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A DroneGo Disaster Relief Response System

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Abstract: To support the Puerto Rico hurricane disaster scenario, we develop a DroneGo disaster response system by establishing the following models. First, we establish a location analysis model for ISO containers based on the coverage of video reconnaissance and the priority comparison between the two required missions–medical supply delivery and video reconnaissance. According to the locations of 11 harbors in Puerto Rico, we select three suitable harbors to position three cargo containers called CON 1, 2 and 3 to conduct the missions. Second, we build two packing configuration models to design the packing configuration for containers. In one model, we recommend a drone fleet for CON 1 and 3 according to reconnaissance conditions, and then put drones into containers in order. In another model for CON 2, we determine the type of drones according to the medical supply demands of hospitals. For both models, the number of drones of each type is determined by the enumeration method and the packing placement is determined by the greedy algorithm. The algorithms are coded in Visual C++ and MATLAB. The computational results show that the space utilizations for the three containers are all above 80.8%. Third, we design a drone flight plan model based on graph theory. According to the time and space constraints of drones, we devise flight plans as well as delivery routes and schedule. The computational results show that the coverage of video reconnaissance is up to 70.1%. Finally, we carry out the error and sensitivity analysis, discuss the strengths and weaknesses of our models, and design the future work. In addition, a two-page memo that summarizes our modeling results, conclusions, and recommendations is given at the end of the paper.

Keywords: Location Analysis Model; Packing Configurations Model; Flight Design Model; Enumeration; Greedy Algorithm

1. Introduction

1.1 Restatement of the problem

The United States suffered the worst natural disaster in history in 2017, including hurricane Maria hitting Puerto Rico. In this disaster, the electric system, the cellular communication networks and roads were destroyed seriously. Furthermore, with the increasing of the affected population, demands for medical supplies and lifesaving equipment increased sharply..

Hence, we are asked to improve response capabilities of HELP, Inc.—a non-governmental organization (NGO)—by designing a transportable disaster response system called "DroneGo". And it needs to perform following missions simultaneously or separately, depending on relief conditions and scheduling:

(1) Medical supply delivery

(2) Video reconnaissance

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The types and dimensions of potential candidate drones, dry cargo containers under ISO standard, drone cargo bays, emergency medical packages (MED) and anticipated medical package demand are given. We are asked to develop a DroneGo disaster response system to meet the requirements of the Puerto Rico hurricane scenario, including:

(1) Recommend a combination of a drone fleet and set of medical packages. Design the associated packing configuration for each of the three ISO cargo containers to transport the system to Puerto Rico.

(2) Identify the best location or locations of the three cargo containers in Puerto Rico.

(3) For each type of drone included in the DroneGo fleet:

a) Provide the drone payload packing configurations, delivery routes and schedule.

b) Provide a drone flight plan, which can enable the fleet to use on-board video cameras to assess the major highways and roads.

(4) Write a 1–2 page memo to the Chief Operating Officer of HELP, Inc. to summarize our modeling results, conclusions, and recommendations.

1.2 Our approaches

To solve the problem, we need to point out some conditions implied in the question as shown below:

(1) The position relationships between containers, drones, bays and MED are shown in the **Figure 1.** Note that cargo bays are affixed to the drone;

(2) Containers equipped with emergency disaster response systems are transported by sea to one or more ports in Puerto Rico;

(3) Drones cannot be recharged after usage. Because the storm, with its fierce winds and heavy rain, knocked down 80 percent of Puerto Rico's utility poles and all transmission lines. At the same time, the flying distance is limited;

(4) The drone H is a tethered aerial communications system designed to provide continuous, long duration operation and enables reliable long-distance communications. So, it cannot perform the missions including delivering packages and video reconnaissance.

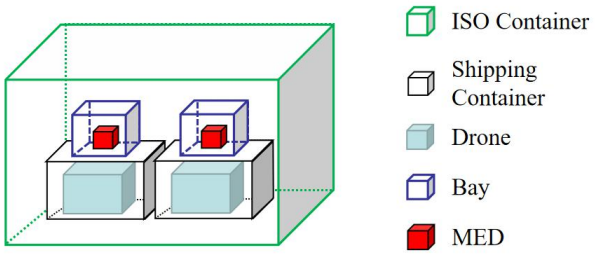

Figure 1. The relationship of the positions between container, drone, bay and MED.

