For office use only	Team Control Number	For office use only
T1 ________________	**1916842**	F1 ________________
T2 ________________		F2 ________________
T3 ________________	Problem Chosen	F3 ________________
T4 ________________	**B**	F4 ________________

2019

MCM Summary Sheet

Analysis and Optimization of Drone Delivery

Summary

Compared to manned aircraft, unmanned aerial vehicles(UAVs) were originally used for missions too ”dull, dirty or dangerous” for humans. Take the hurricane disaster for example, UAVs can deliver medical supplies under the circumstances that highways and roads are totally damaged and offer urgent help to people who need to be rescued.

We are tasked to assist the company, HELP, Inc. to improve the aerial disaster relief response system and satisfy their requirements of delivering pre-packaged medical supplies and providing high-resolution aerial video reconnaissance.

We develop a **basic model** at first, giving priority to voyage. We only select B-type and H-type drones to both cover the farthest voyage and serve the function of communication. As for site selection, we comprehensively consider the population density, voyage of the drone, terrain and altitude, etc. to locate and select three populated locations. We decide the maximum days for supply, which is 36 days, and applying the methods of linear programming and dynamic planning to arrange the delivery routes and video assessment schedules.

Based on the basic model, in order to supply the hospitals for more days and reduce costs, we establish a drone evaluation system and add the F-type drones. Through the linear programming model, we find that one delivery of three ISO containers can last at least 58 days. As for video reconnaissance, we apply a depth-first search algorithm to determine the reconnaissance route and use a dynamic programming algorithm to determine the battery replacement locations.

Keywords: Aerial disaster relief; liner programming; dynamic planning

Contents

1 Introduction

1.1 Background

In September 2017, Hurricane Maria, a powerful Category 4 hurricane with 150 mph winds, made direct landfall on Puerto Rico, bisecting the entire island and drenching it with feet of rain. In the result, there is limited food and cell service, and dozens of remote villages have been completely cut off from everything, especially the power for weeks. What is worse is that due to the widespread flooding, many highways and roads across the island have been blocked. Thus dozens of areas were isolated and without communication. [1]

The situation is even worse since Puerto Rico is an island, which complicates recovery efforts. Supplies have to be flown in or arrive via ship. So, the Unmanned Aerial Vehicle (UAV) always plays a significant role in the rescue operation. And Non-governmental organizations (NGOs) often provide adequate and timely response during or after natural disasters with the help of UAVs. Thus the problem of how to improve response capabilities can always be a heated issue worldwide.

1.2 Restatement of the Problem

An Overview of the Problem

In order to meet the anticipated medical supply demands during a potential similar future disaster scenario, we have to lower the cost of Dronego and supply the local hospitals as longer as possible.

To sum up, there are three main points of improving the DroneGo disaster response system:

- Different drones have different shipping container dimensions, performance characteristics and configurations capabilities which are vital factors for decision makers to choose from and fit the ISO cargo containers to meet the final requirements;

- In order to solve the best-location problem, factors like geography, population and other related issues should be taken account of;
- Choosing the suitable delivery routes is a multi-objective dynamic programming issue. Meanwhile, the demand of video reconnaissance of road networks should be satisfied at least one time a day.

1.3 Literature Review

To simplify the problem, researchers at first applied Mathematical Programming theory and other Modern optimization methods like Genetic Algorithm (GA) and Simulated Annealing (SA) to solve the first sub-task(A), **the Bin-packing Problem**. [2]The second sub-task(B) can be abstracted into **the Location Problem**. The Location problem often uses several methods like Centroid Method, Analytic Hierarchy, Fuzzy Evaluation Method, Branch and Bound, Tabu Search and Genetic Algorithm [3]. As for the last sub-task(C), some researchers adopted the idea of Hierarchical Programming to convert the problem into **multi-travelling salesman problem**. Then an ant colony algorithm is used to find the optimal path. Based on the optimal path, combined with different traversal, different UAV distribution programs and path combination on time consumption are compared, the program portfolio conforming to time limit is screened out, to provide the best working route and scheduling program for the UAV [4].

