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Aircraft application with artificial fuzzy heuristic theory via drone

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Abstract. The drone serves the customers not served by vans. At the same time, considering the safety, policy and terrain as well as the need to replace the battery, the drone needs to be transported by truck to the identified station along with the parcel. From each such station, the drone serves a subset of customers according to a direct assignment pattern, i.e., every time the drone is launched, it serves one demand node and returns to the station to collect another parcel. Similarly, the truck is used to transport the drone and cargo between stations. This is somewhat different from the research of other scholars. In terms of the joint distribution of the drone and road vehicle, most scholars will choose the combination of two transportation tools, while we use three. The drone and vans are responsible for distribution services, and the trucks are responsible for transporting the goods and drone to the station. The goal is to optimize the total delivery cost which includes the transportation costs for the vans and the delivery cost for the drone. A fixed cost is also considered for each drone parking site corresponding to the cost of positioning the drone and using the drone station. A discrete optimization model is presented for the problem in addition to a two-phase heuristic algorithm. The results of a series of computational tests performed to assess the applicability of the model and the efficiency of the heuristic are reported. The results obtained show that nearly 10% of the cost can be saved by combining the traditional delivery mode with the use of a drone and drone stations.

Keywords: heuristic algorithm; multiple traveling salesmen problem; unmanned aerial vehicle

1. Introduction

The study of operations research models and methods for problems involving unmanned aerial vehicles (UAVs) has become quite popular in the second decade of the 2000 s.In addition to applications in last-mile delivery operations as we are considering in this paper, we also find applications related to military operations (e.g., surveillance), environmental protection (e.g., fire prevention), agriculture (monitoring of large areas considering factors such as slope and elevation), emergency logistics (pre-screening of damaged areas and roads), etc.

In logistics distribution, the use of drones has become pervasive. The benefits of using UAVs for parcel delivery are nowadays clear: (i) drones are faster and incur lower unit costs; (ii) drones do not require manual operation; (iii) UAVs are not subject to terrain and traffific conditions; (iv)

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there are many environmental benefifits associated with the use of UAVs (as can be seen, e.g., in Figliozzi 2017 and Goodchild and Toy 2018). It is important to note, however, that there are also some shortcomings related to this delivery mode: (i) the carrying capacity of drones is limited the load capacity of ordinary rotor drones usually does not exceed 50 kg; and (ii) for safety reasons, drones can usually only carry one piece of cargo at a time, and the short driving radius of drones requires frequent trips between customer points and warehouses/distribution centers.

On the other hand, traditional delivery modes (e.g., by road) can satisfy several customers using a single route. Moreover, the capacity of a vehicle is of course greater than that of drones. Overall, this mode can benefit from economies of scale although the distribution cost may be higher. A strong disadvantage is that road transportation is susceptible to traffic conditions and terrain obstacles (Chen 2008, Chen 2007, Hsieh 2005, Chen 2010, Zhao *et al.* 2023).

The above considerations make it clear that by combining the two above transportation modes, we can simultaneously take advantage and circumvent the disadvantages of both. Furthermore, we recently observed technological developments motivating the study of problems such as the one we are considering: the industry has conceived vehicles that can carry a drone and act as drone dock-stations to thus position a drone in a more convenient location for supplying a set of delivery orders. This is the case with the new "vans and drones" concept launched by Mercedes-Benz in which the roof of a van is used as a landing platform for drones (Alimoradzadeh *et al.* 2023, Jafari *et al.* 2023, Khosravikhor *et al.* 2023, Al-Jaafari *et al.* 2023, Shih 2012, Shih 2023).

In this paper, we investigated a multi-mode multiple traveling salesman problem motivated by applications in the context of last-mile distribution. We consider the situation in which a classical transportation mode (e.g., a fleet of road vehicles (vans)) is combined with an alternative that has recently emerged as very competitive under certain circumstances, i.e., in this case, the use of an unmanned aerial vehicle (UAV), known more popularly as a drone.

In many cases, the distance between the demand nodes and the depot prevents the use of drones. When a drone is used for distribution, the demand point is often in the suburbs far away from urban areas. For example, during distribution in some mountainous villages, drones may face undertaking operations such as flying around a mountain, so it would be safer for the drone to take off from a local station and return to the station after distribution. Thus, another possibility is to position a drone in previously authorized sites-hereafter called drone stations-from where its use once again becomes a possibility. This course of action can be accomplished using a special vehicle (truck) that carries the drone as well as the parcels that it will deliver. At the same time, trucks can also travel between stations with the drone and parcels. Therefore, it is more reasonable to set up a drone station and deploy drones from the station rather than a moving truck. The drone can also charge at the station (Lee 2012, Lee 2023, Lin 2009, Lin 2013, Liu 2013, Liu 2023, Akbari *et al.* 2023, Aksoylu *et al.* 2023).