Based on the conditions above, we analyzed the problems and consulted several literature, and then come up with the following approaches:

According to the location of harbors in Puerto Rico and the priority comparison of two missions, we design a location analysis model for three containers.

(1) we build two packing configuration models to design the packing configuration for containers and drones, and obtain the coverage of reconnaissance solving these models.

(2) we design a drone flight plan model based on graph theory. And we obtain flight plans as well as delivery routes and schedule.

(3) Based on models we design, we write a 2-page memo to CEO of HELP, Inc. for introducing the modeling results, conclusions, and recommendations.

2. Symbol

Symbol	Definition	Unit
x_i	The minimum quantity of drones in CON_i, i = 1,2,3	
y_i	The total number of medical packages in CON_i, i = 1,2,3	
L	The length of the standard ISO container	in
W	The width of the standard ISO container	in
H	The height of the standard ISO container	in
L_i	The length of MED_i, i = 1,2,3	in
W_i	The width of MED_i, i = 1,2,3	in
H_i	The height of MED_i, i = 1,2,3	in
s_1, s_2	The quantity of drone B and F	
k	The quantity of MED 1	
l	The quantity of MED 2	
t_1, t_2	The number of drones E and G	
a_1, b_1, c_1	The number of MED1, MED2 and MED3 on drone E	
a_2, b_2, c_2	The number of MED1, MED2 and MED3 on drone G	
z	The cargo capability of drone G	
z_1, z_2	The maximum utilization rate of drones E and G	

Table 1. Symbol table–variables

3. Assumptions with justifications

We make the following assumptions about the whole process to obtain better model results.

3.1 Assumptions about drones

(1) The malfunction of drones is not taken into account, because the time and degree of the drone malfunction are uncertain and there is a slim chance that it will happen. Therefore, it is difficult and unnecessary to discuss the malfunction.

(2) Ignore the velocity influence on drones generated by medical package when transporting. Because each drone carries a different number of packages with small weight. And it is difficult to measure the impact of package weight on the speed of drones.

(3) The influence of flight altitude on video reconnaissance clarity, flight time and flight distance is not taken into account. It is known that the drone can provide high-resolution aerial video reconnaissance but the exact resolution value is uncertain. Another reason is that the flight distance and time are affected by many factors, and flight altitude will not have a significant impact on them.

(4) The impact of storm on drones is not taken into account, because it is difficult for drones to confirm the specific time and area of storm and avoid it after taking off.

(5) Round trip issues are not considered, because charging is not possible when there is terrible storm destroying 80 percent of Puerto Rico's utility poles and all transmission lines.

3.2 Assumptions about containers

(1) We assume the contents of the container can be placed at will without restrictions of forward or reverse placement. There are buffer materials that can protect drones and medical packages in the container. And it can

make the most efficient use of the space in this way.

(2) Assume one drone H is enough for the entire Island according to the communication capacity of H.

4. The models and results

We develop a DroneGo disaster response system to meet the requirements of the Puerto Rico hurricane scenario. We devise models to design five parts in the system including the best location of container, the optimal design of the drone fleet and MED, the packing configurations for the medical packages and the drone cargo bay, the system and the ISO dry cargo container, the plans of routes and a drone flight plan for video reconnaissance as well as schedule. These parts are mutually conditioned. The establishment and solution of our models are as follows.

4.1 The location analysis model for ISO containers

Considering the less constrains of location selecting, we begin by seeking to the suitable locations for containers, where the drone takes off. We design a location analysis model for containers.

4.1.1 Candidate locations

Since containers can only be transported by sea, the candidates have to be set at harbors in Puerto Rico. There are 11 harbors[1] in Puerto Rico which are marked in the world map (as shown in **Figure 2**).

