For office use only	Team Control Number	For office use only
T1 ________________	2103441	F1 ________________
T2 ________________		F2 ________________
T3 ________________	Problem Chosen	F3 ________________
T4 ________________	**B**	F4 ________________

Modelling Drones Network in Fighting Wildfire by Using Drones

Summary

The fighting against the wildfires in southeastern Victoria state of Australia requires the assistance of drones. To determine the optimal number and combination of SSA and Radio Repeater drones, we first need to consider drone position planning. This paper introduces an algorithm based on geographic data and the relative positions of the fire frontline and the Emergency Operation Center, which helps to project the deployment of the drones. Because the drone may have limited communication in the real scene, the centralized solution method needs to grasp the complex situation with much information. The problem of solving the minimum total cost and the maximum safety is transformed into the problem of finding the optimal cooperative distribution. A complex high-dimensional optimization problem is decomposed into a low-dimensional problem with less computation to improve computational efficiency.

After solving the practical problem, we extend our models by applying them to extreme situations. We also predict the possible cost in real time situations in order to achieve a better balance between safety and cost. Meanwhile,we also optimize the repeater location model to better suit the local environment, by constructing a constrained-optimizing model. Ultimately, a budget table will be provided.

Key words: Planning, Multi-drone cooperative, Constrained optimization

Catalogue

1. Introduction

1.1 Background

Wildfire is one of the most dangerous and destructive natural calamities as we all know. From 2019 to 2020, Australia had wildfires in every state during the fire season. Among those states, maximum damage occurred in the New South Wales and eastern Victoria. The picture below shows the detailed situation. The yellow areas are wild fires from October 1st to January 6th, and red showing active fires on January 7, 2020.

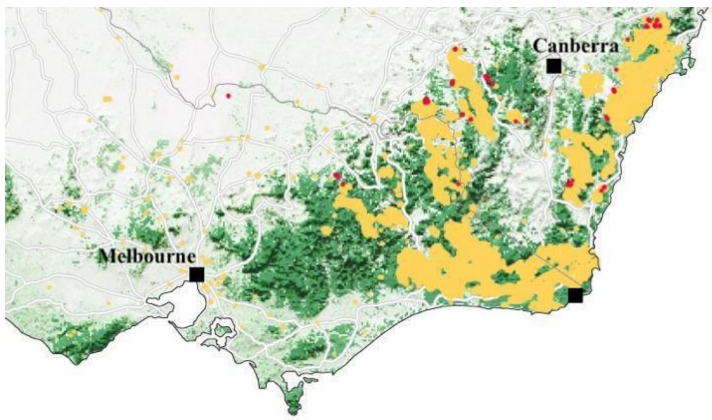

Figure 1 Wildfire Hot Spots in Southeast Australia, Oct 1, 2019 to Jan 7, 2020.

Whenever a wildfire happens, it is important to contain the situation and put out the fire as soon as possible. Before taking any actions, it is important to get the detailed information of the fire spot. For years the firefighters have been using drones for surveillance and situational awareness (SSA) to achieve that. SSA have variable functions. It can report data from the front-line person, locate a person, monitor realtime dynamic changes and help Emergency Operations Center (EOC) to active the crews more effective and more safely.

Apart from rescuing the fire, two-way communication between the EOC and the action group is also important. However, the handheld radios of the action teams have the maximum power of 5 watts, which allows them to communicate with the EOC within the range of 5km over flat, unobstructed ground. When it comes to urban areas, the communication distance is even shorter: 2km.

Consequently, if the fire field is large, the action team would need repeaters to communicate with the EOC. Repeaters are transceivers that automatically rebroadcast signals at higher powers, they can relay radio signals so that the radio range is extended. We use drones to carry the repeaters in order to extend the communication range so that the action team can communicate with the EOC more effectively. The drone is Akme Corporation's prototype WileE-15.2X hybrid drone is projected to cost approximately $10,000 (AUD) when equipped with either a radio repeater or video & telemetry capability. It carries a repeater of 10 watt power and 1.3 kg in weight. The capability of the drone is shown in table 1.

Flight range	Maximum speed	Maximum flight time	Recharge time
30 km	20 m/s	2.50 hour	1.75 hour

Table 1. WileE–15.2X Hybrid Drone Capabilities

Note: Auxiliary batteries for radios or video/telemetry can be swapped while the built-in battery recharges

1.2 Restatement of the Problem

Firstly, we are required to create a model to determine the ratio of the number of the SSA drones compared to the number of radio repeater drones to make the action team communicate more efficient no matter when or on what kind of topography wildfires happen. We need to take account of the balance between capability,safety and cost. The model should also take the size and frequency of the wildfire as parameters. Secondly, our model should be able to adapt the changing of extreme fire events that may happen in the next decade under the assumption of the cost of the drones remain unchanged and the cost of equipment increases.
Then, we are required to create model to modify the locations of radio repeater drones in order to deal with different types of wildfires on different places in figure 2.

