Problem Chosen	2021 MCM/ICM Summary Sheet	Team Control Number
B		2115664

Firewalls Built by Drones

In recent years, with the intensification of greenhouse effect and the decline of precipitation, the frequency of bushfires has been increasing, which has brought huge losses to Australia. The "Super Wildfires" that ravaged Australia at the end of 2019 were a wake-up call for countries around the world! In order to deal with the fire more efficiently, we give consideration to practicality and economy, establish the Joint Control Model of Drones and calculate the optimal purchase strategy of surveillance and situational awareness drones (SSA drones) and radio repeater drones (RR drones). The model can be well adapted to the change of fire in the next ten years. For the purpose of optimization, we also established the cellular automata based network grid model and innovatively put forward the drone cruise strategy.

First, we introduce the definition of economic benefit and establish an economic model. In the first prediction model, we divide fire events into three categories according to size, fire area into three categories according to terrain and set safety functions. Then, based on the economic benefit, safety and other factors, we worked out comprehensive evaluation indexes and selected the disaster data of Victoria State with the highest fire frequency in the past 20 years as reference, 150 000 random fire experiments were carried out by Monte Carlo Method based on the characteristics of historical fires. For the purpose of maximizing the comprehensive evaluation index, we found the best purchase plan for SSA drones and RR drones within the scope of Victoria, namely 1,128 SSA drones and 715 RR drones.

In addition, combined with the fire data in the last ten years, we predict the fire situation in the next ten years by the grey GM(1.2) model. Referring to the comprehensive evaluation index in Model 1, the model was calculated with the data of the next ten years, and it was found that our model had a very good adaptability to the change of fire in the next ten years. We then used some of the cost definitions in the economic model to calculate the cost increase for equipment other than unmanned systems over the next 10 years.

Finally, in order to better describe the effect of actual altitude and fire size on the position of the RR drones and optimize the performance of the drone surveillance system, we build a cellular automata based grid model and a new cruise strategy of the RR drone is proposed. A series of lattice points can be obtained by longitudinal and transverse cutting of a two-dimensional plane. By assigning a value to a grid point, it carries several variables that can represent the different dimensional states of this point. In the RR drone cruise strategy, the drone no longer performs signal relay work near a fixed location, instead, we've developed cruise routes for relaying drones based on previous fires in Victoria, taking full advantage of the flexibility and maneuverability of drones, dramatically reducing the number of drones required. In addition, the reliability and other indicators are introduced to measure the lag of grid information and improve the accuracy of the model.

After the establishment and solution of the model, we also conducted sensitivity analysis for the comprehensive benefit evaluation index (CEI). The analysis results show that our model has good robustness and is suitable for solving practical problems.

Keywords: Joint Control Model of Drones, Monte Carlo Method, GPM, Network Grid Model, Radio Repeater Drone Cruise Strategy

Contents

1. Introduction

1.1 Background

Affected by factors such as greenhouse effect and rainfall, air dryness in most parts of the world is increasing year by year, and the frequency of fire and the harm caused by fire are increasing day by day. However, if we are talking about the most serious one, it must be the "super wildfires" in Australia in 2019 and 2020. By January 8, 2020, the disaster had killed at least 33 people, charred more than 1 billion animals, burned down more than 25 houses and 11.7 million hectares of land. The fire has caused direct economic damage of more than $800 million!

Due to the impact of the fire, various states have introduced a number of policies to support fire agencies to adopt more efficient and safe fire prevention programs to improve the response ability to face fire incidents.

And among many solutions, drone system is one of the most eagerly awaited fire research project, it has flexible Over-the-Horizon (OTH)[1] and good communication ability[2], can overcome the limitation of traditional line-of-sight (LOS) equipment[5] in mountainous area and urban environment, and plays an important role in real-time fire monitoring and better guidance for front-line fire personnel.

Fig. 1. Fire Situation in Eastern Victoria

1.2 Restatement of the Problem

In order to help the “Rapid Bushfire Response” department use drone systems economically and efficiently to monitor and control potential bushfires in Victoria, we aim to address the following issues:

Task1. Establish a model to determine the number and combination of economic and efficient SSA drones and RR drones;

Task2. Assess how well the model will adapt to extreme fire events over the next decade and predict what equipment costs will increase;

Task3. Build a model to optimize the position of the RR drone under different terrains and fire sizes, determine the optimal RR drone hovering position;

Task4. Prepare a budget request to be submitted to the Government of Victoria based on the model established above and the results of analysis and calculation.

