach. We then propose a hybrid multi-start metaheuristic including destroy and repair operators together with a backtracking component.

The approach consists of a destroy-repair and loop aiming to minimize the number of LVs (primary objective). It is followed by an iterated local search loop minimizing the number of vehicles as well as the total distance related cost. Our local search consists of a varibale neighborhood descent combining several local search operators for intra- and inter route improvements. The two inner optimization loops are embedded in a multi-start procedure. We use an exact algorithm to build the *1st-level route* as the number of rendezvous nodes is small. We first construct the *2nd-level route* and then use LVs to connect them. If we have several SAVs belonging to one LV, we can employ a backtracking algorithm to connect the SAV routes with the LV route. The method is applied in the repair and ILS procedures. After a customer node has been inserted into a complete LV-SAV route or after performing moves in the ILS, the backtracking algorithm is applied to check whether the *1st-level route* can be successfully connected, and then the backtracking outputs the solution with the minimum travel cost of *1st-level route* if needed.

4 Results

We performed three types of computational experiments. First, we use CPLEX to provide benchmarks for small instances and estimate the scale of the problem that the solver can manage. Second, we evaluate the performance of the multi-start heuristic, iteration number, different moves and perturbations in the hybrid metaheuristic, and then compare the hybrid metaheuristic results against the CPLEX results to analyze its performance. Third, we implement a sensitivity analysis on the LV/SAV speed ratio to see how the related speed influences the objective of the LV-SAV model.