In **Figure 2**, we label the harbors[2,3] as 1-11 and label the delivery location as ①-⑤ in turn. There, three hospitals marked as ①, ③, and ⑤ are located at the same cities with the harbors marked as 1, 2, 3. Besides, we divide the area of Puerto Rico into the zone I-IV for further analysis.

Figure 2. The harbors and delivery locations.

4.1.2 The analysis of the harbors

Taking the two missions of drones including medical supply delivery and video reconnaissance into account, there are some evaluation criteria such as the priority comparison between two missions and the coverage of reconnaissance to select suitable locations. Here we definite reconnaissance coverage as a circular area, with the location of the container as the center and the maximum flight distance as the radius.

The width and length of the island is 56 km and 142 km. The maximum flight distance among drones is about 52 km. So, it is necessary to choose two container locations in the left and right of the island respectively for video reconnaissance.

First, according to the states of the hurricane that struck the United States territory of Puerto Rico in 2017, the combined destructive power of the hurricane's storm surge and wave action produced extensive damage to buildings, homes, and roads, particularly along the east and southeast coast of Puerto Rico. Thus, we think that the roads destruction of the area IV are more terrible than that of other areas. Besides, there are no hospitals located in the area. Therefore, the mission video reconnaissance has thorough priority over medical supply delivery. We need select a harbor from 10 or 11 as a container location. And the harbor 11 cannot be in use because it is located at the southeast coast suffering extensive damage. So, we identify the harbor 10 as one of the locations to an ISO container called CON 1.

Second, there are four delivery hospitals located in the area I, which need many medical packages. Thus, the mission of medical supply delivery has thorough priority over video reconnaissance as for the area I. We need to select a container location here.

It is clear that there are only two harbors in the area I. Compared with harbor 1, harbor 2 has a shorter distance to other three hospitals. Besides, the reconnaissance coverage of the harbor 2 is larger than

other harbors. In a word, we identify the harbor 2 as one of the suitable locations to an ISO container called CON 2.

Third, on consideration of area II and III, there is only one hospital marked ⑤ lying at the harbor 3 and a large area covered by roads which form a complicated road network. So, it is required to choose a container location in the area II or III. Harbor 3 is nearer to hospital and has a larger reconnaissance coverage than other harbors in the area II or III. Therefore, we identify the position of harbor 3 as one of the suitable locations to an ISO container called CON 3.

From the above discussion, we get the locations for the three ISO containers, which are shown in **Table 2** and **Figure 3.**

Location	Latitude	Longitude
CON1	17.97	-66.11
CON2	18.44	-66.07
CON3	18.47	-66.73

Table 2. The latitude and longitude of the container locations

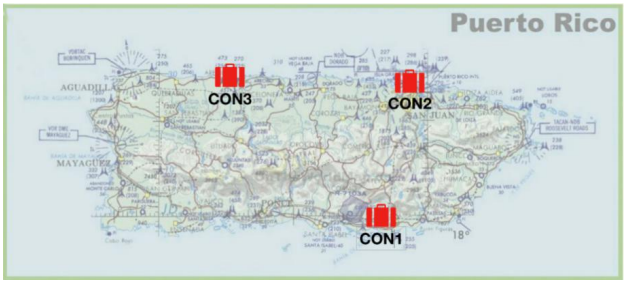

Figure 3. The suitable locations of the container.

4.2 The configuration models

If we need to choose the suitable drone type, then we can begin by excluding some options by analyzing comparison between the maximum payload quantity, occupied space and maximum flight distance. Next, we can configure the drone fleet and medical packages of each hospital in turn, taking the storage capacity of containers and delivery distance into account. Note that round trips are not considered because charging is not possible.

4.2.1 The comparison among different drones

First, by analyzing the characteristics of the potential candidate drones for DroneGo fleet consideration, we obtain the space occupied by drone and the maximum flight distance which are listed in **Table 3**. Note that the drone H is used to communicate but delivery and reconnaissance, so it's unnecessary to consider the characters of H.