2. Notations and Symbol Description

2.1 Notations:

Ignition point: Refers to the phenomenon of accidental fire occurring at a certain time in a certain place. When the fire spreads to the next area due to limited combustible materials, the former area can be considered to have burned out, and the new area of fire is the new ignition point;

SSA drones: The full name of the drone for surveillance and situational awareness;

RR drones: The full name of the Radio Repeater drones.

2.2 Symbol Description:

Table 1.Symble

Symbol	Definition
$\sum C$	Indicators for evaluating the economic benefits of programmes
R_i	When i =1,2, they represent the communication radii of the SSA drone and the RR drone respectively
$f^n_{R_1+2R_2}$	For n days, the frequency of the ignition in the radius R+ R
Br	An indicator of the brightness of a fire as measured by satellite
In	Information on the fire site obtained by front-line personnel and the SSA drones
Se	Safety factor index
d_{ij}	The straight-line distance between the ignition point i and the front-line personnel j
D_{jk}	The straight-line distance between the front-line personnel j and the RR drones k

2.3 Assumptions

1. When longitude and latitude spans are small, we treat the surface of the earth approxi mately as a plane;
2. Assuming that the SSA drones are not affected by the fire and can carry out situational monitoring on the fire site at a relatively close distance (less than 50m); The front-line personnel have a long visual distance, but in order to control the SSA drones to work together, their detection radius is equivalent to that of the SSA drones;
3. Assuming that the dispatch of front-line personnel is very short after the satellite finds the fire site; The front-line personnel did not return until the fire had disappeared. The round-trip distance from the EOC to the ignition site is negligible;
4. Assumming that the RR drones are unable to provide stable signal relay service for front-line personnel and the EOC due to their fast movement during the process between the target location and the EOC.

3. Economic Benefit Analysis

When evaluating efficiency, we usually consider the return on investment and the time it takes to achieve that return. The concept of efficiency also applies to fire fighting, but its meaning at this time is different from the traditional interpretation. As far as fire fighting is concerned, the measure of efficiency is either the value of the protected object or the actual damage. Of course, we hope that the damage should be as small as possible.

3.1 Introduction

We accumulate the actual damage and the manpower and material expenditures spent on fire fighting according to the number of fire points as the evaluation factor of economic efficiency. Before the intervention, the spread of the fire could not be controlled. At this time, the damage caused by the fire cannot be adjusted manually, so this part of the damage can be assessed as absolute damage. After the intervention is initiated, we can control the number of RR drones used, and its number determines how much of the data collected by the SSA drone can be effectively transmitted to the EOC so as to change the actual damage in the process of fire fighting. In addition, wo can get the economic efficiency from the average daily cost of drones, human and material cost actual damage and the absolute damage.

3.2 Economic Efficiency Index

We use the loss caused by the fire and the costs invested in the fire fighting as the measure of economic efficiency:

$$\sum C = \sum C_{RRD} + \sum C_{SSA} + C_{tra} + D_{abs} + \sum D_{\sup} \tag{1}$$

- $\sum C_{RRD}$ -- The loss of the RR drones;
- $\sum C_{SSA}$ -- The loss of the SSA drones;
- C_{tra} -- Other equipment and manpower costs;
- D_{abs} -- Fire loss before the intervention began;
- $\sum D_{\sup}$ -- Fire loss in the process of intervention.

3.3 Economic Efficiency Index Composition Analysis

3.3.1 Fire Fighting Costs

- SSA Drones Costs

We get that the service life of the drone is about 5 years from the reference, so we assume that the service life of the WileE-15.2X Hybrid Drone is five years. We set $\sum C_{SSA}$ as the sum of the Average daily cost of the SSA drones :

$$\sum C_{SSA} = \frac{P_{SSA} \times J_{SSA}}{1825} \tag{2}$$

P_{SSA} is the unit price of SSA drones, J_{SSA} is number of SSA drones purchased and 1825 is the service life of SSA drones.