1.4 The task at hand

- Construct a mathematical model to meet the medical requirements of the local hospitals;
- Propose modifications to improve the process;
- Clarify the situations when the demand requirements exceed the capabilities of the drone fleet we designed. And state the tradeoffs for implementing solutions to address these shortcomings;
- On the basis of the model, give policy and procedural suggestions to improve the disaster response system ”Dronego”.

2 Model Assumptions and Notations

2.1 Assumptions and Justifications

We will need the following assumptions for our models.

1. Flight time with cargo or no cargo affixed can be seen as totally the same;
2. The maximum flight altitude of every drone is 3km;
3. Every drone has its own **alternative batteries** which are sufficient for one day process and are loaded in the very beginning. And these batteries can only be used to replace the old one at a specific warehouse for batteries, that is, they can not be replaced while flying or on other locations. Also, these batteries can only be loaded during video reconnaissance, not delivering process;
4. Since there are buffer materials for unused space, the medical packages and the individual shipping containers for all drones can both be placed horizontally and vertically in their containers;
5. The ISO cargo containers are packed in a large-sized transport aeroplane and will be transported by the aeroplane. Also, the ISO cargo containers do not have load limitations;
6. The major highways and roads we should access by video reconnaissance only in the area surrounded by the given five locations and the area.
7. Medical packages can only be packed in the cargo bay, that is, medical packages can **not** be packed outside drones.

2.2 Notation

We list in **Table1** symbols and notations used in this paper. Some will be defined later.

Table 1: Notation.

Symbol	Description
N_α	packaging method α of medical in bay
$Y_{ij\alpha}$	the amounts of medical-deliver route of starting location i, ending location j and packaging method α
n	days that the hospitals' supplies are sufficient
K	the amounts of medical packages or drone packages
D_p	the total demand of medical *p* of the given five hospitals
m_{ij}	the total amounts of bays that deliver from location *i* to location *j*
m_i^β	the amounts of drone β in supply location *i*
$e_{i_n j_n}$	the battery power consumed during the flight of location i_n to j_n
$t_{i_n j_n}$	the time consumed during the flight of location i_n to j_n

3 Basic Model of Aerial Disaster Relief Response System

We develop a basic model of the Aerial Disaster Relief Response System at first, giving priority to mileage. Thus the type of drove we chose can cover the farthest distance.

3.1 Design of the Model

We divide the model into three submodels according to the sequence given in the tasks of part A.

- **Packing model**: Includes both the medical packing plan in cargo bay and the drones packing plan in the ISO containers.
- **Site-selection model**: Identifies the best location or locations for drones to conduct both medical supply delivery and video reconnaissance of road networks.
- **Delivering&Assess model**: Provides the medical delivery routes, roads access routes and schedules.

3.2 Submodels

3.2.1 Packing model

We divide the packing model into two parts: packing the drones and packing the medical.

Drone-packing

Before packing the drones, we decide which type of drones we should choose. We choose type B and type H for the reason that drone B owns the farthest flying distances and drone H serves the function of communication[1].

Then we consider the packing solution of drones. We assume that using three ISO cargo containers, one H type drone each ISO container for communication and B type drones as more as possible be the optimal solution. In order to calculate the maximum amounts of B type drones, we use the formula

$$\begin{cases} \max K = \sum_{j=1}^{m} \left(\frac{\sum_{i=1}^{n_j} l_i w_i h_i}{V_j} \right) \\ 0 \leq \ x_j + l_i \ \leq \ L_j \\ 0 \leq \ y_j + w_i \ \leq \ W_j \\ 0 \leq \ z_j + h_i \ \leq \ H_j \end{cases} \tag{1}$$

where *i* is the index of drones and L_j, W_j, H_j are the ISO container's interior length, width and height. x_j, y_j, z_j are the coordinates of drone's left rear corner after packing into the ISO container. And l_i, w_i, h_i are the dimensions of the drone, V_j is the volume of ISO_j.

Medical-packing

Since the cargo bay of drone B is type *1*, so there are six proposals that fit the given medical and cargo bay configurations.

[1] With tethered drones Help, Inc. is able to receive and broadcast overhead coverage of what theyre reporting. Although normal drones can already do this, tethered drones can be equipped with a tether that doubles as a power supply and are able to maintain aerial stability because of it. Also, with tethered drones, GPS navigation isnt required anymore.