Direct assignment is assumed for the demand nodes served by the drone, i.e., the drone visits one demand node each time it returns to the station to collect the parcel in the truck for another demand node (before eventually returning for recharging). When all demand nodes assigned to a drone station are served, the truck may position the drone in another drone station or stay in the station.

In this work, we neglect the capacity of the vehicles and we assume that a unique parcel is to be delivered to each demand node. Hence, the problem we are investigating consists of combining a multiple traveling salesman problem (for the fleet of road-delivery vehicles) with a location-allocation problem (for the drone pre-positioning and delivery). The need for previously identifying potential drone stations is motivated by safety regulations in many countries (e.g., the

Federal Aviation Administration (FAA) in the USA) that prevent drones from being launched from moving vehicles.

The decisions to make in our problem comprise (i) the drone stations to visit by the drone-carrying vehicle; (ii) the assignment of demand nodes to drone stations; and (iii) the routes for serving the demand nodes that will be served by vans. The goal is to minimize the total transportation cost and a fixed cost of using the drone stations.

In this paper, we refer to this distribution method to establish a mathematical model about mTSP-LAP and designed a heuristic algorithm to solve it. Finally, we generated an area and some customer points, verified the effectiveness of our proposed model and algorithm through numerical experiments and performed a sensitivity analysis. The main contributions of this paper include: (1) a new logistics distribution model in which using a drone is proposed and a numerical analysis shows that this distribution model is more efficient in cost; (2) for this distribution model, we propose an integer programming model called mTSP-LAP (multiple traveling salesman problem intertwined with a locationallocation problem); (3) for the mTSP-LAP model, we designed a two-stage heuristic algorithm to solve it (Chandrasekaran *et al.* 2023, Chen *et al.* 2023, Hsu 2013, Kuan 2012, Chen 2013, Cheng 2023).

The remainder of this paper is organized as follows. In Section 2, we review the literature related to our work. In Section 3, we discuss an integer optimization model for the problem. The following section-Section 4-is devoted a heuristic algorithm for the problem. The results of the computational tests performed using the mathematical model and the heuristic algorithm are reported in section 5. The paper ends with an overview of the work achieved herein.

2. System description

We consider a connected network $G=(\{0\} \cup N, A)$ underlying the problem. In $\{0\} \cup N$, node 0 represents the depot and N represents the set of demand nodes. A denotes the set of arcs in the network (direct road connections). For every pair i, j e $\{0\}$ U N, we assume that we can compute the cost for linking those nodes by road (e.g., based upon the shortest path between i and j and the per-unit distance transportation cost).

The following parameters defining our problem are considered:

m, number of vehicles for road delivery (vans);

d, number of drone stations;

p, maximum number of drone stations allowed;

f, fifixed cost of using the drone station;

cr_{ij}, traveling cost between nodes i and j ($i,j \in \{0\} \cup N$);

cd_i^k, transportation cost for satisfying node i by the drone from station k ($i \in N$, $k \in D$).

The problem can be mathematically formulated using the following sets of decision variables:

$$y^k = \begin{cases} 1, if\ drone\ station\ k\ is\ used; \\ 0, otherwise. \end{cases} \quad (k \in D)$$

$$s_i^k = \begin{cases} 1, \text{if node } i \text{ is served by the drone from station } k; \\ 0, \text{otherwise.} \end{cases} \quad (k \in D, i \in N)$$

$$z_i = \begin{cases} 1, \text{if node } i \text{ is served by road vehicle (van);} \\ 0, \text{otherwise.} \end{cases} \quad (i \in N)$$

$$x_{ij}^{v} = \begin{cases} 1, \text{if a road vehicle (van) travels directly from node } i \text{ to node } j \text{ by van } v; \\ 0, \text{otherwise.} \end{cases} \quad (i,j \in \{0\} \cup \mathrm{N})$$

We can finally present the following integer programing model for the mTSP-LAP:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{n} (\sum_{v=1}^{m} x_{ij}^{v}) \cdot cr_{ij} + \sum_{i=1}^{n} \sum_{k=1}^{K} s_i^k cd_i^k + \sum_{k=1}^{K} y^k \cdot f \quad (1)$$

$$\sum_{k=1}^{d} y^k \leq p, \forall k \in D \quad (2)$$

$$s_i^k \leq y^k, \forall \mathrm{i} \in \mathrm{N}, \mathrm{k} \in \mathrm{D} \quad (3)$$

$$\sum_{k=1}^{d} s_i^k + z_i = 1, \forall i \in N \quad (4)$$

$$0 \leq \sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{\mathrm{v}=1}^{\mathrm{m}} \mathrm{x}_{\mathrm{ij}}^{\mathrm{v}} = z_i, \forall j \in N \quad (5)$$