Type	A	B	C	D	E	F	G
Max flight distance (*km*)	23.33	52.66[a]	37.33	18	15	31.6	17
Occupied Space ($in.^3$)	66825	32400	150000	19500	23500	72000	37888

Table 3. The type, max flight distance (*km*) and occupied space ($in.^3$) for drones A-G. [a] the maximum flight distance among seven drones.

Then, based on the data given, we calculate the maximum payload quantities for drones A-G according to the following steps:

(1) Consider that each drone carries only the medical package called MED 1.

(2) Based on the weight constraints that each drone has suited drone cargo bay and corresponding maximum payload capability, we can obtain the maximum number

of MED 1 loaded by each drone.

(3) By analyzing the data calculated above, we find that weight constrain is stronger than dimension constrain.

(4) We figure out the maximum number of MED 1 by drones B and D based on the dimension constraint.

(5) Make similar analysis according to steps 1-4 for MED 2 and MED3, respectively. The results are reported in **Table 4**.

Drones			Max quantity (weight)			Max quantity (dimension)		
Type	DCBT	MPC (lbs.)	MED1	MED2	MED3	MED1	MED2	MED3
A	1	3.5	1	1	1			
B	1	8	2	4	2	4	4	2
C	2	14	7	7	4			
D	1	11	2	4	2	5	5	3
E	2	15	7	7	5			
F	2	22	11	11	7			
G	2	20	10	10	6			

Table 4. The max quantity of medical package based on weight or dimension constraints (DCBT represents the drone cargo bay type and MPC represents the maximum payload capability)

In **Table 4**, DCBT is drone cargo bay type and MPC is max payload capability.

Then, exclude some options by analyzing comparison between the maximum payload quantity, occupied space and max flight distance according to the following steps:

(1) Compare drone A and drone B. We can observe that drone A occupies more space, but has shorter flight distance and weaker max payload capability. Therefore, we exclude drone A from the candidate drones.

(2) By comparing drone C with F, it is found that they have similar flight distance, but drone C has weaker max payload capability and occupies more space. Thus, we think that drone F can completely replace drone C.

(3) By comparing drone D with E, it is found that they have similar flight distance and occupied space, but drone D has weaker maximum payload capability. Therefore, we think that drone E can completely replace D.

(4) Because drones B, E, F, and G have their own pros and cons, they cannot be excluded. The final results are reported in **Table 5**.

Drones			Max quantity (weight)		
Type	DCBT	MPC (lbs.)	MED1	MED2	MED3
B	1	8	2	4	2
E	2	15	7	7	5
F	2	22	11	11	7
G	2	20	10	10	6

Table 5. The potential drone type selection to carry packages (DCBT represents the drone cargo bay type and MPC represents the max payload capability)

And then we recommend a drone fleet and set of medical packages to meet the requirements of the Puerto Rico hurricane scenario.

4.2.2 The packing configuration of medical package

After analyzing the data, we can find that

$$\begin{cases} L_1 \geq \max(L_3, W_3, H_3) \geq \max(L_2, W_2, H_2) \\ W_1 \geq \mathrm{mid}(L_3, W_3, H_3) \geq \mathrm{mid}(L_2, W_2, H_2) \\ L_1 \geq \min(L_3, W_3, H_3) \geq \min(L_2, W_2, H_2) \end{cases} \quad (1)$$

where, L_i, W_i, H_i is the length, width and height of MED$_i$ respectively.

It shows that the volume of MED 1 is the largest among the three volumes. And then we have calculated

the maximum number of MED 1 for each drone (M). We determine num as the number of packages that we want put into a drone. If $num \le M$, then those packages meet dimension constrain of the drone. As long as the packages meet weigh constrain of the drone, they can be put into the drone entirely. Hence the way placing medical packages into drone is readily available, it is no longer listed separately.

4.2.3 The configuration model of CON 1 and CON 3

As for the areas II and III, it is clear that the mission for reconnaissance has thorough priority over medical supply delivery, because the container and the hospital are at the same city. So, we can ignore the time that the drone carrying medical packages flies from harbor 3 to hospital ③, which means that all drones in CON 3 can be used for video reconnaissance.