The six proposals for one bay are listed in **Table 2**.

Table 2: proposals of packing the medical in bay 1.

index	**medical type**	**amount**
1	medical 1	2
2	medical 2	4
3	medical 3	2
4	medical 1 ; medical 2	1;1
5	medical 1 ; medical 3	1;1
6	medical 2 ; medical 3	1;1

$$\begin{cases} \max n \\ 2*N_1+N_4+N_5 = D_1*n \\ 4*N_2+N_4+N_6 = D_2*n \\ 2*N_3+N_5+N_6 = D_3*n \\ N_1+N_2+N_3+N_4+N_5+N_6 \leq \max K \\ N_1,N_2,N_3,N_4,N_5,N_6 \in Z \end{cases} \tag{2}$$

From the formula above, we have the final amounts of each type of proposals in **Table 8**(8).

3.2.2 Site-selection model

In order to identify the best location or locations, we take the following principals into consideration.

- The locations we choose should reach the demand hospitals as more as possible;
- The distances between the location we choose and the demand hospitals should be as short as possible;
- The locations we choose should satisfy all the medical demands provided;

- The locations that supply the No.4 hospital(Puerto Rico Children's Hospital) should be as more as possible since the demands of No.4 hospital are the largest among the five hospitals;
- The locations we choose should be **populated places** or hospitals provided which is better for receiving the ISO containers and replacing batteries if needed.
- The locations we choose should be **on or close to the major highways and roads** since the part of video reconnaissance should be carried on later.
- Since the flight routes should avoid the plateau which over 3km above sea level, so the locations we choose can not be set on those plateaus.

We simplify the map given and selected the populated locations(the purple ones) which are on the main roads. Also we assume that the locations we choose are to the east of the No.5 hospital and to the west of the No.1 hospital. **Figure 1** is the map we simplified.

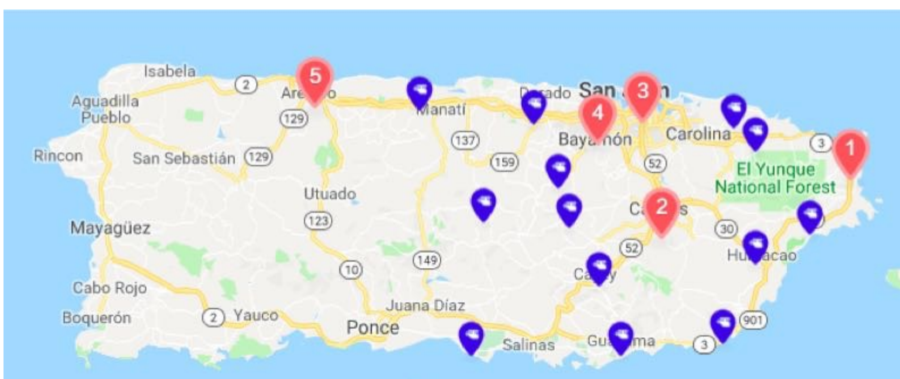


Figure 1: All populated locations

Then we follow the above principles and eliminate the unimportant ones. The populated locations(the purple ones) in **Figure 2** is the ones we selected. And the black circled ones in **Figure 3** are the three final locations we choosed for landing the ISO containers.

Figure 2: Selected populated locations

Figure 3: Best locations

3.2.3 Delivering & Assess model

Delivering process

In order to deliver the medical we loaded as more as possible to the demand hospitals, we list the following constraint conditions.

$$\begin{cases} \max \sum_i \sum_j \sum_\alpha Y_{ij\alpha} \\ 2 * \sum Y_{i51} \leq 3 * n \\ 2 * \sum Y_{i31} + \sum Y_{i34} \leq 3 * n \\ 4 * \sum Y_{i32} + \sum Y_{i34} \leq 3 * n \\ 2 * \sum Y_{i41} + \sum Y_{i44} \leq 6 * n \\ 4 * \sum Y_{i42} + \sum Y_{i44} + \sum Y_{i46} \leq 3 * n \\ 2 * \sum Y_{i43} + \sum Y_{i46} \leq 6 * n \\ 2 * (Y_{711} + Y_{211}) + (Y_{714} + Y_{214}) \leq 3 * n \\ 2 * (Y_{712} + Y_{212}) + (Y_{714} + Y_{214}) \leq 3 * n \end{cases} \tag{3}$$