$$0 \leq \sum_{\mathrm{j}=1}^{\mathrm{n}} \sum_{\mathrm{v}=1}^{\mathrm{m}} \mathrm{x}_{\mathrm{ij}}^{\mathrm{v}} = z_i, \forall i \in N \quad (6)$$

$$\sum_{\mathrm{j}=1}^{\mathrm{n}} \sum_{\mathrm{v}=1}^{\mathrm{m}} \mathrm{x}_{0\mathrm{j}}^{\mathrm{v}} = \mathrm{m} \quad (7)$$

$$\sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{\mathrm{v}=1}^{\mathrm{m}} \mathrm{x}_{\mathrm{i}0}^{\mathrm{v}} = \mathrm{m} \quad (8)$$

$$u_i - u_j + n \cdot \sum_{v=1}^{m} \mathrm{x}_{\mathrm{ij}}^{\mathrm{v}} \leq \mathrm{n} - 1, 1 \leq \mathrm{i} \neq \mathrm{j} \leq \mathrm{n} \quad (9)$$

$$s_i^k \in \{0,1\}, \forall i \in N, \forall k \in D \quad (10)$$

$$x_{ij,}^{v} \in \{0,1\}, \forall j \in N \cup j = 0, \forall i \in N \cup i = 0 \quad (11)$$

$$y^k \in \{0,1\}, \forall k \in D \quad (12)$$

$$z_i \in \{0,1\}, \forall i \in N \quad (13)$$

The objective function (1) represents the total cost that includes (i) the cost of using drone stations; (ii) the transportation costs for the road delivery vehicles as well as for the drone-carrying truck; and (iii) the drone delivery cost. Because the construction of the station is a one-time cost, once the station is set up, its subsequent use, maintenance and other costs can be ignored. Therefore, we consider designing a fixed cost for the station. Constraint (2) represents the maximum number of drone stations allowed. Inequality (3) states that if a drone serves a demand node from one station then the station should be operating. Constraint (4) ensures that every demand node is served by exactly one and only one transportation mode (either by van or by drone). Constraint (5)-(6) means that it is only served by the van at both point *i* and point *j*, and there will be a path of van from *i* to *j*. Constraints (7)-(8) indicate that a total of *m* vans depart from the distribution center and return to the distribution center. Constraint (9) is an MTZ constraint, which ensures that there will be no sub-tours in the path of the vans. Constraints (3)-(6) ensure the synchronization of the vans' path planning with drone station selection and drone path planning (Shariati *et al.* 2012, 2016a, b, Shariati *et al.* 2019, 2020d, e, f, g, h, i, j, 2021a, b, Fan *et al.* 2022, Luo *et al.* 2022b, Wang *et al.* 2022a, Xia *et al.* 2022). When planning the path of the vans, it is necessary to prevent the demand point being served by drone. When making drone distribution decisions, it is also necessary to prevent the demand points being served by vans. Finally, (10)-(13) define the domain of the decisions variables.

Remark 1. *The above* problem *contains a TSP as a particular case and thus it is NP-hard.*

Remark 2. *We can relax the* integrality *constraints on the x-variables as well as the upper bound, thus simply writing that*

$$s_i^k \geq 0, i \in N, k \in D.$$

In fact, it is easy to see that *since the y-variables are integer, there is always one optimal* *solution such that the s-variables are also integer.*

Remark 3. *In the above model, we include the fixed cost ofusing the drone station. However, in our algorithmic procedure to be proposed in the next section and when analyzing the results, we start by ignoring this component and use it last as part of a post-optimization analysis.*

Looking at the above model, we easily identify the "location-allocation" component, Constraints (2)-(3); the "mTSP" component, Constraints (5)-(9); and the linking constraints, Constraints (4)-(6). The hardness of the problem together with many data-driven *applications* in which upon collecting the data a solution must be found in a very short time justifies the development of a heuristic algorithm for the problem. In fact, in many real-world last-mile delivery applications (e.g., food delivery), customers expect to be satisfied shortly after calling to be served and thus we cannot afford waiting too long to obtain an optimal solution to the problem. Nevertheless, in Section 5, we reported on some results obtained by solving the above model with an off-the-shelf solver.

3. Algorithm design of adaptive large neighborhood search

Considering the solution constructed in the first phase, we denote by E a set of edges that will be analyzed in this phase to induce improvements in the solution. Initially, this set contains all the direct road links used by the solution. We denote by C_{incumb} the current solution cost. We also define a set T containing all the demand nodes served by a road tour, which is of course equal to N when we start this improvement phase.

