Cooperative delivery of drones and truck based on K-means algorithm with soft time window

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Abstract

In urban environments, pure surface rapid delivery faces significant challenges. Given the advantages of drones over traditional vehicles, such as direct flight, no road traffic, and no driver or operator requirements, problems have emerged in recent years when drones and truck cooperate to deliver goods in cities. Considering that customers in economically developed areas, such as cities, are highly sensitive to time, this paper establishes a mixed integer programming model for the delivery problem of truck-mounted drones, and considers the mileage constraints of drones, customer time window and other factors, aiming at the lowest total distribution cost. Firstly, the optimal number of stopping points is determined, and the temporary stopping point of the truck is determined by K-means algorithm as the delivery and takeoff point of the drone. Then, the optimal path of the truck and drone is calculated by genetic algorithm, and compared with the traditional truck delivery. The results show that the model is effective and the delivery cost is lower than that of traditional truck delivery.

Keywords

Drone;Truck;Cooperative delivery; K-means algorithm;Soft time window.

1. Introduction

Thanks to the boom of e-commerce, consumers have a growing demand for products, and more and more people choose online shopping with home delivery. In urban environments, pure surface rapid transportation faces significant challenges. These challenges are driving retailers and operators to seek new technologies and concepts to provide cost-effective, flexible and fast delivery services. Given the advantages of drones over traditional vehicles, such as direct flights, no road traffic, and no driver or operator requirements, some companies have proposed drone deliveries. Amazon has developed a drone called Prime Air that can deliver packages weighing up to 5 pounds to customers' homes in less than half an hour [1]; Sf Express, the logistics partner of Alibaba Group, conducted a drone delivery test in Dongguan City in 2013. The drone model could fly at an altitude of 100 meters and deliver goods to some remote areas [2].

Drones have been the focus of research for a decade. Thibbotuwawa et al. [3] proposed an off-line method considering energy consumption constraints and collisions to solve the UAV mission planning problem, adopted a prediction strategy to avoid collisions between UAVs, and established collection-free paths and scheduling within the time range to provide delivery services for customers. Song et al. [4] considered that commercial UAVs could not continue to deliver goods due to the limitations of flight time and loading capacity, and proposed to establish service stations in the delivery area for UAVs to charge and reload products, so that UAVs could provide long-term delivery services. The above literature only considers UAV delivery, but due to the limited flight distance of UAV, it may not be applicable in a wide range of areas. Murray and Chu[5] were the first to model an optimized delivery system for vans and drones, where a drone drives alongside the van and assists with the last mile delivery, a problem they dubbed the Flying Assistant Traveling Salesman Problem (FSTSP); Ha et al. [6] focused on minimizing the total operating cost including transportation cost and waiting penalty, and proposed a mixed integer linear programming formula and two heuristic methods to solve this problem;Agatz et al. [7] pointed out that the series scheduling problem of UAV and truck involves both allocation decision and path decision: allocation decision determines which customer the UAV or truck will serve, and path decision determines the order of customer visit;Wang et al. [8] derived some worst-case results for the UAV-vehicle routing problem, from which they proposed the upper limit of the most likely time savings when using UAVs and vans rather than vans alone.In addition to the above types of delivery, truck-supported drone delivery is another way .Mathew et al. [9] studied the problem of one truck supporting one UAV delivery by providing a special contact point for vehicles and UAVs;Ferrandez et al. [10] introduced a series distribution system for collaborative delivery of trucks and drones. In this model, the UAV takes a truck from the distribution center and arrives at the optimal launching point after being launched from the truck for cargo distribution and then returns to the truck. The optimal launching point of UAV is determined by k-means algorithm, and the truck path is optimized by genetic algorithm. Chang et al. [11] further shortened the total delivery time by transferring clustering centers after applying k-means clustering algorithm and optimizing truck routing.

To sum up, the collaborative delivery of drones and trucks is a hot research topic in recent years. In the series distribution system of cooperative delivery of trucks and drones based on k-means clustering algorithm, the traditional k-means algorithm is not necessarily accurate in determining the number of clustering. Therefore, this paper first determines the optimal number of clustering, and then determines the temporary parking points of trucks by k-means algorithm. Moreover, urban customers are highly sensitive to time, so this paper establishes a collaborative delivery of trucks and drones under the constraints of UAV mileage, customer time window, etc., and drones can be launched for multiple times. A mixed integer programming model aiming at the lowest total distribution cost. The model of truck and UAV collaborative distribution problem is further applied to the analysis of examples to verify.

