Problem Chosen	2021 MCM/ICM Summary Sheet	Team Control Number
B		2101771

Auxiliary Drones Arrangement Strategy for Fighting Wildfires

Summary

Changes in global climate affect the frequency and scale of wildfire. To gain an economical budget for *CFA*, our paper analyzed the trend of wildfire development, drone arrangement for complex topography and the optimal number and mix of two kinds of drones by stepwise modeling.

Firstly, considering the constrains of minimal cost and maximal security, we built three models to analyse the drones' ability in fighting wildfires. **Single flight speed and distance model** offers the proper speed for drone flight. **SSA drone number and observation area model** and **Radio Repeater drones drone number and fire event area model** show the relationship between fire size and drone number. Using **Random Simulation, we** established **Drones Arrangement Model for Rapid wildfire Response**. This model makes sure adequate Radio Repeater drones that can cover all the forward teams on the firing line and adequate SSA drones can detect the whole fire trend timely. To further reduce the cost, we built **EOC distribution model** to minimize the number of drones.

Secondly, we analyzed fire data in Victoria over the past 10 years. We divided our study area into **6x8 blocks** and calculated the quarterly frequency of fire in each block. Regarding fire frequency and size as reference, based on **Cluster Analysis,** we classified 48 blocks into three dangerous level. Based on a series of fire frequency and size, we used **Power function** to establish **Fire Prediction Model** in an iterative way. Then, based on the prediction data of next decade, we used our **Random Simulation Model** to get optimal number and mix of drones for future wildfire fighting. Finally we used **ARMA Model** to predict future equipment cost.

Thirdly, combined the topography factor (especially the mountain chain near east coast), we used **Circular Cone** to simplify the terrains factor and find out the relationship between elevation and quantity of drones. Based on the **Radio Repeater drones drone number and fire event area model**, we described the relationship with series the mathematical formula as well as optimized the model to adapt it into extreme mountain fire. The optimal model minimizes the influence of elevation on communication as well as adjusts the number and mix of drones for fitting different terrains to make sure the most rapid response of forward teams.

Also, we analyzed the model's sensitivity. We changed the value of battery volume and calculated the average response time. The origin data has effect on stability of model, but the results are still acceptable.

Last but not least, based on above analysis, we put forward a **Rapid wildfire Response Scheme** with a budget on it and provide an **Annotated Budget Request** for *CFA* to submit to the Victoria State Government, helping them make decision on fiscal expenditure on fighting wildfire.

Key words: Random Simulation, ARMA Model, Cluster Analysis, Power function

Contents

1 Introduction

1.1 Background

Under global climate changing, extreme wildfire is more active in Australia than before. Eastern Victoria is an active fire area. To put out fire as quickly as possible so as to reduce the loss in economy and environment, CFA has applied drones on fire situation detection and latest information communication between forward teams and EOC. However, drone troops cost a considerable number of fiscal expenditure, so minimizing the number of drones is prominent.

1.2 Restatement of the Problem

Combining the fire data in Victoria and restricted factors provided in the problem statement, we need to solve the following series of problems:

1. Based on the fire data during past 10 years in the study area, find out the fire frequency and fire area annually, so as to find the high frequency area in Victoria. Establish model to arrange two kinds of drones on the area and optimize the number and mix of two kinds considering endurance time of drone, security and economy factors.

2. Based on the fire frequency and fire area calculated above, predict the future 10 years trend of fire frequency and fire area. Evaluate the reasonability of the model when use it on the next decade fire condition. Establish price change model to predict the change in equipment price and calculate the cost change in next decade.

3. Separate Victoria into different level according elevations difference. Establish a model that can provide different strategies to satisfy the required distance of Handheld Radio in each level area.

2 Assumptions and Justifications

Our models rely on the assumptions listed as the following.

- Drones can keep working normally before battery empty.
- Drones can fly at an even speed.
- Each SSA drone has a detection range of 15km and the utilization of detection scale inversely related to the number of SSA drones.
- Forward teams /firefighters are evenly distributed on the edge of the fire line.
- All fire shape are square.
- Emergency Operations Center (EOC) controls the movement of drones within 30km.
- Droves can move under control of different EOC continuously. Expanding total EOC cover range can expand the flight range of droves.
- Drones get charged at EOC.
- Message transfer between EOC does not need radio repeater.
- Fire frequency represents the number of fire events taking place during certain time span.
- Fire event have seasonal characteristics.
- The fire frequency seems as same in a small area(within one block).
- Part of blocks' feature can represent the whole feature in one class
- Same level blocks have similar frequency and size.
- The wind direction is regarded as consistent (from west to east), since there is only a tiny angle change on wind direction as season changes.
- Handheld radio keeps sufficient charge when forward teams work.
- The mountain is a circular cone.
- Fire area in this part is the lateral area of circular cone and fire area is part angle of the lateral area.
- Fire line is the bottom circumference.
- EOC can share information without Radio Repeater drones, and Radio Repeater drones can communicate with each other.
- Forward teams can only put out fire from the bottom of mountain.

3 Notations

Symbols	*Definition*	*Unit*
W	**Battery storage capacity**	$W \bullet h$
k	**Drag coefficient constant**	kg/s
L_{fly}	**Flight distance of drone**	km
v	**Flight speed of drone**	km/h
f	**Flight resistance of drone**	N
P	**Real flight power of drone**	W
P_0	**Ideal flight power of drone**	W
T	**Flight time of drone**	h
Ut	**Utilization of SSA drone detection scale**	
n_{SSA}	**The number of SSA drones**	
S_{SSA}	**SSA drone detection scale**	km^2
S_{fire}	**Single fire area**	km^2
L_{fire}	Fire line length	km
n_f	**The number of firefighters on fire line**	
n_{RE1}	**The number of Radio-repeater drones near fire line**	
n_{RE}	**Total number of VHF/UHF radio-repeater drones**	
a	**the work range of handle equipment**	km
f_i	Annual fire frequency	day
D_i	**The number of the day when the block catches fire**	
S_i^k	**The maximum fire event size**	km^2
S_i	Annual fire size	km^2
P_i	**The number of fire points in one block**	
p	**Power function represent the overall trend**	
a	**Parameter**	
b	**Parameter**	
c	**Parameter**	
λ	**Weight in fitting function**	
$pre(x)$	**Fitting function**	
∇	**First difference of inflation rate**	
X_t	**Inflation rate**	
X_{t-1}	**Inflation rate**	
θ	**The angle of shade of area**	rad
R	**The radius of the mountain see from the top**	km
Δh	**The elevation difference between the fire line and top**	km
$\mathbf{S}$	**Lateral area of circular cone**	km^2

4 Drone management model for "Rapid Bushfire Response"

4.1 Single flight speed and distance model of WileE–15.2X Hybrid Drone

4.1.1 Noun explanation of WileE–15.2X Hybrid Drone Capabilities

Maximum flight speed:

The maximum speed that can be achieved in normal operation;

Maximum flight time:

The maximum speed that can be achieved in normal operation in a proper speed;

Flight range: The maximum distance between drone and EOC;

Charge time: The time of each charge.

4.1.2 model building

In order to make the best use of each flight, we built this model to choose a proper speed, so that a drone can complete a long flight with less charging times.

