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Research on Emergency Supplies Distribution Based on Improved Simulated Annealing Algorithm

Chao Feng, Zihan Zhang, Linyuan Xie, Wengang Chen*

Department of Electrical and Electronic Engineering, Shandong University of Technology, Zibo, Shandong, 255000, China
**Corresponding author: 1727194685@qq.com*

Abstract: *With the improvement of technology and the popularization of 5G network, the use of UAVs is becoming more and more widespread, and the delivery mode of "delivery vehicle + UAV" has become a new and effective delivery mode in the event of an accident. It is very important to use the joint delivery of "delivery vehicle + UAV" to deliver emergency supplies to the designated location in the shortest time possible in case of accidents. In this paper, we focus on the optimization strategy of the distribution mode under the condition of the known distance of the distribution location and other information, and make the optimal distribution route plan and select the optimal starting point according to the known data, so as to improve the efficiency of the distribution of emergency materials. First of all, we adopt the mode of single-truck distribution and solve for the minimum distance in the case of single-truck distribution. On this basis, the transport path of the transport vehicle is solved by using a transport vehicle with an unmanned aerial vehicle to assist in distribution, with other conditions remaining unchanged.*

Keywords: *Minimum Spanning Tree Method; Simulated Annealing; Genetic Algorithm; Optimal Distribution*

1. Introduction

Along with the improvement of technology and the gradual popularization of 5G network, the application of UAVs is becoming more and more widespread, and the distribution mode of "delivery vehicle + UAV" has gradually become a new and effective distribution method. Trucks play an important role in the logistics and distribution process because of their large carrying capacity and wide range of action, but they have low response efficiency in some special scenarios due to poor safety, low accessibility and poor flexibility. With the development of UAV technology and the continuous improvement of the regulatory system, the application of UAVs in the field of emergency response has been explored at home and abroad, but the application of UAVs in the process of logistics and distribution is still limited due to the limitations of their load weight and range[1]. Considering the differences between trucks and UAVs in terms of safety, accessibility and flexibility and their respective characteristics, truck-UAV collaborative applications have gradually become a research hotspot, covering various fields including logistics and distribution, agricultural information collection, catastrophic event response and humanitarian logistics. At the same time, scholars at home and abroad have conducted in-depth discussions on truck-UAV collaborative strategies and collaborative scheduling optimization algorithms, which provide solid basic theoretical and methodological support for the application of truck-UAV systems in reality.

2. Assumptions and notations

2.1 Assumptions

We use the following assumptions.

1) Assume that the 5G network can cover the entire distribution area before the distribution of emergency supplies.

2) Assume that each emergency material concentration location is limited to one distribution vehicle and can only carry one UAV.

3) Assuming that in the distribution process, the time of loading and unloading materials of

distribution vehicles and UAVs and the residence time of distribution vehicles and UAVs in each distribution point is negligible.

4) The maximum weight and maximum range of the UAV are known, and the UAV can serve more than one customer point at a time under the condition that the restrictions are met.

5) The range limit of the vehicle is not considered.

6) The UAV is required to return to the vehicle for pickup and battery replacement after each delivery.

7) Disregarding the service time of the customer point and the pickup and battery replacement time of the UAV

8) Carry enough power for the UAV on the vehicle.

2.2 Notations

The primary notations used in this paper are listed as Table 1.

Table 1: Notations

Parameters	Meaning
S_1	The set of nodes S1=1,2,···,n,n+1, where n is the number of distribution points and n+1 is the initial distribution point
S_2	Set of distribution points, S2=1,2,···,n
S_3	The set of undistributed distribution points, S3= 1,2,···,n
L_m	Collection of delivery points that exceed the maximum load limit for UAVs
L_d	Collection of delivery points whose distances from other delivery points all exceed the maximum flight distance limit of the UAV
P_{start}	UAV take-off point assembly
P_{end}	Collection of UAV recovery points
P_{non}	Non-docking point assembly except for UAV take-off and recovery points
K	Total number of deliveries
n	Total number of distribution points
m_i	Demand for goods at node i
d_{ij}	Euclidean distance from node i to node j
M	The maximum weight of the UAV
D	The maximum flight distance of the UAV
$v^{(u)}$	Average flight speed of UAVs
Z	The sum of the path distance of all nodes after distribution

3. Model building and solving

3.1 Solving for the mode of transport of a single transport vehicle distribution model

3.1.1 Data Processing

Table 2: 1-14 Ground distance relationship matrix (partial)

INF	INF	INF	INF	54
INF	INF	56	INF	18
INF	56	INF	INF	44
INF	INF	INF	INF	INF
54	18	44	INF	INF

The distance relation matrix between places is needed in the minimum spanning tree model, and the distance relation matrix of 1-14 places is obtained from the distance relation transformation according to the distance relation as Table 2.