Hence, we infer that all drones in CON 3 are drone B considering the minimum supply demand and relatively large reconnaissance demand. We use x_i to determine the minimum quantity of drones and y_i to determine the total number of medical packages in CON_i, where i = 1,2,3.

Since cargo bay 1 is fixed on the top of drone B, we think the two as a whole (i.e. a cuboid). The length is 30 inches, the width is 30 inches and the height is 36 inches.

Then we sign the length, width, height of the standard ISO container as *L, M, H* in turns. That is $L = 19'3" = 231\,in.; W = 7'8" = 92\,in.; H = 7'10" = 94\ in.$ If placement of all cuboids is in the same way (i.e. the most regular arrangement), then x_3 = 54. The space utilization rate of CON 3 is

$$\frac{30\times30\times36\cdot x_3}{L\cdot W\cdot H}\times100\%=\frac{30\times30\times36\times54}{231\times92\times94}\times100\%=87.6\%$$

We know that each drone B can carry two MED 1 from **Table 4**. Consequently, we get the total number of MED 1, that is

$$y_3 = x_3 \cdot 2 = 108$$

These medical packages can support Hospital Pavia Arecibo for 108 days.

Basing on our greedy thought and combining drone style, we need to put B into it in a standardized way. We already know that CON 1 can hold 54 B. Therein, six MED 1 can be arranged in the long direction of the container. Similarly, three MED 1 can be arranged in the wide and high direction of the container. That is payload packing configuration of drone B.

There is no hospital in area IV, so there is no need for CON 1 to be equipped with medical packages. It is loaded in the same way as CON 3. However, a drone H needs to be loaded by CON 1 to help video the road networks because of the worst damage.

We also already know that it is more than enough for two drone B's space to be replaced by drone H's, this is an inevitable event. Therefore, we pack drone B and drone H in CON 1 in the same way as CON 3. Therein, H replaces two drone B. That is, there are one drone H and 52 drone B in CON 1. That is payload packing configuration of drone B.

4.2.4 The configuration model of CON 2

Then, we design the combination of the drones in CON 2. The main task of drones is to deliver medical packages for four hospitals. The steps are as follows:

(1) Measure the distance between these hospitals according to latitude and longitude as shown in the **Figure 5.**

(2) Determine the configuration of the drone flying to hospital ①.

We can get the distance between hospitals ③ and ① that is about 46 km, which is larger than the maximum flight distance of many drones. The drone B is the only drone can fly from hospital ③ to hospital ①. So there are several drone B flying to ①, carrying with MED 1 and MED 3. Hence, there is only a drone B flying to hospital ① every day. The supporting days are 5.

(3) Determine the configuration of the fleet flying to hospital ②.

Similarly, we can get the distance between hospital ③ and hospital ② about 25 km. So, the feasible drone is drone B or drone F.

Most importantly, the most efficient allocation is that drones flying to ② carries MED 1 and MED 3 based on the percentage of hospital's demand. We can begin by designing the configuration of drone B, and then design drone F.

We determine the number of MED 1 and MED 3 in a drone B as *m, n*. For filling the cargo space fully, there are only three configuration ways:

• $m = 2,\ n = 0;$ • $m = 1,\ n = 1;$ • $m = 0,\ n = 2.$

Then we sign the quantity of drone B, F as S_1, S_2,

and sign the quantity of MED 1, MED 2 in drone F as *k, l* respectively.

If $m = 2$ and $n = 0$, then $\frac{2S_1 + kS_2}{lS_2} = 2$;

If $m = 1$ and $n = 1$, then $\frac{S_1 + kS_2}{lS_2 + S_1} = 2$;

If $m = 0$ and $n = 2$, then $\frac{kS_2}{lS_2 + 2S_1} = 2$.

Then we obtain the locally optimal solution by using the enumeration method and Visual C++ as listed in **Table 6**.