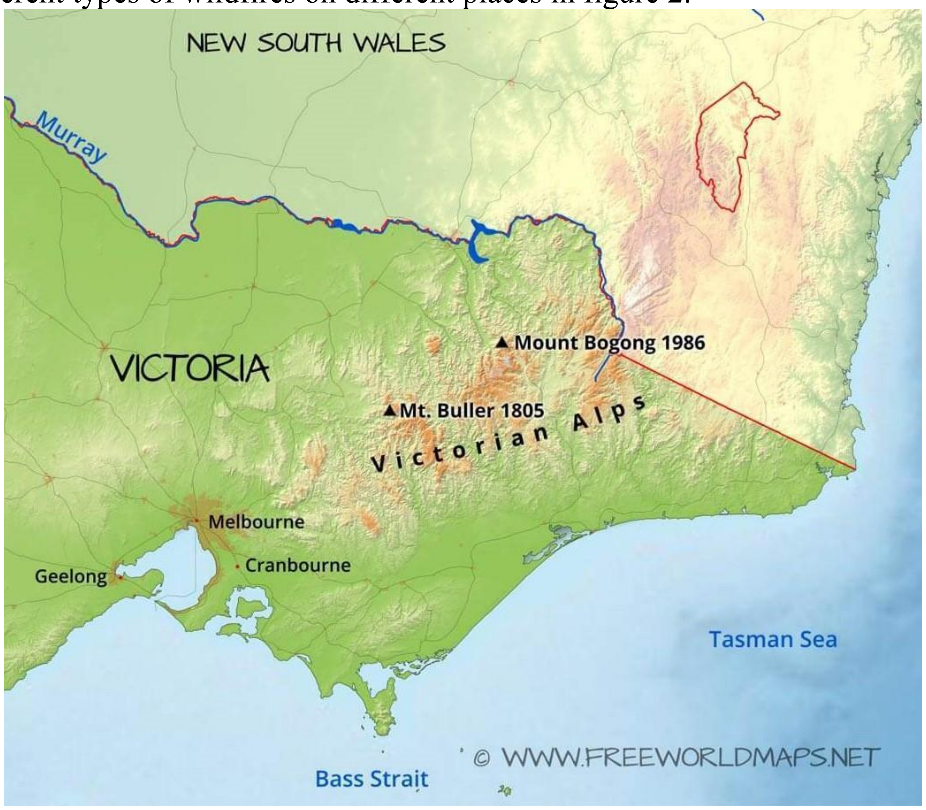

Figure 2: Topographical Map of Eastern Victoria.

Note that elevations range from sea level at the coast to 1,986 meters at Mt. Bogong, Victoria.
Lastly, we are required to write a one or two page annotated Budget Request according to our model.

2 Assumptions and Justifications

- **The drones' flight range and time will not be subject to the elevation and weather condition, neither will the speed**. In reality, the density of air will influence the flight speed and time of drone,and the weather conditions such as fog and the smoke will reduce the radio range. Yet as the repeater drones will be hovering and the SSA drones will not move intensively, these effects are not important.

3 Notifications and Statistics

- **The forward-teams and drones cannot be inside the fire regions, but only on the edges of those regions.** This is reasonable in fire controlling for the safety of life and equipment, and also because the fire shall be stopped from spreading first from the outside.

- **The fires that have radiative power of above 2000Watts are the most threatening and should be disposed of.**

4 Modeling of drone path

4.1 Environment evaluation model

We take into account a lot of factors related to flying drones, given the variety of environments in the mountains. We assume that the scope of fire is a cylinder. Due to wind force and various factors, the fire is not a plane structure but a three-dimensional structure (Hereinafter referred to as the fire disaster area: the threat area).

Considering that the threat area is cylinder:

Threat area: $T=(x_T, y_T, h_T, r_T)$

The central coordinates of the threat area are: (x_T, y_T)

The horizontal projection radius of the threat area is r_T

Threat zone height is h_T

Terrain includes hills and plains, so the terrain function is designed as $z=f_T(x, y)$

The schematic diagram is as follows:

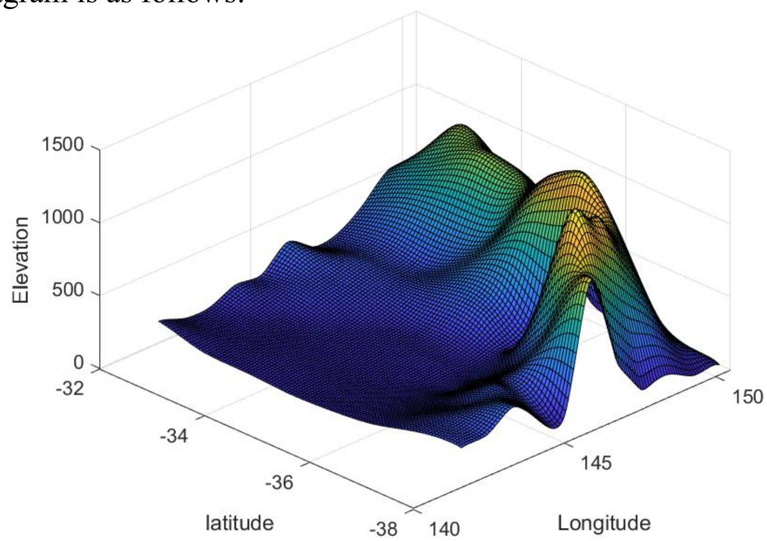

Fig 3: The topography of Victoria and New South Wales

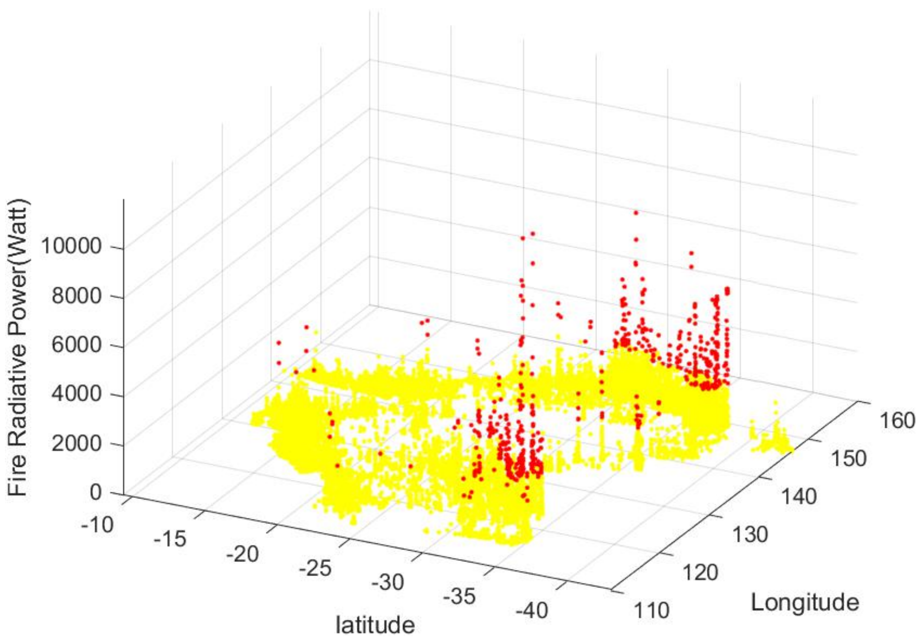

Fig 4 :Near Real Time fire situation in three-dimensional (Red region>2000Watts)

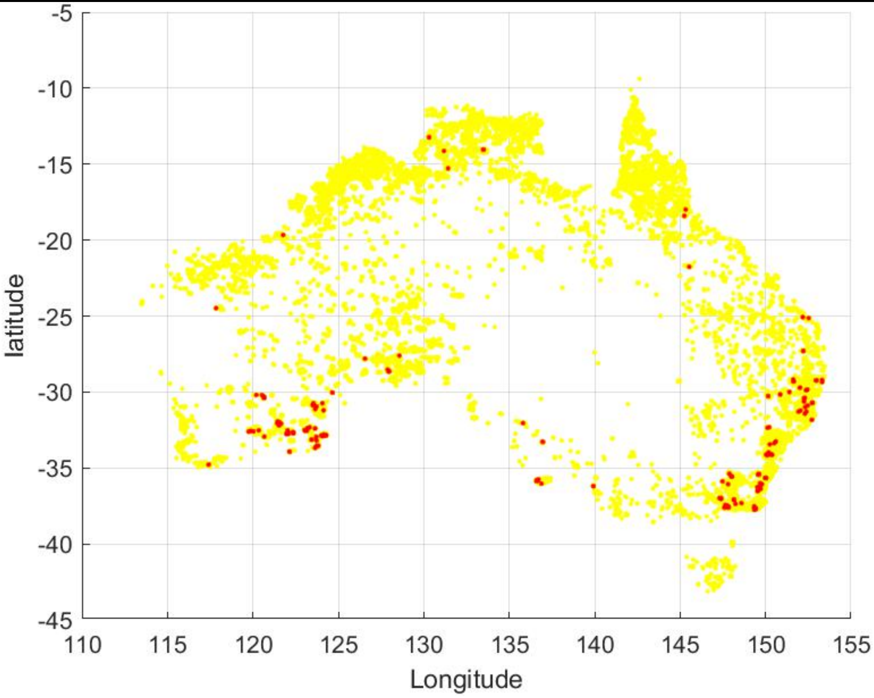

Fig 5:Near Real Time fire situation based on NASA satellite [1]