We assumed that drones can fly at an even speed and the Battery storage capacity W is 20 W·h, the drag coefficient constant of drone movement k is 0.004 kg/s. Using equation set (1), we get the relation equation of Flight distance L_{fly} and Flight speed v (2).

$$
\begin{array}{lll}
\text{Flight resistance} & f = kv^2, \ k = 0.004\,kg/s & (1.1) \\
\text{Ideal flight power} & P_o = fv & (1.2) \\
\text{Real flight power} & P = P_0 + b, \ b = W/2.5h = 8W & (1.3) \\
\text{Flight time} & T = W/P & (1.4) \\
\text{Flight distance} & L_{fly} = vT & (1.5)
\end{array}
\quad (1)
$$

$$L_{fly}(v) = \frac{Wv}{kv^3 + b} = \frac{20v}{0.04v^3 + 8} \quad (2)$$

In order to achieve the least number of charge and rapid fire response, we need to select long flight distance and great flight speed respectively. **Figure 1** shows that 31 km/h (10 m/s) is a proper choice of speed v for long flight distance(10 km) and great efficient respectively.

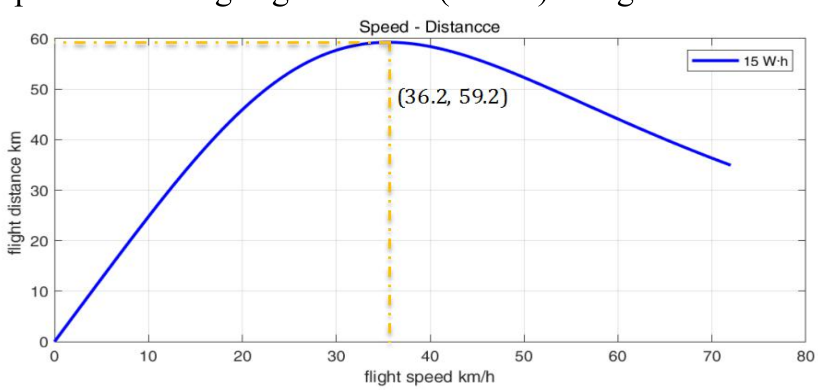


Figure 1 : The relationship of Flight distance and Flight speed

4.2 SSA drone number and observation area model

In order to meet the observational mission needs, we build the SSA drone number and observation area model to get the minimum number required for maximum working area.

We assume each SSA drone has a detection range of 15km and the utilization Ut of detection scale inversely related to the number of SSA drones n_{SSA} (3.1). (3.2) describes the relationship of the number of SSA drones n_{SSA} and their ideal detection area S_{SSA}, showed in **Figure 2**. (4) shows the calculate method of n_{SSA} when single fire area S_{fire} is known.

$$Ut = n_{SSA}{}^{1/6} \quad (3.1)$$
$$S_{SSA} = 15^2 \pi \, Ut \, n_{SSA} \quad (3.2) \qquad (3)$$

$$min\ n_{SSA}\ st.\ S_{SSA} \geq S_{fire} \qquad (4)$$

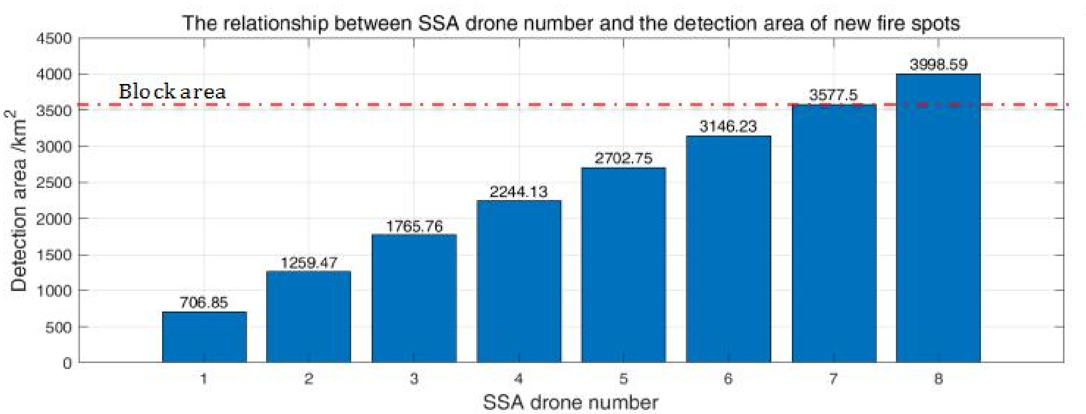


Figure 2 :The relationship between SSA drone number and the detection area of new fire spots

4.3 Radio Repeater drones drone number and fire event area model

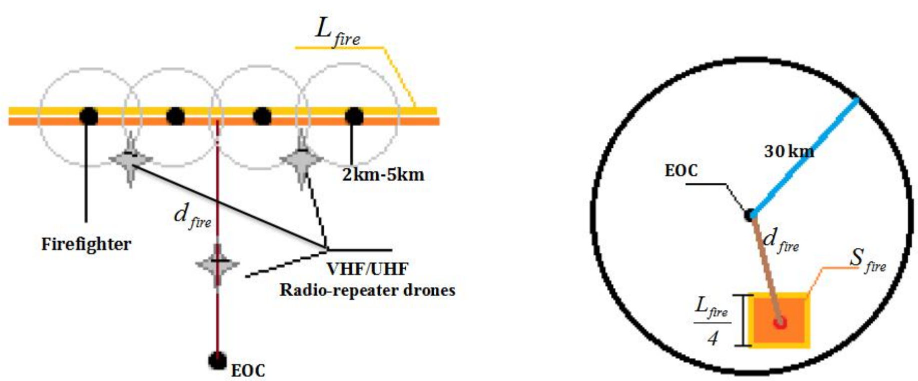


Figure 3 : EOC, firefighters and Radio Repeater drones

We assume that all fire shape are square and firefighters space at regular intervals on fire line. (**Figure 3**) EOC can share information without Radio Repeater drones, and Radio Repeater drones can communicate with each other. (5.1) describe the relationship between fire size S_{fire} and fire line length L_{fire}. The distance between fire points and EOC is closer than 30 km.

In order to make our model brief. We set the distance between two firefighter is 2 km. Thus, we have (6) that describes the relationship of fire size and the number of VHF/UHF radio-repeater drones. a represent the work range of handle equipment.

$$
\begin{array}{lll}
\text{Fire line length} & L_{fire} = 4\sqrt{S_{fire}} & (5.1) \\
\text{Firefighter number} & n_f = \lfloor L_{fire}/2 \rfloor + 1 & (5.2) \\
\text{Near human drone number} & n_{RE1} = \lfloor n_f/2 \rfloor + 1 & (5.3) \\
\text{Total drone number} & n_{RE} = n_{RE1} + \left\lceil \dfrac{d_{fire} - \sqrt{a^2 - 1}}{20km} \right\rceil & (5.4)
\end{array} \qquad (5)
$$

$$
n_{RE} = \left\lceil \frac{\lfloor 4\sqrt{S_{fire}}/2 \rfloor + 1}{2} \right\rceil + 1 + \left\lceil \frac{d_{fire} - \sqrt{a^2 - 1}}{20km} \right\rceil \qquad (6)
$$

4.4 Random Simulation Model for drones management

Forest fire spreads and expands freely in forest land, bringing certain harm and loss to forest, forest ecosystem and human beings. Forest fire is a kind of sudden, destructive and difficult natural disaster.[1] In addition to combustibles and oxygen, external fire sources is essential for forest fires. The appearance of external fire source is highly uncertain, so the occurrence of forest fire has strong randomness. This random characteristics must be considered when do future imitation. The frequency and area data of forest fires over the years reflect the overall characteristics of forest fires. Therefore, based on its overall characteristics, combined with the randomness of fire occurrence, a more suitable future forest fire simulation model can be established.

We use the random simulation to build the drones management model. Using frequency and size data in **Table 1** and **Figure10,** we did random process to imitate the fire events happen in the next decade for many times each year, calculated the best choice of drone management for each time according to equation (4) (6) and finally summarized the average proper choice.