- RR Drones Costs

Same as above, we get:

$$\sum C_{RRD} = \frac{P_{RRD} \times J_{RRD}}{1825} \tag{3}$$

P_{RRD} is the unit price of RR drones, J_{RRD} is number of RR drones purchased and 1825 is the service life of SSA drones.

- Other Equipment and Human Costs

In addition to drones, firefighters, wearable devices, fire trucks, and EOC deployment are also required to included in human and equipment costs for each fire response. Considering that cost is not within the scope of our research and the selected fire data sample is large enough, We can divide the required manpower and material resources into $C_{tra}{}^{s}$, $C_{tra}{}^{c}$, $C_{tra}{}^{e}$ according to the severity of the fire (small fire, medium fire, large fire).

3.3.2 Economic Loss

Since most of the losses caused by fires cannot be assessed objectively, it is difficult to accurately measure the losses caused by fires. First, the value of different vegetation types is not the same, which is often related to its species, age and quality. Furthermore, the ecological value of wild animals and plants is often larger than the economic value. In order to simplify the analysis, we take its economic value as the reference value of disaster loss, which is more objective and fair while ensuring the model is correct. Second, it is also difficult to determine how much forest will be damaged by a fire. It depends on the age of the forest, the type of trees, the surrounding fuel, and climate conditions. It is not a simple discrete value, but a complex multivariate continuous function.

In order to simplify the analysis, we use the common trees in Victoria and the burning range of fires over the years as a reference and calculate the unit forest burning loss and the burning area of each fire by weighted average method. Then we analyze the disaster loss accordingly.

- Disaster Loss Before the Intervention

Because every forest fire will cause a certain loss before we start to fight, and this part of the loss has nothing to do with the rescue process. We use the product of the unit forest burning loss and the average burning range of each fire before we start to fight to find the disaster loss before the intervention Since the average burning range corresponding to small fires, medium fires, and big fires are quite different, the corresponding disaster losses before intervention are also different. Therefore, we define different Disaster losses $D_{abs}{}^{s}$, $D_{abs}{}^{c}$, $D_{abs}{}^{e}$ according to small fires, medium fires, and large fires.

- Disaster Loss During the Intervention

We believe that if the front-line fire data can be sent to the EOC in time and sufficient manner during the rescue process, the EOC can give more accurate instructions, which will help control fires and reduce disaster losses. However Even if all the front-line data can be transmitted to the EOC system in time, part of the forest will still be burned during the rescue process. Based on the experience of previous years, we hold the view that the validity of the data has an exponential relationship with the burned area. We define P_T as the ratio of the amount of data sent by the SSA drone to the amount of data received by the EOC. Combined with the unit forest burning loss, it can be seen that the disaster loss corresponding to each SSA drones during the intervention process $D_{\sup}$ has an exponential relationship with P_T.

$$D_{\sup} = \frac{D_c}{e-1}(e^{1-P_T} - 1) + D_u \tag{4}$$

D_c is the controllable loss and D_u is the uncontrollable loss.

4. Joint Control Model of Drones

4.1 Analysis of Ignition Point Monitoring Characteristics

4.1.1 The Monitoring Range of EOC

We now analyze the detection range of EOC,SSA drones and RR drones. A plane polar coordinate system was established with the EOC as the origin of coordinates. A circle was made with the EOC's origin as the center of the circle and the RR drone communication distance R_1 as the radius, as shown in the figure below:

