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T1	________________	1919141	F1	________________
T2	________________	Problem Chosen	F2	________________
T3	________________	**B**	F3	________________
T4	________________		F4	________________

2019

MCM/ICM

Summary Sheet

A Disaster Response System For Puerto Rico

In 2017, the United States territory of Puerto Rico was hit by the worst hurricane to ever. HELP, Inc. is trying to use a transportable disaster response system called “***DroneGo***” to improve its response capabilities. What we should do is to establish a system to meet both of the requirements as well as possible.

The first step, considering that the package can rotate, we use the three-dimensional packing model to figure out all the drug combinations that can fit into two kinds of UAV cargo bays.

The second step, we use the analytic hierarchy process to give the comprehensive performance scores of each drone. According to the ranking, we chose ***drone E*** and ***drone B*** to carry out two missions separately. And we give the assembly diagram of the drone fleet.

The third step, the concentric movable circle model is proposed to make the maximum exploration mileage obtained with the need of the medicine delivery satisfied.

The fourth step, according to the problem analysis and algorithm mentioned above, we provide the UAV payload packaging configuration, delivery route and schedule.

The fifth step, we replace the main roads by selecting many points on them, and then use simulated annealing algorithm to draw a road map for traversal of all points within a certain range. Then we get the best route in many simulations.

By solving these problems, we design the disaster response system for the company to improve Puerto Rico's ability to respond to disasters. And we provide a solution or reference for similar situations in the future.

Key words: Three-dimensional packing model, UAV, concentric movable circle model.

1. MEMO

To: HELP, Inc. CEO

From: team 1919141

Date: 29 Jan 2019

Subject: ***DroneGo*** disaster response system

The ***DroneGo*** disaster response system we have designed for you can explore major roads and highways across the island in a short period of time, while meeting the demands of delivering medicine to five hospitals.

When selecting the three locations for the response system, we took into account the island-wide road distribution. We designed the system to cover as many trunk roads as possible.

We have given all feasible combinations of medical packages and ***Drone Cargo Bay***, which can be adjusted according to our Table 3 if the hospital's demand changes. When we designed the method of loading the drone fleet into the container, we prepared an extra ***Drone E*** and a ***Drone Cargo Bay***, which can be used at any time if needed.

Given the fact that the hurricane knocked out almost the entire island's electrical system, we take the drone back to the locations of the ***DroneGo*** disaster response system, so that the cargo ship can take the drone that's out of power to the mainland of the United States to recharge. In this way it only takes twice as many drones to carry out a long cruise. Moreover, no drones will be lost in this way, and the drones can be recycled.

We have scored the performance of all the drones and selected two drones to perform the tasks most suitable for him according to the score. However, if the number of ***drone E or B*** is not enough, you can select the drones with the second highest score according to our table to perform the tasks.

The drone flight plan we gave was for the major highways and roads that you asked for, but we designed the system in such a way that we could detect any other road on the map that was within the range of the bigger circle that we drew in ***problem B***.

Please refer to this memo when the condition of the next disaster changes.

Catalogue

2. Background and problems

Hurricane is a violent storm with very strong winds. In 2017, the United States territory of Puerto Rico was hit by the worst hurricane to ever. Buildings, houses and roads were severely damaged particularly along the east and southeast coast of Puerto Rico. Puerto Rico's 3.4 million residents were losing electrical power due to the fierce wind and heavy rain, which accounted for the collapse of 80 percent of Puerto Rico's utility poles and all transmission lines. The power failure lasted for several months and even longer in some locations. Flooding blocked and damaged many roads and highways, making it hard to work out the plan to let emergency services ground vehicles go to the damaged areas. Medical supplies, lifesaving equipment and treatment demands are difficult to ensure.

HELP, Inc. is a non-governmental organization which is trying to use a transportable disaster response system called "***DroneGo***" to improve its response capabilities. And it will use drones to deliver pre-packaged medical supplies and provide high-resolution aerial video reconnaissance.

The problem to be solved in this paper is selecting appropriate locations and rational combination of a drone fleet and set of medical packages. Then, establish the evaluation index system. Thus, what we should do is to establish a system to meet both of the requirements as well as possible.

3. Assumptions and Justifications

In response to the problems raised in this paper, we make the following model assumptions:

- Assume that the three kinds of emergency medical packages can be seen as cuboids.
- Assume that the area of the island is negligible relative to the area of the earth, which means that the island can be viewed as a plane.

4. Model Establishment and Solution

4.1. The solution to problem A

4.1.1. Three-dimensional bin packing model

4.1.1.1. Problem Analysis

In order to ensure the maximum carrying efficiency of the drones, the drones should carry as many pre-packaged medical supplies as possible under the condition of not exceeding the maximum load of themselves. The packages can be rotated to 6 different directions, which is no longer a normal linear programming problem. Therefore, we establish a three-dimensional packing model to solve this problem. Three-dimensional Packing problem is a traditional NP-hard problem, which has a wide range of applications. Ngoi et al use special spatial representation technology to solve the packing problem. Bischoff et al proposed a heuristic algorithm. Dayong He and others proposed a genetic algorithm to solve the complex container loading problem. We use mixed integer programming to approach the solution.

4.1.1.2. Variable Description

Table 1. Variable Description of Three-dimensional bin packing model

Variable	Definition
(L_n, W_n, H_n, V_n)	Length, width, height and volume of the drone ***cargo bay type n***
v_i	Volume of ***package i***
(x_i, y_i, z_i)	Continuous variables for coordinates of ***package i***'s left-bottom-behind corner
$X_{l_i}, Z_{l_i}, Y_{w_i}, Z_{h_i}$	Binary variables
a_{ij}, b_{ij}, c_{ij}	Binary variables

Addition:

$X_{l_i}, Z_{l_i}, Y_{w_i}, Z_{h_i}$: binary variables indicating whether the length direction of package *i* is parallel to the bin's X and Z axes, the width direction is parallel to the Y axis, or the height direction is parallel to the Z axis, respectively, to determine the orientation of package *i*.

a_{ij}, b_{ij}, c_{ij} : binary variables defining the relative placement of package *i* to package *j*: variables will be 1 if package *i* is in front of, to the right of, or on top of package *j*, respectively; otherwise, 0.

4.1.1.3. Establishment of the model

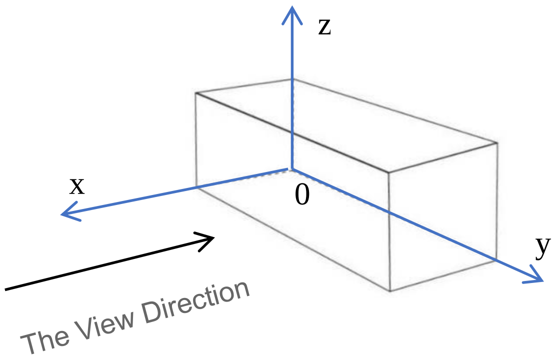

Figure 1

The constraints are as follows:

$$x_i + l_i X_{l_i} + w_i\left(Z_{l_i} - Y_{w_i} + Z_{h_i}\right) + h_i\left(1 - X_{l_i} - Z_{l_i} + Y_{w_i} - Z_{h_i}\right) \le x_j + M\left(1 - a_{ij}\right), i \ne j \quad \text{(1a)}$$

$$y_i + w_i Y_{w_i} + l_i\left(1 - X_{l_i} - Z_{l_i}\right) + h_i\left(X_{l_i} + Z_{l_i} - Y_{w_i}\right) \le y_j + M\left(1 - b_{ij}\right), i \ne j \quad \text{(1b)}$$

$$z_i + h_i Z_{h_i} + w_i\left(1 - Z_{l_i} - Z_{h_i}\right) + l_i Z_{l_i} \le z_j + M\left(1 - c_{ij}\right), i \ne j \quad \text{(1c)}$$

$$x_i + l_i x_i + w_i\left(Z_{l_i} - Y_{w_i} + Z_{h_i}\right) + h_i\left(1 - X_{l_i} - Z_{l_i} + Y_{w_i} - Z_{h_i}\right) \le L, \quad \text{(2a)}$$

$$y_i + w_i Y_{w_i} + l_i\left(1 - X_{l_i} - Z_{l_i}\right) + h_i\left(X_{l_i} + Z_{l_i} - Y_{w_i}\right) \le W. \quad \text{(2b)}$$

$$z_i + h_i Z_{h_i} + w_i\left(1 - Z_{l_i} - Z_{h_i}\right) + l_i Z_{l_i} \le H; \quad \text{(2c)}$$

$$a_{ij} + a_{ji} + b_{ij} + b_{ji} + c_{ij} + c_{ji} \ge 1, i \ne j, \quad \text{(3)}$$

$$X_{l_i} + Z_{l_i} \le 1, \quad \text{(4a)}$$

$$Z_{l_i} + Z_{h_i} \le 1, \quad \text{(4b)}$$

$$Z_{l_i} - Y_{w_i} + Z_{h_i} \le 1, \quad \text{(4c)}$$

$$Z_{l_i} - Y_{w_i} + Z_{h_i} \ge 0, \quad \text{(4d)}$$

$$1 - X_{l_i} - Z_{L_i} + Y_{w_i} - Z_{h_i} \le 1, \quad \text{(4e)}$$

$$1 - X_{l_i} - Z_{L_i} + Y_{w_i} - Z_{h_i} \ge 0, \quad \text{(4f)}$$

$$X_{l_i} + Z_{L_i} - Y_{w_i} \le 1, \quad \text{(4g)}$$

$$X_{l_i} + Z_{L_i} - Y_{w_i} \ge 0. \quad \text{(4h)}$$

Constraints (1) ensure that any two packages *i* and *j* do not overlap with each other. Constraints (2) keep all packages within the drone cargo bay dimension. X_{l_i}, Z_{l_i}, Y_{w_i} and Z_{h_i} are used to calculate the respective mappings of package length, width and height to the corresponding drone cargo bay's X; Y and Z axes. Constraint (3) limits the relative position of any two packages *i* and *j*. Constraints (4) ensure that the binary variables which determine the package position are properly controlled to reflect practical positions.

4.1.1.4. Solution

We get the feasible solution of the above equations:

Table 2. The Type and Number of Drugs the ***Caego bay 1*** can carry

Situation	***MED 1*/number**	***MED 2*/number**	***MED 3*/number**
1	1	0	0
2	0	1	0
3	0	0	1

Table 3. The Type and Number of Drugs the ***Caego bay 2*** can carry

Situation	***MED 1*/number**	***MED 2*/number**	***MED 3*/number**
1	1	0	0
2	0	1	0
3	0	2	0
4	0	3	0
5	0	0	1
6	0	0	2
7	1	1	0
8	1	0	1
9	0	1	1
10	0	2	1

****Annotation***: The two tables above indicate that the type and number of packages the cargo bay can carry in the meantime. For example, ***cargo bay 2*** can carry 2 pieces of ***MED1*** and 1 piece of ***MED2*** at the same time without being overweight.

4.1.2. Comprehensive evaluation of drones based on analytic hierarchy process

4.1.2.1. Problem analysis

In order to satisfy the demand of the delivery of medical package and video reconnaissance of road networks, we use analytic hierarchy process to compare the comprehensive capability of these 7 drones. (We don't think about the ***drone H,*** because its performance is not suitable for this task.)

4.1.2.2. Variable Description

Table 4. Variable Description

Variable	Definition
$(L_{Dk}, W_{Dk}, H_{Dk}, V_{Dk})$	Length, width, height and volume of the ***drone k***
(L_C, W_C, H_C, V_C)	Length, width, height and volume of the Shipping Container

4.1.2.3. Establishment of model

We divide all the influencing factors into three primary factors, each of which contains several secondary factors. The three primary factors are respectively the ability of delivering medical packages (α), the ability of video reconnaissance (β) and portability (γ). The ability of delivering medical packages (α) includes the number of combinations of drones that can carry medicine in cargo bay (α_1), cargo space utilization of drones (α_2) and max payload capability (α_3).According to our calculation, the weight of each drone can realize any combination of medical packages, thus it is meaningless to study this factor.

The ability of video reconnaissance (β) includes two secondary factors: video capable (β_1) and flight mileage (β_2).

In order to maximize the number of drones carried, we proposed portability (γ). After consulting relevant literature, we found that the more similar the shape of the goods' underside is to the shape of the container, the more goods can be loaded by the container. And the smaller the height of the drone is, the more layers container can hold. Therefore we put forward three secondary factors: similarity (γ_1), proportion of height (γ_2) and volume (γ_3).

$$\gamma_1 = \frac{\frac{L_{Dk}}{L_C}}{\frac{W_{Dk}}{W_C}} \tag{5}$$

$$\gamma_2 = \frac{H_{Dk}}{H_C} \tag{6}$$

4.1.2.4. Solution

4.1.2.4.1. Establish judgment matrix and calculate weight

First of all, we divide the importance degree into nine levels from 1 to 9.

Secondly, we construct judgment matrix. Compare the elements in pairs and construct a comparison matrix:

$$B = \begin{bmatrix} B1 & \cdots & Bi \\ \vdots & \ddots & \vdots \\ Bj & \cdots & Bij \end{bmatrix} \tag{7}$$

The composition of the judgment matrix is as follows: firstly, a certain layer of factors in the hierarchical order is given, such as the NTH layer and a factor A_k of its upper layer (n-1). Then, the degree of influence of all factors in the NTH layer on A_k is compared in pairs, and the result of the comparison is written into a matrix table in the form of Numbers, that is, the judgment matrix is formed. B_{ij} is the difference result of importance degree after pairwise comparison.

Thirdly, calculate the weight. We establish the judgment matrixes. P is the judgment matrix of the primary factors. S_α , S_β and S_γ are the judgment matrix of each group of secondary factors.

$$\boldsymbol{P} = \begin{bmatrix} 1, \frac{5}{4}, \frac{5}{2} \\ \frac{4}{5}, 1, 2 \\ \frac{2}{5}, \frac{1}{2}, 1 \end{bmatrix} \quad S_\alpha = \begin{bmatrix} 1, \frac{6}{5} \\ \frac{5}{6}, 1 \end{bmatrix} \quad S_\beta = \begin{bmatrix} 1, \frac{3}{2} \\ \frac{2}{3}, 1 \end{bmatrix} \quad S_\gamma = \begin{bmatrix} 1, \frac{1}{2}, \frac{1}{7} \\ 2, 1, \frac{1}{7} \\ 7, 7, 1 \end{bmatrix} \tag{8}$$

We calculate the weight of the 3 primary factors and 7 secondary factors.

Table 5. The weight of each factor

α_1	α_2	β_1	β_2	γ_1	γ_2	γ_3
0.248	0.207	0.218	0.145	0.0159	0.0253	0.141

4.1.2.4.2. Performance ranking of drone

By referring to relevant materials, we score the performance of each UAV on a percentage scale. The value of each score is multiplied by its corresponding weight and then added. Here is the result.

Table 6. Score of each factor

Type	α	β	γ	Composite scores
A	41.82	88	55.42	61.079346
B	50.91	100	81.4	74.297115
C	86.365	94	46.477	81.8808111
D	53.1825	86	100.01	73.62286425
E	100	86	92.278	93.4957404
F	90.91	32	64.544	64.6878942
G	95.455	86	84.57	90.0287235

On the basis of the Table 6, we take α and γ into consider in the meanwhile to get the comprehensive score of the portability and ability of delivering medicine. And we also do that with β and γ to get the comprehensive score of the portability and ability of video reconnaissance.

Table 7. A composite score of two factors

Drone type	Composite scores of α and γ	Composite scores of β and γ
A	45.70571429	77.14
B	59.62142857	93.7062
C	74.96842857	78.080841
D	66.56178571	90.57933
E	97.79371429	88.004574
F	83.37685714	42.805152
G	92.345	85.43781

4.1.2.4.3. Result

As can be seen from the table, drone E scored the highest in the ability to deliver drugs. The drone B scored the highest on the video reconnaissance. So we choose drones E to deliver medicine packages and B to exploring roads.

Because we only choose E to deliver medicine, the type of cargo compartment used is only 2. According to the table, we use linear programming to solve the minimum number of drones required to complete the drug delivery mission. The number is 8.

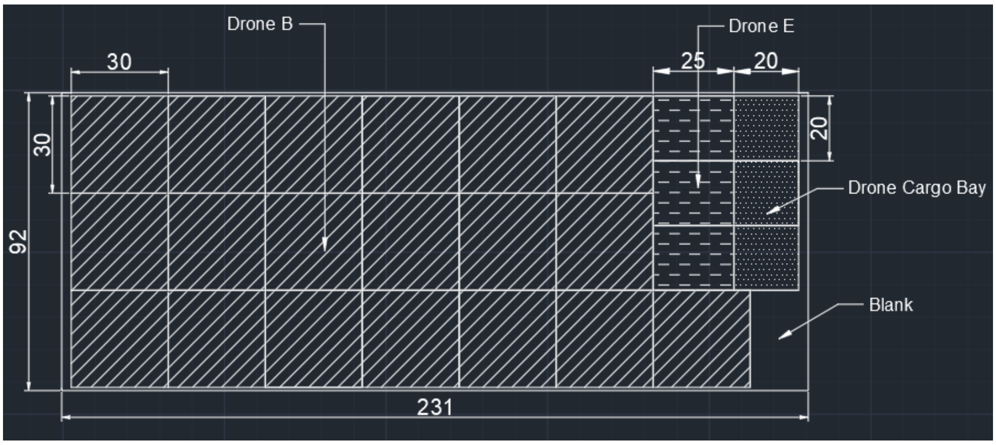

Figure 2

According to the sizes of UAVs, *drone cargo bay 2* and containers, we designed the following packing methods. The figure below is the top view.

The shaded part of the image is the drone or cargo bay of the drone. And buffer materials are filled into the blank area.

After calculation, we find that the structure can be placed up to three layers. This boxed model not only meets the demand for drugs, but also can carry enough *drone B*, which maximizes the exploration range.

Drone Fleet:

drone B: $(3\times6+1)\times3=57$

drone E: $3\times3=9$

Set of Medical Packages:

MED 1: 7 ***MED 2***: 2 ***MED 3***: 4

4.2. The solution to problem B

4.2.1. Use cluster analysis for grouping

4.2.1.1. Variable description

Table 8. Variable description

Variable	Definition
X_i	Longitude of *point i*
Y_i	Latitude of *point i*
x_i	Abscissa of *point i*
y_i	Ordinate of *point i*

4.2.1.2. Establishment of coordinate system

After analyzing the shape of Puerto Rico Island, we simplify it into a rectangular model. We take the point (17.96°,-67.15°) as the bottom left endpoint of the rectangle, and set up the coordinate system at that point.

The conversion formula between abscissa and longitude is:

$$x_i = (X_i + 67.15) \times 111 \times \cos(\frac{17.96\pi}{180}) \tag{9}$$

The conversion formula of ordinate and latitude is:

$$y_i = (Y_i - 17.96) \times 111 \tag{10}$$

Then we find out the corresponding hospital coordinate position in the rectangular model. From left to right, the points of the five hospitals are denoted as M_1, M_2, M_3, M_4 and M_5 in turns. The red dots on the road map and the white dots on the simplified map indicate the location of the hospital. And we approximate the island's main highways as a network of magenta lines.

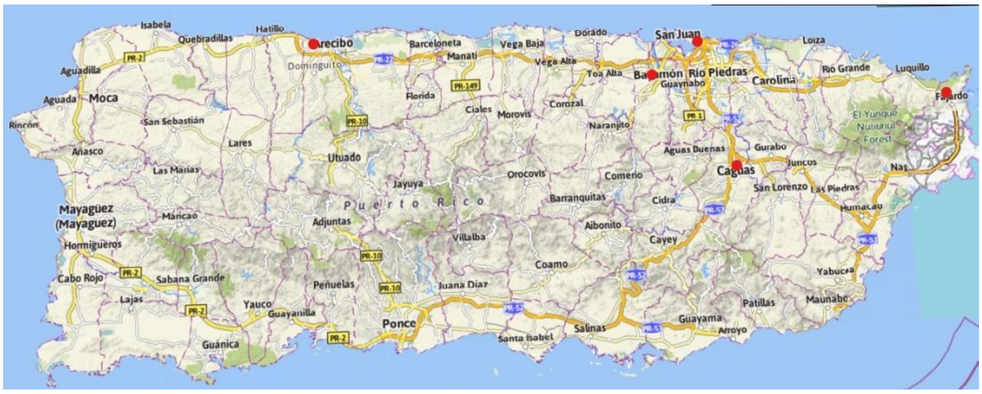

Figure 3

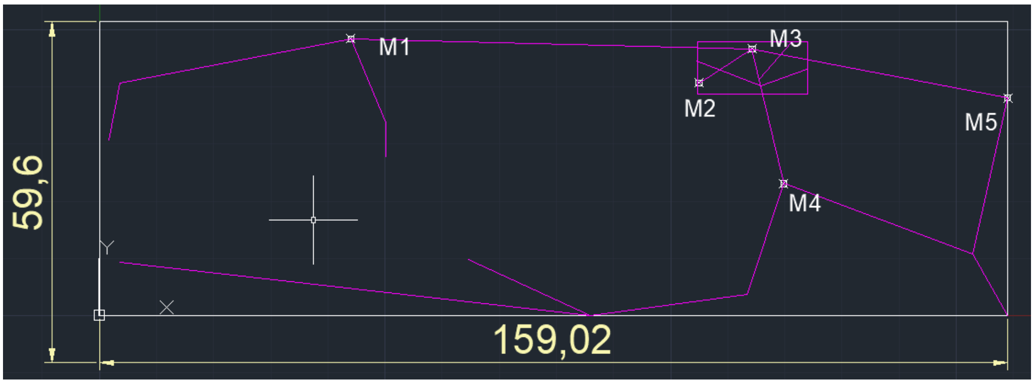

Figure 4

To facilitate the distribution of medical supplies and to maximize the scope of the exploration of the roads, we decide to use three containers simultaneously. We use cluster analysis algorithm to divide the 5 hospitals into three groups. The influencing factors we considered are shown in the table below. Traffic conditions refer to the number of roads near each hospital.

Table 9. The factors of cluster analysis algorithm

Hospital	The number of medical package	abscissa	ordinate	Traffic conditions
Caribbean Medical Center	2	159.02	38.03	2
Hospital HIMA	3	119.75	23.07	3
Hospital Pavia Santurce	2	114.27	46.62	4
Puerto Rico Children's Hospital	5	104.96	40.66	3
Hospital Pavia Arecibo	1	43.99	48.77	2

After calculation, the figure we get is as follows

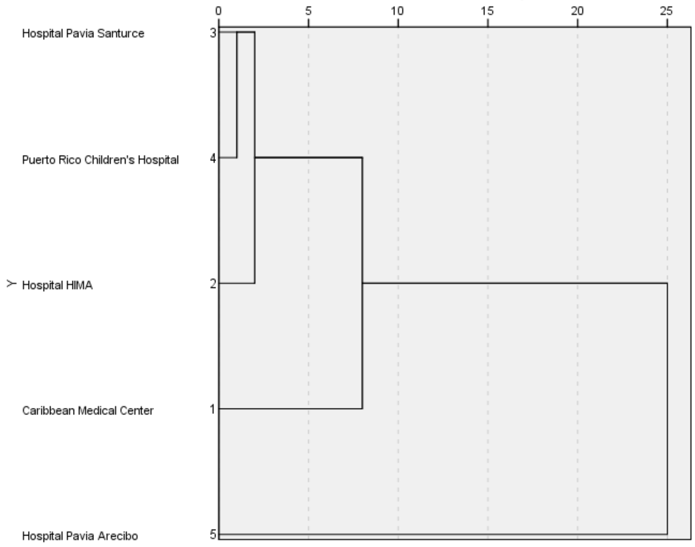

Figure 5

As can be seen from the picture, Hospital HIMA, Hospital Pavia Santurce and Puerto Rico Children's Hospital are divided into a group. Caribbean Medical Center is grouped separately, and so is Hospital Pavia Arecibo.

4.2.2. Concentric movable circle model

In order to ensure that the UAV can fly from the selected location to various hospitals, we draw five circles with each hospital as the center of the circle and the shortest flight distance of the UAV as a radius of 15km. If the UAV flying closest can also be used to deliver medicine to hospitals, then the track of the container to the farthest position of each hospital is the circle with a radius of 15km as mentioned above. See Figure 6.

Annotation: In this case, we think the hospital can temporarily keep the drone delivering medicine, so we don't consider their return trip. For the pathfinder drone, we think about the return trip.

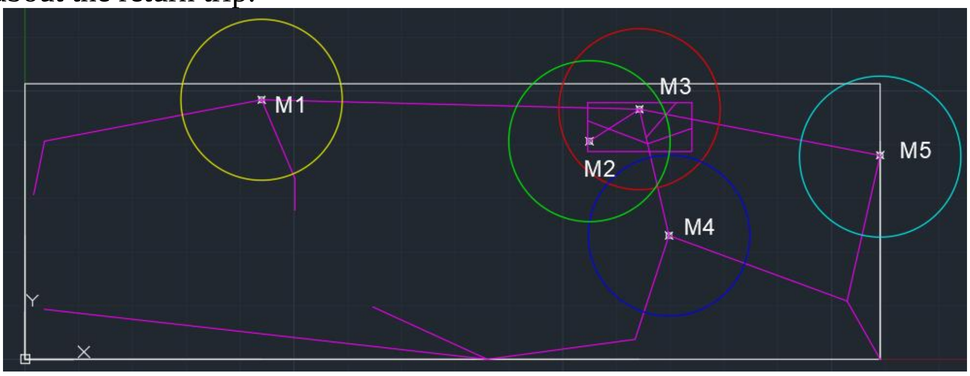

Figure 6

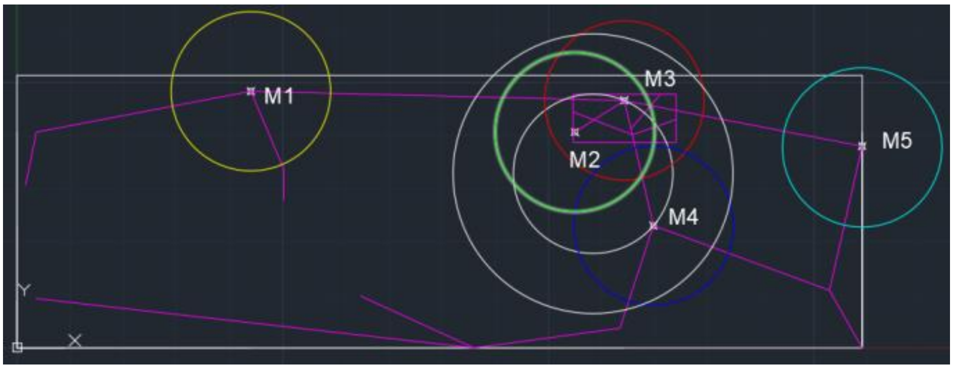

Figure 7

First, in terms of the middle three points, the condition that two of them are on the circle is the limit case of the position of the circle. If M_2 and M_3 are on a circle, the circle will be near the right side of the island. Because the average position of these three points is closer to M_5 than to M_1, the detection area overlaps more. This reduces the scope for exploration. The same is true for M_2 and M_4. When M_3 and M_4 are on the circle, the overlap range is minimal. Let's call this circle as circle O. For ease of observation, we erase some of the used lines in the figure. When the large circle passes through the intersection point K between the circle O' and the rectangle, the UAV can fully explore this area.

Figure 8

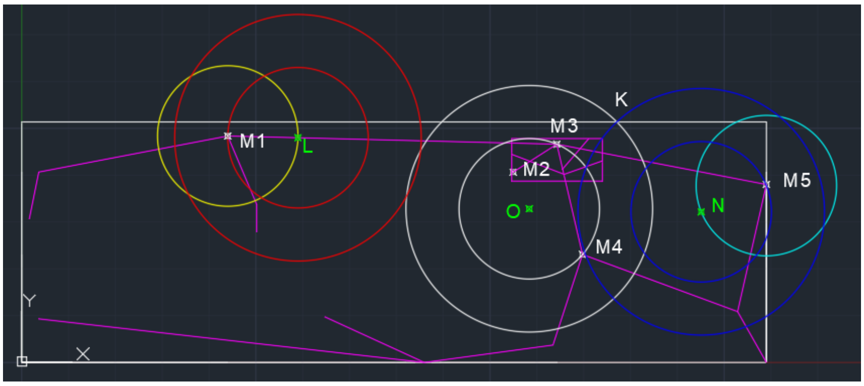

Figure 9

Through the dynamic analysis of circle L, we find that when the center of the circle is the intersection of the highway and the yellow circle (i.e. the diameter of the highway coincides with the circle), the area covered by the red circle is the largest

The green dots in Figure 8 and the black dots in Figure 9 represent the location of the response system. Using geometry, it is not difficult to get the coordinates of three points.

L（18.1238°, -66.1238°）; O （18.3924°, -66.5913°）; N (18.2429°, -65.7715°)

4.3. The solution to problem C

4.3.1. Packing configurations delivery routes and schedule

According to the conclusion of problem A and problem B, we give the timetable.

Table 10. Time table

The Starting Point	Drone type and number	Type and quantity of medicine to be carried	Destination	Departure time	Arrival time	Route
L	E_1	1*MED 1	Hospital Pavia Arecibo	8:00am	8:15am	straight line
O	E_2/E_3	2*MED1+MED3	Hospital HIMA	8:00am	8:15am	straight line
O	E_4	1*MED1+1*MED2	Hospital Pavia Santurce	8:00am	8:15am	straight line
O	$E_5/E_6/E_7$	2*MED1+1*MED2 +2*MED3	Puerto Rico Children's Hospital	8:00am	8:09am	straight line
N	E_8	1*MED1+1*MED2	Caribbean Medical Center	8:00am	8:15am	straight line

4.3.2. Use Simulated annealing algorithm to get the brone flight plan

To provide a drone flight plan that will enable the ***DroneGo*** fleet to use onboard video cameras to assess the major highways and roads in support of the Help, Inc. mission. We use simulated annealing algorithm to solve this problem. In order to study the flight path of UAV, we select the inflection point of each route to represent the position of the road on the basis of simplified model. According to the actual road map, the main roads on the island can be approximated as a combination of straight lines, so our hypothesis is reasonable to some extent.

