The Drone System based on Optimal Combination Algorithm

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Abstract. This paper help CFA design a drones use system that determine the number and the location of SSA drones and Radio Repeater drones to facilitate wildfifires fifighting. we establish a model to determine the optimal combination of SSA drones and Radio Repeater drones. The number of Radio Repeater drones needs to be calculated based on the distance from the EOC to the center of the fire field. For the number of SSA drones, we consider the factors of capability, safety, topography and so on. Through the genetic algorithm, we determine the shortest path of each SSA drones. By data sigmoid normalization and determining the weight through coefficient of variation, we build a comprehensive capability and safety evaluation index to choose the optimal number of SSA drones. Besides, we use DUDC Model to determine the location of hovering radio-repeater drones. We determine the straight line where the Radio Repeater drones are located, and then use the straight line obtained as the abscissa, uniformly determine the coordinate axis direction and use greedy algorithm to solve where should Radio Repeater drones be. Finally, we summarize the model and explain the strengths of the model.

Keywords: Optimal Combination; Genetic Algorithm; Coefficient of Variation; DUDC Model; Greedy Algorithm.

1. Introduction

Wildfires cause huge damage to nature and human society [1]. Many regions of Australia experienced a large number of wildfires during the 2019-2020 fire season, particularly New South Wales and eastern Victoria [2]. It seemed like the end of the world there: thick smoke obscured the sun, houses turned into ruins, animals ran around, and thousands of people fled to the sea. Lives were dying, so the fire fighting must hurry!

Wildfires fighting is a complex and often dangerous process. Thus, it requires a good organization. To support effective control of wildfires, many information systems have been developed by using modern technology [3]. Firefighters of Victoria's CFA carry wearable devices and handheld two-way radios, with the help of the SSA drones and Radio Repeater drones, hence achieving communication between the front lines and the EOC. The specific process of main signal transmission is shown in Figure 1. Therefore, it is necessary to design a reasonable drones use system.

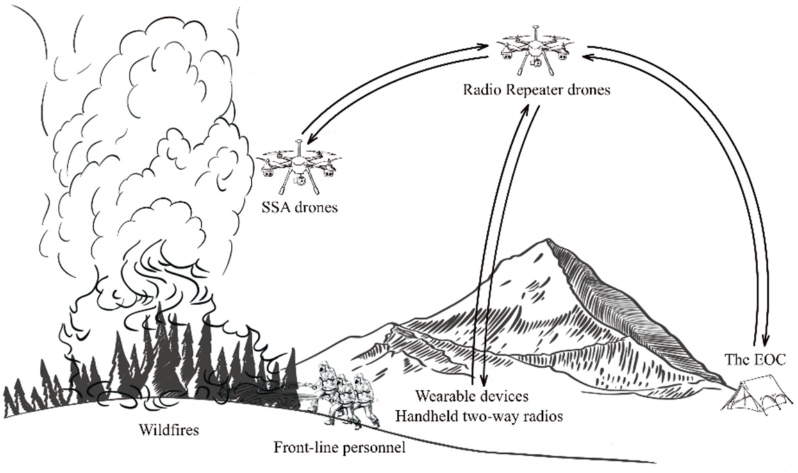

Figure 1. Fighting wildfires

We want to build mathematical models to solve the following problems:

• Determine the optimal numbers and mix of SSA drones and Radio Repeater drones;

• Optimize the locations of hovering VHF/UHF radio-repeater drones for fires of difffferent sizes on difffferent terrains.

2. Model

2.1 Model Preparation

Before structuring the mathematical model, we need to put forward four assumptions about the drone system to simplify the model:

• **The altitude does not affect the flight distance.**

Compared with the horizontal flight distance, the change in altitude is very small and can be ignored. Therefore, the distance between any two points in the model refers to the plane distance.

• **The flying distance of the SSA at the maximum speed is only 160km, and the repeater one can have 180km.**

Since the SSA is always moving, and the repeater is hovering most of the time, it is obvious that the SSA consumes more power.