Result / (m,n)	S_1	S_2	k	l	Space utilization
(2,0)	2	1	2	3	59%
(1,1)	4	1	6	1	68%
(0,2)	1	1	6	1	100%

Table 6. The locally optimal solution and space utilization

We calculate the space utilization rate of drone F on the three results, that are 59%, 68%, 100%. It is clear that when $m = 1$ and $n = 1$, the result is optimal which is listed below:

Drone type	The number of drones	The number of MED 1	The number of MED 2
B	1	0	2
F	1	6	1

Table 7. The optimal configuration flying to hospital ② of CON 2

(4) Determine the configuration of the drones flying to hospital ③.

Because the main task of drones in CON 2 is delivering medical packages and the distance between ③ and CON 2 is short, we choose E and G which have shorter distance. Besides, we get the result imitating the same method as 3. We select G to deliver for ③ and each G load 5 MED 1 and 5 MED 2. And there is only a drone G flying to hospital ③ totally. The supporting days are 5.

(5) Determine the configuration of the fleet flying to hospital ④.

Hospital ④ needs two MED 1, one MED 2 and two MED 3 daily, which is the maximum demand among ones of five hospitals. Besides, the distance between hospitals ③ and ④ is 10 km, which is shorter than the maximum flight distance of any drone.

Among the four drones in **Table 2**, we know that drone G and drone F have similar cargo capacity which is larger than others. But drone G has smaller occupied space and longer flight distance than drone F. So, we choose drone G between drones G and F.

Similarly, among drones B, E and G, we find that drone B has larger occupied space and lower cargo capacity than drones E and G. So, drone B is not an optimal drone. As drones E and G have similar characteristics and same function, we determine drones E and G as parts of our drone fleet.

Notations about equation set are as follows:

(1) t_1, t_2: The number of drones E and G;

(2) a_1, b_1, c_1: The number of MED 1, MED 2 and MED 3 on drone E;

(3) a_2, b_2, c_2: The number of MED 1, MED 2 and MED 3 on drone G;

(4) z: The cargo capacity of drone G;

(5) z_1, z_2: The maximum utilization rate of drones E and G.

Then we think that it is unreasonable that the maximum utilization rate is less than 50% for a plan. We follow the rule of equal proportion, listing the following equation set:

$$\begin{cases} (a_1t_1+a_2t_2):(b_1t_1+b_2t_2):(c_1t_1+c_2t_2)=2:1:2 \\ 0.5\times 15\le 2a_1+2b_1+3c_1\le 15 \\ 0.5\times 20\le 2a_2+2b_2+3c_2\le 20 \\ a_1\le 7, b_1\le 7, c_1\le 5 \\ a_2\le 10, b_2\le 10, c_2\le 6 \end{cases} \quad (2)$$

We get the solution by programming in MATLAB with the enumeration method, the packing configurations of the fleet flying to hospital ④ are listed in **Table 8**.

t_1	t_2	a_1	b_1	c_1	a_2	b_2	c_2	z	z_1	z_2
1	2	2	2	2	3	1	3	0.87	0.93	0.85

Table 8. The solution of equation set (2)

(6) The packing model for CON2 based on greedy algorithms

Packing medical packages into cargo bays is a NP-hard problem[4]. It is difficult to find the optimal solution for large-scale data in practical application[5]. However, we can begin by estimating the volume but size to solve the specific problem in this paper. Under normal conditions in packing, we always try to put boxes with the same size and in larger quantities together, for reducing empty space. And we will consider whether we can put another size of box in the remaining space. That is the basic rule of greedy algorithm[6,7].

We obtained that there is a combination of 6 drones B, 1 drones E, 1 drones F and 3 drones G in CON 2. It's the most complex among containers, so we solve it at the first. If CON 2 can load four drone combinations calculated above at once, then the loading rate has reached 80.8%. It is enough excellent. Next, we just need to think about how to implement the scenario. The following is specific steps:

We put drone B into container firstly. The height of the container is three times as long as the length of drone B. So, we can divide 24 drones into three equal parts and place them in CON 2.

And we can see that the sum of twice the width of drone B and twice the width of drone C equals the width of the container.