Based on the data of each year, our model carry out 1000 cycles of simulation, that is to get 1000 kinds of future fire possibilities. The reason for we do 1000 cycles is that the model outputs swinging before 1000 cycles and become stable around 1000. Through calculating the average optimal solution from the1000 cycles' data, we can avoid the contingency random simulation bring. Beside, in each cycle, 365 small cycles are nested, representing 315 days of a year.

Fire events occurs everyday with **fire frequency** as the probability. Equation (7) describes the calculation of fire frequency. The area of each fire event fluctuates randomly around the predicted value. In order to be in line with the reality, we added some random factors to determine the number and location of the fire events on each day.The flow chart of our random simulation model is shown in **Figure 4**.

See **Appendix** for detailed running results and Matlab program.

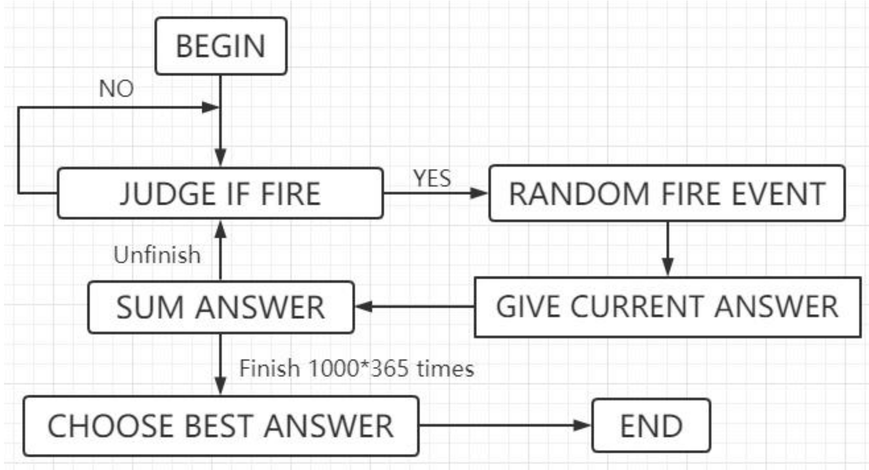
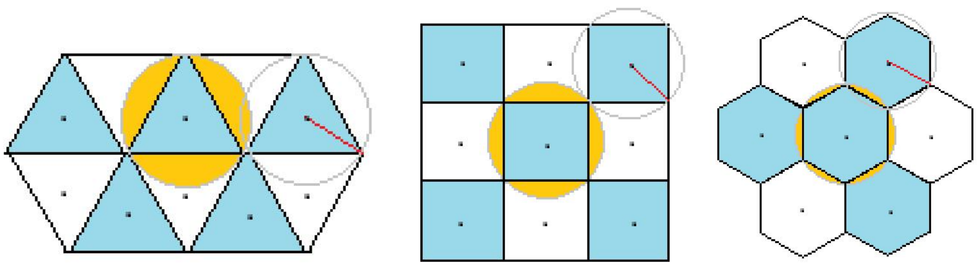


Figure 4: Flow chart of Random Simulation Model

4.5 EOC dietribution model



EOC distribution Model			
r = 30km	pi = 3.14		
shape	regular triangle	square	regular hexagon
monitor area loss	1658.3	1027.43	489.16
each drove/km^2	BIG	MIDDLE	SMALL

Figure 5: EOC distribution model

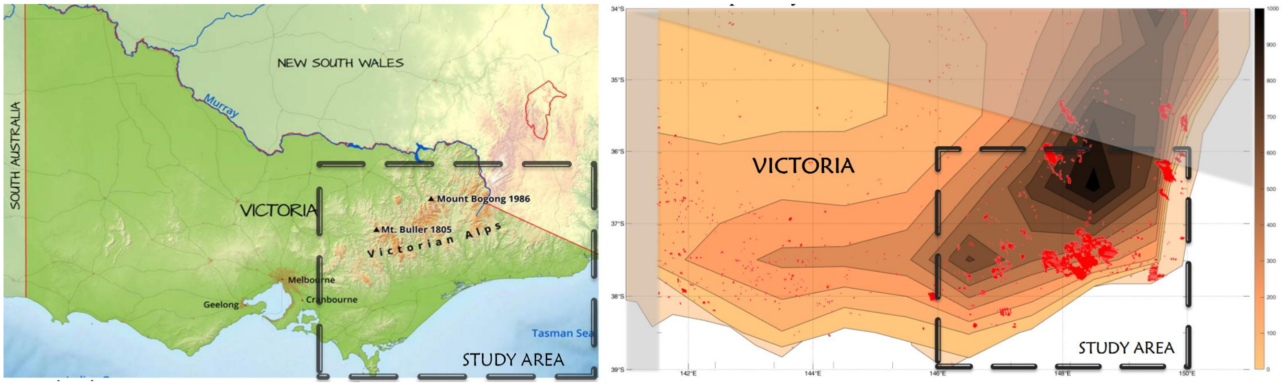
We assumed that drones can move under different EOC's control. Expanding the EOC cover range can expand the flight range of drones. In order to make the control range of EOC fully covered in the fire area, letting the number of drones can be minimized. we have tried three distribution modes of EOC. (Figure 5) After calculating the effective utilization rate of each base station area, we select the hexagon case.

5 Future wildfire events and coping approach in Victoria

5.1 Description of last 10 years' fire events

5.1.1 Study area selection and segmentation

We collected fire events data (Victoria, from 2010 to 2019) from the NASA[2] to calculated fire event size and frequency in our study area (31°S-39°S, 141°E-150°E, Figure 7). The distribution and scale of fire points are highly associated with local climate and weather temperature begins to increase near 2010. Therefore, we chose data after 2010 to keep track on a new pattern of fire events.



6.1/ Physical map of Victoria [3] 6.1/ Contour map of Victoria

Figure 6 : Study area in Victoria

{**Figure 6**} By plotting fire hot point on the contour map, we selected the fire-prone mountainous region in southeast Victoria(31°S-39°S, 141°E-150°E) as our study area.

For convenience and intuitiveness, we divided our study area (31°S-39°S, 141°E-150°E) it into 1×8 blocks equally. Figure 7 shows our segmentation result.

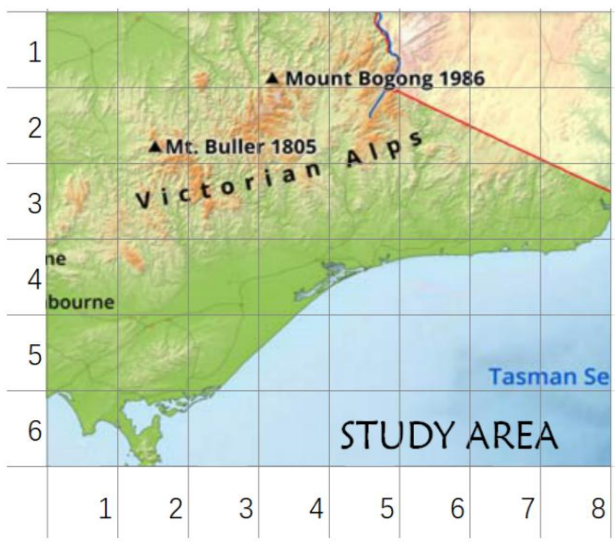


Figure 7 : 1×8 Segmentation result

{**Figure 7**} Each block takes up a square area and was given a number(1 to 48, top-to-bottom, left-to-right). The longitude and latitude spanned by each block are both 0.5°. Each length of the block's side is 10 kilometre and one block area is 3100 square kilometre approximately.

