Problem Chosen	2021	Team Control Number
B	MCM/ICM Summary Sheet	**2100059**

Race Against Fire

Summary

Bushfires caused by natural factors and untimely management have caused incalculable losses in New South Wales and the eastern Victoria, making the establish of "Rapic Bushfire Response" system necessary. In this paper, we constuct a model to design the number, mix and locations of detection and communication equipments for severe bushfires.

Firstly, we preprocess the data and devide the whole area into 11 regions with different fire frequency features and fire event size features. We also use **cellular automata** to simulate bushfires extension. The result verifies the hypothesis saying that bushfires approximately spread in a circle, and large-scale fires happens periodically.

Secondly, we obtain the number and mix of SSA drones and radio repeater drones. In the first step, we find the relationship between coverage radius of SSA drones and the system's capability, safety and economics to build an **optimization model**. Then we use **genetic algorithm** to find the optimal solution of the radius. In the second step, we use the **HIVE model** to find the number of SSA drones. The coverage radius of a SSA drone is the length of hexagonal blocks. Drones' maximum flight distance determines the number of blocks they can govern. Based on the total area and the blocks governed by a drone, we get the requirement of SSA drones is 890. Clusters composed of hexagons, is the area fixed EOCs need to take charge of. Using clusters to cover the whole area, we find the number of fixed EOCs is 177. In the third step, we build a physical model, single fire source model, to find the number of repeater drones needed by a single fire source. By calculate the number of simultaneous burning fire sources, we have the number of working repeater drones globally and simultaneously. Finally, considering the limitation of hovering time, we use linear programming and obtain the total number of repeater drones is 322.

Thirdly, we use the **Markov Prediction Model** to predict the likelihood of extreme bushfire. We use **K-means clustering** to divide fire severity data in past 9 years into two class, extreme and unextreme. By Markov prediction, we obtain the likelihood of extreme bushfire in the next decade for the 35 prediction points. According to the prediction, the number of SSA drones and fixed EOCs is reduced where extreme bushfire could not be happening, and the number of repeater drones and mobile EOCs is increased in the regions where extreme bushfire is more likely to occur. We gain the optimized result: 989 repeater drones 686 SSA drones, 110 fixed EOCs and 45 moving EOCs. The construction and maintenance cost budget is increased by $2504900.

Forthly, we obtain the best distribution solution for Radio Repeater Drones, from the perspetive of macro and micro. At the **macro-level**, we distribute repeater drones to each fixed EOCs based on previous adjustment, so that the emergency system can go to the disaster faster to implement rescue. The response time to emergency is controlled at 46 minutes. In **micro-level**, we build **physical models** and use **unlinear programming** to find the best arrangement for drones reaching the fire front. The spacing of the repeater drones should be the communication radius and the distance from the fire line is $\frac{\sqrt{3}}{2}$ times the communication radius. Then we build an extended fire spread model for fire events covering complex terrian, supplemented by the improved **Rothermel model.** Finally, we analyze a real fire event on March 10, 2019. One happens on the hillside (longitude 146.858 latitude 37.756), the other, happens at the bottom (longitude 146.90 latitude 37.90). We derive the fire source movement speed, actual burn radius, and drones hovering position distribution. The modeling effect can reduce drones requirement by 12%-18%.

Keywords: Cellular Automata, HIVE model, Genetic Algorithm, Markov Prediction Model, Rothermel model

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1 Introduction

1.1 Background

Since July 2019, Australias "Worst ever forest fire" has caused unprecedented losses and negative impacts, with New South Wales and Victoria being the most severely affected. The natural causes of the fire: from late 2019 to early 2020, local temperatures hit Australias highest in more than 70 years, while rainfall was the lowest in more than 110 years. The forest fire also exposed the shortcomings of the volunteer-based fire protection system in Australia, as well as the insufficient mobilization capacity of the federal government, inadequate response and so on. In 2019, the New South Wales declared a state of emergency, and the federal government failed to help, causing the fires to spiral out of control.

To prevent a recurrence of such incidents, Victorias Country Fire Authority (CFA) has decided to establish a division responsible for Rapid fire bushresponse, thereby the potential for future irreparable damage can be reduced. Such a move is necessary and urgent.

1.2 Problem Restatement

(1) **Evaluate the number.** In order to design a "Rapid Bushfire Respond " System, we need to help CFA to determine the optimal numbers and mix of SSA drones and Radio Repeater drones. The frequency and size of the fire should be considered, while the factors of safety, capacity and cost should be balanced.

(2)**Adapt to extreme fire events.** Show the adaption our model can make to deal with extreme fire events in the coming 10 years. Forecating the increment of the cost is necessay as well.

(3)**Optimize the locations.** Basing on fires of different sizes on different terrains, the location of Repeater Radios may be changed. Build a model to optimize the locations of them to better fit the sepecific conditions.

1.3 Model Preparation

1.Preprocessing Bushfire Data

We use official NASA fire statistics from 2011 to 2019 through a search [1], which provides daily brightness temperature of specific fire point in Australia. Use one grid as a statistical object. We obtain the total number of fire points of each grid (figure 1) and the brightness, temperature and heat chart of each grid in 9 years (figure 2).

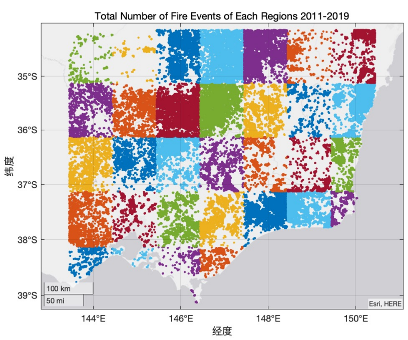

Figure 1

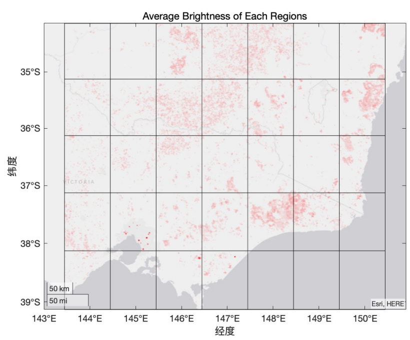

Figure 2

Figure 3

2. Dividing Regions

In order to make the analysis more clear, we distinguish the urban area and the natural area according to whether there is cities; then distinguish plain and multi-undulating area according to the terrain undulating condition. 11 regions are divided as followed (figure 4)

In the later models, relevant parameters (table 2) are the same within the same region.

3. Quantificating the Parameters of Regions

Quantificate the relevant information of each region. The average annual fire frequency on the unit area (grid) of the region is used to quantify the possibility of Fire events in this region, and the average brightness temperature of this region is used to measure the size of fire events in this region. The following regional property table is obtained.

Table 0

Region Number	1	2	3	4	5	6	7	8	9	10	11
Area/grid	3	2	1.5	1	4	1	1	2.5	3	3	5
Average Fire Event Frequency/year ·grid	358.5927	246.17	603.7053	123.22	230.9175	1163.56	185.551	230.5307	221.9633	533.7033	300.3324
Topography	City	Mountain	Plain	Plain	Mountain	Plain	City	City	City	City	City
Average Brightness	328.08	327.855	333.78	323.84	327.2675	338.99	329.345	318.1275	321.5	323.1333	324.388
Relative Fire Event Size \phi	1.0313	1.0306	1.0492	1.018	1.0287	1.0655	1.0353	1 (reference)	1.0106	1.0157	1.0197

4. Fire Simulation Based on Cellular Automata

We hope to find out how forest fires develop. Here we assume that the distribution of forests is both random and relatively uniform. We performed a cellular automata simulation on a square woodland. The probability of tree cell burning was selected as 0.000001, and the probability of tree growth with empty cell was 0.001. Then we simulated the number of forest trees after experiencing two fires, the results are shown in figure 5:

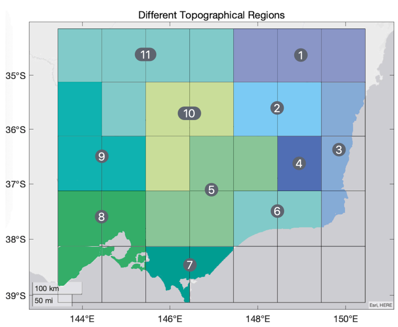

Figure 4

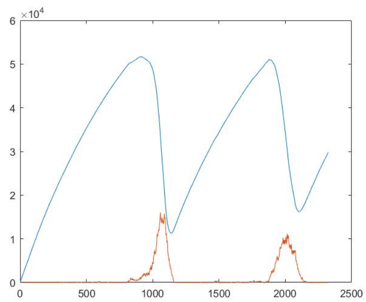

Figure 5

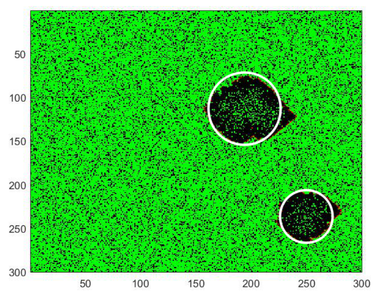

Figure 6

Obviously, we can see that under this condition, there will be a large probability of extreme fire for every certain period (900 days). Then, we select a representative fire situation at a certain moment for observation, and took a circle centered on the fire source as the fire line (as shown in the white line in the figure 6).