3.1.2 Model Building

Vertex v_1 indicates the root of the tree (the starting point of distribution)，There are a total of *n* vertices (all locations). The vertex-to-vertex edge weights are denoted by w, When there are no edges between two vertices, the corresponding weights are denoted by INF (a sufficiently large positive real number)[2], $w_{ii} = INF, i = 1, 2, \cdots n$.

Introduce 0-1 variables

$$x_{ij} = \begin{cases} 1，When\ the\ edge\ from\ to\ is\ in\ the\ tree \\ 0，When\ the\ edge\ from\ to\ is\ not\ in\ the\ tree \end{cases} \tag{1}$$

Objective function

$$z = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}x_{ij} \tag{2}$$

The constraints are divided into four categories as follows.

$$\sum_{j=1}^{n} x_{1j} \ge 1 \tag{3}$$

$$\sum_{i=1}^{n} x_{ij} \ge 1, \quad j = 2, \cdots n \tag{4}$$

The above two constraints are necessary but not sufficient, a set of variables needs to be added and then additional constraints.

$$u_1 = 0,\ 1 \le u_i \le n-1,\ \mathrm{i}，\ \mathrm{j} = 1, 2\cdots, \mathrm{n} \tag{5}$$

$$u_i - u_j + nx_{ij} \le n-1, \quad i = 1, 2;\cdot\cdot n \quad j = 1, 2;\cdot\cdot n \tag{6}$$

In summary, the 0-1 integer programming model for the minimum spanning tree problem[5] is as follows:

$$\min z = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}x_{ij} \tag{7}$$

$$\text{s.t.} \begin{cases} \sum_{j=1}^{n} x_{1j} \ge 1 \\ \sum_{i=1}^{n} x_{1j} = 1, \quad j = 2, 3, \cdots n \\ u_1 = 0, \cdot 1 \le u_i \le n-1, \cdot i = 2, 3, \cdots n \\ u_i - u_j + nx_{ij} \le n-1, \quad i = 2, 3, \cdots n, \quad j = 2, 3, \cdots n \\ x_{ij} = 0 \text{ or } 1, \quad \mathrm{i, j} = 1, 2\cdots, \mathrm{n} \end{cases} \tag{8}$$

3.1.3 Model solving

After building the minimum spanning tree model, the distance matrix of locations 1-14 is brought into the model, and the shortest distance is 582 km and the time is 11.64 hours when location 9 is the initial distribution point.

3.2 Minimum distance solution after changing the condition

3.2.1 Data Processing

According to the distance that the transport vehicle can form in places 1-14 and the distance that the UAV can fly, since the two sets of data are placed in the same table and cannot be used, it is necessary to extract the data separately and form a relationship matrix as in Table 3 and Table 4.

Table 3: 1-14 Ground UAV flyable distance matrix (partial)

INF	20	INF	INF	54
20	INF	56	INF	18
INF	56	INF	15	44
INF	INF	15	INF	INF
54	18	44	INF	INF

Table 4: Matrix of distances that can be traveled by 1-14 ground transporters (partial)

INF	INF	INF	INF	54
INF	INF	56	INF	18
INF	56	INF	INF	44
INF	INF	INF	INF	INF
54	18	44	INF	INF

3.2.2 Model Building

Floyd's algorithm.

Step 1 Find the distance matrix

Matrix $A_k = (a_k(i,j))_{n\times n}$, the element in row $_i$ and column j $a_k(i,j)$ denotes the length of the shortest path whose vertex serial number is not greater than k that passes on the path from vertex $_{vi}$ to vertex $_{vj.}$ The calculation is done with the iterative formula[3].

$$a_k(i,j) = \min(a_{k-1}(i,j), a_{k-1}(i,j) + a_{k-1}(k,j) \tag{9}$$

Step 2 Build the path matrix

Path iteration process.