Taking $2 * \sum Y_{i51} \leq 3 * n$ for example. $\sum Y_{i51}$ means the numbers of the drones which pack medical according to the first pack type (double medical *1*) from all the starting locations to the ending location *5*. Since there are three ISO containers and the demands of location *5* are double medical *1*, *n* days demands should not beyond the medical that three ISO containers could provide. Thus we have the formula

$$2 * \sum Y_{i51} \leq 3 * n. \tag{4}$$

The following formulas constraint that the amount of the delivery medical can not beyond the supply of every ISO landing location.

$$\begin{cases} \sum_j Y_{ij1} \leq N_1 \\ \sum_j Y_{ij2} \leq N_2 \\ \sum_j Y_{ij3} \leq N_3 \\ \sum_j Y_{ij4} \leq N_4 \\ \sum_j Y_{ij5} \leq N_6 \end{cases} \tag{5}$$

Delivery results

We land the ISO containers on location 2,6,7 and arrange drones to deliver medical to locations from one to five and finish all the delivery task on the first day. **Figure 4** is the histogram of demand hospitals and their supplied days. We

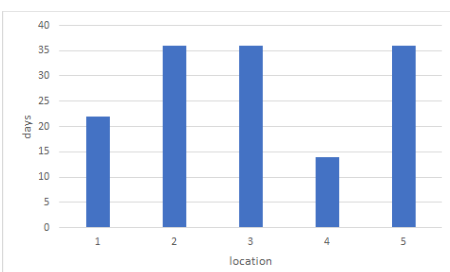


Figure 4: supplied days (before)

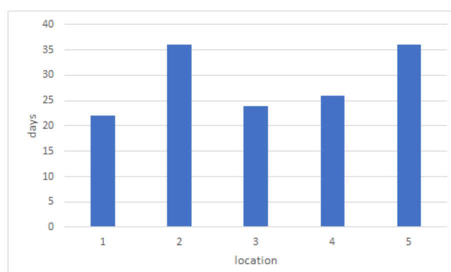
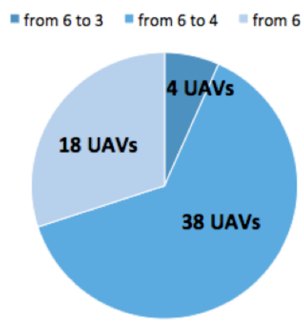


Figure 5: supplied days (after)

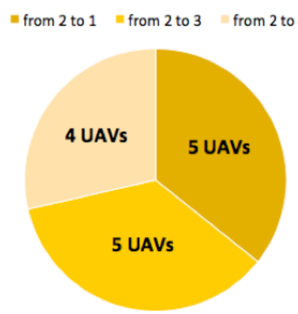
devised the supply for location *4* and *5* to increase the shortest supplied days among the five hospitals and display it in **Figure 5**.

We also obtain the delivery scheme in **figure 6**, **figure 7** and **figure 8**.



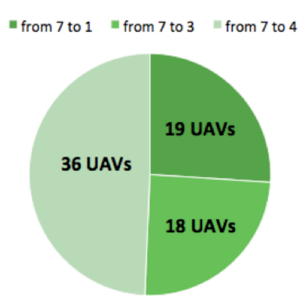
<table>
<tr><td colspan="5">from 6 to 3</td></tr>
<tr><td colspan="5">type2</td></tr>
<tr><td colspan="5">4 UVAs(100%)</td></tr>
<tr><td colspan="5">from 6 to 4</td></tr>
<tr><td>type1</td><td>type2</td><td>type3</td><td>type4</td><td>type6</td></tr>
<tr><td>23 UVAs(61%)</td><td>1 UVAs(3%)</td><td>10 UVAs(26%)</td><td>2 UVAs(5%)</td><td>2 UVAs(5%)</td></tr>
<tr><td colspan="5">from 6 to 5</td></tr>
<tr><td colspan="5">type1</td></tr>
<tr><td colspan="5">18 UVAs(100%)</td></tr>
</table>