5.1.2 Fire event size and frequency calculation and analysis

We selected fire points with 'confidence' (Satellite data parameter, represent data accuray) above 80% as primary data and divided them according to acquire time, longitude and latitude. We assumed that fire frequency represents the number of fire events taking place during certain time span. In our study, **fire frequency** f_i is different from blocks and depend on D_i (the number of the day when the block catches fire in a certain year). In order to ease our data analysis process, we use D_i to represent **annual fire frequency**.

$$f_i = D_i / 365, i \in [1,48] \tag{7}$$

Due to the fact that fire event have seasonal characterics, we divide each year into three quarters: January - April(the first quarter), May - August(the second quarter), September - December(the third quarter).

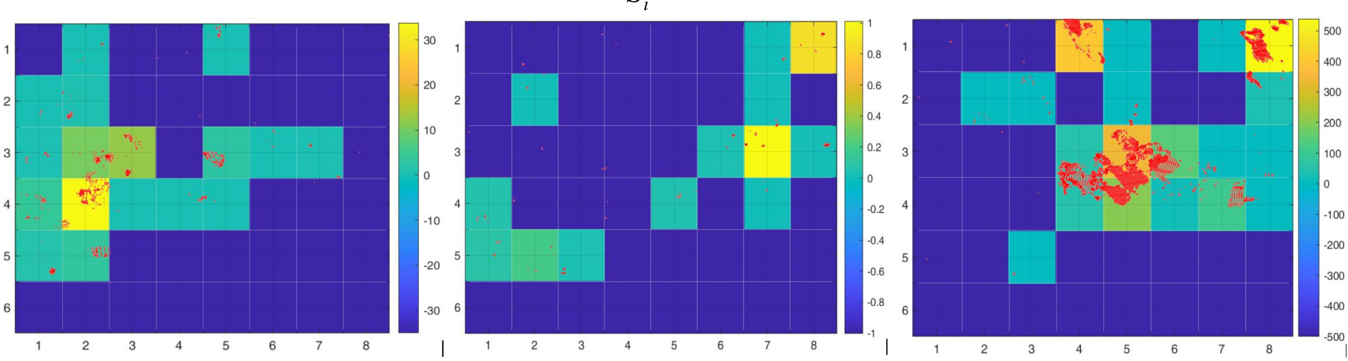
Using envelop line, we calculate the minimum area surrounding all fire hot points in one block in certain quarter. This minimum area represents the maximum fire event size S_i^k in one quarter. The **annual fire size** S_i is based on the average of these minimum areas in different quarter in same year.

$$S_i = \sum_{k=1}^{3} S_{max}^k / 3, i \in [1,48] \tag{8}$$

In order to check if our quarter partition is proper, we use (9) to evaluate how serious fire events are in different block in each quarter. These results are showed in **Figure 8**.

Here P_i represent the number of fire points in one block in certain quarter. $\sqrt{(S_i + P_i)}$ and P_i / S_i indicate the strength of fire events. D_i indicates the durability of fire events.

$$\sqrt{(S_i + P_i)} \times \frac{P_i}{S_i} \times D_i / 10000 \tag{9}$$



8.1/ The first quarter 8.2/ The second quarter 8.3/ The third quarter

Figure 8 : Evaluation result of quarter partition(year 2019)

{**Figure 8**} The red points shows fire hot spots during each quarter. The values calculated from (9) with different quarter data have different order of magnitude (10, 1,100). Thus, this quarter dividing method is suitable in our study.

Through the process above, we get **the annual fire frequency** and **the annual fire size** of each block from 2010 to 2019 for following prediction use. (**Table 1**)

Annual Fire Event Frequency of each block												
	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010	total	number
1	0	2	6	6	8	9	11	19	14	12	87	1
2	3	5	5	5	0	0	0	4	6	6	34	23
3	14	3	3	3	0	0	0	1	1	1	26	29
4	7	10	9	9	10	8	8	8	8	8	85	3
5	21	2	3	3	3	2	2	2	3	3	44	14
6	0	0	1	1	1	0	0	0	0	0	3	35
7	5	6	6	6	0	0	0	4	4	4	35	13
8	8	8	6	3	0	1	1	5	4	4	40	10
9	0	18	18	18	0	0	0	0	0	0	54	16
10	8	0	0	0	0	0	0	0	0	0	8	21
11	7	3	4	4	6	4	4	2	4	4	42	7
12	0	0	5	5	5	0	0	3	3	3	24	31
13	4	0	0	0	0	0	0	0	0	0	4	22
14	11	10	10	2	2	2	2	0	0	0	39	18
15	0	1	1	1	6	6	6	2	2	2	27	17
16	15	0	1	1	1	3	3	3	0	7	34	19
17	20	8	1	1	1	3	2	6	11	11	64	26
18	0	0	0	0	0	0	0	0	0	0	0	38
19	4	5	5	3	0	0	0	6	8	8	39	30
20	0	0	0	0	0	0	0	4	4	4	12	24
21	39	26	26	2	2	2	2	2	2	2	105	12
22	24	26	29	5	4	1	1	0	0	0	90	11
23	2	0	0	0	0	0	0	0	0	0	2	39
24	0	0	0	0	0	0	0	0	0	0	0	40
25	3	3	3	0	0	0	0	0	0	0	9	32
26	1	1	1	0	0	0	0	0	0	0	3	36
27	21	21	21	0	5	5	12	7	7	0	99	5
28	10	10	7	0	2	2	3	1	1	0	36	8
29	6	0	0	0	0	0	0	0	0	0	6	41
30	0	0	0	0	0	0	0	0	0	0	0	42
31	0	0	0	0	0	0	0	0	0	0	0	37
32	11	0	0	0	0	0	0	0	0	0	11	34
33	12	13	9	2	5	5	4	7	7	7	71	4
34	2	2	7	5	9	4	4	3	3	3	42	9
35	0	0	0	0	0	0	0	0	0	0	0	43
36	0	0	0	0	0	0	0	0	0	0	0	44
37	8	10	5	2	0	0	0	0	0	0	25	28
38	3	3	6	6	8	2	2	5	10	10	55	15
39	7	7	14	13	18	5	7	10	15	13	109	2
40	5	5	3	0	0	0	4	4	6	2	29	25
41	0	0	0	0	0	0	0	0	0	0	0	45
42	0	0	0	0	0	0	0	0	0	0	0	46
43	12	12	13	7	7	0	0	3	3	3	60	27
44	2	6	17	25	21	13	3	3	0	0	90	20
45	19	19	17	14	14	5	5	10	13	13	129	6
46	2	2	2	0	0	0	0	0	0	0	6	33
47	0	0	0	0	0	0	0	0	0	0	0	47
48	0	0	0	0	0	0	0	0	0	0	0	48