2. Problem description

Due to the high sensitivity of urban customers to the arrival time of goods, the customer time window is of great significance to the improvement of the operation and service quality of express delivery companies. Traditional truck distribution cannot be efficiently completed. In order to effectively solve the problem of urban distribution, considering the advantages of UAV over traditional vehicles, this paper proposes a collaborative delivery mode of truck and UAV based on the customer time window to reduce the distribution cost.

The cooperative delivery mode of trucks and drones is shown in Figure 1. First, the optimal clustering points are determined, and then the optimal temporary stopping point of trucks is calculated by k-means algorithm. Then, the optimal route from the distribution center to several temporary stopping points is calculated by genetic algorithm. The truck carries one or more unmanned aerial vehicles (UAVs) from the distribution center and travels along the pre-planned route. When it arrives at a temporary stopping point, the UAVs carry several packages and start to deliver them. The truck waits for the delivery of the UAVs to return to the truck, and then travels to the next stopping point and returns to the distribution center after all the packages are delivered. Due to the added time window, there is a sequence of drone deliveries at each docking point.

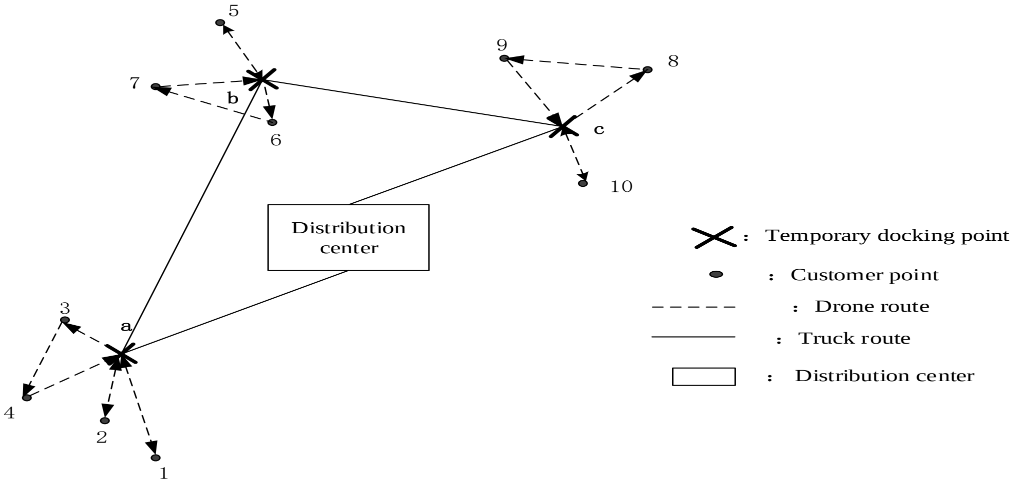

Fig. 1 Collaborative delivery mode of truck and drone

3. Drone and truck cooperative distribution optimization model

3.1. Basic assumption

a. Only one distribution center

b. There's a van and a drone

c. Irrespective of the volume of goods

d. The UAV adopts replacement lithium battery, the replacement time is ignored, and it will be fully charged once it returns to the docking point

e. Regardless of the time spent serving customers

f. The drone will start delivery as soon as the truck arrives at the docking point, regardless of the time the drone takes off and lands

g. Truck load is large enough that one truck can meet the needs of all customer points

h. Drones can transport multiple packages at once

i. Both the drone and the truck are running at a constant speed

j. The cost of carrying a drone in a truck is not considered

3.2. Symbol specification

K is the number of stopping points,K=1,2... ,k;

P = {1, 2,.. ,k} represents the node of the stopping point;

n_k is the number of customers at the Kth docking point, i=1,2... ,;

P_0 ={0,1,2,...,k,k+1} represents all traveling nodes of the truck; {0} and {k+1} represent distribution centers; the truck starts from 0 and returns to k+1;

N_k ={0,1,2,3,..., n_k} represents all flight nodes of UAV in the Kth stopping point, and {0} represents the k stopping point;