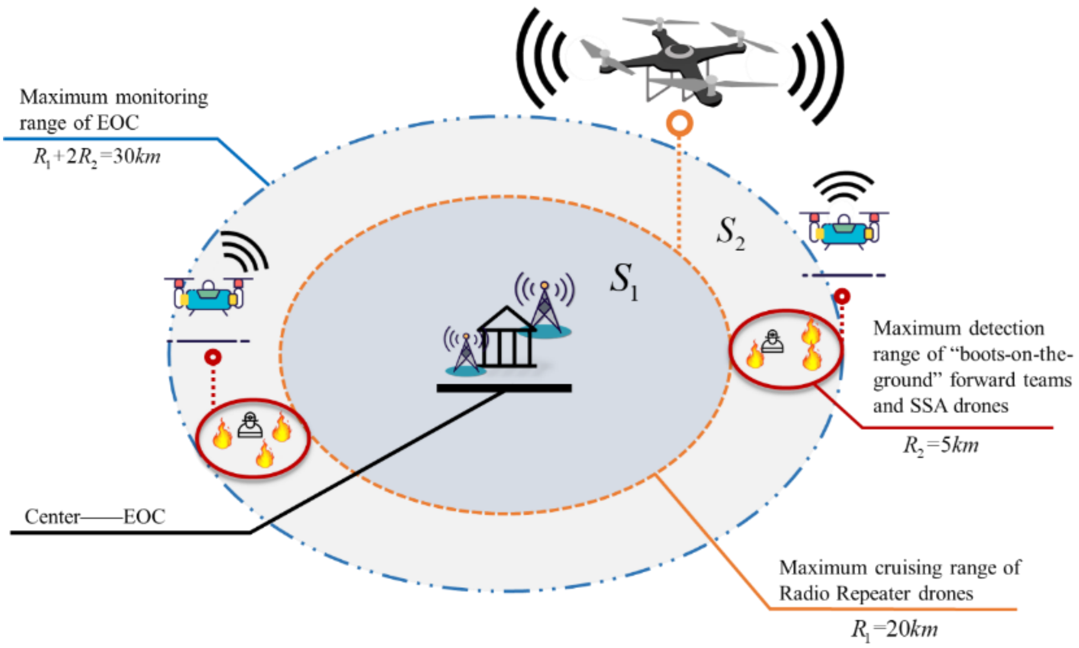

Fig. 2. Fire monitoring and two-way radio communication range diagram

4.1.2 Frequency Analysis of Ignition Points

In order to effectively analyze the fire situation in Victoria, we estimate the fire situation using the ignition points frequency. It may be helpful to determine the relevant parameters as follows:

Delimited area: select a circular area with radius $R_1 + 2R_2$:

It can be considered that the SSA drones and the RR drones have the largest communication radius in flat and open rural terrain. In the terrain blocked by tall buildings in the city; They have the minimum communication radius, which can be expressed as follows:

$$4km \le R_1 \le 20km \quad , \quad 2km \le R_2 \le 5km \tag{5}$$

Therefore, the monitoring range of the EOC is expressed as follows:

$$8km \le R_1 + 2R_2 \le 30km \tag{6}$$

Time period consideration: due to the limited combustible material, an area on fire for a period of time will be extinguished. Gonzalez[3] has studied the spread rate of forest firesp. For 10 hectares of trees, eucalyptus trees (70% of the tree species in Victoria) will generally burn out within 2~3 days from the start of fire if there are no special environmental factors (such as rain, snow, etc.) and human disturbance. Considering the maximum time required to burn out, it can be considered that the time period from the occurrence to disappearance of the ignition point (considered as a rectangular area with an area of 10 hectares) is 3 days($n = 3$).

Ignition frequency of Victoria are analyzed: between 2000 and 2020 in each time period n, radius $R_1 + 2R_2$ circular area may contain the number of ignition points is the ignition frequency. In order to make our model can adapt to the worst situation, we select 20 years under the detection range of different ignition point sizes. Then we choose the biggest point of ignition frequency as the basis of our subsequent modeling analysis.

$$f^n{}_{R_1+2R_2} = \max\{f^n{}_{R_1+2R_2}\}_{\text{all time periods}} \tag{7}$$

Then the maximum frequency distribution of ignition points in different detection ranges can be obtained, as shown in the table below:

Table 2. Table of relation between frequency of maximum ignition point and detection range

Maximum detection radius	8~13km	13~24km	24~30km
Maximum ignition frequency	4	7	11

As can be seen from the above table,there are only three discrete values of the maximum frequency of ignition points within the range of 8~30km.Therefore,we can divide the frequency of ignition points into three categories,namely —— low frequency, medium frequency and high frequency, according to the characteristics of drones communication range under different terrain.