Annual Fire Event Size of each block												
	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010	total	number
1	0	1.77	229	229	456	474	475	540	295	294	2994.46	1
2	347	276	267	267	386	378	378	11.5	30.7	30.7	2371.64	23
3	228	188	162	119	240	121	121	0.02	0.02	0.02	1180.07	29
4	406	375	367	3.18	36.4	36.4	33.9	446	446	446	2595.14	3
5	141	75.4	199	199	209	72.7	72.7	63.3	15.5	15.5	1063.43	14
6	804	725	725	0	81.7	81.7	81.7	0	0	0	2498.16	35
7	90.1	112	106	76.8	0	0	0	66.9	66.9	66.9	585.855	13
8	331	326	312	0	1.14	13.7	13.7	270	257	257	1781.87	10
9	234	234	320	86.1	117	30.7	30.7	0	0	0	1053.53	16
10	332	349	349	16.8	26.8	26.8	26.8	0	0	0	1127.59	21
11	316	301	331	32.1	31.4	92.7	92.7	92.2	72.9	72.9	1435.55	7
12	309	0.67	0.67	0.67	187	187	187	2.85	2.85	2.85	879.699	31
13	136	136	165	33.6	33.6	0	0	0	0	0	503.684	22
14	51.3	12.8	113	113	113	0	0	0	0	0	403.078	18
15	18.7	135	135	135	0	0	0	256	256	256	1189.81	17
16	113	311	311	198	0.78	4.43	4.43	3.65	0	3.67	949.912	19
17	0	0	0	0	0	12.1	12.1	13.3	2.18	2.18	41.7652	26
18	798	798	700	59.8	59.8	0	0	0	0	0	2416.3	38
19	272	25.4	25.4	25.4	0	0	0	216	220	220	1004.94	30
20	417	0	0	0	0	0	0	65.9	65.9	65.9	615.207	24
21	6.06	0	0.71	0.71	0.71	0	0	4.98	4.98	4.98	23.1121	12
22	3.41	3.41	4.25	4.25	5.17	0.91	0.91	0	0	0	22.3176	11
23	406	406	403	0	0	0	0	0	0	0	1214.43	39
24	12.7	12.6	12.6	12.6	0	0	0	0	0	0	50.5793	40
25	359	468	468	108	0	0	0	0	0	0	1402.96	32
26	159	205	247	107	60.9	19	0	0	0	0	797.759	36
27	0	0	0	0	0	0	32.6	32.6	32.6	0	97.8189	5
28	40.8	244	244	244	0	0	0.63	0.63	0.63	0	773.239	8
29	6.67	6.67	0.41	0.36	0.36	0.36	0	0	0	0	14.8312	41
30	46.1	46.5	45.3	0.39	0	0	0	0	0	0	138.238	42
31	55.8	20.1	20.1	0	0	0	0	0	0	0	95.9251	37
32	0	0	0.5	0.5	0.5	0	0	0	0	0	1.51011	34
33	12.5	12.5	12.5	0	0	0	0	175	175	175	563.359	4
34	27.3	27.3	27.3	0	0	0	0	11	11	11	114.987	9
35	0	0	0	0	0	0	0	0	0	0	0	43
36	0	0	0.25	0.25	0.25	0	0	0	0	0	0.74682	44
37	0	0	0	0	0	0	0	0	0	0	0	28
38	0	0	0	0	0	0	0	33	97.8	97.8	228.661	15
39	0	0	0	0	0	0	20	322	346	326	1013.2	2
40	0	0	0	0	0	0	21	21	35.4	14.4	91.7016	25
41	0	0	0	0	0	0	0	0	0	0	0	45
42	0	0	0	0	0	0	0	0	0	0	0	46
43	0	0	0	0	0	0	0	75.3	75.3	75.3	225.791	27
44	0	0	0	0	0	1.87	1.87	1.87	0	0	5.62318	20
45	0	0	0	0	0	105	105	132	185	185	711.943	6
46	0	0	0	0	0	0	0	0	0	0	0	33
47	0	0	0	0	0	0	0	0	0	0	0	47
48	0	0	0	0	0	0	0	0	0	0	0	48

Table 1: The annual fire frequency and the annual fire size of each block from 2010 to 2019

5.1.3 Block classify based on Cluster Analysis

In order to make effective prediction, we gave score to each according to its fire frequency and fire size. The score is the sum of the 'number' showed in Table 1. The lower the score is, the higher the block dangerous level is. We use the scores to do **Cluster Analysis**, dividing those blocks into three class. The classes are showed in **Figure 9**.

Figure 9: Block class

{**Figure 9**} Using **Table 1** as reference, we consider that Level 1 block have no fire risk, Level 2 blocks have lower fire risk and Level 3 blocks have very high fire risk.

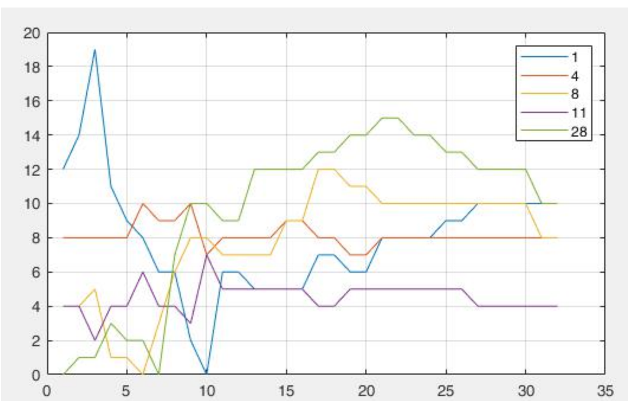
5.2 Prediction of nest 10 years' fire events

Using these results of size and frequency, we give prediction of the fire events in next decade (2020-2029). Assumed that part of block's feature can represent the whole feature in one class, same level block can use similar frequency and size, we give predict data of risk level 2 and 3. According to variation of data in Table 1, we use a simple power function (10) and use weight sum to imitate a 10 year period (11). Let the power function (10) represent the overall trend. Where x represents time, unit is day. Where x represents area, unit is square kilometers.

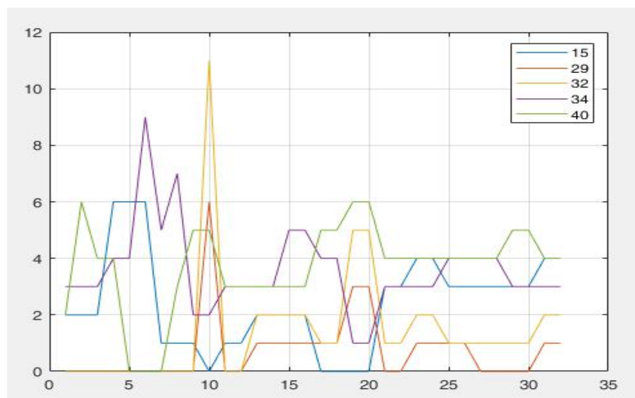
$$p(x) = ax^b + c \tag{10}$$

$$pre(x) = \lambda p(x) + (1-\lambda)p(x-10), \lambda = 0.6 \tag{11}$$

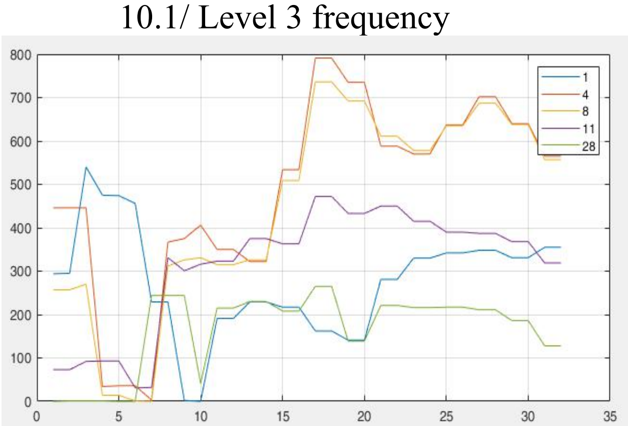
Due to the fact that we only have 10 year's origin data, our prediction is finished by using 10 former year's data as initial data to predict one later year's data each time and the new predicted data with its 9 former data act as the next initial data to continue the prediction. In our prediction, Parameter a, Parameter b and Parameter c are different during each prediction epoch and the weight λ in (11) is constant. Our predict result is showed in **Figure 10**.