D_k represents the UAV voyage set in k docking points, D_k=1,2... ,m;

M is an infinite number;

d_{ij} represents the driving distance of the truck from stopping point i to stopping point j;

l_{kij} represents the flight distance of UAV from node i to node j in the KTH docking point;

V_t represents the average speed of the freight car;

V_d represents the average traveling speed of UAV;

q_i represents the demand of customer points;

C_1 represents labor cost per unit time;

C_2 represents the unit flight cost of UAV;
C_3 represents the unit driving cost of the truck;
D_t represents the maximum mileage of the truck;
D_d represents the maximum range of UAV;
α represents the penalty coefficient of UAV arriving later;
a_i represents the latest service time agreed for customer i;

$$x_{kij}^{d}\begin{cases}1\ In\ the\ K\text{th}\ docking\ point, the\ UAV\ of\ flight\ d\ goes\ from\ node\ i\ to\ node\ j\\ \quad 0 \qquad\qquad\qquad\qquad\qquad\qquad Or\end{cases} \qquad i,j\in N_k;$$

$$y_{ij}\begin{cases}1\ \text{The}The\ truck\ runs\ from\ stop\ i\ to\ stop\ j\\ \quad 0 \qquad\qquad\qquad Or\end{cases} i,j\in P_0;$$

$\mathrm{t}_{\mathrm{ki}}^{\mathrm{d}}$ represents the time when the UAV arrives at customer i for the flight d at the Kth docking point;

$\mathrm{t}_{\mathrm{k}}^{\mathrm{d-1}}$ represents the time when the UAV returns to the stopping point k on voyage d−1, where represents the time when the UAV arrives at the stopping point k just from the previous stopping point with the truck.

$\mathrm{t}_{\mathrm{k0i}}^{\mathrm{d}}$ represents the flight time of the UAV from the stop point k to customer i in the flight d at the stop point k;

t_{k} represents the time for the UAV to leave the docking point k with the truck;

$\mathrm{t}_{\mathrm{kij}}$ refers to the total delivery time of UAV at the docking point k, which is also the waiting time of truck driver;

t_{ij} represents the travel time of the truck from stopping point i to stopping point j.

3.3. Model building

3.3.1. Objective function

$$minC = C_1\left(\sum_{i=0}^{k}\sum_{j=1}^{k+1}\frac{y_{ij}d_{ij}}{V_t}+\sum_{k=1}^{K}\sum_{i=0}^{n_k}\sum_{j=0}^{n_k}\sum_{d=1}^{m}\frac{x_{kij}^{d}l_{kij}}{V_d}\right)+ C_2\sum_{k=1}^{K}\sum_{i=0}^{n_k}\sum_{j=0}^{n_k}\sum_{d=1}^{m}x_{kij}^{d}l_{kij}+C_3\sum_{i=0}^{k}\sum_{j=1}^{k+1}y_{ij}d_{ij}+\sum_{k=1}^{K}\sum_{i=1}^{n_k}\sum_{d=1}^{m}\alpha max\{t_{ki}^{d}-a_i,0\} \tag{1}$$

Objective function (1) represents the lowest total cost for truck and drone to deliver all packages together and return to the distribution center, including labor cost of truck driver, flight cost of UAV, driving cost of truck and penalty cost of late delivery of UAV.