Our procedure iteratively attempts to remove nodes from T when a demand node is scheduled to be served by the drone. This is accomplished by selecting the edge

$$\{j^*, \ell^*\} = \underset{\{j, \ell \in \mathrm{E}\}}{\arg\min}\{c_{j\ell}\}$$

and (separately) computing saved cost among the total delivery cost (road and air) from servicing j^* or ℓ^* with the drone (from the closest drone station to each node). We denote by $C_{j^*}$the total delivery cost if j^* is served by air (the Hamiltonian tour for the depot and cluster j^* belongs to is also recomputed-using nearest-neighborhood computation as before). Similarly, we compute C_{ℓ^*}. Finally, we have the savings:

$$\Delta C_{j^*} = C_{incumb} - C_{\ j^*},$$

and:

$$\Delta C_{\ell^*} = C_{incumb} - C_{\ \ell^*},$$

Now, we distinguish three cases for deciding the course of action to take:

Case 1: $\Delta C_{j^*} > \Delta C_{\ell^*}$ and $\Delta C_{j^*} >0$.

In this case, demand node j^* is removed from T since it will be served by the drone (from the closest drone station).

Case 2: $\Delta C_{\ell^*} > \Delta C_{j^*}$ and $\Delta C_{\ell^*} > 0$.

In this case, demand node is removed from T since it will be served by the drone (from the closest drone station).

Case 3: $\Delta C_{j^*} < 0$ and $\Delta C_{\ell^*} < 0$.

In this case, nodes j^* andremain in the initially established road route and the corresponding edge $\{j^*,\ell^*\}$ is removed from the set of edges (E) to be analyzed.

The improvement phase just described is formally detailed in Algorithm 1. In this algorithm, Γ(.) denotes the cluster to which a node belongs to.

4. Algorithm improvement phase

$T \leftarrow J$;
Define E and compute Cincumb;
while $T \neq \emptyset$ and $E \neq \emptyset$ **do**
$\{j^*,\ell^*\} = \underset{\{j,\ell \in E\}}{\arg\min}\{c_{j\ell}\}$
Compute C_{j^*}, C_{ℓ^*}, ΔC_{j^*}, ΔC_{ℓ^*}
if ($\Delta C_{j^*} > \Delta C_{\ell^*}$ **and** $\Delta C_{j^*} > 0$) **then**
$T \leftarrow T \setminus \{j^*\}$.
Recompute the route for the nodes in cluster $\Gamma(j^*)$plus the depot.
else
if ($\Delta C_{\ell^*} >= \Delta C_{j^*}$ **and** $\Delta C_{\ell^*} > 0$) **then**
$T \leftarrow T \setminus \{\ell^*\}$.
Recompute the route for the nodes in cluster $\Gamma(\ell^*)$ plus the depot.
else
if ($\Delta C_{j^*} < 0$ **and** $\Delta C_{\ell^*} < 0$) **then**
$E \leftarrow E \setminus \{j^*,\ell^*\}$ // edge $\{j^*, \ell^*\}$ is not analysed again.
end if
end if
end if
end while

After Algorithm 1 is executed, we find in set $N \setminus T$ the nodes that will be served by the drone (each one from the closest drone station).

5. Numerical experiments

In this section, we report on a series of computational experiments performed to assess the model and algorithm discussed for the mTSP-LAP, We start by describing the test bed instances used and then we discuss the results.

All algorithms were run on Intel Core i5 macOS High Sierra 64-bit mode, with an operating frequency of 2.7 GHz and a memory of 8 Gb.

5.1 Test data

To generate the demand nodes, a 20,000×20,000 square was considered with (—10,000, —10,000) as the lower-left corner and (10,000, 10,000) as the upper-right corner.

Initially, 30 instances were generated that were divided into two sets. In the first set (instances 1-15), 50 demand points were randomly positioned in the underlying square. Four drone stations