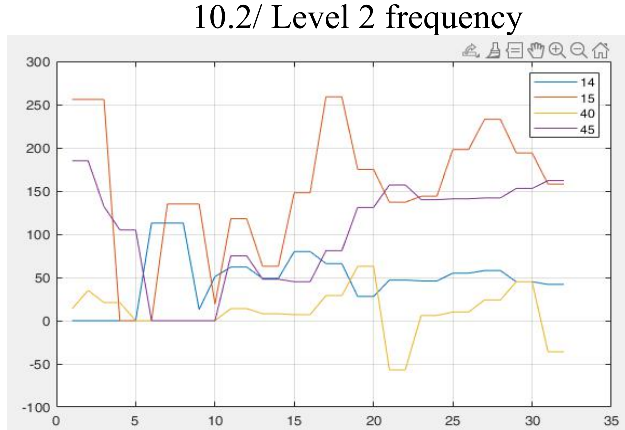
10.1/ Level 3 frequency



10.2/ Level 2 frequency



10.3/ Level 3 size



10.4/ Level 2 size

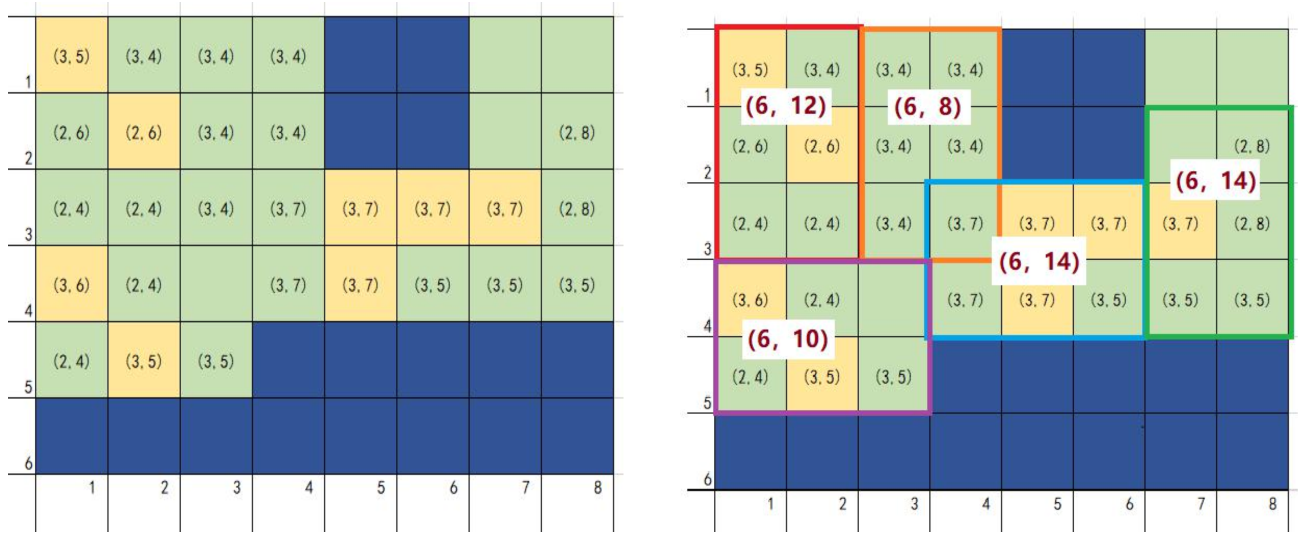
Figure 10 : Prediction of next two decade

{**Figure 10**} Assumed that part of block's feature can represent the whole feature in one class, same level block can use save frequency and size, we give predict data of risk level 2 and 3. We selected representative blocks to predict the trend of each level. See **Appendix** for more detailed prediction data.

It can be seen from the **Figure 10** that different levels of fire blocks have different characteristics.There are obvious differences in numerical value and trend. Most of level 2 blocks' frequency is about 4 days per year, while that of level 3 is 8 days per year. Most of level 2 blocks' fire size is about 100 square kilometers, while that of level 3 is 800 square kilometers. The same level of fire in this year's numerical value is similar, and there are some differences in trend. The similarity of blocks with near geographical location is very high.

Besides, **Figure 10** shows that there is a high probability of serious fire in 2026 and 2027. The curve increases sharply around 2027 (2027 is 17 on x axis).

5.3 Drone management for future wildfires



11.1/ Each drone each block 11.2/ Combined drone number of 6 block

Figure 11 : Drone - Block

In order to determine the drone management strategy to fighting with wildfires in the next decade, we first use our **Random Simulation Mode**l built in 4.4 and fire frequency and size data predicted in 5.2 to calculate get the number of each kind drones needed for each block.(**Figure 11.1**). Subsequently, use **the EOC distribution model** we built in 4.5, we combine some block's drone number and calculate the actual number of drons need to be purchased. Finally, we established drone deployment diagram(**Figure 12**).

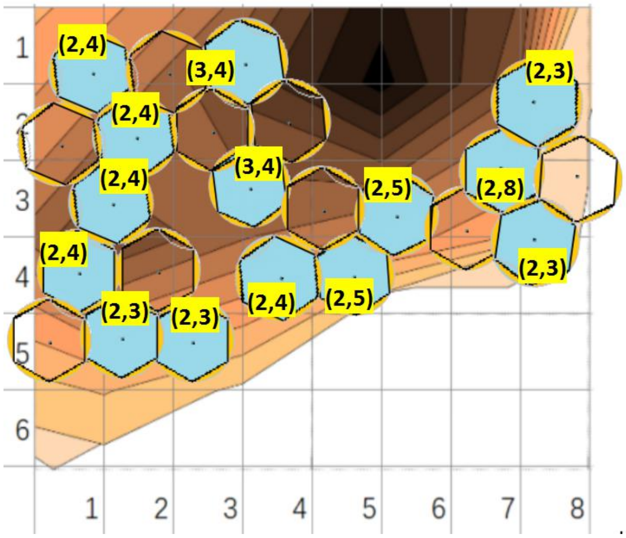


Figure 12 : Drone deployment diagram

{**Figure 12**} Each blue hexagon represents a fixed EOC, with the yellow label indicating its drone in format(SSA, radio-repeater). Each transparent hexagon represents a movable EOC, which not store drone for a long time. It is mainly used for the transfer of control signals, so that the aircraft can move in multiple EOC areas to deal with unexpected fire.

5.4 Equipment cost prediction based on first difference

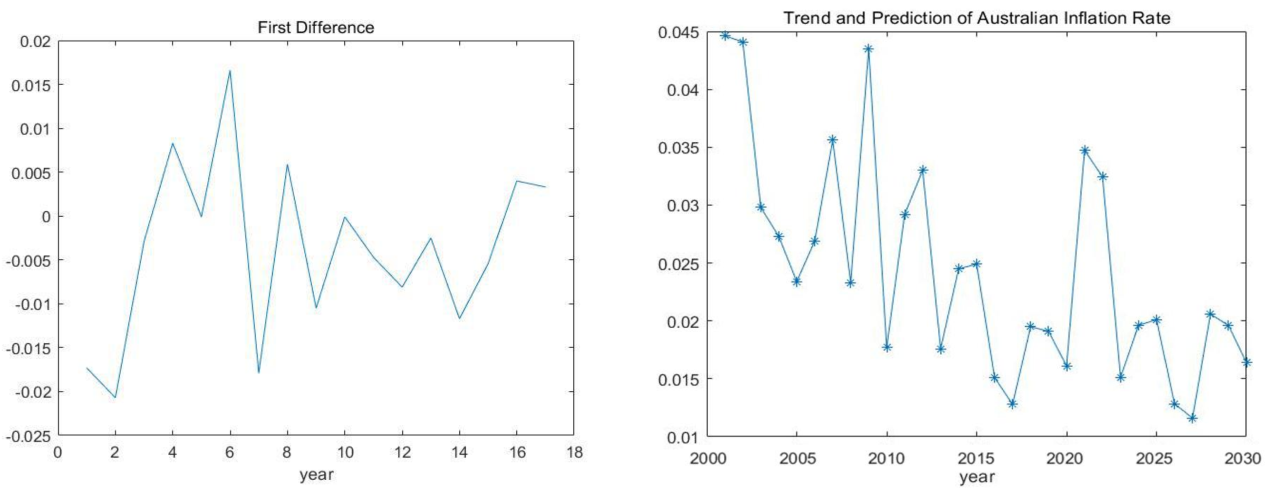


Figure 13 : The result of stationary time serie

We collected Australian inflation rate over past 20 years and used **first difference** (12) to stabilize those data. The result of stationary time series as **Figure 13** shown.

$$\nabla X_t = X_t - X_{t-1} \tag{12}$$

Then, based on the stationary time series, we used **Auto Regressive Moving Average (ARMA) Model** to predict the inflation rate for the future 10 years based on the past 20 years data.