4.2 Modelling the optimal mix of the SSA and the repeater drones

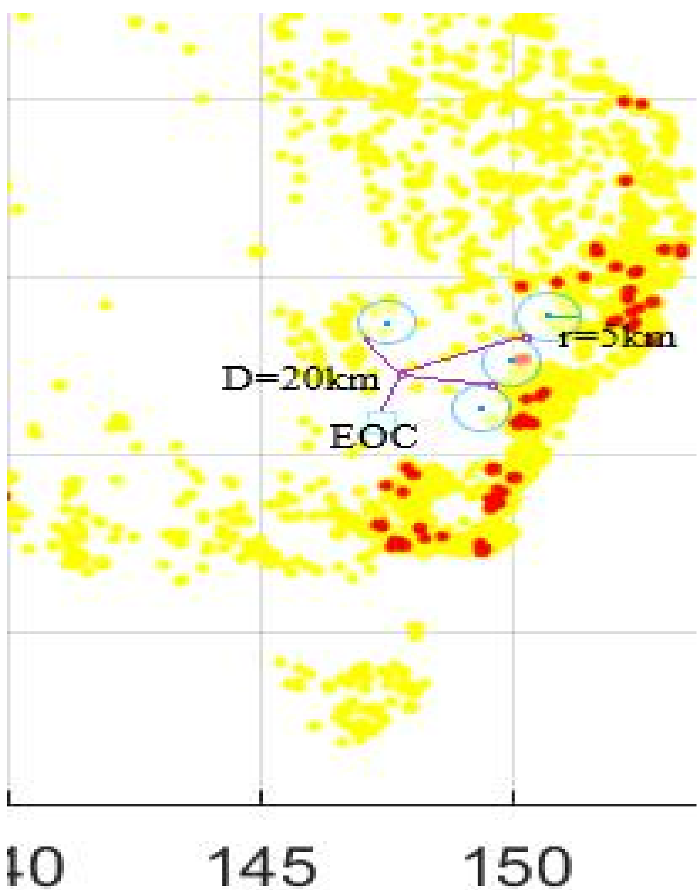

Figure 6: The basic model of the positions of SSA, repeater and EOC (only to express)

In the figure above, the blue dot represents the SSA drones, the circle around each dot is the interaction range of the drone to the "boots-on-the-ground" forward team, the blue rectangle is the position of the movable EOC, and the purple dots represent the radio-repeater drones.

In the south-east region of the Victoria state, the elevation is from 500-1000m.

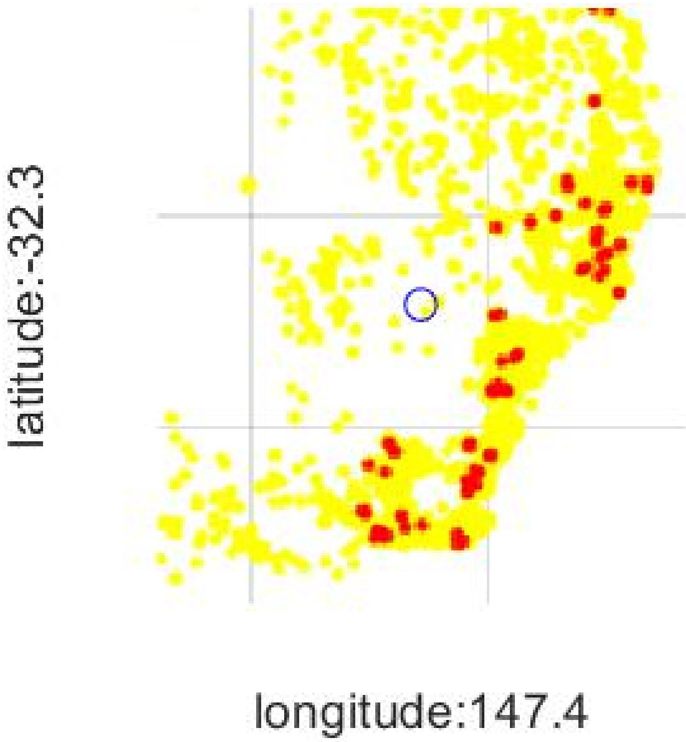

Figure 7: The proper position for EOC

We used computer program to find the geometric center of the southeastern Australia where the fires happen densely. The place is for EOC to be deployed at for the convenience of commanding and assigning of firefighters. According to the data acquired from remote-sensing program[2], this location has a height of 262.7 meters, and is in rural area.

According to BBC News[3], an approximation of 3000 people engage in the fighting of wildfire each day, and the average time of a fire until it is extinguished is 3months.

To ensure safety under common fire stress, we recommend that the red spots, according to figure 8, which indicates concentrated forests and bushes, be controlled in priority.

We use the Great-Circle function to calculate the distance between two points,

$$\widehat{A}\widehat{B} = R_{Earth} \cdot \arccos(\cos(A_{lat})\cos(B_{lat})\cos(B_{lon} - A_{lon}) + \sin(A_{lat})\cos(B_{lat})) \quad (1)$$

We filtered 50 sets of data of the red-dot fires such that the repeater drones will not overlap in calculation of their number. We approximate there is an average height drop of 1000m.
Using the data combined with program, the calculations resulted as follows.

The total distance Dt from the fire to the EOC is:

$$Dt = \sum_{n=1}^{50} \sqrt{(\widehat{A}_{EOC}\widehat{B}_{fire(n)})^2 + 1^2} = 6.3354\times 104 \text{ km} \tag{2}$$

The optimal number of repeater drones Nr is thus:

$$N\mathrm{r} = [\frac{\mathrm{D_t}}{20}] = 3168 \tag{3}$$

The rectangle bracket means to round upward to an integer.

On the frontline of fire-fighting, the curves formed by the connection of red-dots have a total length of D_{fro},

$$D_{\mathrm{fro}} = \sum_{\mathrm{n}=1}^{n} \widehat{A}_{\mathrm{fire(n)}}\widehat{\mathrm{B}}_{\mathrm{fire(n+1)}} \tag{4}$$

Similarly, the value of Dfro is calculated as 292.6km. According to the urban construction showed on map of Australia[2], the urban regions account for a portion of 50km in the frontline.

