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A decomposition-based iterative optimization algorithm for traveling salesman problem with drone☆

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ABSTRACT

This study investigates a new delivery problem that has emerged after the attempts of several e-commerce and logistics firms to deploy drones in their operations to increase efficiency and reduce delivery times. In this problem, a delivery truck that carries a drone on its roof serves customers in coordination with a drone. The drone is considered to complement the truck due to its cost-efficiency and ability to access difficult terrains and to travel without exposure to congestion. This study presents an iterative algorithm that is based on a decomposition approach to minimize delivery completion time. In the first stage of the proposed methodology, the truck route and the customers assigned to the drone are determined. In the second stage, a mixed-integer linear programming model is solved to optimize the drone route by fixing the routing and the assignment decisions that are made in the first stage. Beginning with the shortest truck route, the assignment and the routing decisions are iteratively improved. The solution times of our algorithm are compared with the solution times of the state-of-the-art formulations that are solved by CPLEX. The results demonstrate that our algorithm yields shorter solution times for the instances that we generated with the specified parameters. An optimization-based heuristic algorithm, which obtains solutions for medium-sized instances, is developed by reducing the feasible search area.

1. Introduction

Drones, which are predominantly defined as small unmanned aerial vehicles, are special systems that operate without human operators. Due to the technological developments in these systems, drones have received an increasing amount of attention in various areas, such as the logistics and retail industries, which seek to integrate drones in their operations.

Amazon is the first company to announce an ongoing project to deploy drones for last-mile delivery (Amazon.com). In Amazon’s business model, drones are aimed at directly delivering parcels from a depot to the customers. However, due to technical restrictions, such as the battery life limit and parcel weight, drones are restricted to visiting one customer during each flight and returning to the depot after each customer visit (French, 2015). The drone that returns to the warehouse can only perform the next customer visit after its battery is changed and the next customer's package is loaded. In addition to the technical restrictions, which require improvements in drone technologies, federal regulations (Snider and Welch, 2015) and the issues such as safety and violation of privacy, have prompted criticisms and discussions (Paul, 2015). These criticisms and discussions have caused the emergence of a new last-mile delivery concept that suggests synchronization of a truck and a drone (Wohlsen, 2014). In this delivery concept, a drone that is launched from and picked up by a truck that is equipped to carry a drone on top of the truck concurrently serves customers with the

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truck. This new delivery approach has received a substantial amount of interest. Mercedes-Benz has recently announced a “drone-equipped delivery van” concept vehicle that employs “roof-mounted unmanned aerial vehicles (UAVs) and robotic package-sorting devices” (Banker, 2016). UPS, which has attempted to realize this concept in real life, has announced that it successfully tested the coordinated distribution of a drone and a truck by modifying its traditional delivery truck such that it interacts with the drone (Crowe, 2017).

Inspired by this delivery approach, Murray and Chu (2015) introduced the traveling salesman problem with drone (TSP-D), which they refer to as “the flying sidekick traveling salesman problem”. Their motivation for this operational logistics problem is to investigate the efficiency of this approach, which combines the advantages of vehicles with contrasting features. The traditional delivery vehicle-the truck-has a large load capacity and does not return to the depot before visiting all customers in the delivery network; however, it may be limited in the number of customers it visits due to the land conditions. In urban areas, congestion is a factor that delays this type of vehicle. Although a drone has a load capacity of exactly one, it can easily handle the land conditions and does not have to track the roads. These factors, which delay a truck, are advantages of a drone.

In this paper, we focus on improving the mathematical models suggested for the TSP-D. Since this problem is a recent variant of the traditional traveling salesman problem, a limited number of studies address this topic. The mathematical models developed for the TSP-D are not capable of solving instances with more than 10 customers in a one-hour computational time limit (Agatz et al., 2016; Murray and Chu, 2015). To improve this performance, we propose an algorithm in which an MIP formulation is iteratively solved. This paper proposes a simple heuristic that improves the solution time.

The main contributions of our paper can be summarized as follows:

- We develop an iterative algorithm by decomposing the problem into two stages and solving an MIP model in the second stage of each iteration.
- We compare the solution times of our algorithm with the CPLEX solution times of the state-of-the-art mathematical models. The main contribution of our algorithm is to solve 12-customer nodes problem instances (uniformly generated) within 15 min on average.
- We propose an optimization-based heuristic that can solve instances with 20 customers.

The remainder of the paper is structured as follows: In Section 2, we present a review of the literature on the TSP-D. In Section 3, we describe the problem. The exact algorithm and the proposed heuristic are explained in Section 4. In Section 5, a detailed analysis of the numerical results is provided. Section 6 presents the conclusion.

2. Literature review

An increasing number of studies investigate the efficiency of delivery systems that deploy drones. However, a limited number of these studies focus on the coordinated delivery of a truck and a drone. Since we address the synchronization of both vehicles in our study, only the studies with similar assumptions are considered.

Murray and Chu (2015) is the first study that introduces the TSP-D. They study two different variants of the problem; one of these variants is the focus of this paper. They propose mathematical models and heuristics for both of the problems. The heuristic that is proposed for the problem, which is the subject of this study, is based on a route first-cluster second heuristic. Murray and Chu (2015) construct their heuristic approach on the TSP solution. By obtaining a route for the truck, they partition the truck route into drone tours regarding the cost savings. They present heuristic solutions for the instances with only 10 customers.

A related study by Agatz et al. (2016) generates combinations of truck and drone routes between each possible launch and pickup nodes. They refer to each combination as an “operation” and propose an operation-based formulation. They develop two heuristics based on local search and dynamic programming. Unlike the assumptions made by Murray and Chu (2015), the truck is allowed to meet with the drone at the starting node of the flight.

Ha et al. (2018) investigate the delivery cost of the TSP-D for the first time. They provide two different heuristics that gain inspiration from the route first-cluster second heuristic, which is based on local search and GRASP. They provide the results obtained for large instances with 50 and 100 customer nodes. In another study by Ha et al. (2015), they propose a cluster first-route second heuristic, in which they initially solve a mathematical model that optimally maximizes the path traveled by the drone and then heuristically build the truck route. Another heuristic approach that they propose is based on a route first-cluster second approach. In this version of the heuristic approach, they initially solve the TSP, then partition the truck route into clusters.

The only study that uses metaheuristic is proposed by Ponza (2016). In his thesis, he applies simulated annealing to the TSP-D.

The literature that we briefly mentioned focuses on the traveling salesman problem with a single drone. Wang et al. (2017) is the first study to consider multi-trucks and multi-drones. They investigate this version of the problem from a theoretical aspect that provides worst-case analysis and bounds for several considerations. As an extension, Poikonen et al. (2017) enhance the proposed theoretical investigation.

Ferrandez et al. (2016) investigate the efficiency of not only delivery time but also energy in a truck and drone coordinated delivery system. They consider a single truck and multiple drones in a different version of the TSP-D. In their consideration, the truck carries multiple drones; when it arrives at the launch node, each drone is launched from the truck for parallel visits and returns to the truck as it completes the visits. The customer at the launch node is served by the truck while it waits for the drones. In their study, they optimize the number of launch nodes by Newton’s approach then determine the launch locations utilizing a K-means algorithm. The truck route is determined by a genetic algorithm.