1.4 Our Work

2 Assumption and Justification

a. Assume that the load weight and flight status do not have an impact on flight time and flight distance.

Justification: Since the weight of the drone itself is often much larger than its load, the effect of the load on the battery power is not considered. Second, the effect of flight status (moving or hovering) and flight speed on battery power is a complex statistical problem, and our main concern here is the effect of limited duration and distance on our solution.

b.Assume that the radio communication system battery has no effect on the drone duty duration.
Justification: Since the radio communication system battery can be replaced during drone charging, the time for battery replacement can be directly ignored.

c. Assume uniform vegetation distribution in each terrain area of the forest.
Justification: Since the climate, altitude and terrain of the same terrain area are similar, it is a very natural idea to assume that it is evenly distributed.

d. Assume that the time and power consumption of flying to the destination in the repeater drone duty mission can be ignored.
Justification: Since the setting of our EOC is already very close to the mission location of the repeater drone, it is a natural thing to ignore the time on the road.

f. Assume that the repeater drone needs to cover the entire fireline and that the ground crew has the capability to cover the entire fireline coverage.
Justification: Since all areas on the fire line need to be fought, enough personnel are needed to cover it and the repeater drone needs to provide communication services to all the personnel on the ground in it.

g. Fires do not consider the condition of inhomogeneous (making the fire area non-circular) influences in the same terrain, assuming that the fire line is taken as a circle centered on the fire point as an idealized analysis
Justification: The model complexity grows exponentially and is less efficient due to the series of butterfly effects that inhomogeneous fires can have on the results. This has been shown to be feasible by the cellular automata in the following points.

h. Assume that the degree of ignition is uniformly reduced on the same line of fire, and that there is no sequential relationship for extinguishing.
Justification: If there is a sequential extinguishing situation, it will also lead to uneven fires, and the problems arising from it are similar to the one in 2.g, which will not be repeated here.

3 Notation

Table 1: Notation

Symbol	Definition
r_s, R_s	real visual radius of the SSA drone, actual coverage radius of SSA Drones
γ	ratio of the actual coverage radius to the real coverable radius of SSA drone
H	the radius (edge length) of the hexagon corresponding to different terrain areas
θ	maximum viewing angle of the camera lens (also thermal imager viewing angle)
α	the angle between the vertical line and the bisector of maximum viewing angle
h	drone flight altitude
D_{fire}, D_{max}	maximum measurable fire Radius,maximum fire radius
I_{co}, I_{cap}, I_s	cost, capacity, cafety evaluation indicators
$\xi_{co}, \xi_{ca}, \xi_s$	cost evaluation factor, capacity evaluation factor, safety evaluation factor
R_{ri}	repeater communication radius at different locations
R_{rsl}, R_{rm}, R_{rse}	drone communication radius in slight,medium,severe shadowing scenarios

R_h	range of portable two-way wireless transceivers
M_s, M_r	number of SSA drones, number of repeater drones
$M_{rair}, M_{rcharge}$	the number of repeater drones on duty, the number of backup repeater drones
m_r	number of repeaters required at a single fire source
L	the distance of fire spread in a certain time
D_f, D_d	distance to the fireline from the drone,distance between deployed drones
s_s, S_s	area of hexagonal block, area covered for SSA drone
S_m, S_{region}	area that an SSA drone can govern, area of a region
ε	fire radius correction factor
N_b	number of blocks the drone can fly over
N_{feoc}, N_{meoc}	number of fixed EOCs and number of mobile EOCs
D_a	maximum flight distance of drone
λ	ratio coefficient of the number of fire points and the number of fire sources
η_i	frequency factors for different regions
N_{point}, N_{source}	number of fire points,fire source at the same time
κ	improved Rothermel model ratio coefficients
R_c	current fireline radius
R_{modis}, L_{grid}	resolution of MODIS satellite, the average length of grids
T_{react}, V_{drone}	the reaction time of bushfire, the maximum speed of drones

4 Problem 1 - Number of Equipments We Need

To obtain the number and mix of SSA drones and radio repeater drones, we developed a SSA drones coverage model based on genetic optimization model and HIVE model, and a repeater drones distribution model based on linear programming.

4.1 Coverage Radius Range of SSA Drones

1. Real Visual Radius of SSA Drones

For the camera pixals and thermal imaging pixels, the relationship between the visible area and the minimum of feature is

$$\text{Thermography Resolution } = \text{ Image Resolution } = 2\left(\frac{\text{Field of View (FOV)}}{\text{Smallest Feature}}\right) \tag{1}$$

Let θ be the maximum viewing angle of the camera lens (also the viewing angle of the thermal imager), α be the angle between the vertical line, and the the angle bisector of θ angle, h is the flight height of the drone, r_s is the real visible maximum radius of the drone. The relevant physical model is shown in figure 7.

The physical equations are as follows.

$$FOV + h\tan(\alpha - \theta/2) = h\tan(\alpha + \theta/2)/r_s = h\tan(\alpha + \theta/2) \tag{2}$$

We use the flight height of S24F-6 firefighting drone [2] as the average flight height of 150m, selecting a resolution of 2K (2560x1440), a minimum object identifiable degree (smallest feature) of about 4m, and a θ of 72 degrees. Bringing the formula into calculation, we have α = $51.5°$, r_s = 3.73km.

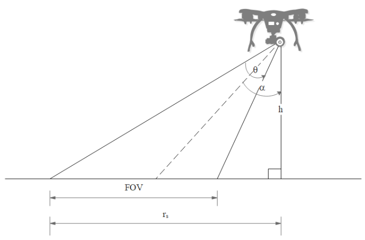

Figure 7

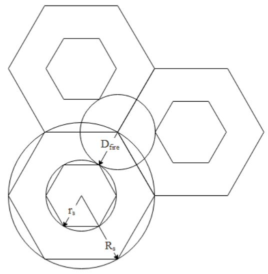

Figure 8

2. Detectable Radius of SSA Drones

In order to explore the most reasonable SSA drone range, cost, safety and capability evaluation metrics were established. In order to obtain the optimal results with balanced demand, we use a genetic optimization model to obtain the actual coverage radius R_s in the baseline area corresponding to the highest comprehensive evaluation index. Then we calibrate the optimal SSA drone coverage radius for different areas according to the frequency of fires.

As shown in the figure 8, the actual coverable radius R_s of SSA drones will have a proportional relationship with the real visible radius r_s. We introduce the covering parameter γ to obtain the following equation.

$$R_s = \gamma \cdot r_s \tag{3}$$

So we need to establish the relationship between indicators and the covering parameter γ $(i.e. \frac{R_s}{r_s})$. Obtain the value of γ when the comprehensive indicator is optimal.

(1)Cost evaluation indicator

Considering the cost of drones here, it relates to the number of SSA drones, and the number of drones is related to the size of the blocks they can cover. We can calculate the area covered by each SSA drone roughly satisfies the following equation

$$S_s = \xi_{co} \frac{3\sqrt{3}R_s^2}{2} \tag{4}$$

S_s is the area of each hexagon, R_s is the SSA drone's actual coverable radius, and ξ_{co} is the cost evaluation coefficient, which combines the number of blocks flown by each SSA drone.