Figure 6: delivery scheme (starting location:6)



<table>
<tr><td colspan="2">from 2 to 1</td></tr>
<tr><td colspan="2">type2</td></tr>
<tr><td colspan="2">5 UVAs(100%)</td></tr>
<tr><td colspan="2">from 2 to 3</td></tr>
<tr><td colspan="2">type1</td></tr>
<tr><td colspan="2">5 UVAs(100%)</td></tr>
<tr><td colspan="2">from 2 to 4</td></tr>
<tr><td>type4</td><td>type6</td></tr>
<tr><td>2 UVAs(50%)</td><td>2 UVAs(50%)</td></tr>
</table>

Figure 7: delivery scheme (starting location:2)



<table>
<tr><td colspan="3">from 7 to 1</td></tr>
<tr><td>type1</td><td colspan="2">type4</td></tr>
<tr><td>17 UVAs(89%)</td><td colspan="2">17 UVAs(89%)</td></tr>
<tr><td colspan="3">from 7 to 3</td></tr>
<tr><td>type1</td><td colspan="2">type2</td></tr>
<tr><td>13 UVAs(72%)</td><td colspan="2">5 UVAs(28%)</td></tr>
<tr><td colspan="3">from 7 to 4</td></tr>
<tr><td>type1</td><td>type3</td><td>type6</td></tr>
<tr><td>11 UVAs(31%)</td><td>23 UVAs(64%)</td><td>2 UVAs(5%)</td></tr>
</table>

Figure 8: delivery scheme (starting location:7)

video reconnaissance process

In video reconnaissance process, we use one drone B to assess the major roads and highways. The drone B assesses all major roads one time per day. Since we assume that the battery drone B packs can maintain one-day-assessment, following is the specific process of **dynamic programming transfer equation**.

$$\begin{cases} i_{n+1} = j_n \\ t_{n+1} = \begin{cases} t_n + t_{i_n j_n}, & e_n \geq e_{i_n j_n} \\ t_n + t_{i_n j_n} + t_c, & e_n < e_{i_n j_n} \end{cases} \\ e_{n+1} = \begin{cases} e_n - e_{i_n j_n}, & e_n \geq e_{i_n j_n} \\ e_{\max}, & e_n < e_{i_n j_n} \end{cases} \end{cases} \tag{6}$$

where *i* is the starting location, *j* is the ending location and e_n is the current power of battery, e_{n+1} is the next state's power of battery. Also, t_n is the current time, t_{n+1} is the next state time and t_c means the battery change duration.

Since the situation here is relatively simple, we can use the above solution. However, when the situation is complex, we adopt the Greedy Algorithm to solve the problem.

$$j_{n+1} = \text{argmin } d_{ij}, \quad j \in V, j \notin J. \tag{7}$$

Figure 9 displays the daily assess routes.

And **Table 3** displays the schedule of video assessing. We assume that taking-off and landing will take 5min each and replacing batteries also takes 5min.

4 Modifications to the current Process

4.1 Modification Goals

Since the video reconnaissance part only need one or two drones, we decide to increase the amounts of drone F, that is, to improve the upper limits of medical

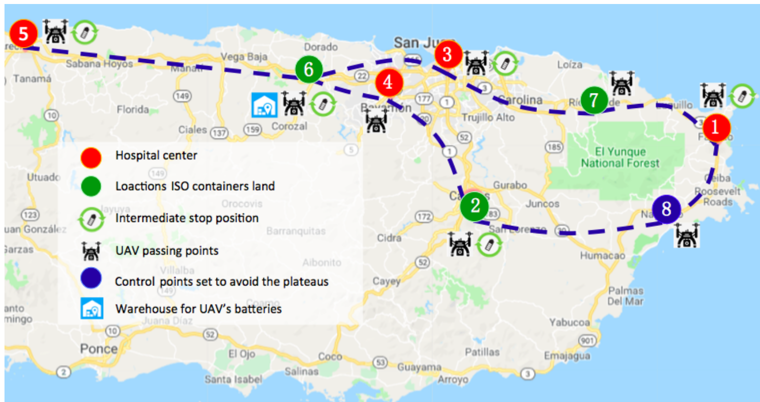


Figure 9: daily assess routes

Table 3: Schedule of video assessing.