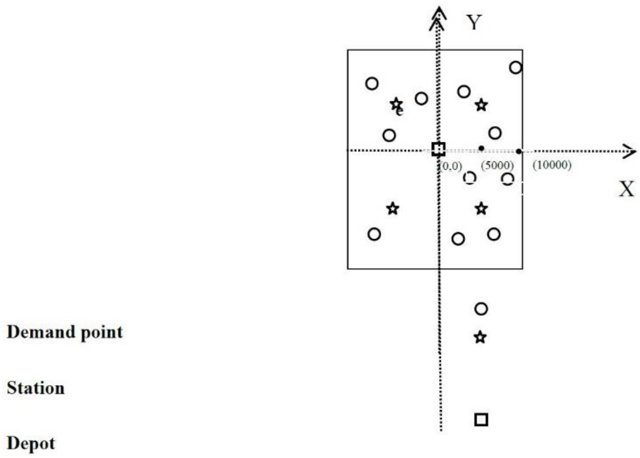

Fig. 2 Schematic diagram of test area

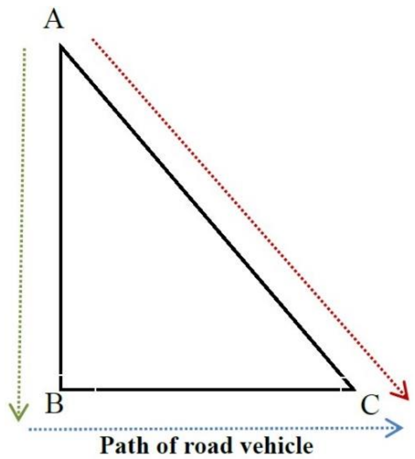

Fig. 3 Different travel distance between the drone and road vehicles with the same starting point and ending point

were assumed, which were positioned in the coordinates (5000, 5000), (—5000, 5000), (5000, —5000), (—5000, —5000). The depot was positioned in the center of the square. Fig. 2 shows a schematic of this area. A fleet with five vans was assumed. The second set of instances (instances 16-30) differ from the above ones by randomly generating 100 demand nodes.

We assume that the drone delivery cost is negatively correlated with the time of delivery (Chaht *et al.* 2015, Zenkour and Abouelregal 2015, Lata and Singh 2019, Pham *et al.* 2021). Pisano and Fuschi (2003). This is accomplished by considering that if the speed of the drone is v times that of the road vehicles, then the delivery cost of the drone for a similar distance is $1/v$ times that of the road vehicles. Due to the fact that the drone can fly in a straight line (which is not the case for the road vehicles which must follow the roads), we assume that the delivery distance of a road vehicle is 1.4 times that of the drone for the same straight-line distance. This is because the distance between two points generally uses Euclidean distance for drone, while road vehicles generally use Manhattan distance. We use an isosceles right triangle to illustrate this problem. As shown in Fig. 3, when moving from point *A* to poϒint *C*, the driving path of the vans is *A* — *B* — *C* and the path of the drone is *A* — *C*. This means that the mileage of the road vehicle is 1.4 times that of the drone.

We first report on the results obtained by the proposed heuristic. At this stage, we ignore the fixed costs for positioning the drone——we only consider the transportation costs (by road and by air). Later, we expand our analysis to consider this aspect. Since the stating step of our heuristic is randomized, we repeated 15 times the procedure for each instance, saving the best solution and the corresponding information.

In Tables 1 and 2, we present the results for the 50-node and 100-node instances, respectively. In these tables, the first column specifies the instance. The following six columns indicate how the demand nodes were distributed among the road vehicles (*Nv*) and the drone (*Nd*). The column headed with *Cv* indicates the total transportation cost associated with the fleet of road vehicles and *Cd* is the total delivery cost for the drone. *Ct* is just the sum of the previous costs, i.e., the total delivery cost. *Ct1* is the total transportation cost for the first-phase solution. Finally, the last column contains the CPU time required to obtain the reported solution.

By observing Tables 1-3, we conclude that the initial solution obtained without considering the drone is improved in the second phase, indicating a clear benefit from using this alternative transportation mode. -*CT Ct* can be regarded as the system cost after adding the drone, and -*CT*1 *Ct*1 is the cost before adding the drone. Through calculation, it can be seen that when the number of demand points is 50,100 and 200, the cost is reduced by 12.96%, 7.16% and 8.49% due to the addition of drone, respectively. This means that the drone can bring incur cost savings of approximately 10%.

Observing the above tables, we also realize that the proposed heuristic approach quickly leads to a feasible solution within 2s (for the tested instances). This is relevant in modern logistics systems when decisions need to be made quickly upon receiving a set of customer orders.

Table 1 Heuristic solutions for the 50-node instances

Instance	*Nv*					*Nd*	*Cv*	*Cd*	*Ct*	*Ct1*	CPU (s)
	*Nv*1	*Nv*2	*Nv3*	*Nv*4	*Nv*5						
1	10	9	8	6	6	11	113,637	20,655	134292	163,650	1.31
2	12	9	9	4	10	6	153,414	13,086	166,501	182,622	1.23
3	9	9	4	15	5	8	139,848	15,283	155,132	180,062	1.42
4	13	7	6	7	9	8	127,088	11,190	138,278	166313	1.41
5	12	12	6	6	5	9	138,987	15,635	154,622	166,009	1.55
6	6	3	6	10	8	17	127,795	29,041	156,837	181,797	1.29
7	10	10	8	8	7	7	142,539	16,719	159,259	184,302	1.25
8	10	3	9	7	9	12	117,422	23,193	140,615	172,407	1.15
9	6	13	10	10	5	6	147,096	10,279	157,375	170,333	1.32
10	9	13	6	9	7	6	150,527	7,575	158,102	170,034	1.21
11	13	8	9	5	7	8	135,932	15,251	151,184	169,927	1.26
12	11	6	5	5	6	17	112,826	28,315	141,141	168,378	1.18
13	10	6	6	6	6	16	119,485	28,029	147,514	180,686	1.22
14	10	7	7	9	9	8	122,340	11,128	133,469	150,187	1.21
15	12	9	10	6	6	7	135,406	14,953	150,360	166,765	1.24