The relationship between the cost and the R_s can be expressed by the cost evaluation index

$$I_{co} = \xi_{co} \frac{2S}{3\sqrt{3}R_s^2} \tag{5}$$

S is the total area of the region, and I_{co} is the cost evaluation index.

(2)Safety evaluation indicator

We define the evaluation of safety as the relationship between the relative loss of life and property and the radius that can be covered by SSA.

Imagine a scenario: assuming the SSA drone is hovering, a fire source keeps spreading outward from the point, and once the fire radius reaches $R_s - r_s$, it will be detected by the SSA drone and subsequent emergency measures will be implemented (figure 8). We define this threshold value of misfire radius as the maximum measurable fire radius

$$D_{fire} = Rs - rs \tag{6}$$

It is easy to see that larger the D_{fire} is, more difficult it is to extinguish the fire, the greater the loss will be caused.So the coverage radius and the loss of life and property safety can be reflected by the exponential function. The safety of life and property brought about by the overfire area can be expressed by the following equation

$$I_s = \xi_s e^{\pi \cdot (Rs - r_S)^2} \tag{7}$$

ξ_s is the safety evaluation coefficient, and I_s is the safety evaluation index.

(3)Capacity evaluation indicator

There are many evaluation indicators in the field of communication with many use ratios, such as SQNR. we draw on the calculation method of evaluation indexes in the field of communication. The capability evaluation index cites the concept of decibels to describe the ability to detect different fire area radii before and after hexagonal amplification. The equation is as follows.

$$I_{ca} = \xi_{ca} \left[1 - \log_{10} \left(\frac{R_S}{r_S} \right) \right] \tag{8}$$

ξ_{ca} is the capability evaluation coefficient, and I_{ca} is the safety evaluation index.

(4)Comprehensive evaluation indicator

Next, the integrated evaluation indicators were obtained based on cost evaluation indicators, safety indicators and capacity indicators.

$$I = \frac{I_{ca}}{I_{co} \cdot I_s} \tag{9}$$

We obtain the simplified formula for the comprehensive indicator.

$$I = \xi \frac{\gamma^2 \cdot (1 - \log_{10} \gamma)}{e^{(\pi(\gamma-1)^2)}} \tag{10}$$

ξ is the integrated correlation coefficient including ξ_s ξ_{co} ξ_{ca}. Combining them into one constant. γ is the ratio coefficient of the R_s and the r_s. By optimizing the model, the coverable radius of SSA is found when the comprehensive evaluation is optimal. Equation 10 can be plotted as figure 9.

The genetic algorithm is used to find the value of γ when I takes the maximum value.

$$MAX(I) = \frac{I_{ca}}{I_{co} + I_s} \Rightarrow \gamma = 1.2023 \tag{11}$$

Finally, we get that the value of R_s is taken as 4.476km when the comprehensive evaluation is the highest.

Different probability of fire occurrence in different regions will lead to changes in the demand for covering radius. We introduce the correction parameter η_i related to the frequency of fires in the

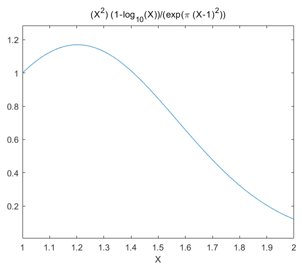

Figure 9

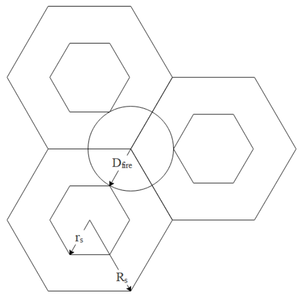

Figure 10

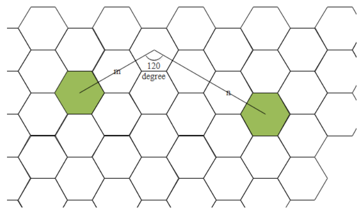

Figure 11

region in the past 10 years based on the optimal solution R_s, and obtained the actual SSA drones coverable radius R_{si} for different regions.The correction formula is as follows.

$$R_{si} = \frac{R_{s0}}{\eta_i} \tag{12}$$

η_i is the frequency parameter of different areas, R_{si} is the coverable radius of different areas, and R_{s0} is the coverable radius derived from the normal case. Results are shown in Table 2 .

Table 2

	1	2	3	4	5	6	7	8	9	10	11	Total
Frequency factor	1.14	1.14	1.14	0.424	1.803	1.803	0.424	0.424	0.424	0.424	0.424	
Actual coverage radius R_{si}(km)	3.926	3.926	3.926	10.55	2.483	2.483	10.55	10.55	10.55	10.55	10.55	4.476
Blocks/drone	5	5	5	2	8	8	3	3	3	3	3	
Area of blocks s(km^2)	40.04	40.04	40.04	289.17	16.02	16.02	289.17	289.17	289.17	289.17	289.17	
Area covered by each drone $S_m(km^2)$	200.2	200.2	200.2	578.35	128.13	128.13	867.52	867.52	867.52	867.52	867.52	
Area of region S_{region} (km^2)	29,734.20	19,822.80	14,867.10	9,911.40	39,645.60	9,911.40	9,911.40	24,778.50	29,734.20	29,734.20	49,557.00	
Number of SSA drones M_s	149	99	74	17	309	77	11	29	34	34	57	890

4.2 Number of SSA Drones

In the field of communication, the base stations are distributed in a sophisticated way so that they can cover a larger area, save costs and maximize the use of resources. The distribution is based on the conclusion from mathematical theory: the number of circles used to cover a plane with circles of the same radius is minimal when the center of the circle is at the positive center of each surrounding hexagon. **We use hive model to optimize the number of drones and the number of fixed EOCs.** In figure 10, r_s is the real visible radius above, R_{si} is the actual coverable radius, and D_{fire} is the maximum measurable fire radius.

1. Number of SSA Drones in Different Regions

We first obtain the size of each hexagonal block based on the coverable radius R_{si} of the different regions:

$$s_s = \frac{3\sqrt{3}R_{si}^2}{2} \tag{13}$$

Since the detection of the drone during flight is continuous, and the block shooting is non-continuous, we need to make a secondary correction to the area it can patrol, and the number of blocks the drone can fly over is calculated as follows.

$$N_b = 1.2 \cdot \frac{D_a}{\sqrt{3}R_s} \tag{14}$$

N_b is the number of blocks that a drone can fly over, and D_a is the maximum flight distance.

Each drone monitors all the blocks that it can fly over. We can get the maximum area that each drone can govern S_m.

$$S_m = N_b \times s_s \tag{15}$$

Since we want the drone coverage area to cover the whole region, we finally divide the area of the region by the governing area of each drone to find the number of SSA drones needed for different regions M_s, and the results are shown in Table 2.

2. Find the number of fixed EOCs

"Rapid Bushfire Respond" system use fixed EOC to manage SSA drones for takeoff, landing, and resupply. Define cluster as the range over which a fixed EOC needs to have governance. We want to find the number and cost of the fixed EOCs.

When we arrange the hexagons, there will be cluster with different numbers and shapes like figure 11. We define different patterns of cluster as (m, n). Where m and n have the following meanings:

When the vertex is at the center of the hexagon, two edges extend as in the figure. The number of blocks spanned by one edge is m and the number of blocks spanned by the other edge is n. Due to the mathematical peculiarities of hexagons, the placement pattern (m,n) with maximum benefit exists for different sizes of clusters.

Next we wish to estimate the distribution and number of fixed EOCs using the concept of cluster. A suitable EOC siting scheme should satisfy the flight constraints of the drones and at the same time enable the most efficient flight scheme for the drones. Note that the cluster used here should conform to the placement pattern with the greatest benefit.

4.2.1 tells that the hexagonal area s_s of different regions are different, and the area of the region that can be governed by SSA drone is also different. Based on the above premise, we selected three cluster patterns for different regions as Cluster(1,2), Cluster(1,4) and Cluster(4,4) respectively. Naturally we get three fixed EOC placements. The following figure shows three types of solution.