• **There can be more than one EOC.**

the number is dynamically adjusted according to the severity of the fire to reduce the invalid flight of the SSA between the fire points with larger intervals.

• **Our repeater signal must cover all fire points.**

To protect firemen's safety, we must ensure that SSA can reach any fire point to ensure the safety of firefighters.

After putting forward the assumptions, we obtained fire data for Victoria from October 1, 2019 to January 7, 2020 from National Aeronautics and Space Administration (NASA). It contains the location and the number of the fire pixels every day.

In our model, if fire pixels are very few and scattered, then they cannot constitute a devastating wildfire. At this time, there is no need to launch the drone system. Only when a large number of fire pixels are gathered into a fire field, we will launch the drone system. At this time, every fire pixel in the fire field should be surveyed.

When facing a fire field formed by the gathering of multiple fire pixels, we will send EOC to rescue. To facilitate the rescue, EOC should be as close as possible to the fire field [4]. But EOC cannot be located inside the fire field, so EOC will be located at a fire pixel on the edge of the fire field. So which fire pixel is EOC located at the edge of the fire field? For safety reasons, we choose the fire pixel furthest from the geometric center of the fire field.

When the EOC location is determined, we will send the drone system to survey and transmit the fire field information. The drone system includes SSA drones and Radio Repeater drones.

2.2 Number of Radio Repeater drones

Each fire field will be covered by one Radio Repeater drone hovering in the center of the fire field at all times [5]. The repeater drone starts from the EOC and returns to the EOC to charge when the battery is exhausted. At this time, another Radio Repeater drone will immediately replace this position to provide signals for the fire field without interruption. Therefore, the minimum number of Radio Repeater drones of each fire field must be two. How many Radio Repeater drones should be allocated to different fire fields needs to be calculated based on the distance from the EOC to the hovering position of the Radio Repeater drone.

If the distance between EOC and Repeater is d and we allocate 2 Repeaters. We have $2.5 - \frac{d}{36} \geq \frac{d}{36} + 1.75$. So, we get d is 13.5km. Similarly, if we allocate 3 Repeaters. We get d is 39km so EOC is out of the coverage of R. Therefore, the number of Radio Repeater drones of each fire field n_r.

$$n_r = \begin{cases} 2, & if\ d \le 13.5 \\ 3, & if\ d > 13.5 \end{cases} \tag{1}$$

2.3 Number of SSA drones

Many SSA drones survey the fire pixels in each fire field at the same time. The SSA drone departs from the EOC for the survey, returns to the EOC for charging when the battery is exhausted, and goes to the survey again when the battery is full [6]. Therefore, the survey of SSA drones is periodic. The survey cycle of each SSA drone is the time between the end of its two charges. The survey route of each SSA drone is fixed, that is, the fire pixels surveyed by each SSA drone are fixed. To ensure efficiency, the fire pixels surveyed by each SSA drone will not overlap, which means that each fire pixel will only be surveyed by a fixed SSA drone. And, according to the rescue requirements we stipulated earlier, all fire pixels in a fire field must be surveyed.

To ensure efficiency and minimize costs, the sum of the paths of all SSA drones should be the shortest. According to the determination of the shortest path, in the end, our model will get the optimal number of SSA drones.

When solving this problem, we consider the following factors:

• **Capability**

The capability of firefighting depends on how much information SSA drones can get from the fire field. We need every SSA drone to survey as many fire pixels as possible. Therefore, we use the number of fire pixels that each SSA drone can survey to characterize its capability. The higher the number, the stronger the capability.

• **Safety**

The unknown situation of the fire field poses a great threat to the safety of front-line personnel. We need every fire pixel to be surveyed as many times as possible, so that EOC can receive the latest fire information as possible to direct the actions of front-line personnel. Therefore, we use the ratio of the number of times a fire pixel will be surveyed by the SSA drone in a cycle to the survey cycle of the SSA drone to measure safety. The higher the ratio, the safer it is.

• **Topography**

The range of handheld two-way radios and repeaters is determined by topography. It is different in flat ground and rugged areas [7]. By observing and analyzing the map of Victoria, we found that the unobstructed ground is located in the coastal areas with lower elevations, while the inland areas with higher elevations are mostly rugged areas. Therefore, we judge whether it is a flat ground or a rugged area based on whether the altitude is higher than 1000 meters. We define,

$$\begin{cases} r_r = r_f \cdot \alpha_1 \\ R_r = R_f \cdot \alpha_2 \end{cases} \tag{2}$$

r_r and R_r refer to the range of handheld radios and Repeater in a rugged area, r_f and R_f refer to the range of handheld radios and Repeater in a flat area, α_1 and α_2 refer to the immunity factor of handheld radios and Repeater. A 5-watt radio has a nominal range of 5 km over the flat, unobstructed ground, but drops to 2 km in an urban area. So, we can calculate $\alpha_1 = 0.4$ based on the known information. We let $\alpha_2 = 0.9$ because the anti-interference ability of the repeater is significantly stronger than handheld two-way radios [8]. Therefore, A repeater has a nominal range of 20 km over the flat, unobstructed ground, but drops to 18 km in an urban area.

• **Fire event size**

Very intuitively, we use the number of fire pixels to measure the fire event size. The fire event size on a given day is the number of fire pixels on that day. The more the number of fire pixels, the bigger the fire event size.

• **Fire event frequency**

We can approximately divide the number of the fire pixels in a day and the number of days corresponding to the same number of fire pixels into 4 different levels, namely: the value of the vertical coordinate when the abscissa is 0-100, 100-500, 500-5000, and above 5000. We use this value as the frequency of fire events.

Table 1. The level of fire events

Level	2	3	4
Date	December 13	December 22	December 30

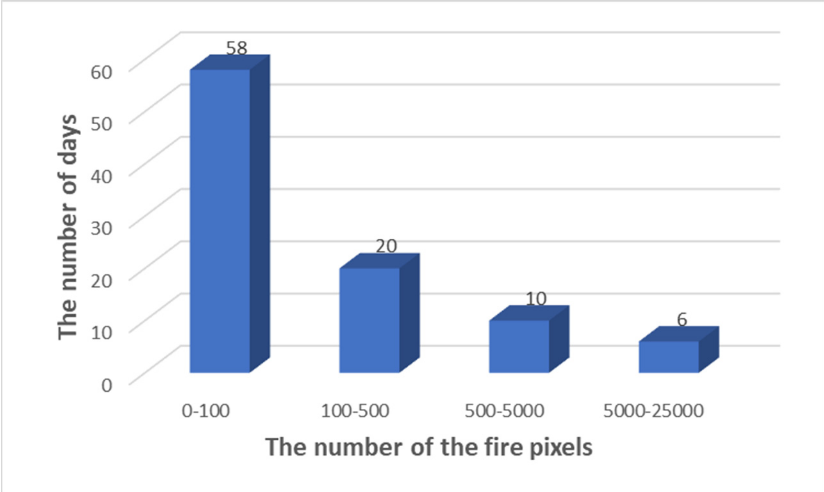

Figure 2. Fire event frequency

In the first level, the fire field is very small and scattered. According to our model, we do not need to deploy the drone system. For the second, third, and fourth levels, we can see that the distribution shape, size and density of the fire field of different days at each level are very similar. Therefore, we can choose a representative day in each level, a total of three days as the object of study. Our choices are shown in Table 1. Then we choose the middle fire field as an example to show our solution process. It is shown in Figure 3.

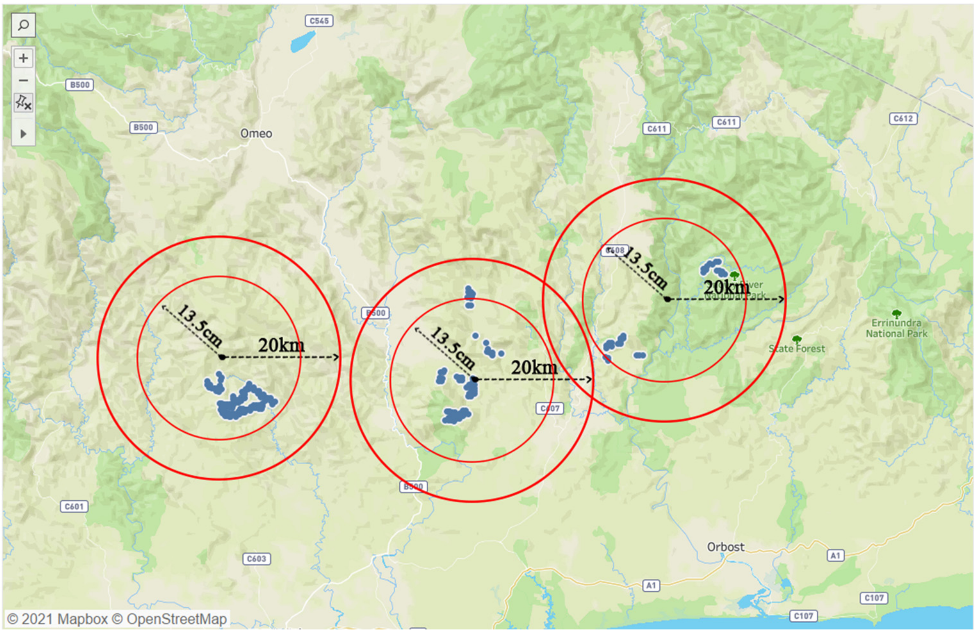

Figure 3. Fire fields on December 13

2.3.1 Determine the Shortest Path

So far, we input different numbers of SSA drones and get different shortest paths. Next, we need to determine which shortest path result is the best, and the number of SSA drones corresponding to the optimal result is the optimal number of SSA drones we finally give. So, how to compare and choose the best result? This requires us to construct an evaluation index.

2.3.2 Build the Evaluation Index

Based on the determined terrain, fire event size and frequency, we obtained the shortest paths corresponding to different numbers of SSA drones. We did not consider the two factors of capability and safety in depth. So next, capability and safety should be taken into consideration!

Due to economic constraints, the number of drones is limited, which makes capability and safety opposed: we require SSA drones to survey as many fire pixels as possible, so it will be difficult to survey every fire pixel as many times as possible. Therefore, we need to build a comprehensive capability and safety evaluation index to balance capability and safety with economics.

• **Data normalization**

The two factors of capability and safety have different dimensions, so it is difficult to carry out a comprehensive comparative evaluation. To eliminate the dimensional influence between factors, we need to standardize the data so that the factors are in the same order of magnitude [9]. We use the *sigmoid normalization* method [10]. It's more realistic than *linear normalization*. If we normalize m to $g(m)$, We have

$$g(m) = \frac{1}{1+e^{-0.1\cdot m+5}} \tag{3}$$

• **Determine the weight**

The construction of the comprehensive evaluation index should not only unify the dimension of the two factors, but also give weight to the two factors. We use the *coefficient of variation* [11] to determine the weight. If we have k indicators, their average $a_1, a_2, \cdots, a_k$, standard deviation $\sigma_1, \sigma_2, \cdots, \sigma_k$, coefficient of variation $\delta_1, \delta_2, \cdots, \delta_k$and weight $W_1, W_2, \cdots, W_k$.For any $1 \leq j \leq k$, we have,

$$\begin{cases} \delta_j = \frac{\sigma_j}{a_j} \\ W_j = \frac{\delta_j}{\sum_{i=0}^{k} \delta_i} \end{cases} \tag{4}$$

The *coefficient of variation* is an important indicator to describe the trend of deviation, reflecting the difference and fluctuation of values. It is equal to the standard deviation divided by the mean in value. Why can the coefficient of variation determine the weight? Because in the evaluation system, if the value of a factor has a large difference, it means that the factor is difficult to achieve, and it is a key factor to reflect the gap between the evaluated objects, so higher weight should be given.

By normalization, we get the results s for safety and c for capability. Meanwhile, we get the a (weight of safety) and b (weight of capability) through the coefficient of variation method. Now we can construct comprehensive evaluation indicators:

$$W(n_s) = as + bc \tag{5}$$

n_s refers to the number of SSA in a fire field and its score is $W(n_s)$. In the middle fire field on December 13, 2019, we select 10 different n_s, calculated and compared the corresponding $W(n_s)$. Finally, we get n_s is 5(Figure 4) and n_r is 3(because $d \geq 13.5km$). Through the genetic algorithm [12], we used Python to get the SSA path graph with population size of 50 and iteration number of 2000(Figure 5).

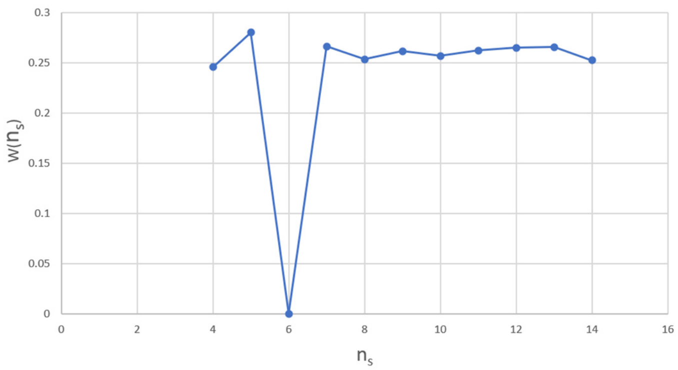

Figure 4. n_s of the middle fire field

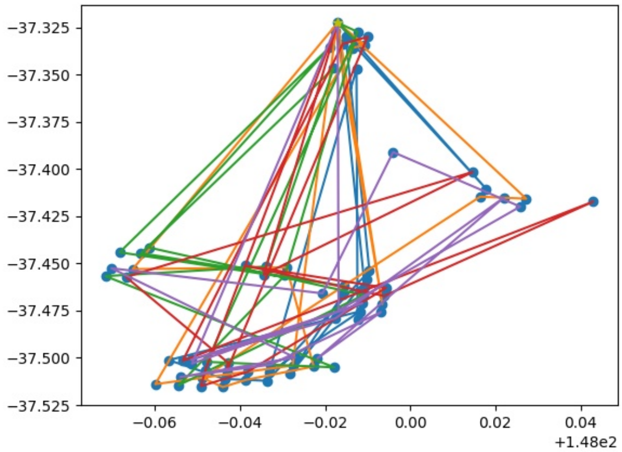

Figure 5. The SSA path graph

Similar to the specific algorithmic process for this fire field, we calculated the optimal number of drones needed for all fire fields for the given three days. The results are following.

Table 2. The results of the given three days

Date	December 13	December 22	December 30
SSA	32	163	1310
Repeater	7	9	13

In order to improve the ability to deal with large-scale fires, we assign the weights of the three levels of 1:2:4 to calculate the optimal number and proportion of drone purchases. We have $N_s = 32 \cdot \frac{1}{7} + 163 \cdot \frac{2}{7} + 1310 \cdot \frac{4}{7} \approx 552$ and similarily $N_r \approx 10$. N_s and N_r refer to the total number of SSA and Repeater.

3. Where should Radio Repeater Drones be

In our previous model, we simply determined the location of hovering VHF/UHF radio-repeater drones to cover all fire pixels in the fire field. Such inaccurate planning may lead to a waste of drones. Therefore, we need to optimize the position of hovering VHF/UHF radio-repeater drones in the model. Our goal is to solve the minimum number of Radio Repeater drones to complete the mission under the premise of surveying all the fifire pixels.

3.1 Model Preparation

Considering the influence of terrain on the signal range of the repeater, since the terrain changes continuously, the signal range of the repeater should change continuously. Unlike the previous model, which simply divides the signal range of the repeater into 18km and 20km, we will establish a continuous function of the range of the repeater signal affected by the terrain. According to the topographic map of Victoria, as before, we can quantify the range of the repeater based on the altitude. Since the minimum altitude of 0m and the maximum altitude of 1986m are given, we use the linear fitting method [13] to specify:

$$R = 18 + \frac{H}{1986} \cdot 2 \tag{6}$$

In this way, the signal range of the repeater is different at different altitudes, and the signal range of a certain point of the repeater will be an irregular graph (the shape of the graph is determined by the altitude of all points). To simplify the model, we classify similar fire fields into a fire district, and the range of the repeater in the entire fire district is determined by the altitude of the geometric center of all fire pixels in the fire district. Therefore, we determine the location of Radio Repeater drones in different fire districts.

3.2 DUDC Model

Back to our goal: Under the premise of surveying all fire pixels, solve the minimum number of Radio Repeater drones to complete the mission.

In the same fire district, the signal range of the repeater is the same. Therefore, our goal is: on a given two-dimensional plane (Victoria), use the smallest fixed radius circle (the range of Radio Repeater) to cover all target points (fire pixels), which is the DUDC problem [14]. The basic mathematical model of the DUDC problem is as Figure 6.

Since there are countless possibilities to place the disc position on the two-dimensional plane, and the DUDC problem is a combinatorial optimization problem, it is difficult to traverse all coverage situations to select the best under the limited budget time, that is, the optimal result cannot be obtained in polynomial time, so this problem has been proved to be an NP-Hard problem [4]. To obtain an approximate optimal solution, combined with the actual situation of the Victorian fire, we observed that most of the fire fields in the fire district were spread out and spread in pieces. Therefore, based on the fire data on December 18, 2019, we make the Radio Repeater drones on the same straight line and solve the DUDC problem based on the greedy algorithm [15] (Figure 7):

