Transportation Research Part C 86 (2018) 597–621

Contents lists available at ScienceDirect

Transportation Research Part C

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

# On the min-cost Traveling Salesman Problem with Drone

Quang Minh Ha[a], Yves Deville[a], Quang Dung Pham[b], Minh Hoàng Hà[c,*]

[a] ICTEAM, Université catholique de Louvain, Belgium
[b] SoICT, Hanoi University of Science and Technology, Viet Nam
[c] University of Engineering and Technology, Vietnam National University, Hanoi (VNU), Viet Nam

ARTICLE INFO

*Keywords:*
Traveling Salesman Problem with Drone
Minimize operational cost
Integer programming
Heuristic
GRASP

ABSTRACT

Over the past few years, unmanned aerial vehicles (UAV), also known as drones, have been adopted as part of a new logistic method in the commercial sector called "last-mile delivery". In this novel approach, they are deployed alongside trucks to deliver goods to customers to improve the quality of service and reduce the transportation cost. This approach gives rise to a new variant of the traveling salesman problem (TSP), called TSP with drone (TSP-D). A variant of this problem that aims to minimize the time at which truck and drone finish the service (or, in other words, to maximize the quality of service) was studied in the work of Murray and Chu (2015). In contrast, this paper considers a new variant of TSP-D in which the objective is to minimize operational costs including total transportation cost and one created by waste time a vehicle has to wait for the other. The problem is first formulated mathematically. Then, two algorithms are proposed for the solution. The first algorithm (TSP-LS) was adapted from the approach proposed by Murray and Chu (2015), in which an optimal TSP solution is converted to a feasible TSP-D solution by local searches. The second algorithm, a Greedy Randomized Adaptive Search Procedure (GRASP), is based on a new split procedure that optimally splits any TSP tour into a TSP-D solution. After a TSP-D solution has been generated, it is then improved through local search operators. Numerical results obtained on various instances of both objective functions with different sizes and characteristics are presented. The results show that GRASP outperforms TSP-LS in terms of solution quality under an acceptable running time.

## 1. Introduction

Companies always tend to look for the most cost-efficient methods to distribute goods across logistic networks (Rizzoli et al., 2007). Traditionally, trucks have been used to handle these tasks and the corresponding transportation problem is modelled as a traveling salesman problem (TSP). However, a new distribution method has recently arisen in which small unmanned aerial vehicles (UAV), also known as drones, are deployed to support parcel delivery. On the one hand, there are four advantages of using a drone for delivery: (1) it can be operated without a human pilot, (2) it avoids the congestion of traditional road networks by flying over them, (3) it is faster than trucks, and (4) it has much lower transportation costs per kilometre (Wohlsen, 2014). On the other hand, because the drones are powered by batteries, their flight distance and lifting power are limited, meaning they are restricted in both maximum travel distance and parcel size. In contrast, a truck has the advantage of long range travel capability. It can carry large and heavy cargo with a diversity of size, but it is also heavy, slow and has much higher transportation cost.

Consequently, the advantages of truck offset the disadvantages of drones and—similarly–the advantages of drones offset the disadvantages of trucks. These complementary capabilities are the foundation of a novel method named "last mile delivery with drone"

* Corresponding author.
*E-mail addresses:* quang.ha@uclouvain.be (Q.M. Ha), yves.deville@uclouvain.be (Y. Deville), dungpq@soict.hust.edu.vn (Q.D. Pham), minhhoang.ha@vnu.edu.vn (M.H. Hà).

https://doi.org/10.1016/j.trc.2017.11.015
Received 20 May 2016; Received in revised form 13 November 2017; Accepted 13 November 2017

(Banker, 2013), in which the truck transports the drone close to the customer locations, allowing the drone to service customers while remaining within its flight range, effectively increasing the usability and making the schedule more flexible for both drone The MILP formulation is as follows and trucks. Specifically, a truck departs from the depot carrying the drone and all the customer parcels. As the truck makes deliveries, the drone is launched from the truck to service a nearby customer with a parcel. While the drone is in service, the truck continues its route to further customer locations. The drone then returns to the truck at a location different from its launch point.

From the application perspective, a number of remarkable events have occurred since 2013, when Amazon CEO Jeff Bezos first announced Amazon's plans for drone delivery (News, 2013), termed "a big surprise." Recently, Google has been awarded a patent that outlines its drone delivery method (Murphy, 2016). In detail, rather than trying to land, the drone will fly above the target, slowly lowering packages on a tether. More interestingly, it will be able to communicate with humans using voice messages during the delivery process. Google initiated this important drone delivery project, called Wing, in 2014, and it is expected to launch in 2017 (Grothaus, 2016). A similar Amazon project called Amazon Prime Air ambitiously plans to deliver packages by drone within 30 min (Pogue, 2016). Other companies worldwide have also been testing delivery services using drones. In April 2016, Australia Post successfully tested drones for delivering small packages. That project is reportedly headed towards a full customer trial in late 2016 (Cuthbertson, 2016). In May 2016, a Japanese company—Rakuten—launched a service named "Sora Kaku" that "delivers golf equipment, snacks, beverages and other items to players at pickup points on the golf course" (News, 2016). In medical applications, Matternet, a California-based startup, has been testing drone deliveries of medical supplies and specimens (such as blood samples) in many countries since 2011. According to their CEO: it is "much more cost-, energy- and time-efficient to send [a blood sample] via drone, rather than send it in a two-ton car down the highway with a person inside to bring it to a different lab for testing," (French, 2015). Additionally, a Silicon Valley start-up named Zipline International began using drones to deliver medicine in Rwanda starting in July, 2016 (Toor, 2016).