Drones G, E and F are all placed according to the same method. Finally, we obtain the view of the container as follows.

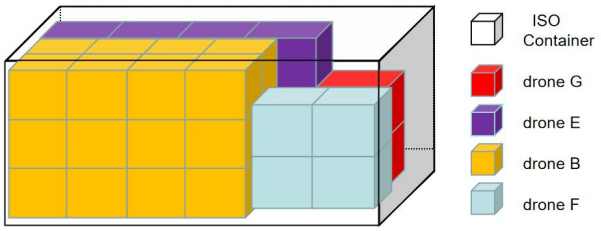

Figure 4. The configuration of CON 2.

In **Figure 4**, there are 4 drones F, 24 drones B, 4 drones E and 12 drones G. Notice that 12 drones G are evenly divided into two layers, arranged in the innermost part of the container.

4.3 The drone flight plan model

In this section, we build a drone flight plan model to list the specific delivery routes, reconnaissance plan and schedule based the models above.

4.3.1 The delivery route and the reconnaissance plan

The road map calculated according to the drone and container configuration is shown below:

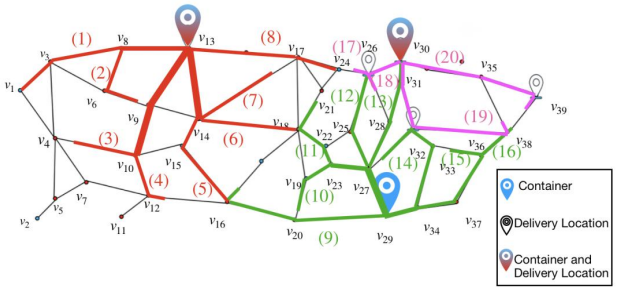

Figure 5. Flight plan.

In **Figure 5**, the routes include delivery routes and reconnaissance routes. The green, pink and red lines represent flight routes from CON 1, CON 2, CON 3 respectively.

The following is delivery route and reconnaissance plan at a time (i.e. a day).

CON / Object	CON 1	CON 2					CON 3
Drone (one day)	8B	1B	1 B	1F	1E	2G	8B
Medical supply delivery route	None	(20)	(19)	(19)	(17)	(18)	CON 3→⑤
Video reconnaissance routes	(9),(10),(11),(12),(13),(14),(15),(16)	(20)	(19)	None	(17)	(18)	(1),(2),(3),(4),(5),(6),(7),(8).

Table 9. The medical supply delivery route at a time

Video reconnaissance of road networks' routes:

By comparing the length of our routes with all routes in Puerto Rico, we can obtain the reconnaissance coverage rate R:

$$R = \frac{755}{1077} \times 100\% = 70.1\%$$

4.3.2 The medical packages delivery schedule

We know how often hospitals need emergency medical packages. To balance the requirements of hospital and video reconnaissance of damaged and serviceable transportation road networks, we make a schedule on considering of meeting the requirements of hospital timely and videoing the road networks as many times as possible. So, we let drones deliver medical packages once time a day.

CON / Object	CON 2				CON 3
Hospital	①	②	③	④	⑤
Drone (one day)	1B	1B and 1F	1G	1E and 2G	8B
Medical supply delivery route	(20)	(19)	(17)	(18)	CON 3→⑤
Delivery days	5	4	5	4	7

Table 10. The medical packages delivery schedule

5. The testing of the model

5.1 Error analysis

In this part, we will analyze the factors that may cause the error of the solution. Many factors will influence the DroneGo disaster relief response system, including the outside environment factors, the system and constrain relationships among objects. In addition to

the influencing factors, the approximation and fitting used in the model building process, as well as the algorithm in the solving process will also bring errors.

5.1.1 Factors of system

(1) Storm

In the Puerto Rico hurricane and potential disaster scenario, storms will disrupt drone operations. However, our system is designed under ideal conditions without considering storm. The fight plan we devised may not be fully realized.

(2) Geographical environment

The terrain and topography will affect the flight altitude of drone, but the errors cannot be estimated because we don't know the specific characteristics of drone.