Flying time		**Routes**	**Duration**
Taking-off time	Landing time		
8:00	8:46	6-5	36min
8:51	9:37	5-6	36min
9:42	10:18	6-4-2	26min
10:23	11:10	2-8-1	37min
11:15	12:00	1-7-3	35min
12:05	12:33	3-6	18min

load thus supplying the hospitals for more days.

4.2 Modifications

Since the transition of the best locations we already selected before can make an impact on the allocation of the medical, we do not change them any more.

Revised packing proposals

The distances between demand location *5* and ISO container landing location *6* beyond the maximum voyage of drone F. Thus we arrange several drone Bs to location *6*. In general, No.1 ISO container packs drone type B, F, H, No.2 and

No.3 ISO containers pack drone type F, H. So, the overall distribution proposal is as follows:

Table 4: Original solutions.

supply locations	**demand locations**
2	2,3,4
6	3,4,5
7	1,3

In order to supply the five demand hospitals at the same intervals, we should build a model, keeping the duration that the five demand locations can sustain from given medical, nearly the same. Due to the fact that supply location *7* only supplies demand location *1* and *3*, demanding relatively less but supplying a lot, we assume that the demand location *6* and *2* will not supply location *3* any more.

Table 5: Revised solutions.

supply locations	**demand locations**
2	2,4
6	4,5
7	1,3

We first use the formulas set in the basic model and calculate specific amounts by the software LoadMaster. And we get 37 drone F and 1 drone H to pack the ISO containers which would be landed on location *2* and *7* later. We assume that the proposal of medical-packing to location *7* only ranges in the following two situations:

$$\begin{cases} MED\,1 : MED\,3 = 1 : 1 \\ MED\,1 : MED\,2 = 1 : 1. \end{cases} \tag{8}$$

Since the amounts of $MED\ 1 : MED\ 2 = 1 : 1$ are more than $MED\ 1 : MED\ 3 = 1 : 1$, we adopt the former one.

The demand location *4* needs the most medical supplies, so we attach more importance on it. We adopt the proposal of $MED\ 1 : MED\ 3 = 1 : 1$ and $MED\ 2$ to pack medical. Since the former proposal could supply two days from four packages and the latter proposal could supply five days and a half from eleven packages, we set the medical packing proportions as $11 : 4$.

We assume that the medical packages we deliver can supply *n* days. Thus the amounts of drones the demand location *1*, *2*, *3*, *5* need should be $n/4$, $n/3$, $n/5$ and $n/2$.

Since our goal is to maximize the supplied days, that is **max** n, thus we have several constraint conditions.

Constraint conditions

The amounts of drone F which supply the location *1* and *3* should be less than the total amounts of drone F in the supply location *7*.

$$\frac{n}{4} + \frac{n}{5} \leq 37. \tag{9}$$

And the medical amounts which supply location *4* should be used more than *n* days.

$$\left(37 - \frac{n}{3} + m_{64}\right) * \frac{11}{15} * 2 \geq n. \tag{10}$$

Also, the amounts of drone F which supplied from location *6* to location *4* should be less than the total amounts of drone F in location *6*.

$$m_{64} \leq S_6^F. \tag{11}$$

Lastly, the amounts of drone B which supplied from location *6* to location *5* should be less than the total amounts of drone B in location *6*.

$$\frac{n}{2} \leq S_6^B. \tag{12}$$

4.3 Results of the revised model

Medical delivery results

We arrange drone B and drone F to deliver all the medical in one day. And the distribution results are in **Table 6**.