Initially

$$R_0 = 0_{n\times n} \tag{10}$$

The iterative formula is.

$$\backslash R_k = (r_k(i,j))_{n\times n} \tag{11}$$

Among them

$$r_k(i,j) = \begin{pmatrix} k & \text{if} a_{\text{k-1}}(i,j) > a_{k-1}(i,j) + a_{k-1}(k,j) \\ r_{k-1}(i,j) & other \end{pmatrix} \tag{12}$$

until the iteration terminates at k=n.

Step 3 Shortest path finding

If $r_n(i,j) = p_i$, then the point v_{p1} is the vertex v_i to v_j 's middle point of the shortest circuit，Then use the same approach to split the search. then by the point v_i to v_j shortest path is $v_{i,}v_{p1},\cdots v_j$.

Optimization of simulated annealing.

Step 1 Mark special points

For all distribution points, vehicles are available for delivery. Since there is a maximum load limit and a maximum flight distance limit for a single UAV flight, the node that exceeds the maximum load limit of the UAV in all distribution points is marked as Lm; the node that exceeds the maximum flight distance limit of the UAV is marked as Ld. All marked points can be delivered by vehicles only, but the node marked as Lm can be used as a single arrival of the UAV under the condition that the flight distance limit of the UAV is satisfied[6].

$$x_{ij,k}=\begin{cases} 1,\ In\ the\ kth\ delivery\ step,\ the\ UAV\ moves\ from\ node\ i\ to\ node\ j \\ 0,\ In\ the\ kth\ delivery\ step,\ the\ UAV\ does\ not\ move\ from\ node\ i\ to\ node\ j \end{cases} \tag{13}$$

$$y_{ij,k}=\begin{cases} 1,\ In\ the\ kth\ distribution\ step, the\ vehicle\ moves\ from\ node\ i\ to\ node\ j \\ 0,\ In\ the\ kth\ delivery\ step, the\ vehicle\ does\ not\ move\ from\ node\ i\ to\ node\ j \end{cases} \tag{14}$$

$$\sum_{k\in K}\sum_{j\in S_1,\mathrm{i}\neq j} y_{ij,k}=1,\quad \forall i\in L_m\cup L_d \tag{15}$$

$$\sum_{k\in K}\sum_{i\in S_1,\mathrm{i}\neq j} y_{ij,k}=1,\quad \forall j\in L_m\cup L_d \tag{16}$$

$$\sum_{k\in K}\sum_{j\in S_1,\mathrm{i}\neq j} x_{ij,k}=0,\quad \forall i\in L_d \tag{17}$$

$$\sum_{k\in K}\sum_{i\in S_1,\mathrm{i}\neq j} x_{ij,k}=0,\quad \forall j\in L_d \tag{18}$$

$$x_{ij,k}\leq\sum_{k\in K}\sum_{h\in S_1,\mathrm{i}\neq j} y_{hj,k},\forall i\in S_1,\forall j\in L_m,\mathrm{i}\neq j \tag{19}$$

$$0<\sum_{k\in K}\sum_{j\in S_2,\mathrm{i}\neq j} x_{ij,k}+y_{ij,k}\leq 2, i=n+1 \tag{20}$$

$$0<\sum_{k\in K}\sum_{i\in S_2,\mathrm{i}\neq j} x_{ij,k}+y_{ij,k}\leq 2, j=n+1 \tag{21}$$

Among them $n_k^{(t)}\geq 1,\forall k\in K$.

Eq. (14) and Eq. (15) ensure that the marked point must be delivered by the vehicle; Eq. (16) and Eq. (17) indicate that the marked delivery point will not be delivered by the UAV; Eq. (18) ensures that if the UAV flies to the superpoint, the vehicle must go to the superpoint; Eq. (19) and Eq. (20) indicate that the UAV and the vehicle can enter and exit from the initial delivery point alone, or the vehicle can carry the UAV together; Eq. (21) indicates that the vehicle serves at least one delivery point per delivery.