We are aware of several publications in the literature that have investigated the routing problem related to the truck-drone combination for delivery. Murray and Chu (2015) introduced the problem, calling it the "Flying Sidekick Traveling Salesman Problem" (FSTSP). A mixed integer liner programming (MILP) formulation and a heuristic are proposed. Basically, their heuristic is based on a "Truck First, Drone Second" idea, in which they first construct a route for the truck by solving a TSP problem and, then, repeatedly run a relocation procedure to reduce the objective value. In detail, the relocation procedure iteratively checks each node from the TSP tour and tries to consider whether it is suitable for use as a drone node. The change is applied immediately when this is true, and the current node is never checked again. Otherwise, the node is relocated to other positions in an effort to improving the objective value. The relocation procedure for TSP-D is designed in a "best improvement" fashion; it evaluates all the possible moves and executes the best one. The proposed methods are tested only on small-sized instances with up to 10 customers.

Agatz et al. (2016), study a slightly different problem—called the "Traveling Salesman Problem with Drone" (TSP-D), in which the drone has to follow the same road network as the truck. Moreover, in TSP-D, the drone may be launched and return to the same location, while this is forbidden in the FSTSP. This problem is also modelled as a MILP formulation and solved by a "Truck First, Drone Second" heuristic in which drone route construction is based on either local search or dynamic programming. Recently, Bouman et al. (2017) extended this work by proposing an exact approach based on dynamic programming that is able to solve larger instances. Furthermore, Ponza (2016) also extended the work of Murray and Chu (2015) in his master's thesis to solve the FSTSP, proposing an enhancement to the MILP model and solving the problem by a heuristic method based on Simulated Annealing.

Additionally, Wang et al. (2016), in a recent research, introduced a more general problem that copes with multiple trucks and drones with the goal of minimizing the completion time. The authors named the problem "The vehicle routing problem with drone" (VRP-D) and conducted the analysis on several worst-case scenarios, from which they propose bounds on the best possible savings in time when using drones and trucks instead of trucks alone. A further development of this research is studied in Poikonen et al. (2017) where the authors extend the worst-case bounds to more generic distance/cost metrics as well as explicitly consider the limitation of battery life and cost objectives.

All the works mentioned above aim to minimize the time at which the truck and the drone complete the route and return to the depot, which can improve the quality of service (Nozick and Turnquist, 2001). However, in every logistics activity, operational costs also play an important role in the overall business cost (see Russell et al., 2014; Robinson, 2014). Hence, minimizing these costs by using a more cost-efficient approach is a vital objective of every company involved in transport and logistics activities. Recently, an objective function that minimizes the transportation cost was studied by Mathew et al. (2015) for a related problem called the Heterogeneous Delivery Problem (HDP). However, unlike in Murray and Chu (2015) and Agatz et al. (2016), the problem is modelled on a directed physical street network where a truck cannot achieve direct delivery to the customer. Instead, from the endpoint of an arc, the truck can launch a drone that will service the customers. In this way, the problem can be favourably transformed to a Generalized Traveling Salesman Problem (GTSP) (Gutin and Punnen, 2006). The authors use the Nood-Bean Transformation available in Matlab to reduce a GTSP to a TSP, which is then solved by a heuristic proposed in the study. To the best of our knowledge, the min-cost objective function has not been studied for TSP-D when the problem is defined in a more realistic way—similarly to Murray and Chu (2015) and Agatz et al. (2016). Consequently, this gap in the literature provides a motivation for studying TSP-D with the min-cost objective function.

This paper studies a new variant of TSP-D following the hypotheses of the FSTSP proposed in the work of Murray and Chu (2015). In FSTSP, the objective is to minimize the delivery completion time, or in other word the time coming back to the depot, of both truck and drone. In the new variant that we call min-cost TSP-D, the objective is to minimize the total operational cost of the system including two distinguished parts. The first part is the transportation cost of truck and drone while the second part relates to the waste time a vehicle has to wait for the other whenever drone is launched. In the following, we denote the FSTSP as min-time TSP-D to avoid confusion.

In this paper, we propose a MILP model and two heuristics to solve the min-cost TSP-D: a Greedy Randomized Adaptive Search Procedure (GRASP) and a heuristic adapted from the work of Murray and Chu (2015) called TSP-LS. In detail, the contributions of this paper are as follows: