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MCM/ICM

Summary Sheet

Little Drone, Great Capability

Summary

In order to support the Puerto Rico hurricane disaster scenario, we develop a DroneGo disaster response system that is able to conduct both medical supply delivery and video reconnaissance of road networks.

After a preliminary analysis of the problem, we start with identifying the best locations of cargo containers and then address the whole problem. When selecting the best locations, we consider both transportation cost and the reconnaissance area. Through establishing **transportation cost function** to solve the optimization problem and calculating the reachable area of each candidate position, we get the best three locations, which are **Fajardo**, **Bayamon**, and **Arecibo**.

Once the locations are determined, we can calculate the quantity of each medicine package in each cargo container and how they are delivered to other locations. Next, we develop a comprehensive indicator to evaluate the performance of each drone type and select the best transport and reconnaissance drones. Then we use EasyCargo to load medicine packages and drones to the container to maximize space utilization. For example, the container at Bayamon is loaded with 18 F, 12 G, 1 H, 300 Med1, 120 Med2, and 180 Med3. More results are shown in the paper.

Given the drone fleet at each location, we develop delivery and reconnaissance plans for each type of drone.

Drones at Fajardo and Arecibo only need to perform reconnaissance mission. For drones at Bayamon, we first optimize their drone payload packing configurations and arrange drones to deliver medicine along the optimal route. Then we establish a **delay time function** to arrange their schedule.

Afterward, we use the grid method to abstract the major highways, and then we use **cellular automaton** to get the optimal scouting plan. **Greedy algorithm** is used to give primary transfer rules and weight functions.

Finally, we apply sensitivity analysis of the parameters used in the model to verify the sensitivity and rationality of the parameters. And then we provide some simple and feasible trade-offs in case of insufficient delivery or reconnaissance ability.

Keywords: Multi-objective optimization, Three-Dimension Knapsack Problem, Cellular Automaton, Greedy Algorithm

CONTENT

I Introduction

1.1 Background

Maria—the worst hurricane to hit Puerto Rico in more than 80 years—destroyed buildings, homes, and roads; knocked out 80 percent of Puerto Rico's utility poles and all transmission lines; and triggered heavy flooding. Maria also eliminated Puerto Rico's pharmaceutical industry, which led to a shortage of more than 40 drugs, especially the massive shortage of Puerto Rican-produced IV bags [1].

Compared to Donald Trump's "incredible success", some non-governmental organizations (NGOs), such as One America Appeal and Caritas de Puerto Rico, responded swiftly and forcefully to the disaster [2]. These NGOs played an extremely important role in providing medicines, treating the wounded, and detecting disasters.

In recent years, with the development of technology, drones have played an increasingly important role in disaster relief. Its functions include transportation, communication, mapping, inspection, rescue, fire, etc. With the increasingly complex task environment, the difficulty of tasks, and the increasing variety of mission types, drones have begun to move from single-station independent missions to multi-additional and multi-type fleet operations.

1.2 Problem statement

To improve NGO's response capabilities, we are required to design a transportable disaster response system called "DroneGo". It will use rotor wing drones to deliver pre-packaged medical supplies and provide high-resolution aerial video reconnaissance.

Our first work is to develop a model to recommend a drone fleet and set of medical packages that will satisfy the requirements of the Puerto Rico hurricane scenario and design the associated packing configuration for each of up to three ISO cargo containers to transport the system to Puerto Rico.

Besides, our second task is to determine the best location or locations to position containers under the consideration of transport capacity and reconnaissance capabilities.

Thirdly, for each type of drone included in the DroneGo fleet, we will provide the drone payload package configuration, delivery route and schedule to meet the identified requirements. Then we will design a drone flight plan that will allow the DroneGo fleet to use the onboard camera to evaluate major highways and roads.

In part II, the CEO of HELP, Inc. asks our team to summarize our modeling results, conclusions, and recommendations so that she can share with her Board of Directors.

1.3 Our Work

For this question, after preliminary analysis, we believe that it is difficult to determine the proportion of medicine packages and drones without determining the locations of the cargo container, let alone associated packing configuration. Therefore, we start with identifying the best locations of cargo containers and then address the whole problem.

To select the best locations, we take transportation cost and reconnaissance capability into account. For the former, we establish a transportation cost function based on the distance and weight of transported goods. Given the constraint of this function, we can use the constraint boundary to find the extrema and then find the location with the lowest cost. For the latter, we consider a position is a better choice if drone starts from this place can cover a larger area and more major highways. We use the maximum radius of potential candidate drones to estimate the reachable area. Finally, we can decide the best locations.

Once the locations are determined, we can calculate the quantity of each medicine package in each cargo container, so the type and number of the drone can be determined. Then we use simulation software EasyCargo to load cargo container. All the drones and medicine packages are packed to minimize unused space. Finally, we get the packing configuration of each container.

Now we can get the drone fleet at every location. Next step is to develop a delivery and scouting plan.
For the delivery mission, our goal is to use as few drones as possible, which means we have to optimize the drone payload packing configurations. According to the distribution of the main roads and the flight distance limit of the drones, we can determine the ratio of the drones performing two missions simultaneously and their routes. Besides, since the drone must land to be unloaded, we consider the ground unloading capacity in order to prevent crowding and hovering, and establish the schedule for specific drone type.
For reconnaissance mission, our goal is to cover all the major roads as soon as possible. we first use the grid method to abstract the targeted highways, and then we use cellular automaton to simulate to get the optimal plan. Greedy algorithm is used to give primary transfer rules and weight functions. Afterward, we apply sensitivity analysis of the parameters used in the model to verify the sensitivity and rationality of the parameters. Finally, we analyze the advantages and disadvantages of the model and then provide some simple and feasible treatment strategies in case of insufficient delivery or reconnaissance ability due to excessive demand for drugs.

II Assumptions and Symbols

2.1 Assumptions of the initial data

We make the following assumptions to complete our model through this paper. Further improvements of these simplified assumptions will be achieved later with more reliable data.

1. The local power facilities in Puerto Rico were destroyed by the hurricane and the drone could not be recharged.

Reason: According to the background, the storm, with its fierce winds and heavy rain, knocked down 80 percent of Puerto Rico's utility poles and all transmission lines, resulting in loss of power to essentially all of the island's 3.4 million residents. One month after the disaster, most hospitals still relied on a fuel generator to supply electricity, and only offered the most critical services to save power [3]. So there was not enough power supply for the drone to charge.

2. The drone can perform the tasks of medical transportation and road reconnaissance at the same time.

Reason: According to the given information, we know that selected drones should be able to perform these two missions – medical supply delivery and video reconnaissance – simultaneously or separately.

3. Ignore the transportation costs of standard ISO containers, which means that the choice of location only considers the capacity of medical transportation and road reconnaissance.

Reason: According to the information given by the question, transportation costs are difficult to measure.

4. Drugs shipped to Puerto Rico should meet the needs of two months.

Reason: Puerto Rico remains in dire straits and the medical crisis continues more than two months after Hurricane Maria slammed into the US territory, according to humanitarian organizations and US legislators [4].

5. A tethered drone is essential for each shipping location

Reason: The tethered drone can be used for emergency communication guarantee after the disaster. The communications facilities in Puerto Rico were completely destroyed after the disaster, so the tethered drone is essential for each shipping location [5].

2.2 Symbols and definitions

We will define the following variables here as they are widely used throughout our paper. Additional variables may be defined later but will be confined to a particular section.

Table 1 Symbols and definitions

Symbols	Definitions
$C_{Trans(a,b)}$	The transportation cost between two locations
C_{Total}	The total transportation cost
M	Medicine weight
Ω	Record the cuboid corresponding to the large container as Ω
V_{Left}	Remaining space after packing
$Dist(a, b)$	The distance between two location a and b
m_{Medi}	The quality of the medical package i.
n_{Medi}	The quantity of the medical package i.
$\alpha(\mathrm{point})$	The expected value of each type of different types
u_{q_i}	The value of each road in the current state
$\theta(u_{qi})$	The strength of the pheromone of the road point

Table 2 codes for location names

P_i	*Location Name*
P_1	Caribbean Medical Center, Fajardo
P_2	Hospital HIMA, San Pablo
P_3	Hospital Pavia Santurce, San Juan
P_4	Puerto Rico Children's Hospital, Bayamon
P_5	Hospital Pavia Arecibo, Arecibo
$P_{Humacao}$	Humacao
P_{Coco}	Coco

III Models and Results

According to our understanding of Problems A and B, we believe that the proportion of medical packages in each container is determined by the locations of the container transport, and the choice of drone type is determined by the combination of the locations and the number of the medical packages. In order to solve Problem A, we must first analyze problem B.

3.1 Container transportation location selection model

According to the requirements of the title, we evaluate each optional location from the perspective of transportation cost and reconnaissance scope and then make a comprehensive comparison to get the best location choice.

3.1.1 Model Preparation

Attachment 1 provides a total of five optional container shipping locations. From west to east, we record them as P_1, P_2, P_3, P_4, P_5 in turn. By calculating the latitude and longitude distance, we know that the linear distance between P_5 and P_4 is 60.63km. Then we analyzed the 8 types of drones provided in Attachment 4. It can be seen that the drone mileage of drone B is the largest, which is 52.67km without loading the goods. That is, the maximum cruising range of the drone is less than the distance between P_5 and P_4. As a result, all drones are unable to ship medicines from other alternative shipping locations to P_5. Similarly, no drone can transport medicines from P_5 to other locations. Therefore, it is necessary and only necessary to transport one container to the P_5 to meet the requirements of the P_5, and the remaining two containers are placed in the other four locations.

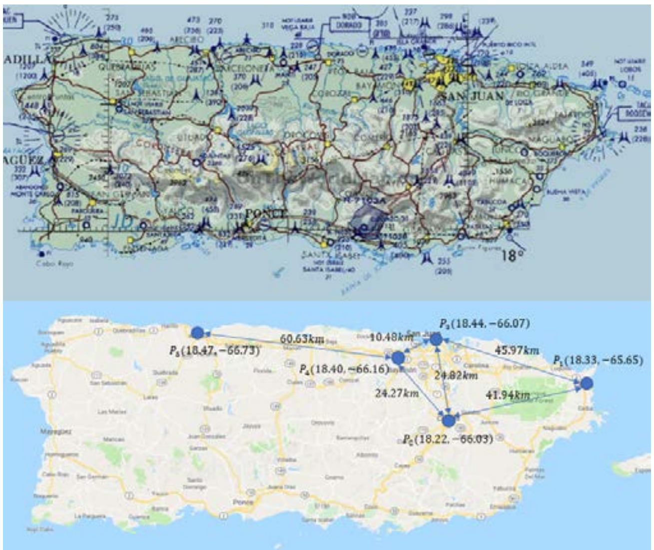


Figure 1 Straight-line distance diagram

A model for selecting the most two locations from four selectable locations for container transportation is given below.

3.1.2 Transportation Cost Evaluation Model

Here we define the concept of opportunity cost, which is the "cost" that is generated by not enjoying the benefits associated with alternative choices [6]. In the current situation, according to the assumption that the drone cannot be charged locally, the electricity consumed during transportation is the main transportation cost. The definition $C_{Trans(a,b)}$ is the transportation cost between two locations, U is the complete set of (a, b) combination and C_{Total} is the total transportation cost. We know that transportation costs are directly proportional to the total quality of the drug and the distance traveled [7]. For the sake of simplicity, the coefficients are normalized. We get the transportation cost between any two locations is

$$C_{Trans(a,b)} = Dist(a,b) \cdot M = \sum_{i=1}^{3} Dist(a,b) \cdot m_{Med_i} \cdot n_{Med_i} \tag{1}$$

$C_{Trans(a,b)}$ means transportation cost between two points a and b; M denotes medicine weight; m_{Med_i} and n_{Med_i} represent the quality and quantity of the medical package, respectively. Therefore, the total cost is

$$C_{Total} = \sum_{(a,b)} C_{Trans(a,b)}, \quad (a,b) \in U \tag{2}$$

In summary, the optimization goal of this question is to consider how to select the location P_i, P_j of the container to minimize C_{Total}.

We can calculate the straight-line distance by giving the latitude and longitude information to the problem, and the figure below shows the empowerment map of the linear distance between five locations.

Table 3 Straight-line distance

	Straight-line distance
$Dist(P_1, P_2)$	$41.94km$
$Dist(P_1, P_3)$	$45.97km$
$Dist(P_1, P_4)$	$54.38km$
$Dist(P_2, P_3)$	$24.82km$
$Dist(P_2, P_4)$	$24.27km$
$Dist(P_3, P_4)$	$10.48km$
$Dist(P_4, P_5)$	$60.63km$

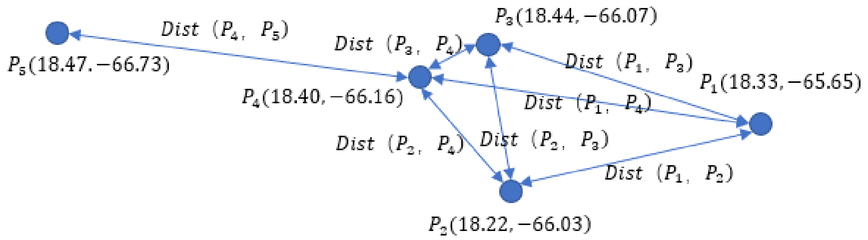


Figure 2 Empowerment map

Considering that the maximum range of the drone is 52.67 kilometers, it can be seen from the above figure that for the drone in the P_1, the medicine can only be sent to P_2 and P_3, but not to P_4. For the same reason, for the drone in the P_4, the medicine can only be sent to P_2 and P_3, but not to the P_1.

According to the data in Attachment 4, the ratio of total daily drug demand for the four locations except P_5 is Med 1: Med 2: Med 3= 6:2:4. So we might assume that the ratio of the total amount of medical packages is 6:2:4. Based on the linear distance between locations and the demand for medicines, we divide the location selection into two scenarios.

- **Scenario 1: Container transported to the same location**

When the containers are transported to the same location, we can only choose P_2 or P_3 in order to ensure that the drone can transport the medical package to three other locations. When P_2 is selected, the medical package shipments to the P_1, P_3, P_4 are respectively (1,0,1), (1,1,0) and (2,1,2). Therefore, the total transportation cost is

$$C_{Total} = \sum_{k\in[1,4],k\in Z,k\neq 2} C_{Trans(P_2,P_k)} = \sum_{k\in[1,4],k\in Z,k\neq 2} \sum_{i=1}^{3} Dist(P_2, P_k) \cdot n_{Medi} \cdot m_{Medi} \quad (3)$$

Figure 3 Scenario 1: Container transported to the same location

- **Scenario 2: Container transported to two different locations**

When choosing two locations $P_{j1}, P_{j2}, j_1 \neq j_2, j_1, j_2 \in \{1, 2, 3, 4\}$, the proportion of drugs in each container will vary. The P_j's daily demand for the three medical packages is (A_j, B_j, C_j), and the specific value has been given by Attachment 4. If the number of three drugs in the container at P_{j1} is (a, b, c), then the number of three drugs at P_{j2} is $(6-a, 2-b, 4-c)$. Assume that the number of three medical packages transported from P_{j1} to P_k is $(a_{j1,k}, b_{j1,k}, c_{j1,k})$, the number of three medical packages transported from P_{j2} to P_k is $(a_{j2,k}, b_{j2,k}, c_{j2,k})$, then transportation cost is

$$\begin{aligned} C_{Total} &= \sum_{k\in[1,4],k\in Z,k\neq j_1,j_2} (C_{Trans(P_{j1},P_k)} + C_{Trans(P_{j2},P_k)}) \\ &= \sum_{k\in[1,4],k\in Z,k\neq j_1,j_2} \begin{aligned}\{&Dist(P_{j1}, P_k)\cdot\delta_{j1,k}(a_{j1,k}m_{Med1} + b_{j_1,k}m_{Med2} + c_{j_1,k}m_{Med3}) + \\ &Dist(P_{j2}, P_k)\cdot\delta_{j2,k}(a_{j2,k}m_{Med1} + b_{j_2,k}m_{Med2} + c_{j_2,k}m_{Med3})\}\end{aligned} \end{aligned} \tag{4}$$

where

$$\delta_{j,k} = \begin{cases} 0 & if \ \ j,k = 1,4 \ \ or \ \ j,k = 4,1 \\ 1 & else \end{cases} \tag{5}$$

$\delta_{j,k}$ indicates that the medical package cannot be transported by drone between P_1 and P_4. Path selection can be divided into two categories depending on the value of the parameter. The left figure below shows the case where the transport path is three, and the right figure shows the case where the transport path is four.

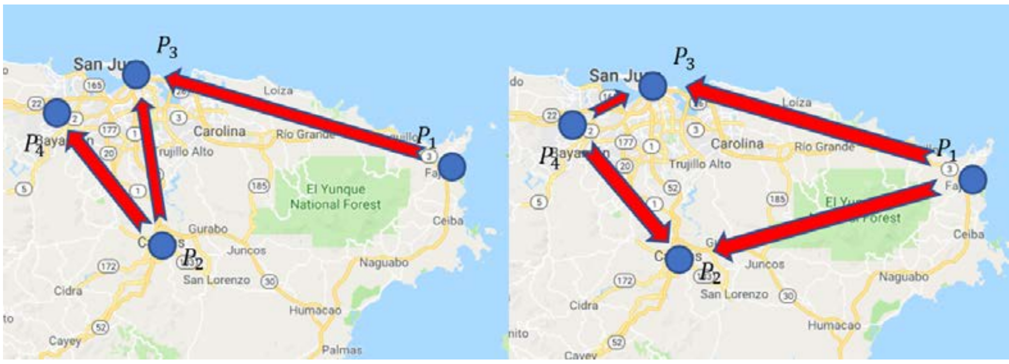


Figure 4 Scenario 2: Container transported to two different locations

At this time, the transportation method is unique, so that the unique value can be calculated and the result is obtained. For the delivery point at P_3, the calculation is similar.

Our optimization goal is to find the minimum value of C under the constraint bar.

$$\min C_{Tatol} \tag{6}$$

And the constraint on transportation costs is

$$\begin{cases} 0 \le a \le 6, 0 \le b \le 2, 0 \le b \le 4 \\ (a_{j1,k} + a_{j2,k}, b_{j1,k} + b_{j2,k}, c_{j1,k} + c_{j2,k}) = (A_k, B_k, C_k) \\ \quad , \text{when } k \in [1,4], k \in Z, k \ne j_1, j_2 \\ a - \sum_{k\in[1,4],k\in Z,k\ne j_1,j_2} a_{j1,k} = A_{j1} \\ b - \sum_{k\in[1,4],k\in Z,k\ne j_1,j_2} b_{j1,k} = B_{j1} \\ c - \sum_{k\in[1,4],k\in Z,k\ne j_1,j_2} c_{j1,k} = C_{j1} \\ 6 - a - \sum_{k\in[1,4],k\in Z,k\ne j_1,j_2} a_{j2,k} = A_{j2} \\ 2 - b - \sum_{k\in[1,4],k\in Z,k\ne j_1,j_2} b_{j2,k} = B_{j2} \\ 4 - c - \sum_{k\in[1,4],k\in Z,k\ne j_1,j_2} c_{j2,k} = C_{j2} \end{cases} \tag{7}$$

The second equation indicates that the medical demands of the two locations receiving the medical requirement are met. The third to sixth equations indicate that the remaining medical packages can meet local demands, after completing the medical package shipment.

3.1.3 Results and Analysis

Through the analysis of the above different situations, the relationship between different location combinations and costs can be obtained. Results are as follows:

Table 4 Total cost of Medical Delivery

Combination	P_1	P_2	P_3	P_4	C_{Total}
1,3	1,0,2		5,2,2		225.4
2,4		3,0,2		3,2,2	251.95
2,3		3,0,2	3,2,2		335.95
1,2	1,0,1	5,2,3			391
3,4			2,1,1	4,1,3	400.25
3			6,2,4		530.1
2		6,2,4			600.95
1,4	1,0,1			5,2,3	212.1

As we can see from Table 2, when the combination of locations is P_1, P_4 and P_2, P_4, the transportation cost is relatively low. And their specific drug delivery methods are as follows.

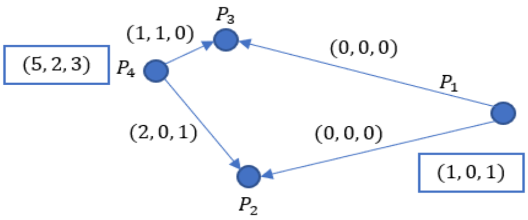


Figure 5 (P1, P4)'s medical delivery methods

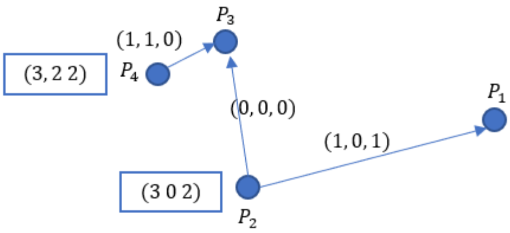


Figure 6 (P2, P4)'s medical drug methods

According to the topographic map given in Attachment1, we consult the relevant literature and find that there is a mountain barrier between P_1 and P_2. In most areas, the altitude is over 1000 feet, and it is difficult for the drone to pass straight. For medical transport between P_1 and P_2, drones can only fly along the main road. However, the length of the main road exceeds 60km, which exceeds the endurance of the drone. Therefore, when selecting P_2 and P_4 as container transportation locations, the drone cannot actually complete the medical delivery task. From the perspective of medical transportation, choose P_1, P_4, P_5 as the best location to position cargo containers is reasonable.

Figure 7 Topographic maps of Puerto Rico [8]

3.2 Video Reconnaissance Performance Analysis

For each of the possible combination we have discussed above, we should also take their video reconnaissance performance into consideration. The best combination should cover the largest scope of reconnaissance. Given the maximum scouting radius r_i of drones at a specific position P_i, we can get P_i's reconnaissance area. To simplify our analysis, we use Type-B drone's maximum scouting radius as r_i. And then we can get each position's available area, which is shown in Figure 2.

Figure 8 Maximum reconnaissance area

Figure 2. clearly shows that the combination (P_1, P_4)'s largest reconnaissance area is almost tangent. And From the weighting graph, the straight-line distance between P_1 and P_4 is 54km, which is exactly twice the maximum reconnaissance radius of the drone. For other combinations of locations, there is a large overlap between the scopes of reconnaissance, which wastes the reconnaissance capability of the drone to some extent. So P_1, P_4, P_5 is the best location to position cargo containers, from the perspective of medical transportation.

3.3 Comprehensive Analysis

From the results in 1.2 and 1.3, we can get the best placement point combination is (P_1, P_4, P_5). Under this circumstance, the specific drug delivery method can be obtained as shown in Figure 4.

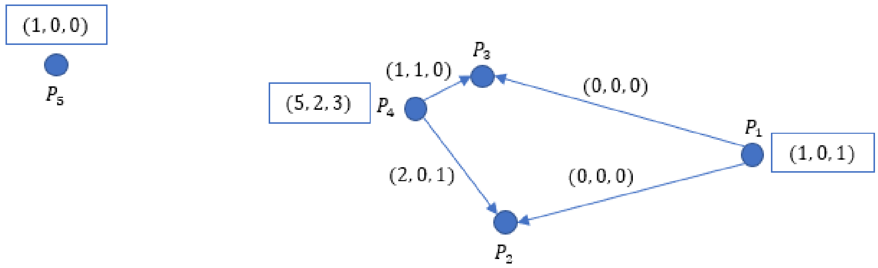


Figure 9 Medical Delivery Methods

3.4 Three-dimensional knapsack loading

3.4.1 Model Establishment

Packing combination is essentially a Finite-Circle Method [9]. The question is about how to stack different shapes of objects in a limited space to minimize the remaining space. Record the cuboid corresponding to the large container as Ω. The shipping containers corresponding to the eight types of aircraft are recorded in alphabetical order as $SC_i (i = 1, 2, \cdots, 8)$. Record $Med1, Med2, Med3$ as M_1, M_2, M_3 respectively. For this problem, we consider how to discharge 11 different sizes of cuboids into Ω under the premise of meeting the medical demand, transportation capacity, and reconnaissance ability, so that the remaining space V_{Left} is minimized.

A rough picture is as follows.

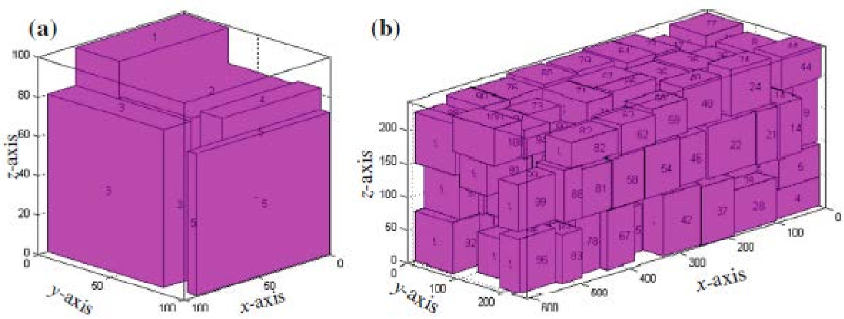


Figure 10 An example of packing problem [10]

Assuming that the lower left corner of the large cube Ω is the origin, for each small cube Γ in Ω, its center coordinates and the placement angle M uniquely determine its position. The solution to this problem can be given by the following formula.

$$\begin{cases} \forall i \in \{i, 2, \cdots, n\} \\ \Gamma_i(x_i, y_i, z_i, \theta_i\} \subset \Omega \\ \forall i_1, i_2 \in \{1, 2, \cdots, n\}, i_1 \neq i_2 \\ \Gamma_{i_1}(\mathrm{x}_{i_1}, y_{i_1}, z_{i_1}, \theta_{i_1}) \cap \Gamma_{i_2}(\mathrm{x}_{i_2}, y_{i_2}, \mathrm{z}_{i_2}, \theta_{i_2}) = \phi \\ V_{Left} = V_\Omega - \sum_{i=1}^{n} V_{\Gamma_i} \end{cases} \quad (8)$$

where each Γ is any kind of SC_i, $i \in \{1, 2, \cdots, 8\}$, M_1, M_2, M_3.

Now we can determine that the best combination of locations is P_1, P_4, P_5, and the ratios of the three drugs shipped to the three locations are 1:0:1, 5:2:3, 1:0:0. According to the hypothesis, the total amount of drugs should meet the demand of at least two months, so the corresponding dose of P_1, P_4, P_5 is (60,0,60), (300,120,180), (60,0,0) in turn. In the previous analysis, it can be known that P_1 and P_5 do not need to carry out drug transportation, and only need to complete the reconnaissance task. So we will consider P_4 separately, and consider P_1 and P_5 together.

3.4.2 Packing Configuration for Cargo Container Positioned at P_1 and P_5

Since medicine at P_1 and P_5 are self-sufficient, drones at these two places only need to conduct reconnaissance tasks. Therefore, we package drone which has the best scouting performance, along with required medicine packages, into their cargo containers. According to our analysis before, Type-B drone, with its highest speed, farthest flight, and relatively small volume, is the best choice. Besides all the required medicine packages and a *Drone Type H*, we should pack B into containers as many as possible and minimize the unused space at the same time. Now this problem is simplified to find the best solution to load five different cuboids into Ω, where four of them are fixed, so we only need to determine the number of *Type-B drone.*

To address this problem, we use EasyCargo to simulate. For position P_1 and P_5, given all the size data of drones and medicine packages shown in Attachment 2 and Attachment 5, we set the number of SC_8 to 1 and M_1, M_2, M_3 to (60,0,60), (60,0,0) separately. We choose the *Ignore Separation into Priority Groups* mode to get the optimal packing configuration for P_1 and P_5, which is shown below:

Table 5 P1 and P5 packing configuration detail

P_1 (above) and P_5 (below) Packing Configuration				
$B(pcs)$	$H(pcs)$	$MED1(pcs)$	$MED3(pcs)$	$Total\ Volume(ft^3)$
74	1	60	60	992.27 (86%)
74	1	60	0	980.86 (85%)

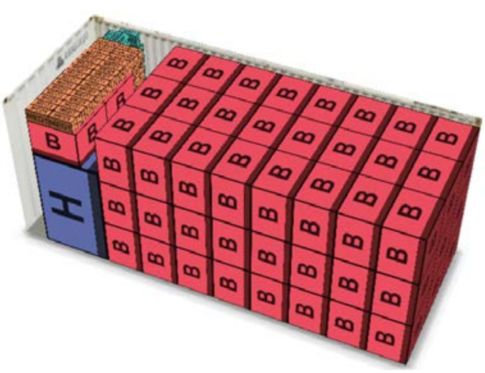


Figure 11 P_1 packing configuration

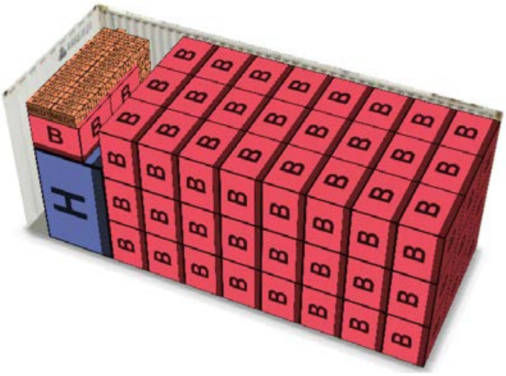


Figure 12 P_5 packing configuration

For the cargo container transported to P_1, we could clearly see from above figure and table that the packing result is in line with our analysis and expectation.

For the cargo container transported to P_5, we could see its packing configuration clearly from above table and figure. In the case of closest packing, the result above shows that the space utilization are 86%, 85%, and the number of Type-B drone packed is 74.

3.4.3 Packing Configuration for Cargo Container Positioned at P_4

P_4 has to deliver medicine packages to P_2 and P_3, apparently Type-B drone is not the best choice for transportation task, so we need to analyze the specific situation and the transport performance of each drone type in detail.

First, it is apparent that Type A is not better than Type B in all aspects of volume, maximum speed, flight duration, etc. so under no circumstance will we take Type A as our candidate drone. From Table 3, we could know that the straight-line distance between P_2 and P_4 is 24.27km. Only Type B, C, and D can cover such a distance. Using EasyCargo to analyze Drone Cargo Bay Type2, we find that for those drones equipped with this kind of cargo bay, their cargo capacity totally depends on their max payload capability, which means they can load all the goods within their load-bearing range. Applying the analysis above, we could find that Drone Type F is better than C in all aspects. Despite its relatively large volume, its cargo capacity far exceeds B. So F is the optimal type to deliver medicine packages to P_2. Furthermore, from Attachment 2 we could know that the max payload capability of F is 22 lbs. Given the weight and quantity of MED1(120 pcs, 2 lbs.) and MED2(60 pcs, 2 lbs.), we get the following optimal arrangement: nine F loaded with eleven MED1, ten F loaded with six MED3 and two MED3 by simple calculation.

Second, the straight-line distance between P_3 and P_4 is 10.48km, which is reachable for all drone types, so we just need to choose the drone which performs best in transporting. We finally choose Drone Type G, which has a relatively small volume and strong delivery capacity (second only to F). The max payload capability of G is 20 lbs. and the weight and quantity of MED1 are 60 pcs, 2 lbs. while MED2 is 60 pcs, 2lbs. For each G, we just put MED1 and MED2 in equal proportions, which is to say, we finally have 12 G and each is loaded with 5 MED1 and 5 MED2.

After loading all of the medicine packages, transportation drones, and a Drone Type H, we need to load B in the rest space as many as possible to ensure scouting tasks and minimize unused space. Now this problem is simplified to find the best solution to load 7 different cuboids into Ω, where 6 of them have fixed quantity, so we only need to determine the number of Type-B drone.

Same as above, to address this problem, we use EasyCargo to simulate. We choose the *Ignore Separation into Priority Groups* mode to get the optimal packing configuration for P_1 and P_5, which is shown below:

Table 6 P4 packing configuration detail

B (pcs)	F (pcs)	G (pcs)	H (pcs)	MED1 (pcs)	MED2 (pcs)	MED3 (pcs)	Total Volume (ft^3)
18	19	12	1	300	120	180	1006.51 (88%)

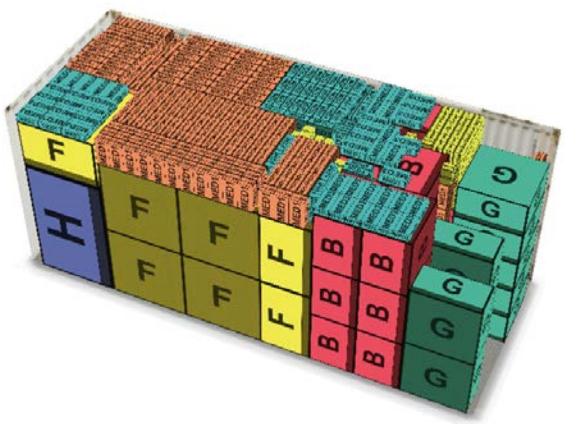


Figure 13 P_4 packing configuration

From the result, we could see clearly how drones and medicine packages are packed in the container. We finally loaded 18 Type B and the space utilization is 88%.

3.5 Drone payload packing configurations, delivery routes, and schedule

Now that we have got the specific locations and packing contents of each shipping container. Then we can analyze each location in detail to sort out the best transportation plan and reconnaissance plan of each drone type. It should be noted that among the three locations we selected, only the drones at P_4 the need to perform transportation tasks. The drones at P_1 and P_3 only have reconnaissance missions.

3.5.1 Drone Payload Packing Configurations

In fact, in problem 2 we have completed the packing configurations for each selected drone's cargo. The results are shown in the table below.

Table 7 Cargo Configuration

F drone payload packing configurations		
9 pcs	10 pcs	
MED1	MED1	MED3
11	2	6

G drone payload packing configurations	
12 pcs	
MED1	MED2
5	5

3.5.2 Delivery Routes and Schedule

As F-type drone has no reconnaissance capability, it only needs to complete the transportation task in the shortest time. And the terrain from A to B is relatively flat, so the drone can fly in a straight line.

The schedule is mainly based on the unloading time of the drone. Despite the small size of the drone, the hospital area in the disaster area is limited and the manpower is scarce, so the unloading capacity is relatively low. The drone must be lowered to the ground before it can be unloaded. When multiple drones arrive at the same time, if the unloading is not timely, it is likely to cause congestion. The drone can't land and can only hover in the air, which leads to time cost and a waste of electricity. Therefore, choosing a reasonable departure time is critical to reducing congestion costs.

Suppose the hospital's average unloading time for three kinds of the medical package is x_1, x_2, x_3. For two different loading methods, the total unloading time is $11x_1$ and $2x_1 + 6x_3$ respectively. Record the time point when the first F-type drone sailed as the initial time point. Then the departure time of the i-th ($1 \le i \le 19$) drone is:

$$t_i = \sum_{k=1}^{i-1} \{\varepsilon_k \cdot 11x_1 + (1-\varepsilon_k)\cdot(2x_1 + 6x_3)\}$$
$$\varepsilon_k = \begin{cases} 1 & \text{when } 11MED_1 \\ 0 & \text{when } 2MED_1 \text{ and } 6MED_3 \end{cases} \tag{9}$$

Where ε_i indicates the proportion of the drone using two loading methods.

For the main roads from P_3 to P_4, the situation is slightly special. Here, we first give the main road map between and around the P_2, P_3 and P_4.

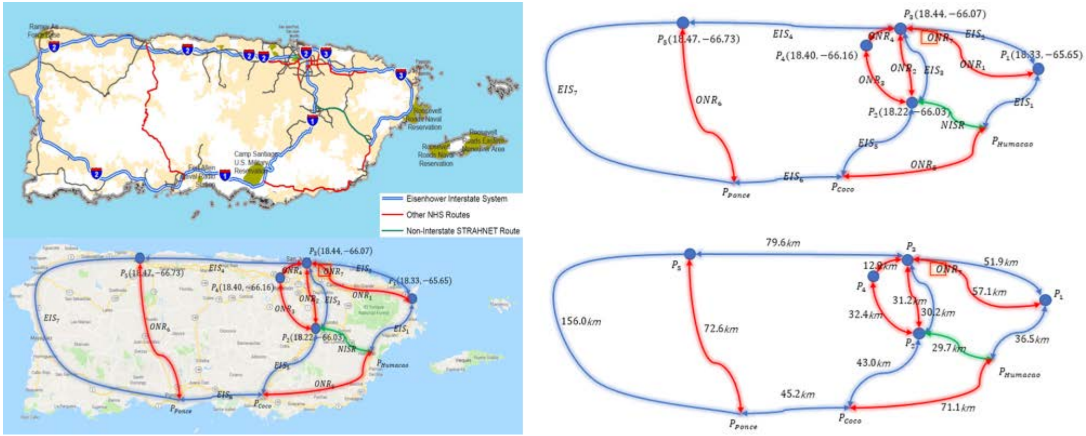


Figure 14 National Highway System: Puerto Rico [11]

The two main roads between P_3 and P_4 are short, and two G-type drones can be arranged to complete the detection task during transportation, the remaining drones fly in a straight line to complete the transportation mission. Set the average flight speed of the G-type drone at full load to V_{full}. In order to obtain road information as soon as possible, we arrange for the two drones that first proceeds to carry out the transportation mission to perform reconnaissance missions. And arrange the drone to first reconnoiter the road ONR_4. Then the departure time of the i-th ($1 \le i \le 12$) drone is

$$t_i = \begin{cases} 0 & i = 1 \\ \dfrac{d_{ONR_4}}{V_{full}} + 5(i-2)(x_1 + x_2) - \dfrac{Dist(P_3, P_4)}{V_{full}} & 2 \le i \le 12 \end{cases} \tag{10}$$

It can ensure that the drone arrives continuously without causing congestion.

Table 8 Drone transport schedule from P4 to P2

t_1	0	t_{11}	50min
t_2	5.5min	t_{12}	53.83min
t_3	11min	t_{13}	57.67min
t_4	16.5min	t_{14}	61.5min
t_5	22min	t_{15}	65.33min
t_6	27.5min	t_{16}	69.17min
t_7	33min	t_{17}	73min
t_8	38.5min	t_{18}	76.83min
t_9	42.33min	t_{19}	81.67min
t_{10}	46.17min		

Table 8 shows the schedule of x_1=30s, x_2=10s, x_3=25s, and the drones of type-F with only Med1 are taken off preferentially from P_2 to P_4.

Table 9 Drone transport schedule from P4 to P3

t_1	0	t_7	20.05min
t_2	3.38min	t_8	23.38min
t_3	6.72min	t_9	26.72min
t_4	10.05min	t_{10}	30.05min
t_5	13.38min	t_{11}	33.38min
t_6	16.72min	t_{12}	33.72min

Table 9 shows the schedule of x_1=30s, x_2=10s, x_3=25s, $V_{full} = 50km/h$, and the drones of type-F are taken off from P_4 to P_3.

3.6 Drone reconnaissance plan

For P_1, P_4, P_5, we still divide them into two situations and discuss them.

3.6.1 Drone reconnaissance plan for P_1 and P_5

As shown in Figure 14 and Attachment 1, the main road that the B-type drones from P_1 can reconnoiter includes $EIS_1, EIS_2, ONR_1, NISR$. However, due to terrain restrictions around P1, drones can only reconnoiter along the main road. Therefore, it is only necessary to send three drones from the P_1 to conduct reconnaissance along the three main roads and return to half of the maximum range distance. If it is necessary to continuously detect the main road conditions, the B-type drones can be dispatched in batches for reconnaissance.

For P_5, the situation is similar to P_4 and there are also 3 main roads around. Therefore, the reconnaissance plan is basically the same.