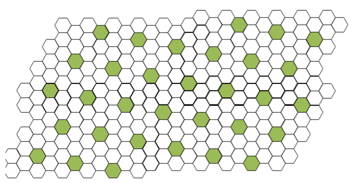

Figure 12

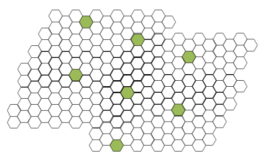

Figure 13

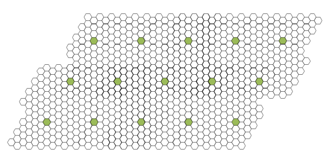

Figure 14

Finally, the number of fixed EOCs that need to be placed in each area is calculated as follows.

$$N_{seoc} = \frac{S_{region}}{n_{(m,n)} \cdot s_s} \tag{16}$$

N_{seoc} is the number of fixed EOCs needed in the region, S_{region} is the area of the region, $n_{(m,n)}$ is the number of hexagons contained in the (m, n) pattern, and s_s is the area of a hexagon. The final number of fixed drones in each region is shown in Table 3.

Table 3

Region	1	2	3	4	5	6	7	8	9	10	11	Total
Type of cluster	(1,4)	(1,4)	(1,4)	(1,2)	(4,4)	(4,4)	(1,2)	(1,2)	(1,2)	(1,2)	(1,2)	
Number block in one cluster	21	21	21	7	128	128	7	7	7	7	7	
Number of fixed EOC $N_{fixedEOC}$	35	24	18	5	19	5	5	12	15	15	24	177

4.3 Repeater Drones for a Single Fire Source

Ground crew fights fires on the fire line, the repeater hovers near the fire line, and the mobile EOC is set up outside the maximum fire radius. Before calculating the total number of repeater drones , we first design the repeater drones required for a single fire source. See figure 15.

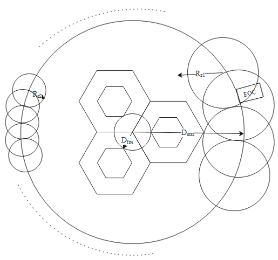

Figure 15

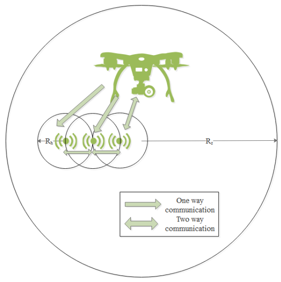

Figure 16

The maximum demand for repeater drones will occur in the most severe fire conditions, so we simply consider the case where the repeater drones are distributed on the fireline corresponding to the maximum burn radius.

The communication radius of the repeater drone will determine the minimum distribution density (see 6.2 for the specific arrangement). With the length of the fireline and the density of drones distributed on it, we naturally get the required number of drones.

1. Solution for the limited range of portable two-way radios

See figure 16, for the limitation of portable two-way radio transmitter (2km-5km), it is highly likely that the ground transmitter will be unable to transmit signals to the repeater drones.
Suppose an extreme situation arises where only one repeater drone is able to provide a signal transmission service within range. The "ground force" can use the option of interactive transmission from ground equipments. As shown in figure 16, the ground crew transmits the signal to the adjacent ground crew in the direction of the repeater. And person aggregates the information and transmits it to the drone, i.e. it is feasible for the "ground team" to transmit the signal to the repeater.

2. Repeater drones communication radius in different geographical environments

Different geographical environments have an impact on the coverage area of the repeater.

As shown in the figure 17, the simulation gives the corresponding curves of normalized coverage radius and outage probability for three typical shadow fading channels: severe, moderate and slight.

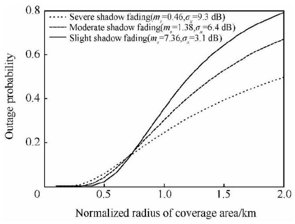

Figure 17

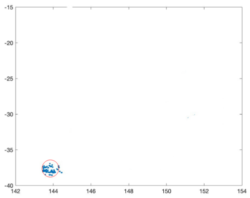

Figure 18

Table 4

Classification of Regions	Plain	Multiple Undulating	City
R_r	20 km	16km	13.33km

Within the acceptable range of termination probability, the maximum coverage radius approximately satisfies the following equation.

$$R_{rsl} = \frac{4}{5} R_{rm} = \frac{2}{3} R_{rse} \tag{17}$$

R_{rsl} is the drone coverage under slight shadowing scenario, R_{rm} is the drone coverage under moderate shadowing scenario, R_{rse} is the drone coverage under severe shadowing scenario.

Applied to the scenario in this question, the city is a severe shadowing scenario, the multi-undulating area is a moderate shadowing scenario, and the plain is as light shadowing scenario. Since we know that the repeater drone covers the largest area in the plain area, corresponding to a radius R_{rsl} of 20 km, we can deduce the radius of repeater drone coverage in different terrain areas, as shown in table 4.

3. Maximum fire radius

Our discussion is based on the premise that the maximum fire range that caused by a single fire source is a constant. In 4.1.2, we discuss that the fire will definitely be monitored by SSA aircraft after spreading to D_{fire}. In addition, there will be fire fighting and the fire has a limited ability to spread. So there will be a maximum fire range.

According to the simulation of metacellular automata, we get that the forest fire spreads in a roughly circular manner. We define the radius corresponding to the maximum fire extent area as the maximum overfire radius D_{max}. Next, we will calculate the maximum fire radius D_{max} for different areas.

We statistically find the points in the entire region that have the highest concentration of fires that best reflect the prevailing characteristics from January to February 2019. We found a series of fire points in Region 8 that spread in an approximately circular fashion (as shown in the figure 18). Use the radius of this circle as the D_{max} of the region.

From measurements we have D_{max} in this region is about 33.6 km. For other fire regions that do not have circular characteristics can be considered as a superposition of circles that form a proportion to this circle.

Each region has a degree of fire corresponding to the brightness in Table 5. The larger the value of this feature, the greater the spreading ability of the wildfire, resulting in a larger D_{max}. So we take D_{max0} of a known region (Region 8) as a reference and correct it to obtain the maximum fire radius D_{maxi} for different regions.

$$D_{maxi} = \varepsilon_i D_{max0} \tag{18}$$

ε_i is the fire radius correction factor, values are shown in table 5.

Table 5

Region Number	1	2	3	4	5	6	7	8	9	10	11	average
Brightness	328.08	327.86	333.78	323.84	327.27	338.99	329.35	318.13	321.5	323.13	324.39	325.67
Fire radius correction factor	1.0313	1.0306	1.0492	1.018	1.0287	1.0655	1.0353	1	1.0106	1.0157	1.0197	1.0232
Fire radius D_{max} (km)	34.652	34.627	35.255	34.203	34.565	35.802	34.786	33.6	33.956	34.129	34.261	34.381

4. Number of repeater drones required for a single fire source

The number of repeater drones required for a single point in each area can be calculated by the formula

$$m_r = \frac{2\pi \times D_{max}}{R_r} \tag{19}$$

Using communication radius R_{ri} in table 4 and the maximum overfire radius D_{maxi} in table 5, we obtain the number of repeater drones required at a single point in each region, as shown in figure 19.

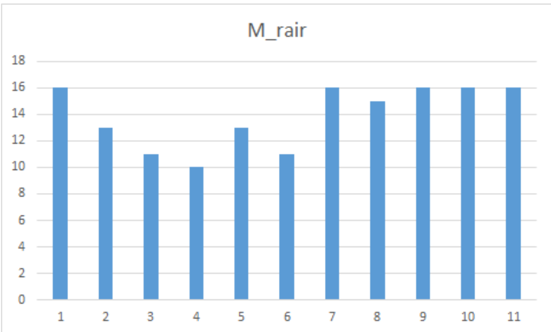

Figure 19

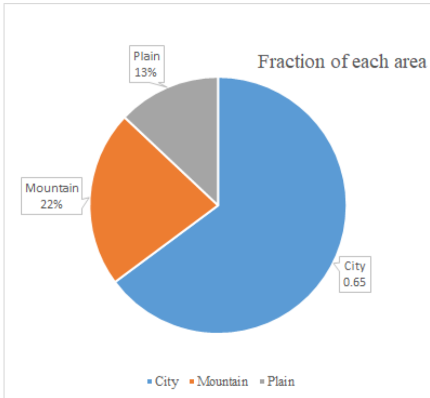

Figure 20

5. Communication between EOC and repeater drones during fire spread

In this section, we hope to find the maximum number of repeater drones required for a single fire by distributing the drones on the fireline corresponding to the maximum fire radius. However, in practice, the actual fire radius is often smaller than the maximum radius D_{max}. Therefore, in the real situation, we will make some of the repeaters hover on the real fire line and the rest of the drones are arranged along the radius to perform the task of transmitting signals to the outer EOC.