(3) Effect of cargo loading on velocity and time of drone

Payload will release velocity of drones, but the velocity given is flight time without cargo. That will bring errors.

5.1.2 The Error in modeling and solving process

In the process of abstracting the road network, we turn the curve into straight, which will lead to errors in the calculation of reconnaissance coverage. However, considering that drone can shoot at high altitude, the curvature of the road has little effect on reconnaissance, so the error is small.

5.2 Sensitivity analysis

Some inputs of our model may be hard to be obtained or there may be some deviation in our inputs. So, it's possible that these kinds of situation will influence the solution of our model. To understand the situations above, we implement a sensitivity analysis to test the robustness of our model. The analysis results show that our model does not exhibit a chaotic behavior and shows good sensitivity.

Our sensitivity analysis will be based on factor variation method, in order to see how the result (include supporting days and reconnaissance coverage rate) of the model changes when the input parameters change. Because the drones and MED in CON 1 and CON 3 are mainly used to video reconnaissance and ones in CON 1 are evenly used to the two missions, we will analyze the following parameters:

(1) The number and ratio of different drones in CON 1 and CON 3 (P1).

(2) The number and ratio of different drones and medical packages in CON 2 (P2).

We have obtained the optimal solution of the model. We will use it as a contrast to do sensitivity analysis. The parameters of the optimal solution are set as follows.

Hospital	①	②	③	④	⑤
Supporting days	5	6	5	4	108
***R* (Reconnaissance coverage rate)**	70.1%				

Table 11. The optimal solution

5.2.1 Sensitivity to the P1

We change parameter 1, and observe the changes of supporting days of CON 3 and reconnaissance coverage rate. The sensitivity of P1 by calculation is obtained, as shown below:

P1	-5%	-2%	0%	2%	5%
Supporting days	-2.58%	0.12%	0%	1.33%	2.87%

Table 12. Sensitivity of P1 for supporting days of CON 3

P1	-5%	-2%	0%	2%	5%
R	-7.23%	-4.17%	0%	3.56%	5.27%

Table 13. Sensitivity of P1 for reconnaissance coverage rate

We can see that the support days of CON 3 are positively correlated with the number and ratio of different drones.

We can see that the support days of CON 3 is very

sensitive to the parameters of different drones in the context of ±5%. It proves that the model we established is suitable for various drones and it is more relevant to drone number parameters. On the other hand, the supporting days of CON 3 is not very sensitive to the parameters of drone. But we can understand that it has great changes in the context of ±3% by analyzing the data. That is to say, the drone type cannot change too much, which shows that our model can produce good result.

5.2.2 Sensitivity to the P2

Observe the influence of the number and ratio of different drones and medical packages in CON 2 on the optimal strategy.

P1	-5%	-2%	0%	2%	5%
Supporting days	-6.34%	-3.33%	0%	4.21%	5.25%

Table 14. Sensitivity of P2 for supporting days of CON 2

We can see that the supporting days of CON 2 is very sensitive to the medical packages in the context of ±5%, and there is a positive correlation between them. This is consistent with the common sense and can prove that our model is suitable.

6. Conclusion

6.1 Strengths and weaknesses

6.1.1 Strengths

(1) Our model analyzed map fully, and abstracts the road network ignoring unnecessary factors, making model easy to solve.

(2) This model does a lot of analysis on the data given. It makes the drones plan and schedule as well as configurations accurate.

(3) For the sensitivity of the model, it proves that out model is well adapted to the practical situation.

(4) There are lots of tables and figures in our model, which make the results clear.

6.1.2 Weaknesses

(1) Our model takes too much factors into account, causing the solving process is tedious and the way to solve is difficult.

(2) There are a lot of assumptions about drones because complex environment and unclear problem. Hence, our model needs improvement when used for other situations that differ greatly in background.

6.3 Future Work

(1) The results should be optimized to be more accurate by improving or designing the algorithm and using more computing power. For example, we can improve the greedy algorithm to optimize the configuration.

(2) We can consider more factors such as fight altitude and terrain to generalize our system to different disaster scenarios.

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