Step 2 Single path planning

Due to the power limitation of the UAV, the UAV is assigned as many delivery points as possible within the radius of the farthest flight distance of the UAV and under the condition that the maximum weight limit of the UAV is satisfied, so as to improve the full load rate and the range utilization of the UAV. For a given flight radius, the maximum number of delivery points that can be served by a UAV in a single delivery is limited, and the end point of a single arrival is recorded after each allocation is completed. The UAV needs to replenish its power after one delivery. The end point recorded by the UAV's single path planning is the end point of the vehicle for this delivery, and as many delivery points are assigned to the vehicle as possible under the premise of meeting the early arrival. Due to the limitation of delivery time, the maximum number of delivery points that the vehicle can serve in a single delivery is limited[4].

$$\max\sum_{i\in S_3,\mathrm{i}\neq j}\sum_{j\in S_3} x_{ij,k}+y_{ij,k},\quad \forall k\in K \tag{22}$$

$$\sum_{i\in S_3,\mathrm{i}\neq j}\sum_{j\in S_3} x_{ij,k}d_{ij}\leq D,\quad \forall k\in K \tag{23}$$

$$\sum_{i\in S_3,\mathrm{i}\neq j}\sum_{j\in S_3} x_{ij,k} m_i d_{ij} \le D \quad \forall k\in K \tag{24}$$

$$\sum_{i\in S_3,\mathrm{i}\neq j} x_{ij,k} \le 1, \quad \forall j\in S_3, \quad k\in K \tag{25}$$

$$\sum_{j\in S_3,\mathrm{i}\neq j} x_{ij,k} \le 1, \quad \forall i\in S_3, \quad k\in K \tag{26}$$

$$\sum_{i\in S_3,\mathrm{i}\neq j} y_{ij,k} \le 1, \quad \forall j\in S_3, \quad k\in K \tag{27}$$

$$\sum_{j\in S_3,\mathrm{i}\neq j} y_{ij,k} \le 1, \quad \forall i\in S_3, \quad k\in K \tag{28}$$

$$S_3 = S_3 - C_k^{(u)} - C_k^{(t)}, \quad \forall k\in K \tag{29}$$

Eq. (33) is maximizing the number of nodes served by a single UAV and vehicle; Eq. (23) ensures that the weight of cargo carried by a single UAV does not exceed the maximum weight of the UAV; Eq. (24) ensures that the total distance of a single UAV delivery does not exceed the maximum flight distance of the UAV; Eq. (25) and Eq. (26) indicate that among all nodes not being delivered, the UAV enters and leaves that node no more than 1 time; Eq. (27) and Equation (28) indicates that among all nodes not being delivered, the vehicle enters and leaves the node no more than 1 time; Equation (29) ensures that after each assignment of a single delivered node, it is removed from the set of nodes not delivered from the previous 1 time.

Step 3 Overall path optimization

Take the end point of the single delivery path record as the starting point of the next delivery path, and repeat Step 2 until all the delivery points are delivered. The delivery distance of vehicles and UAVs is added up, and the shortest total delivery distance is used as the objective function to optimize the path selection for each delivery.

$$\min Z \sum_{k\in K}\sum_{i\in s_1, i\neq j}\sum_{j\in s_1}(x_{ij,k}d_{ij} + \varepsilon y_{ij,k}d_{ij}) \tag{30}$$

$$\sum_{k\in K}\sum_{j\in s_1, i\neq j}(x_{ij,k} + y_{ij,k}) = 1, \forall i\in P_{non} \tag{31}$$

$$\sum_{k\in K}\sum_{j\in s_1, i\neq j}(x_{ij,k} + y_{ij,k}) = 1, \forall j\in P_{non} \tag{32}$$

$$\sum_{k\in K}\sum_{j\in s_1, i\neq j} y_{ij,k} = 1, \forall i\in (P_{start}\cup P_{end}) \tag{33}$$

$$\sum_{k\in K}\sum_{j\in s_1, i\neq j} y_{ij,k} = 1, \forall j\in (P_{start}\cup P_{end}) \tag{34}$$

$$\sum_{k\in K}\sum_{j\in s_1, i\neq j} y_{ij,k} = 1, \forall i\in P_{start} \tag{35}$$

$$\sum_{k\in K}\sum_{j\in s_1, i\neq j} y_{ij,k} = 1, \forall j\in P_{end} \tag{36}$$