Therefore, we randomly select points on the major highways and roads, obtain the longitude and latitude of each point, and convert them into the corresponding coordinates of the parameter space with the longitude and latitude conversion formula. We used the simulated annealing algorithm to draw a road map for traversal of all points within a certain range. And then we plot it many times to get as many routes as we can. And then we plot it many times to get as many routes as we can.Among these routes, the route covering road the most effectively and less than 52.67km (i.e. the farthest flight mileage can be achieved) and was selected. This is the best route we can get.

We also compared the calculated paths with the original maps. As shown in the figure below

a. At point L

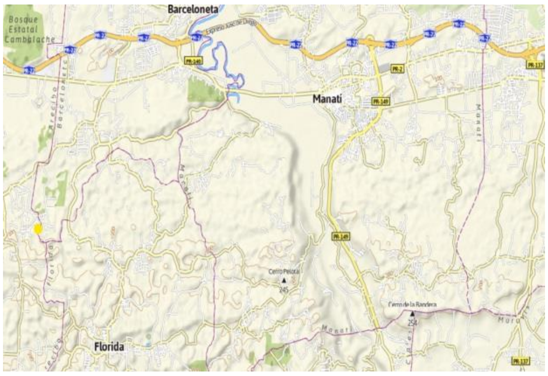

Figure 10

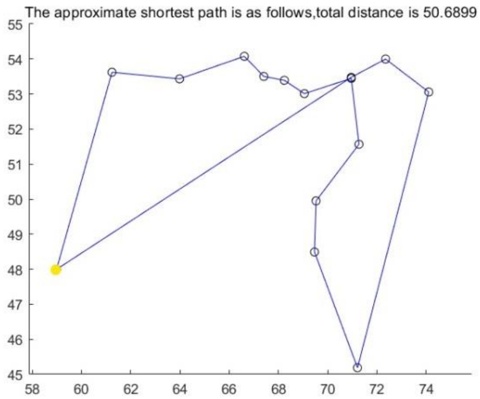

Figure 11

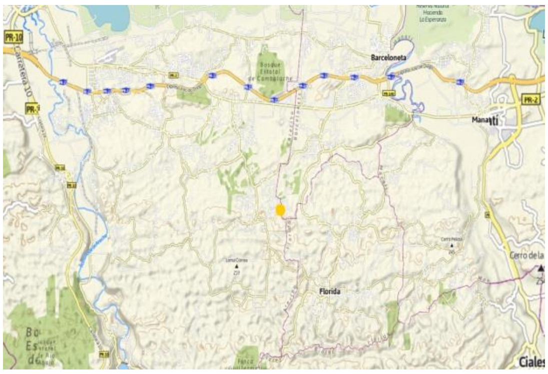

Figure 12

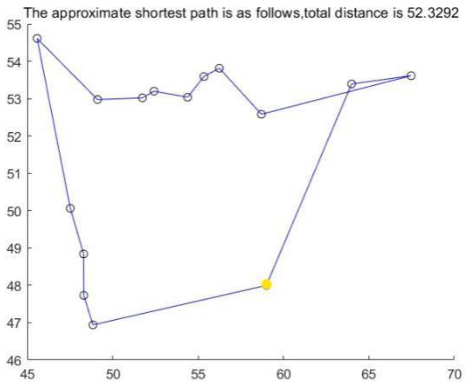

Figure 13

b. At point O

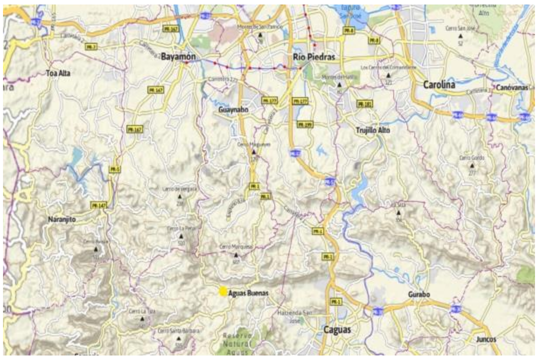

Figure 14

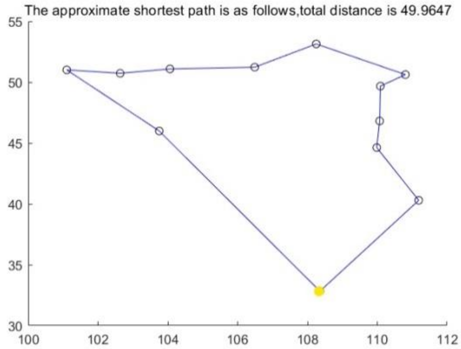

Figure 15

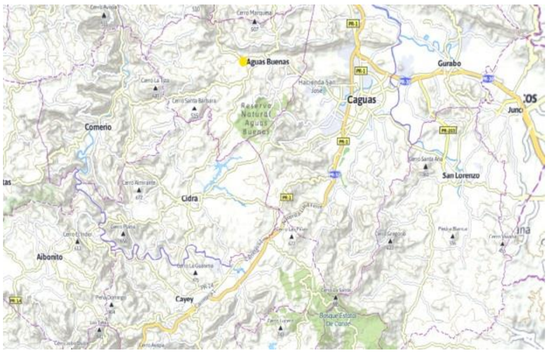

Figure 16

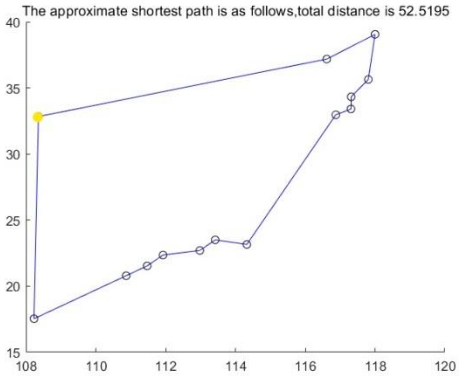

Figure 17

Figure 18

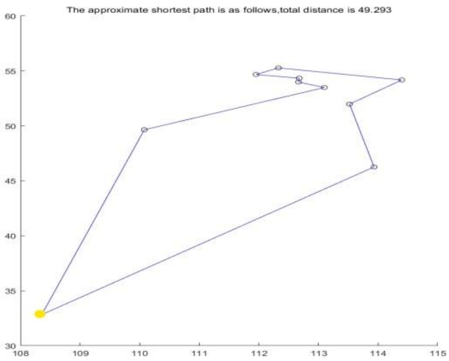

Figure 19