Table 6: Distribution results.

supply locations	demand locations	drone type	drone amounts	medical type
6	5	B	29	MED 1
6	4	F	11	MED 2
6	4	F	13	MED 1:MED 3=1:1
6	Null	H	1	NULL
2	2	F	20	MED 1:MED 3=2:1
2	4	F	17	MED 1:MED 3=1:1
2	Null	H	1	NULL
7	3	F	12	MED 1:MED 2=1:1
7	1	F	15	MED 1:MED 3=1:1
7	Null	H	1	NULL

And the days the five demand locations can maintain are in **Table 7**(7), from which we can see that the minimum days among the five hospitals is 58 days which improved a lot from the basic model.

Video assessment results

Figure 10 is the routes of the revised video assessment.

And **Table 9**(9) is the schedule of the revised video assessment.

Table 7: Supplied days.

demand locations	maximum days
1	60
2	60
3	60
4	60
5	58

Figure 10: Revised daily assess routes

5 Model Evaluation & Sensitivity Analysis

Sensitivity Analysis

We test the sensitivity of our model by increasing the demand of different medical. As for different demand locations and different type of medical, according to **Figure 11**, when the medical demand increases, the sustained days for the demand five hospitals decrease slowly. Some even keeps the same. Thus we can conclude that our model is insensitive to the changes in demand.

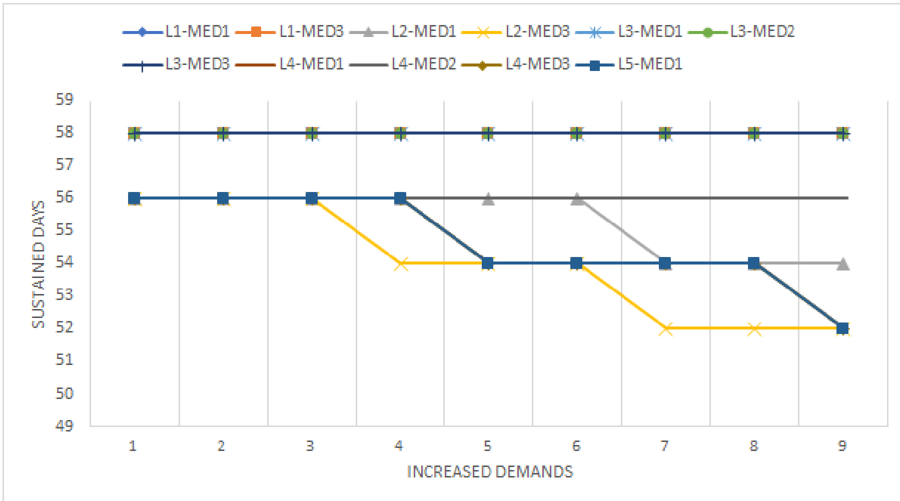


Figure 11: Sensitivity

6 Conclusion

6.1 Strengths and Weaknesses

Strengths

- Our model can allot the medical supplies evenly. The three ISO containers can provide medical supplies for five demand hospitals for at least 58 days.
- Our model is relatively cost saving for we only use one or two drones to assess the major roads among those demand hospitals.
- The arrangement of drone fleets in our model is kind of reasonable. We use drone B as both a long-distance delivery UAV and a video-assessment UAV. We also take drone F to deliver medical supplies which are of large quantities to short-distance locations.
- Our model also takes emergency into consideration. When emergencies like paralysis of power grid take place, we adopt the proposal of carrying enough alternative batteries and setting a battery warehouse.

Weaknesses

- Our model does not consider the impact of load, that is, we assume the distances drones can reach are the same whether they carry cargos or not.
- We build the our model regardless of drone recycling.
- The reconnaissance range of UAV is kind of small.

Memo

Distinguished Chief Operating Officer of HELP, Inc:

To help you better design the transportable disaster response system, DroneGo., we start with the basic task of medical supply delivery and video surveillance to satisfy your demands. Also, we wish to meet the requirements of saving time, economizing fuel-consuming and achieving the goal of cost-saving to the greatest extent possible. Thus we build a multi-objective optimization model to offer some feasible proposals.

First of all, we established a drone evaluation system that considers the factors such as load, navigation distance, type of bay carried, with or without communication systems and cameras. We recommend that the design scheme be a fleet of drones consisting of type B, F and C. After the formation of the selected fleet, the container capacity should be considered to properly ship the drone and the drugs in its cargo compartment. In order to satisfy the medical needs in the greatest extent, we have determined the assembly scheme of the ISO containers by applying the three-dimensional packing model under the constraints of ISO containers and drone cabin load.