The result of our calculation based on the premise of "distribution on the maximum line of fire" can make the demand of the fire situation be satisfied at any moment. So we will continue to maintain this premise.

4.4 Number of Repeater Drones

We want to find the total number of repeater drones required within the entire NSW region and eastern Victoria area. We first find the number of repeater drones required for each fire site, and then multiply this number by the number of simultaneous fire sites burning in the global area to obtain the total number of repeater drones required at the same time. Then, considering that the hovering repeater drones have limited hovering time, we find the total number of repeater drones that meet the hovering requirement for the whole day according to the planning model.

1. Demand for repeater drones at the same moment

In the discussion in 4.4, we learned that different terrains correspond to different drone communication radius R_r, and different regions have different maximum fire radii D_{max}. In other words, the number of drones required for a single fire resource is different in different regions.

To calculate the global total and make the total calculation more reasonable, we obtain a single point model that "unifies the terrain characteristics and fire size characteristics of 11 regions". The steps to get this model includes:

(1)D_{max}: According to Table 5, the average D_{max} is 34.3809 by averaging the values of D_{max} with different area weights to obtain the length of fire line C that needs to be covered by drones.

(2) By the proportion of the three types of terrain (see the pie chart in figure 20) to get the ratio of the demand for three types of terrain drones, and the three types of communication radius drones placed in proportion to the fireline corresponding to D_{max}. The unification schematic is shown in figure 15.

After the obtained universal single point model, the number of repeat drones required for a single point, M_{rair}, is calculated. The calculation formula is as follows.

$$M_{rair} = \frac{2\pi D_{max} \times fraction}{R_r} \tag{20}$$

Based on the known data, we obtain the following results.

Table 6

	City	Mountain	Plain	Total
Proportion	0.648148	0.222222	0.12963	1
Proportion of C(km)	140.0139	48.00474	28.00287	216.0216
R_r(km)	13.333	16	20	
M_{air}	10.50131	3.000296	1.400144	14.90175

On average, 14.9 repeater drones are required per fire resource.

Since we want to get the total number of repeater drones needed in whole area, **we need to know the number of simultaneous fire sources in the whole region** after getting the number of drones needed for a single fire point.

In data prepocessing, the fire points in the nearby area may be caused by the same fire source, i.e., the problem of fire spread that we discussed earlier. We empirically concluded from the observation and analysis of the simulation results of the cellular automata that there is the following relationship between different fire points N_{point} and fire sources N_{source}

$$N_{source} = \lambda \cdot N_{point} \tag{21}$$

where λ=4.37.

We obtain the number of simultaneously existing fire points N_{point} in each region by processing the raw data, and the number of simultaneously existing fire sources in each region by the above equation is shown in the table 7.

To a conclusion, **the number of simultaneous fire sources** N_{source} **is 12.6.** Based on the above pervasive solution, we are able to obtain **the number of drones required per fire source point as 14.9**, so **the number of repeater drones required in different regions at the same moment is 189**.

Meanwhile, the mobile EOCs correspond to the fire source points one by one, and each fire source point corresponds to a mobile EOC, so we can get the number of mobile EOCs needed in each region, see table 7.

Table 7

Region Number	1	2	3	4	5	6	7	8	9	10	11	Total
M_{rair} / fire source	16.32958	13.59817	11.07554	10.74529	13.57382	11.24765	16.3925	15.83364	16.00136	16.08271	16.14522	14.90175
Number of fire source simultaneously	1.838824	1.021908	1.181979	0.070844	3.872698	3.628192	0.204382	0.310355	0.130403	0.131657	0.247014	12.63826
total M_{rair}	30	14	13	1	53	40	3	5	2	2	4	189
Number of mobile EOC	2	1	1	0	4	4			1			13

2. Total demand for repeater drones

As the firefighting stage personnel 24/7 fire fighting, repeater drones also need to work 24 hours a day. However, due to the limitation of the repeater drone battery power, we need a backup repeater drone, when the drone power is insufficient to recharge at the right time, and use a fully charged drone to perform tasks in this area, forming a virtuous cycle. For this problem we use integer programming to explore the number of drones needed.We require the minimum number of repeater drones and the objective function is

$$min(M_r) = M_{rair} + M_{rcharge} \tag{22}$$

In addition we restrict that the repeater drones on duty should be larger than the demand calculated above. The relevant constraints are formed for the battery time as shown below.

$$M_{rair} \geq 189 \quad 1.75 \cdot M_{rair} \leq 2.5 \cdot M_{rcharge} \tag{23}$$

We finally obtain the result $M_{rair} = 189, M_{rcharge} = 133, M_r = 322$

That is, **332 repeater drones are required throughout the region** to meet 24/7 firefighting needs.

4.5 Result: Mix of SSA and Radio Repeater Drones

The optimal numbers and mix of SSA drones and Radio Repeater drones are as Table 8 shown.

Table 8

Region Number	1	2	3	4	5	6	7	8	9	10	11	total
Number of SSA drones M_s	149	99	74	17	309	77	11	29	34	34	57	890
Number of repeater drones M_r	52	24	23	2	90	70	6	9	4	4	7	322
Total number of drones	201	123	97	19	399	147	17	38	38	38	64	1212
Number of fixed EOCs N_{feoc}	35	24	18	5	19	5	5	12	15	15	24	177
Number of mobile EOCs N_{meoc}	2	1	1	0	4	4			1			13

5 Problem 2 - Dealing with Extreme Fire Events

The reason of the sudden disasters from late 2019 to early 2020 is that temperatures were the highest recorded in Australia in more than 70 years, and rainfall was the lowest in more than 110 years.

Apparently it's of great possibility of the occurrence of such sudden disasters in future. Since the "Rapid Bushfire Respond" System we proposed in Problem 1 is based on the average number of wildfire hot spots over 2011-2019, the rapid response of extreme fire events is still room for improvement. In problem 2, we analyze the likelihood of extreme fire events over the next decades. Then we prepare an optimizing plan to address extreme conditions and provide evaluation of the increment of cost.

5.1 Prediction of the Likelihood of Extreme Fire Events

Markov chains is applicable in forecasting when the transition probabilities between states stay constant with time in a specific period. It's featured for non-after-effect property, which means the states of future is merely related to the current states, not the previous. The likelihood of extreme fire events has the Markov character, whose future states are not depend on the states in the past years and whose transition probabilities are stable, so Markov method is suitable for the following analysis.

Step 1 Rasterization

We rasterize the area in New South Wales and eastern Victoria, considering the detailed and concrete condition of different locations. The whole area is divided into 35 grids and each grid covers 1 longitude and 1 latitude, which are shown as figure 21.

Step 2 Input Data Processing and Sate Transition Table

Taking Grid 2 for instance, with data processing, we get the average number of fire spots of each grid of each year as table 10.

Table 9

Grid/Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
2	407	315	289	266	355	210	335	461	262

K-means clustering is used to convert the continuous fire spots number to discrete state space $E = \{1, 0\}$. 1 represents extreme fire events occur, while 0 represents there aren't extreme fire events occurring. The sate transition table of 2011-2019 of Grid 2 is shown as table 9.

Table 10

Grid/Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
2	1	0	0	0	1	0	1	1	0

Step 3 Transition Probabilities

Referring to the state transition table, the one-step transition matrix of Grid 2 is $P = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{3}{4} & \frac{1}{4} \end{bmatrix}$. Since $\sum_{j=1}^{N} P_{ij} = 1$, it's a stochastic matrix, which is proved that the Markov chain is homogenous. Moreover, we checked whether it's ergodic. The result of ergodicity of our transition matrix ensures the accuracy of prediction.

$$\begin{cases} \pi_j = \displaystyle\sum_{i=1}^{N} \pi_i P_{ij} \quad j = 1, \cdots, N \\ \displaystyle\sum_{j=1}^{N} \pi_j = 1 \end{cases} \tag{24}$$

Furthermore, we take the state of 2019 as initial state. The initial state of Grid 2 $P_0 = [1\ 0]$. Thus, we can calculate the probability of state 0 and 1 occurring in 2020-2031 by P_0 multiplying n-step transition matrix P_n.

Step 4 Result Analysis

After calculation we can find that the predicted probabilities fluctuate around the final stable probabilities as figure 22, proving that the Markov chains are homogenous.

The result is that **probabilities of extreme fire events not occurring of Grid 1, 4, 5, 6, 8, 10, 13, 16, 28, 29, 30, 32 is 1** (the bright blue bubbles in figure 24) and **probabilities of extreme fire events occurring of Grid 2, 17, 18, 20, 22, 24, 27, 33, 34 is relatively high (over 0.22)**(the green bubbles in figure 24) . The radius of bubble reflects the probability of extreme fire events occurring.

5.2 Adjustment on the Number of Equipments

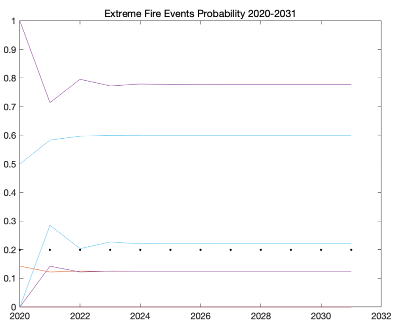

Figure 21

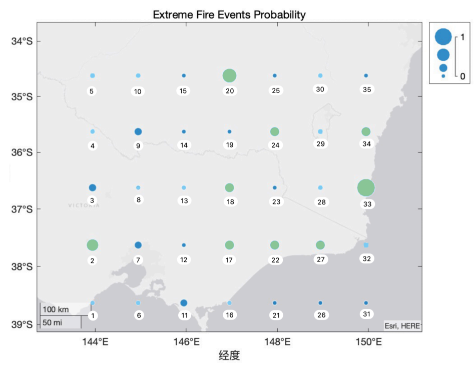

Figure 22

SSA Drones

It's not possible of extreme fire events occurring in Grid 1, 4, 5, 6, 8, 10, 13, 16, 28, 29, 30, 32. Thus we can reduce the SSA drones of these area to adapt to the extreme condition. The calculation results can be seen in Table 11.

Repeater Drones

Since the data we searched is based on the satellite MODIS, the ratio of the number of fire points N_{point} and fire sources $N_{sources}$. λ is related to the resolution of MODIS R_{modis} . On the condition of extreme fire events, more fire points are caused by a fire source, because they are intensive and interacted. As a result we summarize the formula to calculate λ as the following.

$$\lambda = \begin{cases} \pi \cdot D_{max}^2/(R_{modis}^2) & N_{point} \geq 500 \\ \pi \cdot \dfrac{D_{max}}{2}^2/(R_{modis}^2) & 40 \leq N_{point} < 500 \\ 4.63 \cdot N_{point} < 40 \end{cases} \tag{25}$$

Since the probabilities of extreme fire events occurring of Grid 2, 17, 18, 20, 22, 24, 27, 33, 34 is relatively high, we should increase the repeater drones of these grids to handle extreme conditions. We find the maximum fire points per day of each grids in 2019 as the simultaneous fire points for extreme condition. The concrete result shown in table 11.

Table 11

Region Number	Original A Drones M_a	Original repeater Drones M_z	M_{rair}/ fire source	Simultaneous fire points for extreme condition N_{point}	Fire source for extreme condition N_{source}	Original fixed EOC N_{feoc}	Reduced fixed EOC N_{feoc}	Reduced M_a	Increased M_z
1	149	52	16	0	0	35	23	100	52
2	99	24	13	711	6.0043	24	12	50	133
3	74	23	11	1222	10.32	18	12	50	193
4	17	2	10	0	0	5	0	0	2
5	309	90	13	244	8.2421	19	19	309	183
6	77	70	11	2058	17.38	5	5	77	325
7	11	6	16	0	0	5	3	6	16
8	29	9	15	40	1.3514	12	5	24	35
9	34	4	16	0	0	15	6	12	16
10	34	4	16	0	0	15	10	23	16
11	57	7	16	7	1.5119	24	15	35	18
total	890	322			44.8088	177	110	686	989

Table 12

	Construction Unit Price ($/item)	Maintenance Unit Price ($/item/year)	Change of Quantity	Increment of Cost ($)
SSA Drones	10000	2000	-204	-2448000
Repeater Drones	10000	2250	667	8170750
Fixed EOC	60000	4510	-67	-4322170
Moving EOC	30000	4510	32	1104320
Total Increment				2504900

5.3 Result: Increment of Purchase

According to the number adjustment we analyzed above, we obtain a budget table to show the increment of cost caused by disaster prediction.

6 Problem 3 - Optimizing Locations of Repeaters

6.1 Macro-level Optimize Model – Geographical distribution of equipments

According to the result predicted in problem 2, we optimize the geographical location distribution of SSA and repeater drones, as well as fixed EOC and mobile EOC, in order to improve the speed of response of bushfire. Furthermore, we discuss the diversity of one region by dividing the area into more exquisite grid. In total, our macro-level optimization strategy can be explained in the following steps.

Step 1 Modify the quantity of drones of the plan, including reduce SSA and increase the repeater drones.

Step 2 Repeal the fixed EOC in the grids with no probability of extreme fire events and set up more moving EOC in the grids with the probability of extreme fire events.

Step 3 Locate the repeater drones into each fixed EOC so that once the severe bushfire burning the repeater drones and moving EOC can take their places as soon as possible. Concretely, emphasize the grids with the probability of extreme fire events while make an average allocation within the grids.

Step 1 and 2 we have discussed in problem 2, so we pay more attention on step 3 in this problem. Table 13 displays the specific distribution.

To evaluate the optimization effect, we calculate maximum reaction time T_{react} .

$$T_{react} = L_{grid}/\sqrt{N_{feoc}}/V_{drone} \tag{26}$$

With the referring optimization, the **reaction time of bushfire can be limited in 0.7722 hours (46 minutes)** .

6.2 Micro-level Enhancement Model Specific Arrangement Method

Problem 1 focuses on repeater drones at a specific location at a specific moment. In order to optimize the locations, we deepen the model for the calculation of repeater drones in the first question from a microscopic perspective.

Table 13

Grid	2		3		7		9		11		12		14		15		17		18	
M_z / grid	31		16		4		2		16		22		8		2		110		28	
N_{feoc} / grid	5		5		5		5		3		5		5		6		5		5	
N_{feoc} with same M_z	4	1	4	1	4	1	2	3	2	1	3	2	3	2	2	4	5		2	3
M_z/ fixed EOC	6	7	3	4	1	0	1	0	5	6	4	6	2	1	1	0	22		5	6
Grid	19		20		22		23		24		25		27		33		34		35	
M_z/ grid	8		14		162		23		133		26		163		85		113		26	
N_{feoc}/ grid	5		6		3		5		12		12		2		6		6		12	
N_{feoc} with same M_z	2	3	2	3	3		2	3	11	1	10	2	1	1	2	3	1	5	10	2
M_z / fixed EOC	1	2	3	2	54		4	5	11	12	2	3	81	82	1	0	18	19	2	3

1. Ideal Fire spread model

We first discuss the case where a fire caused by the same fire source spreads only on an even flat surface.

Since the length of the fire line is much larger than the radius of the repeater drones launch, in the microscopic scenario we can consider the fire line as a straight line for the physical model analysis. See figure 23, we improve the physical model as follows.

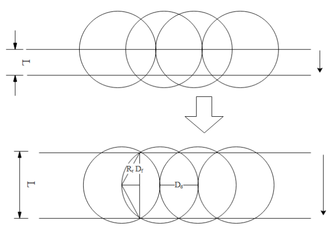

Figure 23

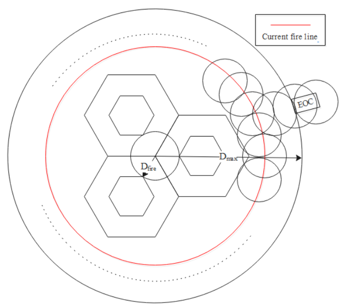

Figure 24

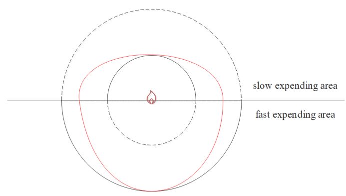

Figure 25

L is the distance of fire spread in a certain time in the microscopic category, D_f is the distance of the location where the drone is deployed from the fire line, R_r is the communication radius of the drone,D_d is the distance between the deployed drones.

The distribution of repeater drones needs to satisfy the following three conditions.

$$D_d \leq R_r \quad 2D_f = L \leq 2R_r \quad R_r^2 = D_f^2 + (\frac{D_d}{2})^2 \tag{27}$$

We want to find the maximum interval of repeater drones as the ideal layout state under the constraints $MAX(D_d)$ We obtain the maximum interval of $D_d = R_r$ In the case of satisfying the maximum interval, D_f and L satisfy the relation $2D_f = L = \sqrt{3}R_r$

According to the above calculation results, combined with our emergency point allocation rules, the best hovering scheme given is as follows.

(1) When the mobile EOC and the repeater drone initially arrive at the fire, the drone should hover at a distance of $\frac{\sqrt{3}}{2}R_r$ outside the fire line, and the spacing between the drones is R_r. In order to transmit the signal to the EOC outside the distance of D_{max}, other repeater drones in the region will be lined up along the radius outward, as shown in the figure 24.

(2) The fireline continues to move outward, and when the fireline burns more than $\sqrt{3}R_r$ away, re-arrange the drones according to the rules as above.

2. Extended fire spread model

In actual forest fire scenarios, the fire spreads across different elevations, different areas or has a certain slope angle of the terrain. We next perform drones location optimization for this more general scenario.

Wang Zhengfei's forest fire spread model belongs to the empirical model [5], which mainly considers the relationship between the rate of forest fire spread and wind direction, wind speed, combustible material type and terrain and slope, and its specific equation is $V_f = K_1 + K_2 \cdot 14.1895 \cdot e^{0.1547 \cdot V_w} / \lambda$

V_f is the fire spread speed (m/min) at each combustion point (fire boundary), V_w is the wind speed (m/s); K_1 is the combustible (damping) coefficient, K_2 is the slope (damping) coefficient; is the wind aspect ratio coefficient; e is the natural logarithm. Where K_1, K_2 is the wind speed correction coefficient is obtained by empirical data statistics, according to this equation we can get the fire spread speed V_f and the maximum overfire radius of the fire in different directions D_{max}.

We want to simulate a conclusion that includes multiple terrain type based on fire spread characteristics. For this we apply a modified Rothermel-based model [5] to simulate fire line at progressively higher elevations. The real fireline situation is obtained as shown by the red line in the figure 25.

In order to calculate the true fireline length, we introduce two circles (black lines in the figure 25).

To find the relationship between the irregular true fireline length and the two circles, we introduce the scale factor κ

$$\kappa = \frac{Circumference_{large-circle} + Circumference_{small-circle}}{2 \cdot Circumference_{irregular-area}} \tag{28}$$

We substitute the result of the calculation from 4.4.3 into equation 28.

The length of the red line is obtained from the simulation results. In a certain range, the scale factor κ is approximately equal to 1, i.e. So we can superpose the previous ideal Fire spread model to describe this extended fire spread model.

3. Actual fire repeater drone position optimization Since the fire source point is random, we need to select specific locations, then practice and test the above optimization scheme for real scenarios, and give the drones deployment scheme. The calculation methods on the issues of spacing, time, and number can be summarized as the following steps.

(1)According to 4.3.4, the total number of repeaters required for fires in different terrains M_rair is obtained.

(2) Locate the EOC outside the distance of R_{max} in the direction of the fastest descent of the downhill gradient.

(3)According to 6.2.1, the drones communication radius R_r should be used as the drones spacing D_d, and the distance $D_f = \frac{\sqrt{3}}{2}R_r$ from the fire line.

(4)The number of duty drones to be deployed immediately, based on the real fireline perimeter calculation method in 6.2.2.

$$NumberOfDrones = \frac{2\pi(R_c + D_f)}{D_d} + \frac{[D_{max} - (R_c + D_f)]}{D_d} \tag{29}$$

D_d is the distance between relay drones at the time of arrangement, D_f is the distance from the current fireline at the time of arrangement, and R_c is the radius of the current fireline.

(5) According to the velocity formula in 6.2, we obtain the fireline spread velocity v. The drones repeatedly adjusts the deployment position according to the above scheme as the fire spreads, and the movement time is

$$TimeToMove = \frac{2D_f}{v} \tag{30}$$

Next, we select two specific locations for calculation as shown in the figure.

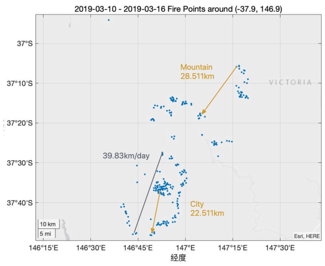

Figure 26

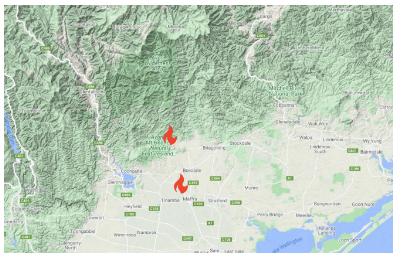

Figure 27

The lower fire source in the figure 27 is at (Lng146.90 Lat-37.90), which belongs to urban terrain with low elevation; the higer fire source is at (Lng146.858 Lat-37.756), which is located at the foot of the mountain. Assuming that the fire is discovered on March 10, 2019, the initial fire radius and spread rate v is obtained from the real fire data at this location. Basing on the calculation method above, we obtain two deployment options for the locations.

Location 1

The current fire radius is 22.51km. We need to arrange 15 repeater drones at a distance of 11.54km from the current burning fire line (the spacing between drones is 13.33km), 1 mobile EOC at a distance of 22.47km from the fire line, and finally, 1 additional drone to connect the system around the fire line to the EOC and to rearrange the above steps every 13.91 hours.

Location 2

The burn area is divided into a high elevation portion and a low elevation portion. For the high altitude part, the current fireline radius is 28.51km, we need to place 9 drones at a distance of 13.856km from the current burning fireline (the spacing between drones is 16km) and rearrange the high altitude placement steps every 13.21 hours; for the low altitude part, the current fireline radius is 22.51km, we need to place For the low altitude part, with the current fireline radius of 22.51km, we need to place 8 drones at a distance of 11.54km from the current burning fireline (with a spacing of 13.33km between drones), 1 mobile EOC at a distance of 22.47km from the low altitude fireline, and finally an additional drone to connect the system around the fireline to the EOC, and rearrange the low altitude placement steps every 13.91 hours.

In the previous model, we only considered the number of repeater drones, to make demand and supply fit. Here we provide a further physical model of the location and calculate the exact drone location using an actual fire example. In the optimized location problem, we take into account the fire spread process, where the drones need to change their hovering positions at certain intervals to provide more efficient and economical coverage of the communication service. This model also provides a more detailed description of the interval positions between drones and the speed of fire propagation. It is also worth to notice that the model has a large improvement in the number of relay drones needed for smaller fires, ranging from 12% to 18%.

7 Conclusion

(1) The number of required SSA drones is 890 and the number of fixed EOCs is 177 obtained by integrating the optimization model and the HIVE model.

(2) The number of repeater drones is 322 and the number of moving EOCs is 13 based on linear programming and physical modeling.

(3) According to the prediction of Marcov model, we adjust the the number and distribution of associated drones and EOCs. The increment in budget caused by extreme fire event is found to be 2,504,900 AUD.

(4) The micro-macro physical model, supplemented with an improved Rothermel model, is used to obtain an optimal location plan. We give specific arrangement plan for a more universal situation, i.e. fire spread at places covering different terrian. In addition, we choose real fire event at specific place. Through specific analysis, we get the exact locations of repeater drones and moving EOCs.

8 Model Testing

1. Sensitivity analysis of programming model in Problem 1

Since the original charging time is 1.75h, by changing the battery charging time and iterative analysis we can find the characteristics that make the planning result change as shown in the figure below.