Table 2 Heuristic solutions for the 100-node instances

Instance	*Nv*					*Nd*	*Cv*	*Cd*	*Ct*	*Ct*1	CPU (s)
	*Nv*1	*Nv*2	*Nv3*	*Nv*4	*Nv*5						
16	17	23	16	17	18	9	198,811	17,094	215,906	229,946	1.46
17	21	15	17	18	16	13	189,731	21,345	211,076	227,679	1.54
18	19	13	25	15	14	14	184,557	25,328	209,886	235,061	1.52
19	25	17	16	18	15	9	192,922	14,741	207,664	216,955	1.39
20	24	17	19	17	12	11	181,101	18,086	199,188	221,455	1.34
21	16	21	18	18	18	9	201,996	18,845	220,841	234,924	1.38
22	27	15	15	11	24	8	184,406	14,446	198,853	212,975	1.34
23	19	22	21	16	16	6	197,820	8,836	206,656	215,279	1.38
24	29	17	12	17	14	11	186,802	21,234	208,036	222,414	1.24
25	16	19	17	18	19	11	183,013	17,503	20,0516	216,542	1.31
26	19	21	16	17	13	14	205,168	22,882	228,051	238,546	1.30
27	25	11	24	14	15	11	189,285	16,857	206,143	215,230	1.36
28	19	23	19	14	14	11	189,143	23,237	212,381	246,054	1.39
29	17	23	16	17	18	9	198,811	17,094	215,906	229,946	1.41
30	21	15	17	18	16	13	189,731	21,345	211,076	227,679	1.37

Table 3 Heuristic solutions for the 200-node instances

Instance	*Nv*					*Nd*	*Cv*	*Cd*	*Ct*	*Ct1*	CPU (s)
	*Nv*1	*Nv*2	*Nv*3	*Nv*4	*Nv*5						
31	35	34	45	33	35	18	254,266	19,018	273,284	290,939	1.485
32	33	39	39	45	24	20	259,140	19,354	278,495	305,646	1.597
33	30	46	29	37	34	24	257,069	24,542	281,611	306,607	1.572
34	36	34	32	35	41	22	252,711	25,386	278,098	310,107	1.382
35	38	37	27	41	41	16	281,079	16,447	297,527	321,781	1.119
36	44	39	31	37	34	15	274,188	16,896	291,085	313,768	1.046
37	33	40	20	29	43	26	236,098	30,817	266,915	297,613	1.147
38	33	38	43	31	37	18	269,573	21,984	291,557	310,474	1.082
39	36	30	30	48	38	18	277,145	17,011	294,156	303,216	0.952
40	27	45	29	38	37	24	248,671	22,406	271,077	298,525	1.018
41	30	42	36	28	46	18	247,344	22,877	270,222	286,188	0.967
42	34	39	29	40	34	24	250,964	27,014	277,978	307,722	1.173
43	36	26	43	37	44	14	238,983	16,440	255,424	291,446	1.073
44	35	43	30	29	41	22	255,351	21,349	276,701	311,830	0.992
45	26	39	41	35	40	19	257,140	17,030	274,171	310,330	0.947

For a small number of demand nodes, our problem can be solved up to proven optimality using a general-purpose solver. This fact allows us to assess the quality of our heuristic for at least a few small instances. We considered the MIP solver of IBM ILOG CPLEX release 12.10. Unfortunately, the instances presented in Section 5.1 are too large for the plain use of a general solver. For this reason, we used the same methodology as before to generate a few smaller instances: we generated instances with 12, 15 and 20 demand nodes. Five instances were generated