3.3.2. Constraint condition

$$\sum_{j=1}^{k+1}y_{0j}=\sum_{i=0}^{k}y_{i,k+1}=1 \tag{2}$$

$$\sum_{j=0}^{n_k}x_{k0j}^{d}=\sum_{i=0}^{n_k}x_{ki0}^{d}=1 \tag{3}$$

$$\sum_{j=1}^{n_k}x_{kij}^{d}=1 \tag{4}$$

$$\sum_{d=1}^{m}x_{kij}^{d}l_{kij}\le D_d \tag{5}$$

$$\sum_{i=0}^{k}\sum_{j=1}^{k+1}y_{ij}d_{ij}\le M \tag{6}$$

$$x_{kij}^{d}=\{0,1\},\forall k\in P,\forall i\in N_k,\forall j\in N_k \tag{7}$$

$$y_{ij}=\{0,1\},\forall i\in P_0,\forall j\in P_0 \tag{8}$$

$$t_k^{d-1}+t_{k0j}^{d}=t_{ki}^{d} \tag{9}$$

$$t_k-t_k^0=t_{kij} \tag{10}$$

$$t_{k-1}^{0}+t_{ij}=t_k^0 \tag{11}$$

indicates that the truck starts from the distribution point and returns to the distribution point; (3) indicates that the UAV starts from and returns to the stopping point; (4) means that all customers are served and served only once; (5) indicates that the flight distance of UAV in each voyage does not exceed the maximum range of UAV; (6) means that the driving distance of the truck does not exceed the maximum mileage; (7) represents the value range of decision variables; (8) represents the value range of decision variables; (9) Service time window of UAV; (10) represents the total service time of UAV at the docking point k; (11) represents the service time window of the truck.

4. Algorithm design

4.1. K-means algorithm

K-means algorithm is an iterative clustering analysis algorithm. The process involves randomly selecting K objects as the initial clustering center, then calculating the distance between each object and each seed clustering center and assigning each object the nearest clustering center. Cluster centers and the objects assigned to them represent a cluster. For each allocated sample, the cluster center is recalculated based on the existing objects in the cluster. This process is repeated until some termination condition is met.

The traditional K-means clustering algorithm is not necessarily accurate in determining the number of clusters, so this paper first finds the optimal number of clusters and then carries out subsequent calculation. NbClust package in R language is used to determine the optimal number of stops.

4.2. Genetic algorithm

Genetic Algorithm (GA) is a parallel random search algorithm based on natural selection and genetic genetics. It is an effective optimization method to find the global optimal solution without any initialization information. It treats all solutions to a problem as a population, improving the quality of the solution through continuous genetic manipulation such as selection, crossover, and variation.

Genetic algorithms are implemented by python programming.

5. Example verification

5.1. Example data

At present, drones have advantages over traditional vehicles, which can be used for urban distribution of customers with high time sensitivity. Therefore, urban areas of Sichuan Province is chosen as the research area of truck and UAVs collaborative distribution in this paper. There is a truck carrying a drone in this area to deliver goods for 10 customers. The test example data is shown in Table 1. The coordinates of the distribution center are randomly generated. The time window starts from 0. For example, [0,360] means that the latest delivery time is 360 minutes. See Table 2 for the time window known in advance. See Table 3 for specific model parameters.

Table 1 Customer point information

Customer point	Latitude	longitude
1	104.1760	30.6872
2	104.0790	30.5706
3	104.1114	30.6300
4	104.0740	30.6850
5	101.6891	26.5710

6	101.5769	26.5928
7	101.7169	26.5850
8	105.4436	28.9026
9	105.4322	28.8558
10	105.4322	28.8833

Table 2 Customer time window

Customer point	1	2	3	4	5	6	7	8	9	10
Time window	[0,780]	[0,960]	[0,960]	[0,790]	[0,960]	[0,600]	[0,720]	[0,300]	[0,360]	[0,360]

Table 3 Model parameter

Parameters	Parameter value
Payload quantity of cargo (pieces)	10
Customer demand	1
Maximum load of truck (number of pieces)	M
Maximum range of truck (km)	M
Maximum range of UAV (km)	20
Average speed of trucks (km/h)	80
Average speed of UAV (km/h)	100
Driving cost of truck per kilometer (yuan /km)	3.2
Driving cost of UAV per kilometer (yuan /km)	0.18
Labor cost per unit time (yuan /h)	19.2
Penalty parameter (yuan /min)	1.8

5.2. Solving procedure

In the first step, the NbClust package of R language is used to determine the optimal stopping point of the truck, as shown in Figure 2. The optimal clustering number is 3, and the coordinates of the distribution center are generated randomly. Then, the k-means clustering algorithm of R language is used to obtain the optimal stopping point and the position of each customer, as shown in Figure 3. Table 5 shows the information of distribution centers and docking points.