$$P_{non}\cup P_{start}\cup P_{end} = S_1 \tag{37}$$

$$P_{start}\cap P_{end} \neq \varnothing \tag{38}$$

$$\sum_{k\in K}\sum_{i\in P_{non},i\neq j} x_{ij,k} = \sum_{k\in K}\sum_{h\in P_{non},j\neq h} x_{jh,k}, \forall j\in P_{non} \tag{39}$$

$$\sum_{k\in K}\sum_{i\in S_1,i\neq j} y_{ij,k} = \sum_{k\in K}\sum_{h\in S_1,j\neq h} y_{ij,k}, \forall j\in S_1 \tag{40}$$

$$x_{ij,k}\in\{0,1\}\forall i\in S_1; j\in S_1; k\in K \tag{41}$$

$$y_{ij,k}\in\{0,1\}\forall i\in S_1; j\in S_1; k\in K \tag{42}$$

The objective function equation (26) is to minimize the total distribution distance of UAVs and vehicles; equation (27) and equation (28) indicate that all non-docking distribution nodes are distributed by UAVs or vehicles only once; equation (29) and equation (30) indicate that vehicles at UAV send and receive nodes enter and exit only once; equation (31) indicates that UAVs at UAV takeoff nodes fly out only once; equation (32) indicates that UAVs at UAV recovery nodes UAVs landing only once; equation (33) and equation (34) ensure that all nodes are fully allocated and the take-off and recovery points of the UAV can be the same node; equation (35) ensures that the UAV is conserved for the non-stopping point access flow; equation (36) ensures that the vehicle is conserved for all nodes access flow; equation (37) and equation (38) give the range of values of the parameters. Eq. (6), Eq. (7), Eq. (39) to Eq. (42) together give the access rules when the initial distribution point is used as the UAV send/receive point or non-docking point, and the UAV can take off from the distribution center for recovery or be carried in and out by the vehicle, and neither the UAV nor the vehicle will visit the initial distribution point again in the middle.

3.2.3 Model solving

Step 1 Setting of control parameters

Step 2 Initial solution generation and encoding

The initial solution is randomly generated by using the coding method of integer arrangement, and each integer corresponds to 1~14 locations, and the distribution center is 9. The initial solution can be divided into several different parts, and each part, i.e., the set of UAV and transportation vehicle paths for different distribution trips. The order of each number determines the distribution order of the corresponding nodes. Starting from the distribution center, each node is added to the distribution path of UAVs and vehicles in order of arrangement, and each node is added to calculate whether the constraint is satisfied, and if the condition is not exceeded, the next node is added until the constraint is exceeded and the customer points are allocated in the next trip. Repeat the allocation k times to get the distribution path of all trips, and combine the order of distribution path of each trip, that is, the total distribution path.

Step 3 Solve the transformation

The current solution is updated by transforming the current solution to generate a new combination of paths. The main exchange rules used in this paper are single-point crossover and 2-opt transformation. The single-point crossover is to randomly generate two integers in the interval [1,14], and transpose the nodes in the middle part of the corresponding positions of the two integers in the current solution. 2-opt is to randomly generate two integers in the interval [1,14], and transpose the nodes in the middle part of the corresponding positions of the two integers in the current solution..

Step 4 Metropolis Guidelines

$$\mu = \begin{cases} 1, Z' < 0 \\ \exp(\frac{-Z'}{T}), Z' > 0 \end{cases} \tag{43}$$

If $Z' < 0$, then accept the new path with probability 1; Otherwise, with probability $\exp(Z'/T)$ acceptance of new paths.

The distance matrix of the UAV and the distance matrix of the transport vehicle are brought into the solution, and the minimum time required to complete the transport is 6.32 hours.

4. Conclusion

Improvements are made on the single-variable intelligent annealing algorithm, because the flight speed of the UAV is greater than that of the car, so as much as possible to make the UAV delivery, while the UAV is limited by the range and load, the car needs to be used as an auxiliary. Therefore changed to a two-level intelligent annealing model, the first level priority UAV delivery, the second level car-assisted delivery, to solve the problem of the range of the UAV and the maximum load problem, in the premise of meeting the completion of the car delivery, the end point of the UAV delivery as the end point of the car single time with the UAV delivery. The method transforms the bivariate of UAV and car delivery into the univariate of the shortest transportation distance of UAV and car within the single duration of no-home, and realizes the application of the bivariate solution optimization method of intelligent annealing algorithm to obtain accurate results.

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