Table 4 Result comparison of the CPLEX and heuristic algorithm

# Nodes	Instance	CPLEX		Heuristic		Gap (%)
		Time (s)	Obj. Value	Time (s)	Obj. Value	
12	1	0.31	43,678	0.14	46,223	5.51%
	2	0.43	57,828	0.57	63,184	8.48%
	3	3.69	41,913	0.54	46,655	10.16%
	4	0.58	40,998	0.59	41,591	1.43%
	5	1.32	41,385	0.64	48,051	13.87%
					Average	7.89%
15	6	5.19	69,049	0.69	77,102	10.44%
	7	3.92	62,492	0.56	67,288	7.13%
	8	6.56	54,857	0.59	60,906	9.93%
	9	5.06	68,510	0.62	72,492	5.49%
	10	4.79	63,735	0.61	72,446	12.02%
					Average	9.00%
20	11	42.15	71931	0.62	82,284	12.58%
	12	51.34	58,409	0.65	61,231	4.61%
	13	63.60	72,075	0.59	77,574	7.09%
	14	86.03	74,872	0.62	81,916	8.60%
	15	75.34	66,668	0.56	75,224	11.37%
					Average	8.85%

Table 5 Result comparison with the closest related studies in the literature

Work	Transportation Mode	Algorithm	|N|	CPU Time (s)
Yurek *et al.* (2018)	1 van | 1 drone	Approximate	12	760
Kitjacharoenchai *et al.* (2019)	5 vans | 1 drone	Approximate	50	105
Gambella *et al.* (2018)	1 ship | 1 helicopter	Exact	11	2
Current paper	5 vans | 1 truck+drone	Approximate	100	2

in each case. In all cases, two drone stations were assumed.

In Table 4, we present the obtained results. Observing this table, we see that as the number of nodes grows, the CPU time required by the solver significantly increases. In terms of the quality of the solutions provided by the heuristic, we observe that an average percentage gap of 7.89%, 9.00% and 8.85% was obtained for 12-, 15- and 20-node instances, respectively. Although the above values are high, we note that the solution time of the heuristic algorithm does not significantly increase with the increase in the scale of customer points, and the accuracy does not decrease. This means that in reality, when there are large-scale packages to be processed, calculation does not require a significant amount of time, which increases the time for service and improves customer satisfaction.

In Table 5, we provide some information allowing a comparison between our work and those most closely related in the literature. Because this paper is different from the research of other scholars in terms of the use mode of drone, it is difficult to compare the accuracy of each algorithm, so we can only compare the performance of the algorithm in time efficiency. We recall that the TSP-D model proposed by Yurek *et al.* (2018) includes a road vehicle and a drone. The

Table 6 Additional insights: the role of |S|

Instance	|*N*|	|*S*|	*Nd*	*Cv*	*Cd*	*Ct*	*Ct*1
1			18	179,930	24,618	204,548	234,137
2			16	181,540	18,767	200,308	230,217
3	100	8	16	158,448	25,871	184,319	204,171
4			20	161,082	24,490	185,573	227,783
5			16	183,349	19,282	202,631	222,207
6			9	178,341	19,156	197,497	230,574
7			10	208,044	14,450	222,495	231,871
8	100	4	16	174,369	24,145	198,514	214,577
9			13	184,023	21,512	205,535	230,024
10			13	198,390	22,337	220,727	244,474
11			11	142,226	21,929	164,156	190,179
12			7	138,284	12,024	150,309	177,649
13	50	4	9	144,913	15,579	160,492	181,440
14			8	139,571	13,315	152,886	162,157
15			9	150,660	18,316	168,976	191,979
16			2	155,314	2,309	157,624	160,250
17			4	134,223	8,391	142,615	152,921
18	50	2	9	135,037	20,709	155,747	171,207
19			5	142,300	11,157	153,457	166,087
20			6	130,233	16,194	146,427	159,687

Table 7 Impact of drone versus road vehicle speed

Instance	*Vd* : *Vv*	*Nd*	*Cv*	*Cd*	*Ct*	*Ct*1
1	2	22	169,475	27,702	197,178	234,272
2	2	17	163,546	21,538	185,084	215,305
3	2	23	185,330	27,716	213,047	248,834
4	2	20	168,813	27,685	196,498	228,232
5	2	26	158,925	27,952	186,878	241,791
6	1.5	13	201,063	21,331	222,394	244,888
7	1.5	14	190,563	16,394	206,958	226,255
8	1.5	16	177,214	24,367	201,582	228,749
9	1.5	11	200,534	23,542	224,076	244,735
10	1.5	12	178,668	19,868	198,536	234,980
11	1	5	203,664	11,901	215,565	216,547
12	1	5	193,208	14,761	207,969	222,553
13	1	7	197,116	18,978	216,094	238,438
14	1	5	200,120	8,610	208,731	216,657
15	1	5	203,085	7,615	210,701	225,908

results presented in that work indicate that the heuristic proposed by those authors tackles instances with up to 12 customer points within a reported CPU time of 760*s*. In the MTSP-D problem investigated by Kitjacharoenchai *et al.* (2019), there are multiple road vehicles and a drone. The authors reported that the heuristic they proposed finds feasible solutions for instances with 5 vehicles, 1 UAV and 50 demand nodes within 105.1*s*. Finally, the capacitated vehicle routing problem studied by Gambella *et al.* (2018) involves one helicopter docked on a ship. This is a problem in which the function of the helicopter is similar to that of the drone in our work, which explains why we also quote that paper. The authors designed an exact algorithm that can solve instances with up to 11 demand nodes within 2.15*s*.