Figure 13 shows that the inflation rate has a decrease trend and float in about 3-year period. According to economic law, not only the increasing quantity of equipment but also inflation influence the cost for fire suppression. The specific predicted inflation rate and the expected equipment cost are presented in **Table2**.

Year	Predicted Inflation Rate	EOC		Repeater		Handheld Radio		Camera and Sensors on SSA drone		Drones		Electricity		Total Cost
		Quantity	Cost	Quantity	Cost	Quantity	Cost	Quantity	Cost	Quantity	Cost	Quantity	Cost	
2021	0.0347	14	1400000	47	56400	188	225600	15	30000	62	620000	297.6	134.2	2332134.2
2022	0.0324	14	144536	46	56988.5	184	227953.9	14	28907	60	600000	288	134.1	1058519.7
2023	0.0151	14	142114	47	57251.6	188	229006.6	14	28423	61	610000	292.8	134.0	1066929.0
2024	0.0196	14	142744	47	57505.4	188	230021.8	13	26510	60	600000	288	132.4	1056913.2
2025	0.0201	14	142814	50	61206	200	244824	17	34683	67	670000	321.6	148.0	1153675.4
2026	0.0129	14	141806	58	70497.8	232	281991.4	24	48619	82	820000	393.6	179.8	1363094.2
2027	0.0116	14	141624	56	67979.5	224	271918.1	25	50580	81	810000	388.8	177.4	1342279.0
2028	0.0206	14	142884	56	68584.3	224	274337.3	20	40824	76	760000	364.8	167.9	1286797.5
2029	0.0196	14	142744	55	67293.6	220	269174.4	21	42823	76	760000	364.8	167.7	1282202.9
2030	0.0164	14	142296	56	68302.1	224	273208.3	20	40656	76	760000	364.8	167.2	1284629.6

Unit of Cost:AUD($)

Table2 : Total cost prediction

6 Optimal Elevation Model

Considering the elevation factor and to simplify the model, we assume that:

The mountain is a circular cone.

Fire area in this part is the lateral area of circular cone and fire area is part angle of the lateral area.

EOC can share information without Radio Repeater drones, and Radio Repeater drones can communicate with each other.

Forward teams can only put out fire from the bottom of mountain.

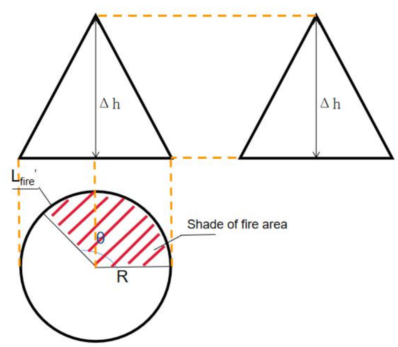


Figure 14 : Optimal elevation mode

As Figure 14 show,θ is the angle of shade of area,R is the radius of the mountain see from the top,Δh is the elevation difference between the fire line and top. We improve the way of fire area calculation, and use the (14) to provide a optimal quantity of drones.

Fire line length $$L_{fire}' = \frac{2S}{\sqrt{\Delta h^2 + R^2}} \cdot \frac{\theta}{2\pi} \quad (13.1)$$

Firefighter number $$n_f' = \left[L_{fire}' / 2 \right] + 1 \quad (13.2)$$ (13)

Near human drone number $$n_{RE1}' = \left[n_f' / 2 \right] + 1 \quad (13.3)$$

Total drone number
$$n_{RE}{}' = n_{RE1}{}' + \left[\frac{d_{fire} - \sqrt{a^2 - 1}}{20km} \right] \tag{13.4}$$

$$n_{RE}{}' = \frac{\left[\frac{2S}{\sqrt{\Delta h^2 + R^2}} \cdot \frac{\theta}{2\pi} \Big/ 2 \right] + 1}{2} \div 2 + 1 + \left[\frac{d_{fire} - \sqrt{a^2 - 1}}{20km} \right] \tag{14}$$

The advantage of the optimal model is that it decrease the deviation of fire area brought by elevation and will deploy firefighters and repeater drones on mountains more precisely so as to put out fire as soon as possible. It is practical to deal with the bushfire on the Victoria eastern coast mountains.

7 Sensitivity Analysis

7.1 Impact of battery volume on drone flight ability

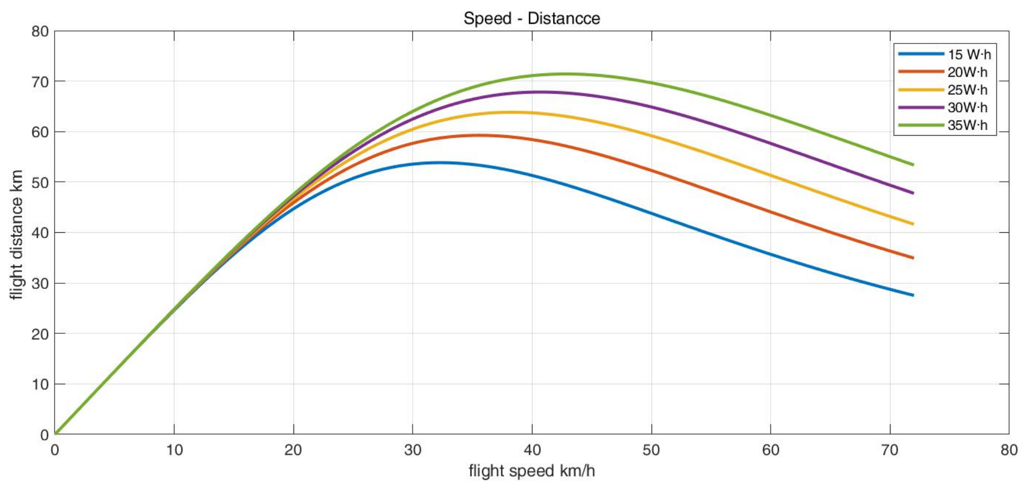
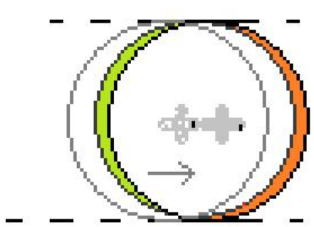
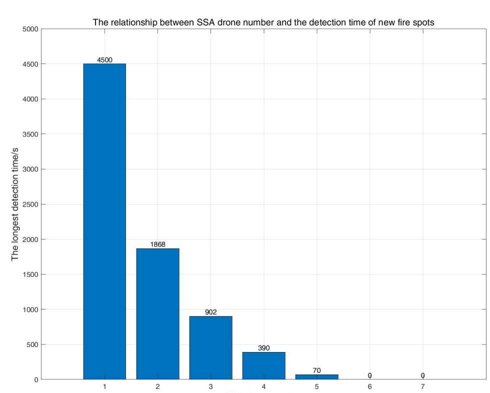


Figure 15 : Impact of battery volume

We change the battery volume at an interval of 5 W·h, from 15 to 35 W·h. As **Figure 15** shown, when flight speed below 15km/h, flight distance is similar among the drones with different battery;while above 15km/h, drone flight distance increase with battery volume going up.