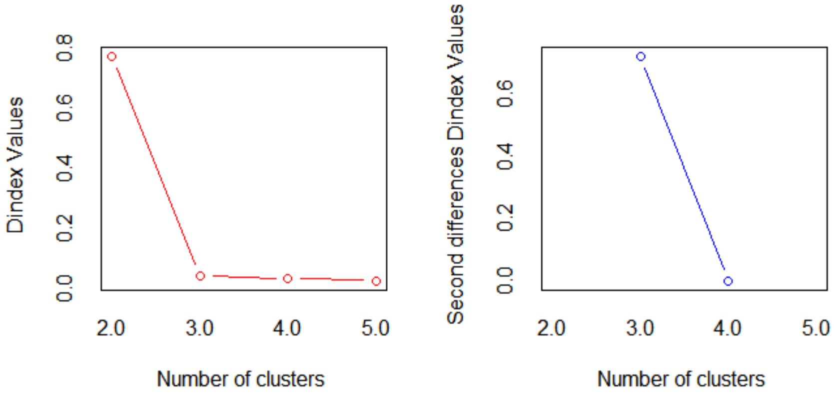

Fig. 2 Optimal number of clusters

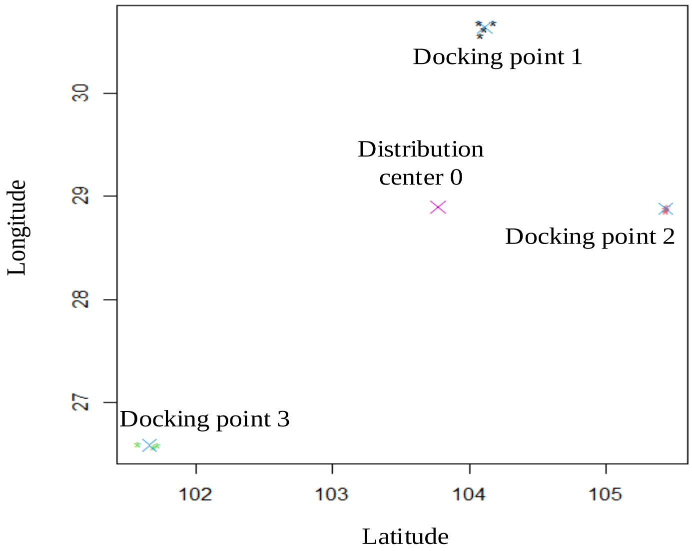

Fig. 3 Optimal docking points and customer locations

Table 4 Distribution center and docking point information

	Latitude	Longitude
Distribution center 0	103.7731	28.8963
Docking point 1	104.1101	30.6432
Docking point 2	105.4360	28.8806
Docking point 3	101.6610	26.5829

Table 5 Customer information of each docking point

Docking point	Customer point
Docking point 3	8
	9
	10
Docking point 2	5
	6
	7
Docking point 1	1
	2
	3
	4

In the second step, genetic algorithm is used to obtain the optimal path of the truck through python programming, and the results are shown in Table 6.

Table 6 Optimal path for truck

Genetic algorithm to figure out the truck route	Distribution point 0→ Docking point 3→ Docking point 2→ Docking point 1→ Distribution point 0
Distance	1207.398km

The third step is to solve the objective function by genetic algorithm. The delivery sequence of UAV at each docking point is shown in Table 7. In order to demonstrate the superiority of cooperative delivery of drones and trucks, the final result is shown in Table 8 after comparison with traditional delivery.

Table 7 Drone delivery sequence

	Docking point 3	Docking point 2	Docking point 1
Delivery sequence	① →10→8 ② →9→	① →6→ ② →5→7→	① →1→ ② →4→ ③ →3→2→

Table 8 Comparison of two transport modes

	Truck path(km)	Drone delivery route(km)	Time(h)	Penalty cost(元)	Cost(元)
Traditional delivery	1246.408	/	15.580	213.249(Late at customer point 6, 8)	4500.892
Coordinated delivery	1207.398	84.629	15.939	17.810(Late at customer's 1, 4)	4202.741

In conclusion, in the collaborative distribution mode, trucks and drones first arrive at docking point 3 from the distribution center. Since there is no conflict between the time Windows of customer points at docking point 3, the delivery order can be changed arbitrarily. However, due to mileage constraints, packages can be delivered to customer 10 and customer 8 together, and they can be delivered to customer 9 after returning to docking point 3. After the delivery is completed at stopping point 3, the drone starts to stop point 2. At stopping point 2, the drone first delivers customer point 6, then customer point 5 and customer point 7. After the delivery is completed, we will continue to stop point 1. Since customer point 1 is late, we will first deliver customer point 1, then customer point 4, and finally deliver the remaining customer points. In the traditional distribution mode, customers are late at 6 and 8 and late for a long time, resulting in more costs. By comparison, the lowest cost of collaborative delivery is 298.151 yuan lower than that of traditional delivery. Collaborative delivery has advantages over traditional delivery, which can effectively reduce the transportation cost.