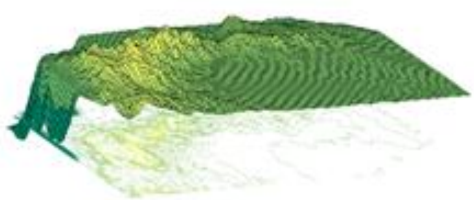

Fig. 3. Topographic map of eastern Victoria

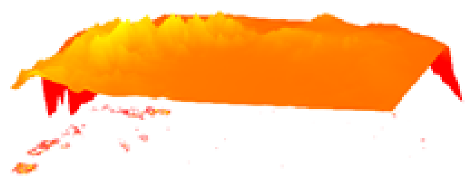

Fig. 4. Fire map for East Victoria from 11.1 to 11.7

4.1.3 Ignition Points Size Analysis

When a fire occurs in an area, it is first detected by personnel on the ground or remotely observed by satellites, and then fire heat and monitors are dispatched. Komesaroff[6] believes that it is appropriate to use the measurement of fire brightness(Br) obtained by satellite observation as the judgment index of fire size. It is defined as Br and the size of fire is divided into the following three categories according to Br:small fire, $300 \le Br \le 400$;medium risk fire, $400 \le Br \le 450$;big fire, $Br > 450$. The ignition points of each size can be considered to be randomly and uniformly distributed within a limited range. To investigate the relationship between the size and number of fires in Victoria from 2000 to 2020, the following statistical analysis can be made:

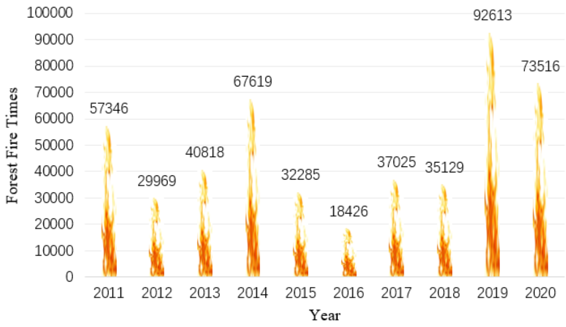

Fig. 5. Fires in Victoria from 2011 to 2020

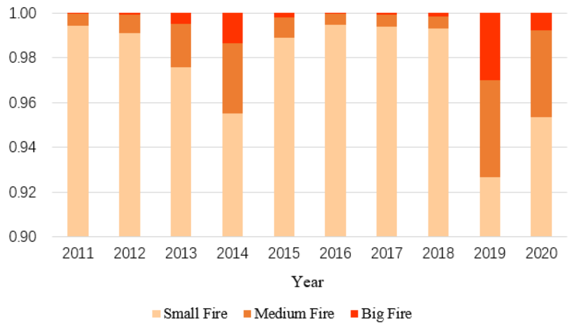

Fig. 6. Frequency of ignition points of different sizes

4.1.4 Contradictory Analysis of Security and Information Acquisition

When a fire occurs, the closer ground personnel are to the fire site, the more detailed the fire data will be obtained. However, SSA drones can detect the fire situation in a close distance, so the information obtained by it can be considered as a constant value. Therefore, information acquisition can be expressed as follows:

$$In_{person} = \frac{k_{person}}{r} \quad , \quad In_{SSA} = K_{SSA} \tag{8}$$

$$In_{total} = In_{person} + In_{SSA} \tag{9}$$

In the above formula, In_{person} represents the information acquisition recorded by front-line personnel, In_{SSA} represents the amount of data acquired by the SSA drones, In_{total} represents the information acquisition obtained at a certain ignition point. K_{person} and K_{SSA} is the proportionality coefficient.

However, the closer the front line personnel are to the fire site, the higher the risk they will assume. Our definition of safety is as follows:

$$Se = \frac{Br}{d} \tag{10}$$

In the above formula, d represents the straight-line distance between front-line personnel and the fire site.

4.2 Optimal Configuration Planning of Drones

4.2.1 Personnel and equipment allocation strategy

The basic strategy is: after the discovery of a new fire site, the front-line personnel will be dispatched to the ignition point site for monitoring according to the location and Br of the fire. We adopt a simple and efficient personnel and equipment allocation method: if the ignition point is small or medium-sized, the monitoring team should wear a set of fire monitoring equipment; If it is a large ignition point site, the monitoring team shall carry two sets of fire monitoring equipment (the equipment includes SSA drones and front-line personnel wearing equipment).