7.2 The longest response time Analysis





We calculated the longest response time (from EOC to fire point) of the model, and found that SSA of 2 or 3 is not the optimal solution, but the result is acceptable.

8 Model Evaluation and Further Discussion

8.1 Strength

Drones Arrangement Model

Hexagon can maximize the utilization of EOC and SSA drones, leading a minimal cost.

Fire Prediction Model

Drones Arrangement Model

We separated the studied area into small blocks, centering the characteristic of fire data and making it can be observed directly.

Optimal Elevation Model

The model shape mountain into basic geometric model, simplify the calculation process and give the direct relationship among fire area, elevation and quantity of drones.

8.2 Weakness

The deploying position of firefighters is ideal, single firefighter is hard to put out a fire in 1km scale in reality. We did not assume that there are any spare drones to replace the empty charge drones, which make bias in cost prediction and drone exchange.

Fire Prediction Model

Some fire data with low confidence are abandoned in data process, thus losing some key information.

Optimal Elevation Model

The model only consider the fire on the top part of a mountain, it can not fit the situation fire occurs at the mountain bottom. Besides,the model assume that mountain is a circular cone while part of mountains are not in such a regular shape. Therefore, the model is unsuitable with mountains in complex shapes.

9 Conclusion

We build model to find the best number and mix of drones with consideration on safety and economy, seen as **Figure12** , with a budget for these equipment. Though predicting the worst fire frequency and area , our model provide a solution to face the worst condition so that the government can adapt the fire condition in the future 10 years. Combining the influence of the inflation rate change and number of drones , we predict that the cost for wildfire in 10 years will increase at a high speed. Therefore, detecting fire trend closely and timely is what the government will pay more attention to.

10 Annotated Budget Request

Rapid Fire Response System Budget Request

Project: **Rapid Fire Response System**			Date:**2021.2.8**	
Category	**Unit price ($AUD)**	**Quantity (Unit)**	**Total Price**	**Explanation**
Ⅰ.Equipment				
Drone	10,000	82	820000	
Camera and Sensors on SSA drone	2,000	24	48619	Unit price refer to the 10W repeater price on Internet
Radio Repeater	1,200	58	70497.8	Unit price refer to the 10W repeater price on Internet
Mobile EOC	100,000	14	141806	Unit price refer to the price of mobile macrocell base station on Internet
Handheld Radio	26.58	232	281991.4	Unit price is provided by Amazon
Ⅱ.Source				
Electricity	0.451	393.6 (kWh)	179.8	Unit price is provided by Internet

Note: the budget request is for 2021 reference only

References

[1] https://baike.baidu.com
[2]https://www.nasa.gov
[3]WWW.FREEWORLDMAPS.NET

Appendix

Prediction of fire frequency in next decade											
block	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	6	6	5	5	5	5	7	7	6	6	8
8	7	7	7	7	9	9	12	12	11	11	10
4	8	8	8	8	9	9	8	8	7	7	8
11	5	5	5	5	5	5	4	4	5	5	5
28	9	9	12	12	12	12	13	13	14	14	15
15	1	1	2	2	2	2	0	0	0	0	3
45	20	20	19	19	23	23	23	23	20	20	20
40	3	3	3	3	3	3	5	5	6	6	4

Prediction of fire size in next decade											
block	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1	191	191	229	229	217	217	162	162	141	141	281
8	315	315	326	326	509	509	736	736	692	692	611
4	350	350	322	322	534	534	791	791	735	735	588
11	323	323	375	375	363	363	472	472	433	433	450
28	215	215	230	230	208	208	265	265	139	139	221
15	118	118	63	63	148	148	259	259	175	175	137
45	75	75	48	48	45	45	81	81	131	131	157
40	14	14	8	8	7	7	29	29	63	63	0

Number and Mix of drones required each block					
Level 3			Level 2		
block/year	SSA	UHF/VHF	block/year	SSA	UHF/VHF
1/2020	3	5	11/2020	3	5
1/2021	2	5	11/2021	3	5
1/2022	3	5	11/2022	2	5
1/2023	3	5	11/2023	3	5
1/2024	3	5	11/2024	2	5
1/2025	2	5	11/2025	2	5
1/2026	3	5	11/2026	3	4
1/2027	3	5	11/2027	2	4
1/2028	2	5	11/2028	3	5
1/2029	2	5	11/2029	3	5
1/2030	2	5	11/2030	3	5
4/2020	2	5	15/2020	2	3
4/2021	2	6	15/2021	2	3
4/2022	2	6	15/2022	2	4
4/2023	3	6	15/2023	3	4
4/2024	3	6	15/2024	3	4
4/2025	3	6	15/2025	3	4
4/2026	2	6	15/2026	NaN	NaN
4/2027	2	6	15/2027	NaN	NaN
4/2028	2	5	15/2028	NaN	NaN
4/2029	3	5	15/2029	NaN	NaN
4/2030	2	5	15/2030	2	4
8/2020	3	5	40/2020	2	4
8/2021	2	5	40/2021	3	4
8/2022	3	5	40/2022	2	4
8/2023	2	5	40/2023	3	4
8/2024	2	6	40/2024	2	4
8/2025	2	6	40/2025	3	4
8/2026	2	6	40/2026	2	5
8/2027	2	6	40/2027	2	5
8/2028	2	6	40/2028	3	5
8/2029	2	6	40/2029	3	5
8/2030	3	6	40/2030	2	4
28/2020	2	6	45/2020	3	8
28/2021	3	6	45/2021	3	8
28/2022	2	6	45/2022	3	8
28/2023	2	6	45/2023	3	8
28/2024	2	6	45/2024	2	8
28/2025	3	7	45/2025	3	8
28/2026	2	7	45/2026	3	9
28/2027	2	7	45/2027	2	8
28/2028	2	7	45/2028	2	8
28/2029	3	7	45/2029	2	8
28/2030	2	7	45/2030	2	8

```
%% main
result=zeros(110,3)%(SSA, RE)
for year=1:1:11
    for num=1:1:8
        block=predecade_fre(num,1)
        Ni=predecade_fre(num,2:12)% (10)
        Si=predecade_fre(num,2:12)% (10)
        Nit = Ni(year);
        Sit = Si(year);
        x=get_Droves(Nit,Sit);
        result(num+(year-1)*10,:)=[block,x]
    end
end
```

```
%% random simulation function
function x=get_Droves(Nit,Sit)
    T=1000; %max time
    T_min=0; %mn
    k=T-T_min; %repeat year
    SSA = [707,1260,1766,2244,3146,3578,3998];
    x=[0,0]; %initial answer
    pp = Nit/365 %fire frequency
    while(T>T_min)
        for I=1:365
            if (rand<pp)% catch fire or not
            xnew=[0,0]
            nfire=randi([1 3])%random fire number
            for J=1:nfire
                dfire=26*rand%random location
                Sfire=1.2*Sit*rand%random fire size
                a= randi([2 5])%random location feature
                Nssa = find(SSA>Sfire,1);
                Nre = ceil(0.5*ceil(2*(Sfire^(0.5))))+floor((dfire-(a^2-1)^(0.5))/20);
                xnew(1)=xnew(1)+Nssa;
                xnew(2)=xnew(2)+Nre;%sum
            end
            x(1) = xnew(1)+x(1);
            x(2) = xnew(2)+x(2);
            end
        end
        T=T-1;
    end
    x(1) = ceil(x(1)/k/Nit);
    x(2) = ceil(x(2)/k/Nit);%average
    disp('Proper answer is: ')
    disp(x)
end
```