Therefore, according to figure 6's demonstration, the SSA drones required are:

$$NS = [\frac{242.6}{10} + \frac{50}{4}] = 37\ . \tag{5}$$

With this result, if each day 3000 people could be mobilized in the fighting of fires, each SSA can be assisting **81** personnel that are inside the circle with radius of 5km or 2km.

Due to the capability of the batteries, every time a drone returns for recharging, it will take 1.75 hours, while the mission time is 2.5 hours. The repeater drones shall either return to EOC or to the forward teams depending on the distance. To better enhance the stability of the communication network in fire-fighting procedure, it is recommended that the numbers of SSA drones be doubled to **74**, and the number of the radio-repeater drones be tripled to **9504**.

The frequency of the fires happening should also be taken into account.

Reading from the fires data from Nov. 1st, 2019 to Jan. 9th, 2020, it is observed that on average a fire with radiative power over 2000Watts happens **every two days**, and to distinguish a fire of such scale takes 3 months. So, within the 3 months period there could happen other 45 fires, which strongly suggests that the equipment of such a number of drones for the network is rational. This model is built with the data for common cases, not the extreme ones.

5.Predicting in the next decade

5.1 Predicting extreme situations

If we want to see whether our module can be applied to every situation. We need to consider the extreme situation. In this case, we consider that all the possible position that may have wildfire starts burning simultaneously. Then we will use our model to calculate the number of SSA and repeaters we need. We will also predict the possible equipment cost increasing due to the mass range of wildfires.

To predict all possible places of wildfires, we need to consider the elevation, the distribution of woods, and the type of trees to predict the place and range of the wildfire. We also need to consider real-time situation since some places may have wildfires even we do not predict that. So we will add the possible position to the real-time situation to achieve comprehensive analysis.