4.2.2 Drones Position and RR Drones Endurance Time Analysis

The polar coordinate system was established with the EOC as the center of the circle, and the relevant position relations were determined as follows:

- $(r^0{}_i, \theta^0{}_i)$ represents the location of the ignition point i ; $(r^1{}_j, \theta^1{}_j)$ represents the position of the front-line personnel forward unit j ; $(r^2{}_k, \theta^2{}_k)$ represents the location of the RR drone k .
- Distance between the ignition point i and the front-line personnel forward unit j :

$$d_{ij} = \sqrt{{r^0{}_i}^2 + {r^1{}_j}^2 - 2r^0{}_i r^1{}_j \cos(\theta^0{}_i - \theta^1{}_j)} \tag{11}$$

- Distance between the front-line personnel forward unit j and the RR drone k :

$$d_{jk} = \sqrt{{r^1{}_j}^2 + {r^2{}_k}^2 - 2r^1{}_j r^2{}_k \cos(\theta^1{}_j - \theta^2{}_k)} \tag{12}$$

RR drones' journey time to and from the target position is as follows:

$$t_{move} = \frac{2r^2{}_k}{v} \tag{13}$$

Since the time of replacing the battery of the RR drones is ignored, the relationship between the battery life, working time and travel time of the RR is as follows:

$$t_{endurance} = t_{move} + t_{work} \tag{14}$$

The RR drones can only provide stable two-way radio communication service during working hours. During the journey to and from the EOC, data monitored by front-line personnel and the SSA drones could not be transmitted to the EOC in a timely manner, and the EOC could not guide the work of front-line personnel based on the actual fire situation. Therefore, both the quantity and the reliability of the information acquisition have decreased. And the information quantity of the ignition point obtained by monitoring needs to be revised as follows:

$$In_{total} = \frac{t_{work}}{t_{endurance}} (In_{person} + In_{SSA}) \tag{15}$$

4.2.3 Determine the best combination of drones

In order to objectively select the combined scheme of the SSA drones and the RR drones, the Monte Carlo method is adopted to carry out 50000 independent multi-objective programming analyses in each monitoring radius. In each test, ignition points were randomly placed within the radius, and the size of the ignition points was determined by the frequency of the ignition points. The following multi-objective planning strategy was applied to find the optimal number of drones and the combination scheme. Finally, the combination scheme with the most suitable experimental frequency was selected out of 50000 experiments.

To provide the best possible monitoring of all ignition points within the detection range of a single EOC, a combination of front-line personnel, fire monitoring equipment, and the number and location of RPs is required. To test the capability of the model simply and intuitively, we used the following Comprehensive Benefit Evaluation (CEI) index to evaluate the comprehensive monitoring effect of our model:

$$\text{CEI}=\frac{\sum_{1}^{j}\sum_{1}^{i}(\beta_{ij}\text{Se}_{ij}+\beta_{ij}\text{In}_{total}-\sum_{each\ item}^{all\ item}\beta_{each\ item}C)}{\sum_{1}^{k}\beta_{k}t_{act}} \tag{16}$$

β_{ij} , β_{k} , $\beta_{each\ item}$ is the weighted coefficient in the multi-objective programming approach.

Establish the following multi-objective plan for each Monte Carlo experiment:

$$Max\ \text{CEI}$$
$$s.t.\begin{cases} Se_{ij} > Se_{ij\ allow} \\ \sum_{each\ item}^{all\ item} C < \sum_{1}^{i}\beta_{i}D_{i\ \text{sup}} + D_{abs} \\ \dfrac{t_{move}}{t_{endurance}} < \dfrac{C_{tra}+\sum_{1}^{j}C_{i\ SSA}}{\sum_{1}^{k}C_{k\ RRD}} \end{cases} \tag{17}$$

The following optimal schemes are obtained for selection (for each ignition frequency, only the schemes that occur more than 2000 times are listed).