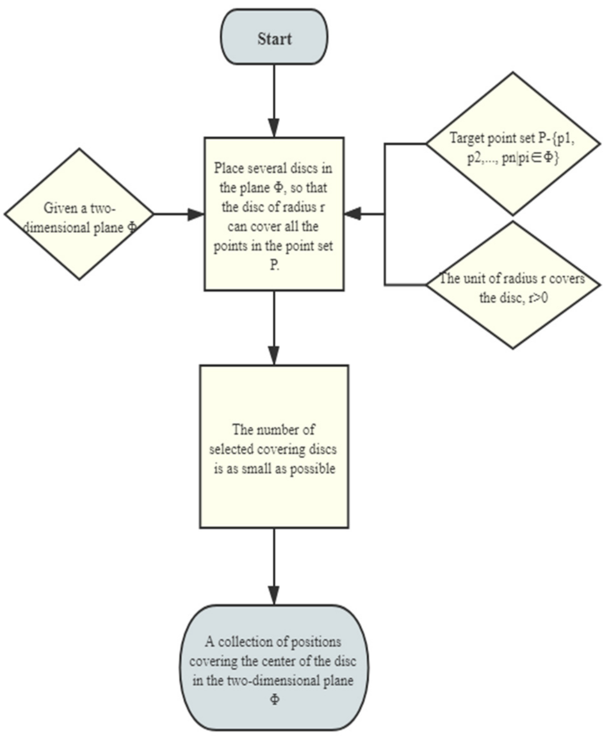

Figure 6. The DUDC problem

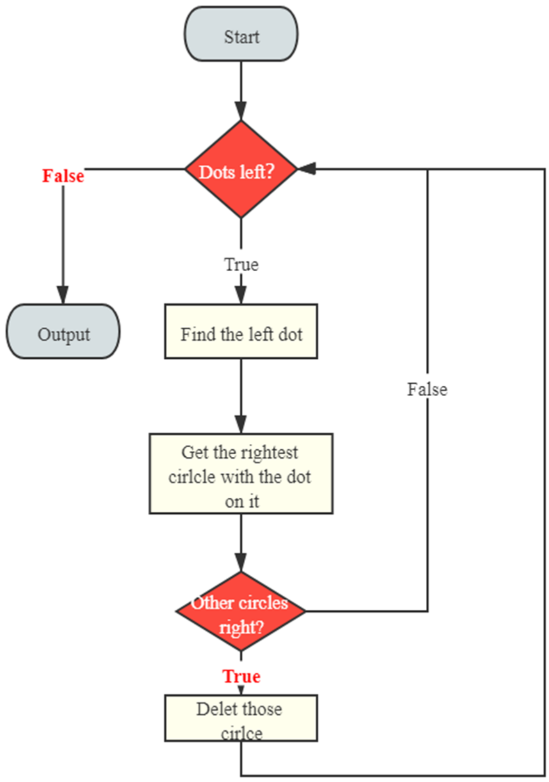

Figure 7. The greedy algorithm

• Determine the straight line where the Radio Repeater drones are located: coordinate the latitude and longitude (with latitude and longitude (0°, 0°) as the coordinate axis zero-point, latitude and longitude as the x_1 axis, and longitude as the y_1 axis). If all the fire pixels are linearly fitted to get a straight line, the calculation is too large. Therefore, we calculate the geometric center of each fire field and fit the straight line with the linear ordinary least squares.

$$f(x) = a_1 x + a_2 \tag{7}$$

$$\min \sum (y(x_i) - f(x_i))^2 \tag{8}$$

• Using the straight line obtained in step 1 as the abscissa, uniformly determine the coordinate axis direction (rightward is the positive direction).

3.3 Calculation Results

Table 3. The latitude and longitude of the three repeaters

December 13	December 22	December 30
32	163	1310
7	9	13

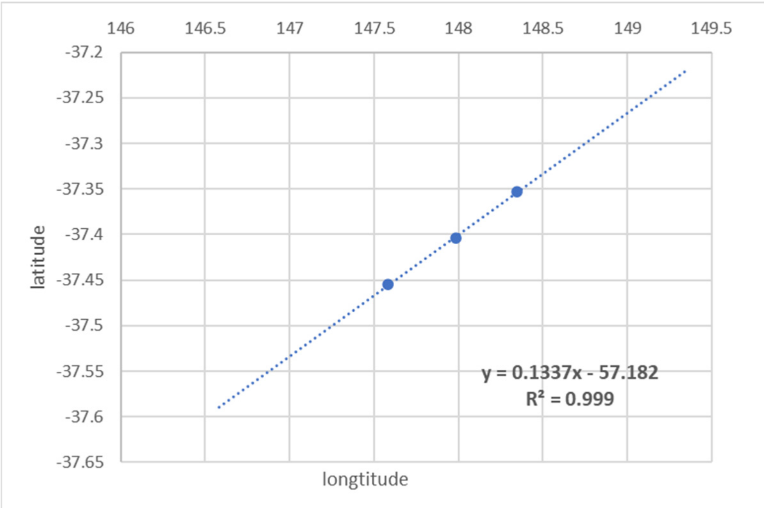

Figure 8. The curve of the three repeaters

4. Sensitivity Analysis

Since the model uses the coefficient of variation method when considering safety and economic capability, it can be clearly seen that economic capability has a far greater impact on the results than safety, so only the sensitivity analysis of terrain and safety factors to the results is considered here.

Firstly, because the terrain factors reflect the effective range of the repeater, the situation on December 22 was used as a test, and the repeater range was fluctuated by 11%. As shown in the figure below, it can be seen that the change in the number of repeaters is not very significant.