5.3 Additional insights

In this section, we provide some additional insights into the results. First, we investigated the impact of the number of drone stations and their cost. Afterwards, we discussed the role of the drone speed.

5.3.1 Number of drone stations

To investigate the impact of the number of drone stations on the results, we designed two additional trials. In the first one, we fixed the number of demand nodes (*N*) at 100, and considered 8 and 4 stations (*S*). In the second trial, we fixed the number of demand nodes at 50, and assumed 4 and 2 stations. The remaining parameters were obtained as explained in Section 5.1.

The results can be observed in Table 6. When the number of drone stations increases, the drone usage also increases. This is explained by the reduction in the travel distance between the drone and the demand nodes when more stations are available. In turn, this helps reduce the delivery cost.

Thus far, we ignored the fixed cost of using the drone stations. The results we obtained thus far help us analyze this cost component. If the fixed cost of using a drone station is too high then the savings obtained by using the drone can easily vanish. The results in Table 6 help us to foresee what are reasonable costs for the stations that compensate their use. For instance, considering instance 8, we see that the estimated reduction obtained in the total transportation cost by using the drone vanishes for a fixed station cost slightly above 4000.

5.3.2 The impact of the drone speed

One assumption we made when generating the test bed data was that the drone delivery cost is negatively related to the delivery time. For this reason, it is relevant to investigate the impact on the results of the relation between the drone speed and the van speed. For this purpose, three sets of controlled trials were designed. In the first set, the speed of the drone is set to 200% of the van's speed (instances 1–5); in the second set trials,the unit cost of the drone is set to 150% of the van's unit cost (instances 6–10); fifinally,for the third set, we assume that the speed of the drone and van are the same (instances11–15). The number of demand nodes was fifixed equal to 50 and four drone stations were considered. The results are summarized in Table 7. In this table, the column headed with *Vd:Vv* contains the ratio between the speed of the drone and that of the van.

Observing the results, we conclude that when the speed of the drone is 200% the speed of the van, the use of the drone leads to a signifificant decrease in the total transportation cost—whilst the number of demand nodes visited by the drone increases signifificantly. In this case, we also observe that the negative correlation assumed between the delivery cost and the delivery time leads to a total cost reduction of approximately 20%. Fig. 4 shows the fuzzy diagram for detection.

When the speed of the drone is 150% more than that of the van, the number of demand nodes visited by the drone is approximately equal to ten, and the cost of the entire distribution system is reduced by approximately 10%.

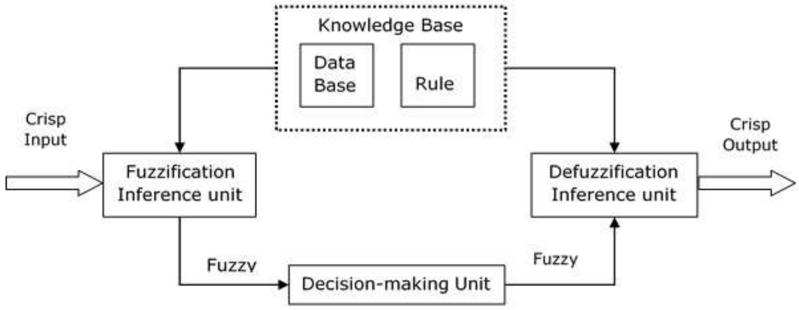

Fig. 4 fuzzy diagram for detection

Finally, we can hardly see a significant reduction in the total delivery time when the drone and the van have similar speeds. This is an indication that when the van is not much affected by traffic congestion, it may compensate to use it more intensely, which is of course encouraged by the economies of scale associated with road delivery.

6. Conclusions

In this paper, a multiple traveling salesman problem was combined with a locationallocation problem in the context of a multi-mode last-mile logistics distribution system. The contributions of this paper include: (1) A traditional delivery mode making use of a set of road vehicles (vans) was combined with the use of a drone. Considering some factors, instead of directly deploying the drone from the road vehicle, we used trucks to transport the drones and parcels to the preset station and then the drone was sent to the customer service point. Trucks thus move between the stations with drones. (2) An integer programming model was proposed for the problem. In the model, we fully consider the synchronization of the drone and vans' path planning. (3) A two-phase heuristic algorithm was also developed for finding feasible solutions to the problem in a short time. In the algorithm, according to the mechanism framework of cost saving, we can achieve the ideal result by exchanging the way that demand points are served (by drone or vans).

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