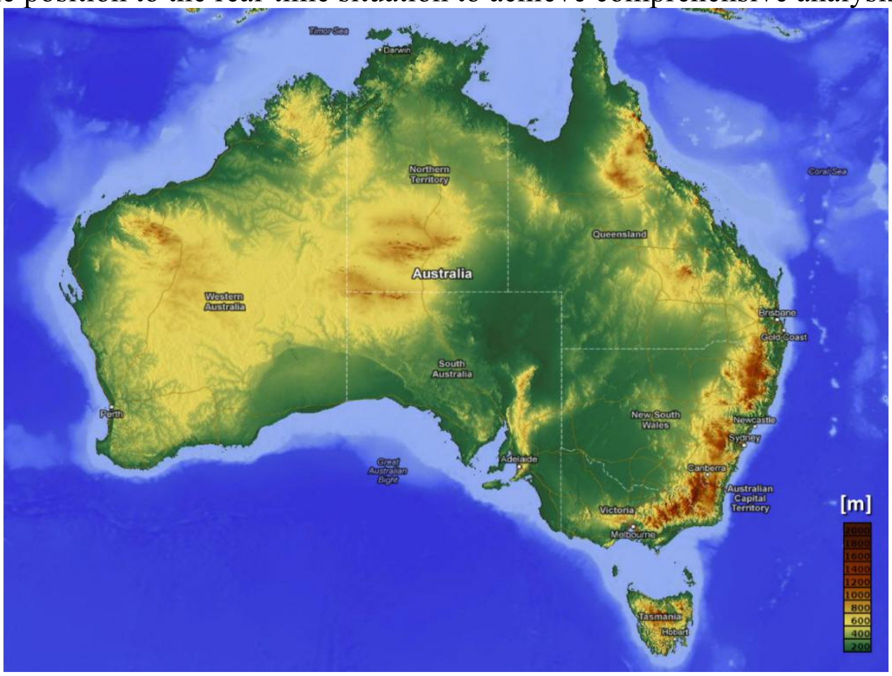

Figure 8: The elevation of Australia

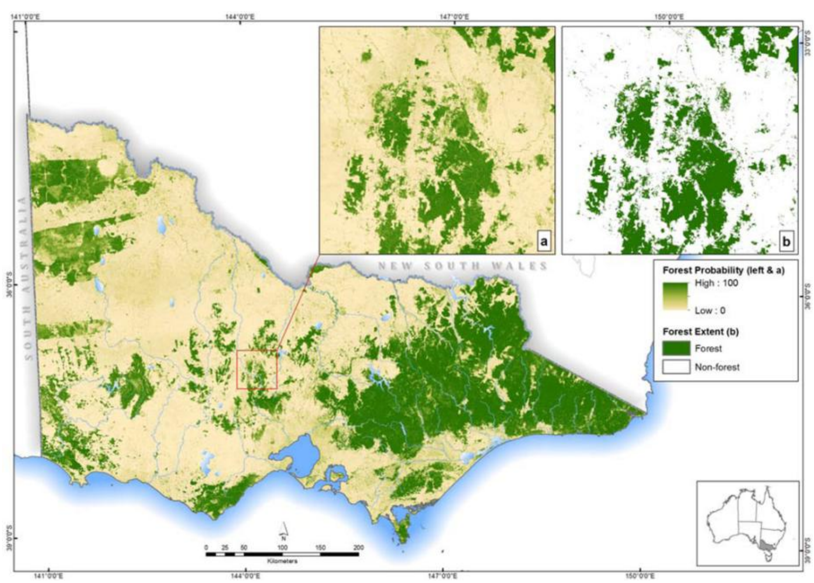

Figure 9: the forest distribution map

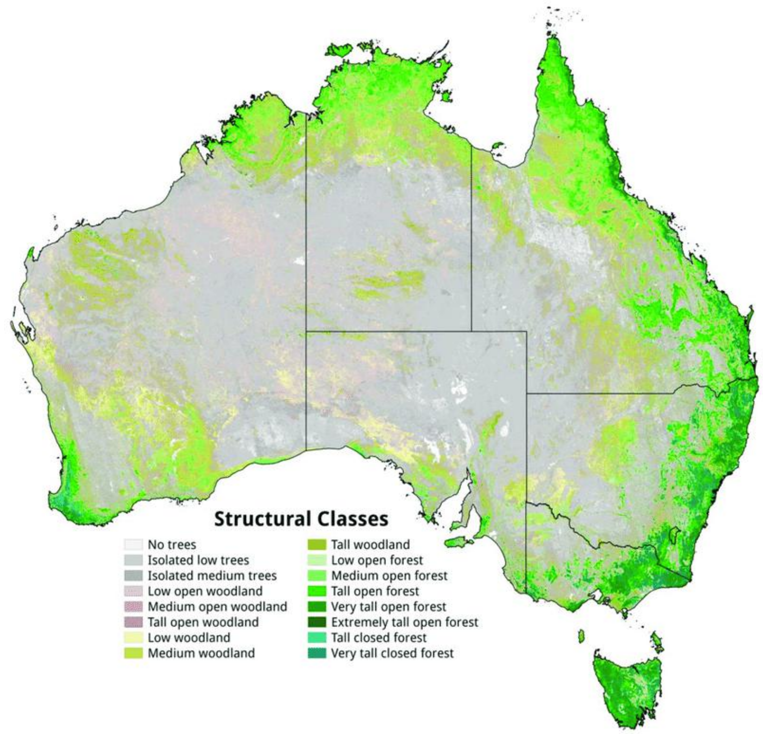

Figure 10: the general type of trees.

Apart from that, we also need to consider the weather and the temperature of these areas during the fire season. We can see from the data of weather report that from October 1, 2019 to January 7, 2020, the most possible time of the extreme situation may occur starting from the medium of December,2019 to the medium of January [4]. In the duration it appears to be constantly dry and hot weather. We compare the real-time situation with the map, we found that most places of wildfires occur in the places of “very tall open forest” and “extremely tall open forest” areas. Then, along with the data of woods, we can predict that the possible place of wild fire apart from the real-time situation. We tagged them in the picture with blue points.

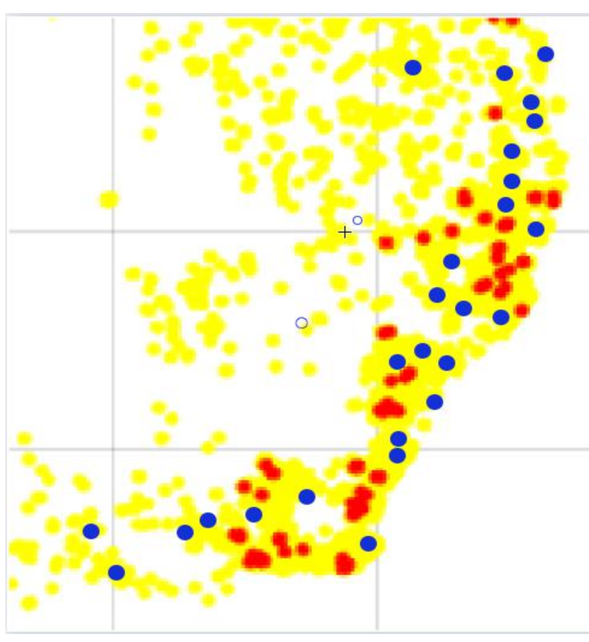

Figure 11 : extreme situation

We apply our model to this situation, since we assume the EOC is fixed, it located at the geometric center of the southeastern Australia where the fires happen densely. Then we apply the Great-Circle function to calculate the distance between two points. Subsequently, we calculate the total distance from the fire to the EOC.

Ultimately, by applying formulas (1)-(5) and extended data, we get the number of repeater is: **Nr=4076**, which is tripled to **12228**; the number of SSA is: **NS=53**, which is doubled to **106**. then we find out than even in extreme situation, our model can get a rather reasonable outcome. So in the next decade, if the extreme situation happens, we only need to get the range and scale of the wildfire, then we can calculate the number of SSA and repeaters by applying our model.

5.2 Predicting equipment cost increases in the next decade

When extreme situation happens, then range of wildfires becomes larger and the frequency becomes higher, which means we will need more SSA drones and repeater drones to put out those wildfires and for the "Boots-on-the-ground" Forward Teams to communicate with EOC more efficiently. Also, the cost of surveillance will become larger, since we need to know the place and scale of wildfires at the first time. For example, we will need more wildfire-monitoring cameras to be placed in different places [5]. Also, when rescuing the wildfires, if the scale of the fire is larger, we need more "Boots-on-the-ground" forward teams, and the equipment of the "Boots-on-the-ground" forward teams need to be more high spec. Such as the exposure suits needs to be more thick, the sensor equipped on SSA drones need to be more high spec so that when the smoke is thick, the sensor can still find the crew and monitor the health condition of the team members properly.

6. Modelling the optimization of the positions of the repeater drones

We have up to now evaluated the number of the repeater drones, however, the positions of those drones are undetermined. The positions of the drones should be variable of topography and the scale of fires. We apply **optimization** algorithm to estimate the answers.

We don't take the gradient of the southeastern Victoria to be the branch of the drones network, as that would mak
e the branch longer and cost more drones. Plus there is only little cost by the altitude fall on the length of the branches. The branches of the drone network should be **straight line**.

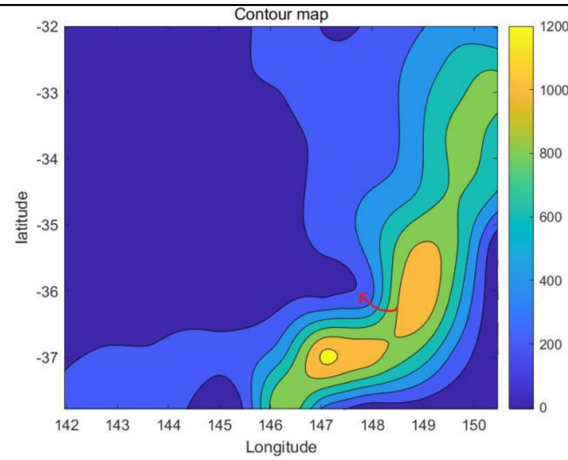

Figure 5: The red curve shows the gradient

The closer to the EOC or to the front line the repeater drones are, the easier they can return and be recharged, relating to the factor of **distance**, and the distance from the frontline to the EOC will make the value of distance compensate firstly decrease and then increase. Meanwhile, the lower the altitude is, the faster the drones can return due to the air dynamics, relating to the factor of **elevation**. Besides, the stronger **the fire at a site** is, the stronger signal it needs to transfer more sensor and communication data.

We take 3000 locations for the pending positions of the repeater drones.

location	1	2	3	4	5	6	7	8	9	10	...	3000
Distance from the frontline	0	20	40	60	80	100	120	140	160	180	...	/
Data it can receive/transfer (value means quantity)	10000	9999	9998	9997	9996	9995	9994	9993	9992	9991	...	6832
DV (distance compensate)	3000	2999	2998	2997	2996	2995	2994	2993	2992	2991	1500(Middle Point)	/
dV (data transmission compensate)	3000	2999	2998	2997	2996	2995	2994	2993	2992	2990	≈0 (At EOC)	/

Table 1: Model of the position related to performance

The performance **P** is:

$$P = \sum_{j=1}^{3000} ((D_V u)_j + (d_V u)_j) \tag{6}$$

Subject to

$$\left\{ \begin{array}{l} \sum_{j=1}^{3000} M_j \leq 3168 \\ \sum_{i=1}^{3168} S_i(j) \leq \sum_{j=1}^{3000} S_j \\ u \in \{0,1\} \end{array} \right\} \tag{7}$$

Where $\mathbf{S_i}$ **(j)** is the isolated area of the effective range a repeater drone, $\mathbf{M_j}$ is the number of drone at each one of the 3000 pending positions; $\mathbf{S_j}$ is the area of a pending position. The value of u depends on whether that place has a drone.

The solving of the optimal value of performance **P** and the corresponding positions of the repeater drones requires more data in order for our program to run better. But elementary analysis through computer simulation indicated that, the straight-line branches are correct, and the connection of the 50 positions from the frontline to the EOC has given a satisfying model that ensures the communication while economizing the repeater drones.

7.Sensitivity Analysis

7.1 Sensitivity Analysis of Model One

As has been analyzed in the model, the proportioning of the Repeater drones and the SSA drones cater to the recent situation of wildfires by meeting the demand of safety and economy, but the model is sensitive to the variation of multiple factors.

In order to measure the robustness, we construct a testing model.

7.2 The track-cost function

Track cost refers to the loss of drone during flight. The cost function in this paper mainly includes threat cost, range cost, and altitude cost function.

7.2.1 Threat cost function

Since the impact of the fire will affect the flight of the drone, the threat cost refers to the possibility that the drone is flying through the fire.

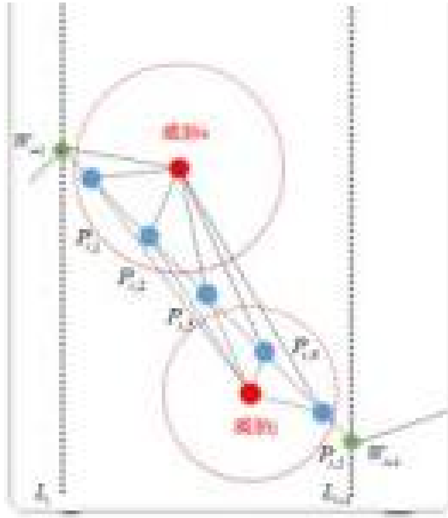

Figure 12：Schematic of threat cost calculation

The red circle represents the fire. We take k points in the j-th track $w_j w_{j+1}$ and denote them as $p_j = (p_{j,1}, p_{j,2}, p_{j,3}, p_{j,k})$

Threat cost calculation formula:

$$f_{threat} = \sum_{j=1}^{n} \sum_{i=1}^{m} \sum_{q=1}^{k} \frac{l_{Tj}}{k} f_{TAi}(p_{j,q}) \tag{8}$$

Where, n is the number of track segments, m is the number of fires, and l_{Tj} is the length of track covered by fire in segment j. $f_{TAi}(p_{j,q})$ is the influence degree of the i-th threat to point $p_{j,q}$, which can be calculated according to the following formula:

$$f_{TAi}(p_{j,q}) = \begin{cases} 0 & d_i > R_T^i \\ \frac{K_i}{d_i} & d_i \le R_T^i \end{cases} \tag{9}$$

d_i is the distance between the current node in the track segment and the i-th threat center.

7.2.2 Drone range cost function

The range is the distance the drone flies from the initial point to the designated target point. By shortening the range, the drones can be less dangerous, but also save on fuel and costs.

The cost function of drone range is:

$$f_{length} = \sum_{j=1}^{n} l_j \tag{10}$$

Where, l_j is the length of the j-th track segment

7.2.3 Height cost function

Because flying at high altitude can affect the signal. Therefore, the drone should fly as low as possible without being burned by fire.

The height cost function is:

$$f_{\text{height}} = \sum_{j=1}^{N} \begin{cases} \dfrac{z_j - f_T - H_{\min}}{N} & z_j > f_T + H_{\min} \\ \dfrac{f_T + H_{\min} - z_j}{N} & z_j < f_T + H_{\min} \end{cases} \tag{11}$$

Where, N is the number of SSA drone track ascending points, (x_j, y_j, z_j) is the coordinate of the drone, $f_T(x_j, y_j)$ is the terrain height corresponding to any track point, and $H_{\min}$ is the minimum altitude allowed to fly by the drone. According to normal wildfire report, the height of a fire could be 30 meters, so the SSA drone should have a $H_{\min}$ of 50 meters.

7.2.4 The probability cost function of hitting the ground

The impact cost is the total number of track points across the terrain by the track curve.

The formula is as follows:

$$f_{hit} = \sum_{j=1}^{N} C_j, C_j = \begin{cases} 0 & z_j < f_T(x_j, y_j) \\ 1 & z_j \ge f_T(x_j, y_j) \end{cases} \tag{12}$$

Therefore, the flight path cost function of drone is:

$$\min f = \omega_1 f_{threat} + \omega_2 f_{length} + \omega_3 f_{height} + \omega_4 f_{hit} \tag{13}$$

Where, $\omega_1, \omega_2, \omega_3, \omega_4$ is the weight coefficient of the evaluation index, and satisfies $\sum_{j=1}^{4} \omega_i = 1$. The more important the evaluation index is, the larger the corresponding weight coefficient is.

7.3 The constraint

7.3.1 Shortest voyage constraint

When the drone adjusts its flight attitude, the j-th track l_j section shall be greater than the shortest direct flight distance.

The constraint expression is：

$$l_j \ge l_{\min} \quad j = 1 \cdots n \tag{14}$$

7.3.2 Maximum voyage constraint

Drones cannot fly indefinitely because of the limited capacity of the batteries they carry. Let l_{max} is the maximum allowable flight range.

The constraint expression is:

$$\sum_{j=1}^{n} l_j \le l_{\max} \tag{15}$$

8.Strengths and Weaknesses

8.1 Strengths

(1) We applied “algorithm” to construct the model, which is capable of calculating the ratio of two types of drones to satisfy both safety and economy. We also took the position of EOC into account.

(2) As we proved, our model can adapt to possible extreme situations in the next decade. We also considered the possible budget increasing. Which means our modules are robust when the parameters changes.

(3) Our modules is changeable, which means they can be used to solve many other kinds of problems, as long as we apply proper parameters in them.

8.2 Weaknesses

(1) Our model considered too few locations of EOC. In real situations, the EOC ought to be mobile and can be deployed near emergency.

(2) The model doesn’t involve the influence of weather conditions, including fog, rain and the smoke caused by the fires.

(3) We didn’t construct a mathematical model for the time constraints of any drones, but only made an approximation.

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9.Modelling an annotated Budget Request

Fire Budget Application				
1 、Drones equipment				
Number	Items	budgeted quantity	price per unit	Total budget
1	SSA drones	80.0	$5,000.00	$400,000.00
2	WileE–15.2X Hybrid Drone	10,000.0	$10,000.00	$100,000,000.00
3	high definition & thermal imaging cameras	100.0	$500.00	$50,000.00
4	telemetry sensors	100.0	$200.00	$20,000.00
5	Drone insurance	10,080.0	$1,000.00	$10,080,000.00
	Total			$110,550,000.00
2、Personnel expenditure				
Number	Items	budgeted quantity	Salary of Personnel (Month)	Total budget
1	Users of SSA drones	100.0	$2,300.00	$230,000
2	Users of Radio Repeater Drones	10,000.0	$2,300.00	$23,000,000
3	Drone commander	100.0	$3,000.00	$300,000
4	Maintenance personnel of drones	100.0	$2,500.00	$250,000
	Total			$23,780,000

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