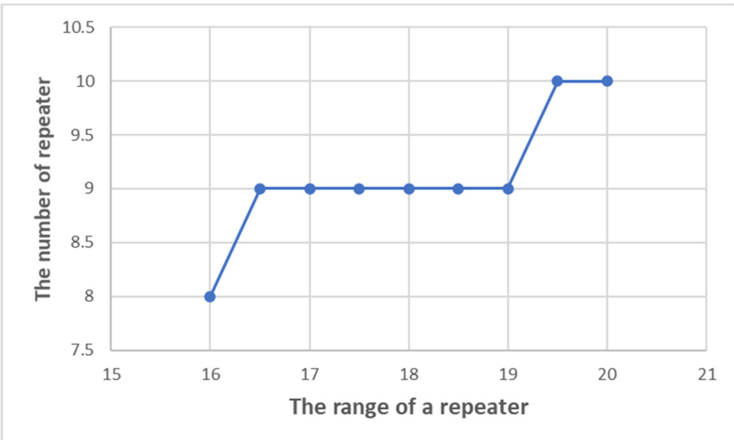

Figure 9. The sensitivity of the number of repeaters

Furthermore, since the safety factor mainly depends on the number of SSAs, the situation on December 22 is used as a test, and the repeater range is fluctuated by 16%. As shown in the figure below, we can see that the score has changed significantly. As the economic ability has been known from the above, it has a greater impact on the model.

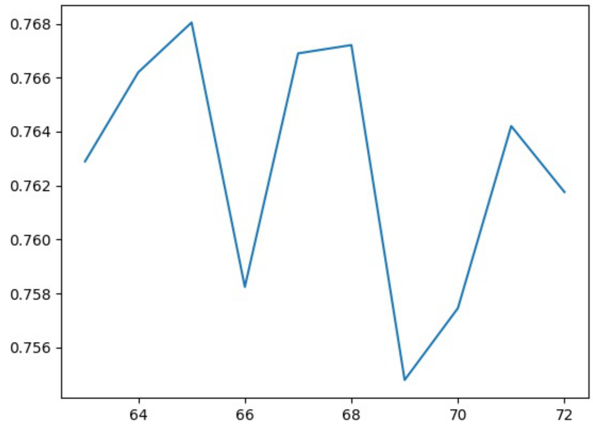

Figure 10. The sensitivity of the economic ability

Therefore, when the terrain changes, the model is not sensitive to changes; when the safety and economic capacity change, the model changes significantly.

5. Conclusion

Nowadays, Wildfires cause huge damage to nature and human society. We takes the 2019-2020 fire season in Australia as an example and help CFA design a drones use system that determine the number and the location of SSA drones and Radio Repeater drones to facilitate wildfires fighting.We obtained fire data for Victoria from October 1, 2019 to January 7, 2020 from NASA. It contains the location and the number of the fire pixels every day. We assume that only when a large number of fire pixels are gathered into a fire field, we will launch the drone system.

Firstly, we establish a model to determine the optimal numbers and mix of SSA drones and Radio Repeater drones. The number of Radio Repeater drones needs to be calculated based on the distance from the EOC to the center of the fire field which is the position of the Radio Repeater drone as assumed. For the number of SSA drones, we consider the factors of capability, safety, topography, fire event size and frequency. Secondly, we divide the fire event into 4 different levels based on our real data, choose 3 representative days as the object of study. Through the genetic algorithm, we determine the shortest path of each SSA drones. By data sigmoid normalization and determining the weight through coefficient of variation, we build a comprehensive capability and safety evaluation index to choose the optimal number of SSA drones. Finally, we use DUDC Model to determine the location of hovering VHF/UHF radio-repeater drones. We determine the straight line where the Radio Repeater drones are located, and then use the straight line obtained as the abscissa, uniformly determine the coordinate axis direction to solve where should Radio Repeater drones be.

In conclusion, our model has four following strengths:

• The most important data of our model-Australian fire data, is the most real data obtained from NASA. Modeling known fires is used to deal with fires that may occur in the future, so that the model has extremely high practical value and credibility.

• The model is practical and highly adaptable. It takes into account various factors such as the working ability of the drones system, the safety of frontline personnel and the economic utility of government departments, and can adapt to disaster relief scenarios of different terrains and different fire scales.

• The genetic algorithm based on the multi-traveling salesman problem can give the UAV route planning as quickly and accurately as possible when there are too many fire spots, and realize the "Rapid Bushfire Response".

• The greedy algorithm based on the DUDC problem can quickly give an approximate optimal solution to the position of the repeater UAV in a tight fire situation, improving the efficiency of the rescue team.

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