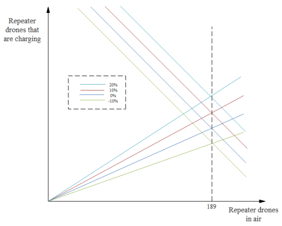

Figure 28

Table 14

Change in λ	-0.05	0	0.05	0.1
λ	4.1515	4.37	4.5885	4.807
M_{rair}	198	188	179	171
M_r	337	322	305	291
Change in M_r	0.052632	0	-0.04762	-0.09091
Total drones	1227	1212	1195	1181
Change in total change	0.01405	0	-0.0124	-0.02397

We found that as the ratio of charging to power consumption hours varied, the number of spare drones required changed in equal proportion. This variation is as expected and within an acceptable range of variation. Therefore, this model sensitivity is acceptable.

2. Analysis of the variation of the ratio coefficient λ in Problem 1

λ is the ratio coefficient between the number of fire points and the number of fire sources. In problem one, we choose the value empirically. We change the rate of change here to -5%, 5% and 10% of the original rate of change to observe the range of the rate of change of the total number of drones (see figure 14).

From the graphical analysis, it is clear that since the change in the scale factor will have an effect on the number of drones, but the final resulting rate of change is small and within an acceptable range, we can assume that this model satisfies the sensitivity requirement.

3. Error Analysis about Prediction based on Markov Chains

Overall, we use the data in 2011-2018 to calculate transition matrix and states of each grid in 2018 as initial states to forecast the probability of the two states occurring in 2019. Besides, the mean square error MSE is chosen to reflect the difference between the predicted value and true value in 2019.

$$MSE = \sum_{i=1}^{n} \frac{1}{n}(f(x_i) - y_i)^2 \tag{31}$$

Table 15

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Expectation	0	0.25	0.16667	0	0	0	0.14286	0	0.16667	0	0.14286	0.125	0	0.875	0.875	0	0.28571
Real Value	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
0.28571	0.875	0.5	0	0.28571	0.125	0.28571	0.875	0	0.28571	0	0	0	0	0	1	0.28571	0.125
1	0	0	0	1	1	1	0	0	1	0	0	0	0	0	1	1	1

Finally, we get the result of $MSE = 0.6883$ which is acceptable.

4. Sensitivity Analysis about the Threshold of State Division

The detailed k-means clustering process in 5.1 is that removing the extreme value and getting 3 clusters, then combining 2 clusters in 1. The reason is that considering the features of data, we don't want the numbers of 2 clusters enormously unbalanced. Thus the threshold of state division is subjective to some extent. As a result we change the method of k-means cluster to get 2 clusters directly and compare the new threshold 461 to the original one 335.

Finally we get new MSE = 0.8069 with a little increase, and Grid 2, 14, 15, 17, 18, 20, 22, 24, 25, 27 with great probability of extreme fire events which covers the most of the original results. As a result the Markov Chains Prediction Model is not sensitive about the threshold of state division to some extent.

9 Model Evaluation and Further Discussion

9.1 Strengthen and Weakness

1. Strengtheness

(1) Confirm the reasonableness of model assumptions by cellular automata.
(2) Optimize the number of SSA drones using a HIVE model.
(3) Our model considers the task of building fixed and mobile EOCs Establish integrated safety, capacity and cost evaluation metrics based on different communication and physical models and find their exact optimal solutions by genetic algorithms.
(4) Using MODIS satellite system data accurate to days from 2011-2019 for fire frequency and area estimation with high accuracy.
(5) Not only get the number of repeater drones that need to be at the post at this moment, we also consider the battery problem and find out how many additional drones are needed for substitution by linear programming.
(6) Not only considered the macroscopic distribution of drones in different geographical locations but

also considered the microscopic drones for different regions and different terrain for a real location specific fire and EOC arrangement.

2. Weakness

(1) The method of dividing the area into 11 regions are not accurate enough. This method ignores the specific geographic shape. Using grids may lead to loss in detail.
(2) Since the repeater drone needs to reach the posittion and hover first, we do not consider the power consumption on the journey to the post.
(3) We default to the maximum flight distance that the drone can reach, but the impact of load and flight status on flight time and flight distance is often not negligible.
(4) Ground personnel often do not have the ability to cover the entire line of fire, which will lead to waste of some of the drone resources on our model.
(5) The real situation of different fire points interacting with each other is often unavoidable, and if added to their interactions, our model will have a waste of some of the drone resources.
(6) The budgeted unit price for EOC construction and equipment maintenance is not thoroughly investigated by the market.

9.2 Model Promotion

(1) In problem 2, we used yearly frequency of each grid to gain the transition matrix. We can use the in put data with a higher resolution (i.e. monthly or daily data), so that the prediction result can be more reliable.

(2) The memory size of the SSA equipment, which may limit the flight range and period of the drones can be considered as well.

(3) The Rothermel model can be further used to discuss the full range of fire conditions, including irregular shapes and other influencing factors for further exploration.

References

[1] MODIS Statistics from 2011 to 2019,NASA, `https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms`

[2] S24F-6 Firefighting drones `http://www.zfiuav.com/Item/Show.asp?m=114&d=119&sdclkid=ASDixLApbsopA5gD`

[3] Statistical model for coverage area of drones repeater platform,Qiuming Zhu, etc., Journal of Aviation,2014,35(01):223-229.

[4] Research on post-disaster transitional temporary building design strategy, Yao Qin, Hunan University,2014.

[5] Improvement of forest fire simulation algorithm based on Rothermel model, Miao S., etc,Geographic Information World,2012,10(06):14-21.

Budget Request

Victoria Government :

Australias bushfire has caused unprecedented losses and negative impacts in the past, with New South Wales and Victoria being the most severely affected.

We commissioned a professional team to build a model for "Rapid Bushfire Respond" system based on the severity of the disaster condition and the emergency needs. A budget report for the establishment of the system is hereby provided for your consideration.

The emergency response system we have established hopes to redeploy the stations and equipments for New South Wales and Eastern Victoria based on existing system, so as to achieve the purposes of (1) Be able to carry out comprehensive monitoring of fires throughout the territory (2)For emergency disasters, can quickly send EOC and related equipment to the disaster area to control the bushfire.

The emergency system we plan to establish mainly consists of the following parts:

Handheld Radios

Carried by the "boots-on-the-ground" forward teams to communicate with nearby signal receivers, like SSA drones and repeater drones.

SSA Drones + Fixed EOC

Equipped with high definition and thermal imaging cameras and telemetry sensors ,taking response to SSA. They fly over areas they dominating, in order to monitor the signal from handheld radios then report them to fixed EOC. Fixed EOC manage and communicate SSA drones.

Repeater Drones + Moving EOC

Drones equipped with higher power radios can extend signal to a larger range. Repeater drones hover aound the front line, monitoring the signals from handheld radios and send them to moving EOC. Moving EOC manage and communicate repeater drones.

In order to ensure the capacity of disaster prevention and control, we evaluated the emergency requirement of different regions future according to data from 2011 to 2019 as well as the likelihood of the extreme fire events in next decade. We designed the quantity and distribution of EOC and drones to meet the requirement.

Construction Cost

	Unit Price ($/item)	Quantity	Cost ($)
SSA Drones	10,000.00	686	6,860,000
Repeater Drones		989	9,890,000
Fixed EOC	60,000[4]	110	6,600,000
Moving EOC	30,000	45	1,350,000
Total	18,526,000		

Maintenance Price

	Unit Price ($/item)	Quantity	Cost ($)
SSA Drones Maintenance	2,000	686	1,372,000
Repeater Drones Maintenance	2,250	989	2,225,250
Fixed EOC Maintenance	4,510	110	496,100
Moving EOC Maintenance		45	202,950
Total	4,296,300		

To sum up, constructing the system requires initial investment $18,526,000. $4,296,300 are needed to maintenance the system annually.

This is the budget report for setting up a "Rapid Bushfire Respond" System. If you have questions or need more details, ask us. We are looking forward to working with the Victoria government to build a more safe and effective emergency response system, protecting more people's lives and property. We could become the winner in the race against the fire.

Country Fire Authority