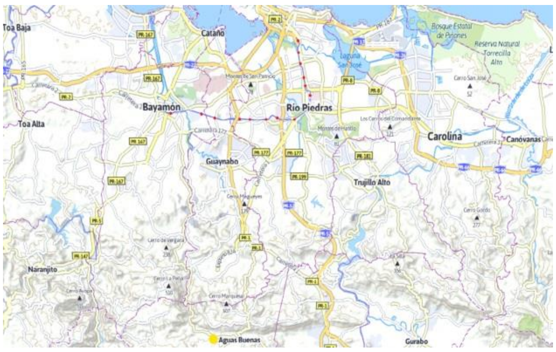

Figure 20

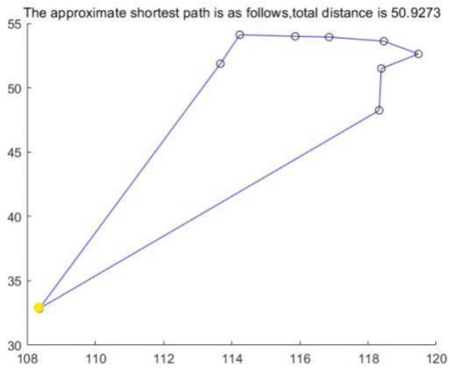

Figure 21

c. At point N

Figure 22

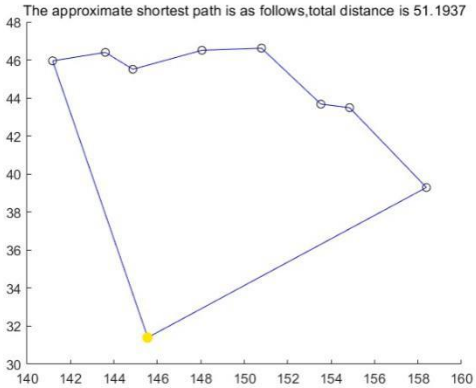

Figure 23

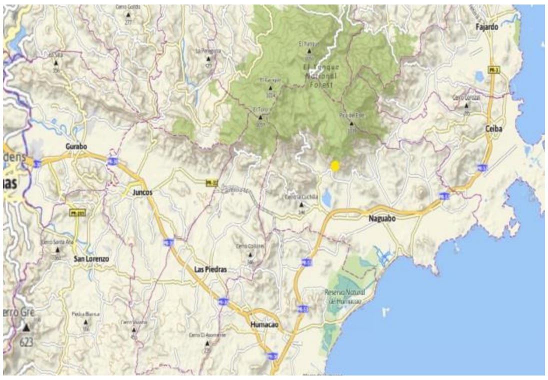

Figure 24

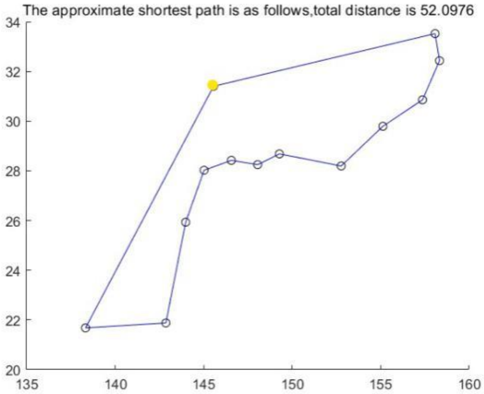

Figure 25

5. Model Evaluation and Promotion

5.1. The advantages of the model

- We consider the rotation of the medical packages. By rotating the cartridge, the type of arrangement is increased which improves the space utilization of the cargo compartment.
- The complexity of the packing problem is greatly reduced by selecting the drones with the highest scores only to finish two missions separately.
- We creatively use simple geometric model (i.e. concentric movable circle model) to cover as many roads as possible while solving the medicine delivery problem.
- We use the idea of replacing lines with many points, making it possible for drones to fly along roads.
- Some of the parameters in our model are easy to adjust which makes our model

very general.

5.2. Disadvantages of the model

Because there is not enough time, we don't consider about the schedule very well. The time may look like quite arbitrary. But it is when we think the hospitals need the medicine most.

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