3.6.2 Drone reconnaissance plan for P_4

The traffic network around P_4 is complex, and three optional locations, including the capital city of San Juan, are within the scope of the B-type drone. Therefore, it is important to efficiently and accurately obtain information about the surrounding transportation network.

There are 18 B-type drones available for reconnaissance. Our mission is to plan the reconnaissance route of 18 drones so that the drone can complete the reconnaissance of the main road as soon as possible while saving electricity and optimizing efficiency.

For this problem, we use the idea of cellular automata, using greedy algorithm, giving initial point positions, grid classification and change rules, state transition rules, transferred weight functions and abort conditions. The simulation simulates the best course of action and the shortest reconnaissance time.

- **Map meshing**

We divide the rectangle with a latitude range of [18.14N, 18.55N] and a rectangle with a precision range of

[66.34W, 65.92W] into a 50×50 grid with the upper left corner as the coordinate origin. The main reconnaissance main roads $ONR_2, ONR_3, EIS_3, ONR_7$ correspond to the grid points in the figure, and the total number of points that need to be accessed is 68, which is recorded as $q_1, q_2, \cdots, q_{68}$. Thus, the problem translates into how to access the most route points in the shortest possible time and to ensure a smooth return to the starting point.

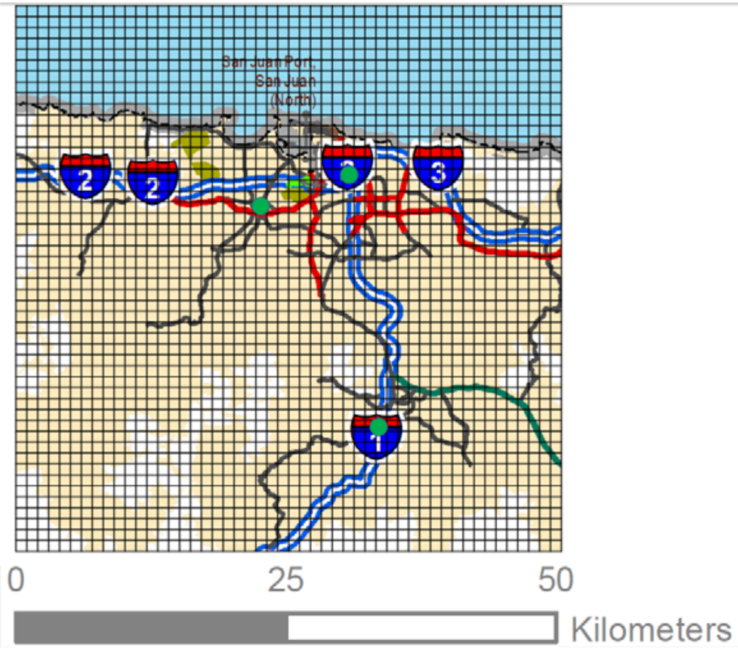


Figure 15 Map Meshing

- **State transition rule**

Assuming that the drone in the current state is on a certain point, the drone in the next state can move to one of the eight grid points around the grid point.

- **Grid classification and change rules**

For each point in the grid map, it is divided into three types: empty space, accessed point, and unvisited point, respectively assigned -1, 0, 1. The unvisited point refers to the drone that has not passed in the current state. point. Empty space is the non-road grid point where the drone has not flown. The accessed point is the point that the drone has already passed. Thus, after each state update, if the drone passes the point, the point assignment becomes 0.

- **Departure rule**

The coordinates of the starting point P_4 in the grid are (19, 22), and the number of aircraft that are set at the same time is 18. The initial direction of the drone must be directed to the right side, and at the same time set off for reconnaissance.

- **Transfer weight function**

For any grid $\text{point} = (x, y, u)$, where x, y represents horizontal and vertical coordinates and u is the assignment of the grid point. Define the weight function of this point as:

$$\phi(x, y, u) = \alpha(u)\sum_{i=1}^{58} \theta(u_{qi}) \frac{1}{d(\text{point}, q_i)} \tag{11}$$

where

$$\alpha(u)=\begin{cases}0.2 & u=-1\\ 0.1 & u=0\\ 0.7 & u=1\end{cases}$$

$\alpha(\text{point})$ represents the expected value of each type of different types. u_{q_i} indicates the value of each road in the current state. 0 means that the point has been visited, and 1 means that the point has not been visited.

$$\theta(u_{q_i})=\begin{cases}0 & i=0\\ 1 & i=1\end{cases}$$

$\theta(u_{qi})$ measures the strength of the pheromone of the road point. If the road point has been visited, the information becomes 0, otherwise, the information is 1. $d(\text{point}, q_i)$ represents the grid point distance from the point to point q_i. The greater the value of the weight function, the higher the priority for accessing that point.

- **Abort condition**

For each drone, calculate the distance s_1 that has passed in the current state. For a point P_i where the next state can go, calculate the distance s_2 between the point at the current state and the point P_i, and the distance s_3 from the point P_i to the starting point. If any of the 8 points that can be reached for the next state, $s_1+s_2+s_3<52.6$ is satisfied, then the reconnaissance ends. At this time, the drone returns along a straight line. If all drones stop reconnaissance, the simulation ends and record the maximum flight mileage of the 18 drones.

In another case, if there is a drone in the current state, it can be reconnaissance, but there is no point assigned to 1, that is, the main road is probed. Then the reconnaissance stops, all drones return in a straight line, and the simulation ends. Record the maximum flight range of the 18 drones at this time.

Finally, divide the maximum flight range by the speed of the B-type drone and get the total time spent on the reconnaissance.

In the initial state, 18 drones were randomly set in five directions along the east side. After updating the state twice, the simulation function is simulated with the weight function, and the total time spent, the number of remaining unvisited road points, and the route of the aircraft are recorded. The results are as follows. The left picture shows the total route map of the drone formation, and the right picture shows some typical route maps.

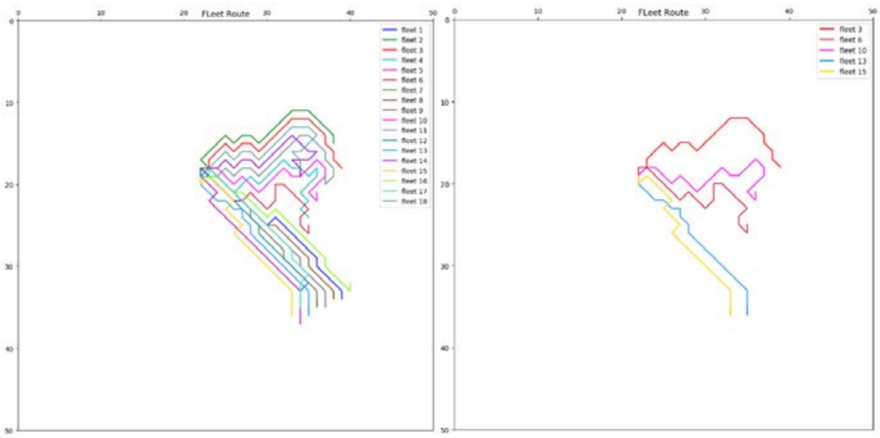


Figure 16 Drone fleet total and typical route map

IV Sensitivity Analysis

In simulation, the key rule of cell transfer comes from the construction of the weight function, and the parameter u of the weight function reflects our estimate of the actual situation of the drone arrival location. For three different locations, perform sensitivity analysis and consider the sensitivity of the three values $\alpha(-1)$, $\alpha(1)$, and $\alpha(0)$.

- **Sensitivity analysis of** $\alpha(-1)$

The parameter $\alpha(-1)$ refers to the expected value of the unvisited open space selected in the state transition, and the model estimate is 0.2. Adjust parameter values, then substituted into the program for fitting calculation, the result is shown in the following table:

Independent variable	Independent variable rate of change	Dependent variable value	Dependent variable rate of change	The rate of change ratio	Mean of the rate of change ratio
0.2		20.2234			
0.25	0.25	19.9088	0.015556237	0.062224947	0.056
0.3	0.5	19.7785	0.021999268	0.043998536	
0.35	0.75	19.4639	0.037555505	0.050074007	

From the table, we could know that, when $\alpha(-1)$ changes by 1%, the reconnaissance time changes by 0.056%, so $\alpha(-1)$ is not sensitive to the reconnaissance time.

- **Sensitivity analysis of** $\alpha(1)$

The parameter $\alpha(1)$ refers to the expected value of the unvisited targeted point selected in the state transition, and the model estimate is 0.7. Adjust parameter values, then substituted into the program for fitting calculation, the result is shown in the following table:

Independent variable	Independent variable rate of change	Dependent variable value	Dependent variable rate of change	The rate of change ratio	Mean of the rate of change ratio
0.7		20.2234			
0.8	0.1429	19.4493	0.038277441	0.267861728	0.218
0.9	0.2857	19.0771	0.056681864	0.198396442	
1	0.4286	18.595	0.080520585	0.187868841	

From the table, we could know that, when $\alpha(1)$ changes by 1%, the reconnaissance time changes by 0.218%, so $\alpha(1)$ is not sensitive to the reconnaissance time.

- **Sensitivity analysis of a** $\alpha(0)$

The parameter $\alpha(0)$ refers to the expected value of the visited point selected in the state transition, and the model estimate is 0.1. Adjust parameter values, then substituted into the program for fitting calculation, the result is shown in the following table:

Independent variable	Independent variable rate of change	Dependent variable value	Dependent variable rate of change	The rate of change ratio	Mean of the rate of change ratio
0.1		20.2234			
0.12	0.2	20.5379	0.015551292	0.07775646	0.085
0.14	0.4	20.9828	0.03755056	0.093876401	
0.16	0.6	21.2234	0.04944767	0.082412783	

From the table, we could know that, when $\alpha(0)$ changes by 1%, the reconnaissance time changes by 0.085%, so $\alpha(0)$ is not sensitive to the reconnaissance time.

V Strength and Weakness

Strengths:

- **Our model is practical and reliable.**
  We consider the possible effects of various real-world factors when modeling. For example, due to the power outage caused by the hurricane, we believe that the drone cannot be charged; the H tethered drone is used to transmit signals; the route of the drone is limited by altitude, etc.
  When it comes to performing specific tasks, we consider the performance of the drone in all aspects to choose the best one and maximize utilization.
- **Sensitivity analysis.** We do a sensitivity analysis to test the accuracy of our model. Based on the outcomes, we safely draw the conclusion that the simulation in our model fits the actual situations.
- **Good flexibility.** According to our analysis, our model can always find the optimum solution under various kinds of conditions.

Weaknesses:

- **Inaccuracy.** When planning the reconnaissance path, we used the grid method to handle the major highways and roads. Since the path is continuous, such a method will lose part of the information. In addition, it is difficult for this method to consider the performance of the drone, such as the maximum turning radius, resulting in biased results.
- **Local optimum.** When planning the drone cruise path, we use the greedy algorithm to optimize. Although the greedy algorithm greatly improves the efficiency of the solution, sometimes the greedy algorithm cannot find the global optimal solution because they do not consider all the data.
- **The data we obtained is limited.** For the lack of data, we have to simulate the models abstracted from the reality to obtain the data we need which may be different from the real data.
- **Simplifying assumptions.** To simplify the model, we make a few assumptions which may affect the result of our model.

VI Trade-offs when exceeding the capabilities of drones

In fact, optimal delivery locations, transportation routes, and reconnaissance routes are all based on the need to meet the two-month drug demand. If we adjusted our model to meet the demand for drugs for three months and still using P_1, P_4 as the container shipping point, then we can find that the number of F-type and G-type drones that need to be transported at P_1 to a minimum of 21 and 18, respectively. After simulating with EasyCargo, we found that it was impossible to accommodate all the items in one container. This situation shows that when the demand for drugs is increasing, we cannot meet the needs of each place. Based on the actual situation, we propose two trade-offs.

If a disaster occurs in the populated area, like near the capital, there will be an urgent need for medical supply. Then we consider changing the shipping point to P_2 and P_3, and transporting medical supplies to P_1 with B-type drone. Sacrificing part of scouting ability and medicine demand of P_1, we give priority to the supply of the populated area.

If the scouting mission is given more priority, we then reduce the number of F and G in the container while increasing the number of B. Despite P2 and P3 cannot get abundant medicine to apply, we can inspect all the major highways as soon as possible.

VII Memo

MEMORANDUM
TO: the CEO of HELP, Inc.
FROM: Team#1900068

Our team has designed a DroneGo disaster response system to support the Puerto Rico hurricane disaster scenario.

Considering the severe damage caused by the hurricane, we plan to provide two months of medicine packages supply to the five cities in the disaster area. As up to three locations can be chosen as transportation point, we recommend Fajardo, Bayamon, Arecibo as the best three positions to transport cargo containers. The reason why we choose Arecibo is that it is so far from the other cities that none of the potential drones can deliver medicine package to it. As for the rest four locations, we prefer to choose a combination which has the lowest delivery cost and can cover the largest scouting area. Applying the principles above, we find Fajardo and Bayamon are optimal.

Since the situation varies, the packing configuration of each container is quite different. We properly arrange the number of drones and medicine packages to ensure that all work can be carried out smoothly and efficiently. Specifically, we evaluate the performance of each candidate drone type and select the best transport and reconnaissance drones. We optimize the configuration of each container transported to minimize unused space. The configuration of each container is shown as below:

	B(pcs)	F(pcs)	G(pcs)	H(pcs)	MED1(pcs)	MED2(pcs)	MED3(pcs)
Fajardo	74			1	60		60
Bayamon	18	19	12	1	300	120	180
Arecibo	74			1			60

For the transportation plan, we calculate that Fajardo and Arecibo do not need to consider transportation issues, only need to consider the problem of reconnaissance road conditions. Moreover, since there are few main roads around these two locations, the road network is relatively simple, and the non-main road area has mountain barriers. Therefore, it is only necessary to send drones to reconnaissance along the main road.

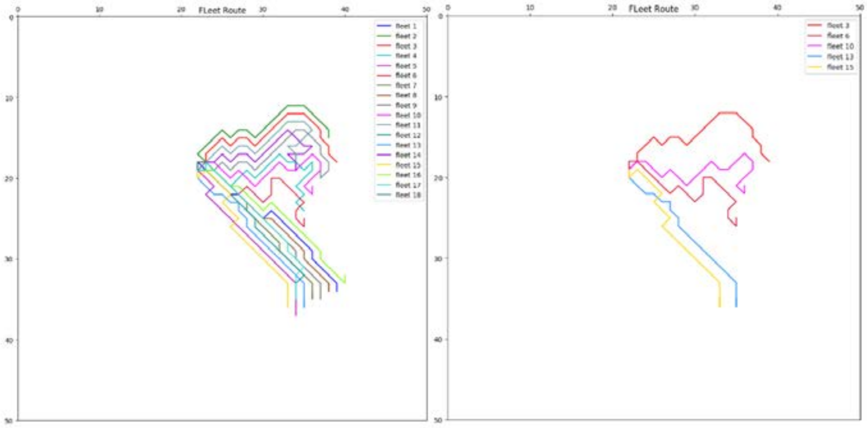
For Bayamon, we recommend that all 19 F-type drones be used to load medicines to San Pablo, and 12 G-type drones to deliver medicines to San Juan, one of which will Fly on the main road between San Juan and Bayamon, and transport the medicine while detecting the road surface. All the other drones will fly in a straight line, ensuring that they reach the destination as fast as possible. Specifically, the charging method for the Cargo bay of each drone is given in the following table.

F drone payload packing configurations		
9 pcs	10 pcs	
MED1	MED1	MED3
11	2	6

G drone payload packing configurations	
12 pcs	
MED1	MED2
5	5

In order to reduce the cost of congestion, we recommend that the drone take-off schedule is scheduled at uniform intervals based on the unloading time. Of course, the specific time will be adjusted according to the parameters of your local unloading capacity.