There are many factors should be considered while choosing a location to place a ISO container: population density, voyage of the drone, terrain and altitude of Puerto Rico, etc., and finally we choose the three best placement locations among the five medical centers and many populated areas given. After obtaining the specific information of the placement locations, we established a linear programming model to maintain the medical supplies in one delivery ISO container for 58 days, saving the money and time cost of placing the ISO containers. We also use the drones to provide urgently needed medical supplies which are quite sufficient for the hospital centers.

Video reconnaissance is also a crucial part of the system. Considering the problem that the drone's voyage is too short to cover the whole mission routes, we make the assumption that the B-type drone can carry alternative batteries. Establish a topology map of the mission road network in the disaster area, apply a depth-first search algorithm to determine the reconnaissance route, and use a dynamic programming algorithm to determine the locations and flight schedule for replacing the battery.

Our recommendations:

- Since the hybrid formation of the drones can improve the delivery capacity of medical supplies under the premise of finishing the reconnaissance mission, we recommend your company to adopt this kind of drone fleet.
- We also recommend your company to increase the endurance of the drones and increase the number of reconnaissance drones by adding the part of drone battery delivery.

We sincerely hope that our proposals could provide useful information for your company.

Sincerely,

Team #1916842

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Appendices

Appendix A: Tables and Equations

$$max\ K = 79 \tag{13}$$

Table 8: final packing proposals.

medical type	amount
1	41
2	5
3	23
4	2
5	0
6	2

Appendix B: Others

The Drone Flight Plan

The Drone Flight Plan for video reconnaissance can be decomposed into the following parts:

- **Taking off position:** The starting location of the flight route for video reconnaissance.
- **Terminal position:** The last location of the flight route for video reconnaissance.
- **Intermediate stop position:** The location drone lands in order to replace the battery.
- **Taking off time:** The starting time of the flight route for video reconnaissance.

Table 9: Schedule of video assessing.

Flying time		**Routes**	**Duration**
First 29 days			
Taking-off time	Landing time		
8:00	8:47	7-3-6	37min
8:52	9:28	6-4-2	26min
9:33	10:20	2-8-1	27min
10:25	10:51	1-7	16min
Other days			
Taking-off time	Landing time		
8:00	8:47	7-3-6	37min
8:52	9:38	6-5	36min
9:43	10:29	5-6	36min
10:34	11:10	6-4-2	36min
11:15	12:02	2-8-1	37min
12:07	12:33	1-7	16min

- **Terminal time:** The ending time of the flight route for video reconnaissance.
- **Intermediate stop time:** The landing time of the drone on one location in order to replace the battery.
- **Intermediate take-off time:** The starting time after landing on one location to replace the battery.
- **Battery replacement interval:** The duration of replacing the battery.

Matrix 7 is the distance matrix among the seven locations.

$$\begin{bmatrix} 0 & 47.5510 & 46.0751 & 56.5716 & 116.0096 & 69.3348 & 20.5627 & 15.8098 \\ 47.5510 & 0 & 20.2862 & 20.0914 & 80.8967 & 34.2219 & 45.7986 & 31.7412 \\ 46.0751 & 20.2826 & 0 & 10.4965 & 69.9345 & 23.2597 & 25.5124 & 52.0238 \\ 56.5716 & 20.0914 & 10.4965 & 0 & 60.8053 & 14.1305 & 36.0089 & 51.8326 \\ 116.0096 & 80.8967 & 69.9345 & 60.8053 & 0 & 46.6748 & 95.4469 & 112.6379 \\ 69.3348 & 34.2219 & 23.2597 & 14.1305 & 46.6748 & 0 & 48.7721 & 65.9631 \\ 20.5627 & 45.7950 & 25.5124 & 36.0089 & 95.4469 & 48.7721 & 0 & 36.3725 \\ 15.8098 & 31.7412 & 52.0274 & 51.8326 & 112.6379 & 65.9631 & 36.3725 & 0 \end{bmatrix} \tag{14}$$