In order to study the impact of the number of UAVs on the cost of the delivery mode proposed in this paper, the number of UAVs is increased. The results show that increasing the number of drones can not only reduce the delivery time, but also reduce the delivery cost, which is more convenient for customers who have low tolerance for delivery time in urban areas. For example, at docking point 1, the addition of a drone prevents the customer from arriving late at point 4, thus avoiding excess penalty costs. The specific results are shown in Table 9.

Table 9 Distribution planning results of different UAVs

	Truck path(km)	Drone delivery route(km)	Time(h)	Penalty cost(元)	Cost(元)
A drone	1207.398	84.629	15.939	17.810(Late at customer	4202.741

				point 1, 4)	
Two drones	1207.398	84.629	15.606	10.468(Late at customer point 1)	4189.017

6. Conclusion

This paper studies the problem of cooperative delivery between trucks carrying drones based on K-means algorithm and trucks acting as temporary stops of drones. A hybrid integer programming model is established, which considers the mileage constraints of UAS, customer time window and other factors, and aims at the lowest total distribution cost. The results show that this model can effectively complete the logistics transportation task, and can effectively reduce the transportation cost compared with traditional distribution. In economically developed urban areas, customers have high requirements on the arrival time of goods, and delayed delivery will lead to penalty costs. Therefore, the addition of time window plays an important role in improving the service quality of logistics companies. It is also found that increasing the number of UAVs can reduce the excess cost of time window brought to logistics companies.In the future, the algorithm will be improved to further increase the speed in large-scale computation.

References

[1] Pierce. Delivery drones are coming: Jeff bezos promises half-hour shipping with amazon prime air. The Verge December 2013; Available from: https://www.theverge.com/ 2013/12/1/ 5164340 /delivery-drones-are-coming-jeff-bezos-previews-half-hour-shipping.

[2] Zhang. Alibaba tests drone delivery service to overcome domestic logistics hurdles. World Wide Web Technology February 2015; Available from: https://tech.huanqiu.com/article/9CaKrnJHvbo.

[3] Thibbotuwawa, A., et al., Planning deliveries with UAV routing under weather forecast and energy consumption constraints. IFAC-PapersOnLine, 2019. 52(13): p. 820-825.

[4] Song, B.D., K. Park, and J. Kim, Persistent UAV delivery logistics: MILP formulation and efficient heuristic. Computers & Industrial Engineering, 2018. 120: p. 418-428.

[5] Murray, C.C. and A.G. Chu, The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery. Transportation Research Part C: Emerging Technologies, 2015. 54: p. 86-109.

[6] Ha, Q.M., et al., On the min-cost Traveling Salesman Problem with Drone. Transportation Research Part C: Emerging Technologies, 2018. 86: p. 597-621.

[7] Agatz, N., P. Bouman, M. Schmidt..Optimization Approaches for the Traveling Salesman Problem with Drone[J]. Transportation Science, 2018,52(4): 965-981.

[8] Wang, X., S. Poikonen, B. Golden.The vehicle routing problem with drones: several worst-case results[J]. Optimization Letters, 2016,11(4): 679-697.

[9] Mathew, N., S.L. Smith,S.L. Waslander.Planning paths for package delivery in heterogeneous multirobot teams[C]//IEEE.Transactions on Automation Science and Engineering, 2015,12(4): 1298-1308.

[10] Mourelo Ferrandez, S., et al., Optimization of a truck-drone in tandem delivery network using k-means and genetic algorithm. Journal of Industrial Engineering and Management, 2016. 9(2).

[11] Chang, Y.S. and H.J. Lee, Optimal delivery routing with wider drone-delivery areas along a shorter truck-route. Expert Systems with Applications, 2018. 104: p. 307-317.