For the reconnaissance situation, we have established a reconnaissance model for the dense road traffic network near the capital of San Juan. We have planned an optimal route for 18 B-type drones for reconnaissance so that they can start from Bayamon and fully explore the main roads in the shortest 18.4 minutes. The specific drone trajectory is as follows. The left picture shows the total route map of the drone formation, and the right picture shows some typical route maps.



Finally, we need to emphasize that the results of the model are based on the assumption that the drug demand is 2 months. If the demand for drugs is significantly increased, our model will not be able to carry enough drones to transport medicines at each location. In this regard, we give two trade-offs for your reference.

If you give priority to medicine delivery, we recommend changing the location to San Pablo, San Juan, and Arecibo. We recommend using F-type drone to deliver medicines from San Pablo to Bayamon. For the rest space, load type B drone as many as possible. In this way, at the expense of reconnaissance capabilities, the drug can be delivered to the designated location as much as possible. As for Arecibo, the situation remains the same.

If you want to get quick access to the main road traffic information, we recommend that the container shipping points be still Fajardo, Bayamon, and Arecibo. At this point, you may sacrifice San Pablo and San Juan's drug supply, carry as many B-type drones as possible, in order to return the ground information as soon as possible. We believe our system is able to conduct both medical supply delivery and video reconnaissance of road networks.

Thank you for your consultation.

Sincerely,
Team#1900068

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Appendix

Program

```
#include <iostream>
#include <vector>
#include <math.h>
#include <algorithm>
#include <time.h>
#include <cstdlib>
#include <Windows.h>

using namespace std;

class drone {
public:
	int cur_x, cur_y;
	double rest_dis;
	bool over;
	vector<int> route;
};

int drone_num = 18;
drone fleet[18];
double farest = 52.6;
int dir[8][2] = { { -1, 0 },{ -1, 1 },{ 0, 1 },{ 1, 1 },{ 1, 0 },{ 1, -1 },{ 0, -1 },{ -1, -1 } };
int start[2] = { 19, 22 };
int map[51][51];
int alpha_return = 1;
vector<vector<int> > waitList;


bool safe(int x, int y)
{
	if (x >= 0 && x <= 50 && y >= 0 && y <= 50)
		return true;
	else
		return false;
}

double judge_new(drone t, int x2, int y2)
{
	if (!safe(x2, y2)) return -2;
	bool can_return = 0;
```

```
    double dis = sqrt((t.cur_x - x2) * (t.cur_x - x2) + (t.cur_y - y2) * (t.cur_y - y2));
    if (t.rest_dis - dis - alpha_return >= sqrt((start[0] - x2) * (start[0] - x2) + (start[1] - y2) * (start[1] - y2)))
can_return = 1;

    double weight = 0;
    if (map[x2][y2] == 1)
        weight = 0.7;
    else if (map[x2][y2] == 0)
        weight = 0.16;
    else weight = 0.2;

    double v = 0;
    for (int i = 0;i < waitList.size();i++)
    {
        int m = waitList[i][0];
        int n = waitList[i][1];
        double d = sqrt((x2 - m) *(x2 - m) + (y2 - n) * (y2 - n));
        v = v + 1.0 / d;
    }
    if (can_return == 1) return weight * v;
    else return -1;
}

int best_move_dir(int map[51][51], drone t)
{
    int cur_x = t.cur_x;
    int cur_y = t.cur_y;
    vector<double> value;
    for (int i = 0;i < 8;i++)
    {
        int x2 = cur_x + dir[i][0];
        int y2 = cur_y + dir[i][1];
        double v = judge_new(t, x2, y2);
        value.push_back(v);
    }
    vector<double>::iterator max = max_element(begin(value), end(value));
    if (*max == -1) return -1;
    else
    {
        int max_dir = distance(begin(value), max);
        if (cur_y + dir[max_dir][1] < 22) return 2;
        else return max_dir;
    }
}
```

```
void move(int map[51][51], drone& t, int move_dir)
{
	int mx = dir[move_dir][0];
	int my = dir[move_dir][1];
	t.cur_x = t.cur_x + mx;
	t.cur_y = t.cur_y + my;
	if (map[t.cur_x][t.cur_y] == 1)
	{
		for (int i = 0;i < waitList.size();i++)
		{
			if (waitList[i][0] == t.cur_x && waitList[i][1] == t.cur_y)
			{
				waitList.erase(waitList.begin() + i);
				break;
			}
		}
	}
	map[t.cur_x][t.cur_y] = 0;
	double move_dis;
	if (mx * my == 0) move_dis = 1;
	else move_dis = sqrt(2);
	t.rest_dis = t.rest_dis - move_dis;
	t.route.push_back(move_dir);
}

double print_route(drone* fleet)
{
	double longest = 0;
	for (int i = 0;i < drone_num;i++)
	{
		if (farest - fleet[i].rest_dis > longest)
			longest = farest - fleet[i].rest_dis;
		cout << "fleet " << i << ": ";
		for (int j = 0;j < fleet[i].route.size();j++)
			cout << fleet[i].route[j] << ", ";
		cout << "rest route: " << fleet[i].rest_dis;
		cout << endl;
	}
	return longest;
}

void initialize()
{
```

```
    for (int i = 0;i < drone_num;i++)
    {
        fleet[i].cur_x = 19;
        fleet[i].cur_y = 22;
        fleet[i].rest_dis = farest;
        fleet[i].over = 0;
    }

    map[15][32] = 1;
    map[16][32] = 1;
    map[17][32] = 1;
    map[18][32] = 1;
    map[20][32] = 1;
    map[14][33] = 1;
    map[18][33] = 1;
    map[19][33] = 1;
    map[14][34] = 1;
    map[18][34] = 1;
    map[19][34] = 1;
    map[19][35] = 1;
    map[14][35] = 1;
    map[18][34] = 1;
    map[15][36] = 1;
    map[16][36] = 1;
    for (int j = 0;j < 51;j++)
    {
        for (int i = 0;i < 51;i++)
        {
            if ((j == 34 && (i >= 33 && i <= 37)) || (j == 35 && ((i >= 31 && i <= 33) || (i >= 27 && i <= 29)))
|| (j == 34 && ((i >= 29 && i <= 37) || (i == 27))) ||
                (j == 33 && (i == 26 || i == 27 || i == 31 || i == 30)) ||
                (j == 32 && (i == 26 || i == 30 || i == 29)) ||
                (j == 31 && (i >= 16 && i <= 26 || i == 29)) ||
                (j == 30 && (i == 16 || i == 28 || i == 29)) ||
                (j == 29 && i == 28) || (j == 28 && ((i >= 25 && i <= 28) || (i >= 19 && i <= 20))) || (j == 27
&& (i >= 18 && i <= 25))
                ) map[i][j] = 1;
            if (map[i][j] == 1)
            {
                vector<int> t;
                t.push_back(i);
                t.push_back(j);
                waitList.push_back(t);
            }
```

```
                else map[i][j] = -1;
            }
        }
}

int main(void)
{
        double aver = 0;
        initialize();
        for (int k = 0;k < 500;k++)
        {
                int rest_num = drone_num;
                int iter = 0;
                while (rest_num != 0 && waitList.size() != 0)
                {
                        Sleep(1000);
                        srand((unsigned int)time(0));
                        for (int i = 0;i < drone_num;i++)
                        {
                                if (!fleet[i].over)
                                {
                                        if (fleet[i].route.size() < 2)
                                        {
                                                int dir;
                                                dir = rand() % (4 - 0 + 1);
                                                move(map, fleet[i], dir);
                                        }
                                        else
                                        {
                                                int move_dir = best_move_dir(map, fleet[i]);
                                                if (move_dir == -1) //结束探查，返回出发点
                                                {
                                                        fleet[i].over = 1;
                                                        rest_num--;
                                                        cout << "fleet " << i << " is run out of fuel." << endl;
                                                }
                                                else
                                                        move(map, fleet[i], move_dir);
                                        }
                                }
                        }
                        print_route(fleet);
                        cout << waitList.size();
                }
```

```
        double longest = print_route(fleet);
        if(waitList.size() != 0) cout << "waitList:" << waitList.size() << endl;
        aver += double(longest / double(79.0 / 60));
    }
    cout << "average time:" << double(aver / 500.0) << endl;
    getchar();
    return 0;
}
```