Table 3. Monte Carlo simulation under different monitoring range of the best scheme table

Monitoring scope	Combination scheme		Quantity	Frequency
	SSA drones	RR drones		
8~12 km	5	2	47282	94.56%
12~24 km	10	5	4861	9.72%
	9	5	39605	79.21%
24~30 km	12	9	2894	5.79%
	13	9	5670	11.34%
	14	10	38116	76.23%

According to the data analysis in the table above, the best scheme for a EOC under different terrains and different monitoring radii can be determined:

- For the monitoring radius of 8~12 km, 5 SSA drones and 2 RR drones are the best;
- For the monitoring radius of 12~24 km, 9 SSA drones and 5 RR drones are the best;
- For the monitoring radius of 24~30 km, 14 SSA drones and 10 RR drones are the best;

After further comprehensive consideration of the urban and rural distribution of Victoria and the total land area of Victoria, we believe that when the Rapid Bushfire Response Department is established in 2021, the purchase of the SSA drones are 1128 and RR drones are

715 is the best purchase plan.

5. Model adaptability analysis

5.1 problem analysis

To illustrate how the model adapts to the changing likelihood of extreme fire events over the next decade and project what equipment cost increases will occur, first of all ,we should predict the trend of the fire situation in the next ten years. Then we can analyze the adaptability of the model to future fires, and get how the equipment cost will change through the comparison.

5.2 Fire forecast for 10 years

Considering that fire conditions are closely related to rainfall, temperature, wind speed and other factors, we adopt the grey prediction model here. Its training speed is fast, and it has strong interpretability, which can achieve better prediction effect.

5.2.1 Determination of the EOC Location

- In the next ten years, the Australian government will not carry out substantial transformation of forest areas, which means the nature of Australia's forests in the next ten years will not change significantly compared to now;
- In the next ten years, environmental factors such as rainfall and temperature will change following the predicted trend;
- when an extreme fire occurs, the probability of adding large, medium and small ignition points each day obeys the prediction in Model 3;

5.2.2 Relevance evaluation

In order to ensure the prediction effect and prevent the increase of the error due to the large difference in the magnitude of the data, the data should be preprocessed before starting the calculation. Before the prediction calculation, the correlation analysis should be performed, and if the correlation between the reference series and the predicted series is low, the influence of the reference series can be ignored. The following calculation series are all raw data series.

Select reference series and comparison series:

$$x_i = \{x_i(k) \mid k = 1,2\ldots,n\} \quad , \quad x_j = \{x_j(k) \mid k = 1,2\ldots,n\} \tag{18}$$

k represents time, then the correlation coefficient of the above two series at time k is:

$$\xi(k) = \frac{\min_j \min_t \left| x_i(t) - x_j(t) \right| + \rho \max_j \max_t \left| x_i(t) - x_j(t) \right|}{\left| x_i(k) - x_j(k) \right| + \rho \max_j \max_t \left| x_i(t) - x_j(t) \right|} \tag{19}$$

ρ is the resolution coefficient, we set $\rho = 0.5$ here. Put in the data to calculate we get:

$$\begin{array}{cccc} & x_5 & x_6 & x_7 \\ x_1 & 0.875 & 0.683 & 0.346 \\ x_2 & 0.706 & 0.655 & 0.534 \\ x_3 & 0.747 & 0.779 & 0.589 \\ x_4 & 0.84 & 0.819 & 0.577 \end{array} \quad (20)$$

By comparing the correlation coefficients, it can be found that the total number of fires and the proportion of big, medium and small fires have a strong correlation with rainfall and temperature, but a weak correlation with illumination. Then, We take the data of the past ten years and use the GM (1,2) forecasting model to predict.

5.2.3 GM (1,2) forecast

Take the forecast of the total number of fires as an example, take the total number of fires series. Then we get the GM (1,N) model:

$$x_1^{(0)}(k)+az_1^{(1)}(k)=\sum_{i=5}^{6}b_i x_i^{(1)}(k) \quad (21)$$

a is the system development coefficient, $b_i x_i^{(1)}(k)$ is the driving term and b_i is the driving coefficient.

From this, the total number of fires in the next ten years can be obtained, and the prediction of the proportion of different types of fires can also be obtained using the same method. Therefore, we get the total number of fires and the proportion of different types of fires in the next ten years as follows:

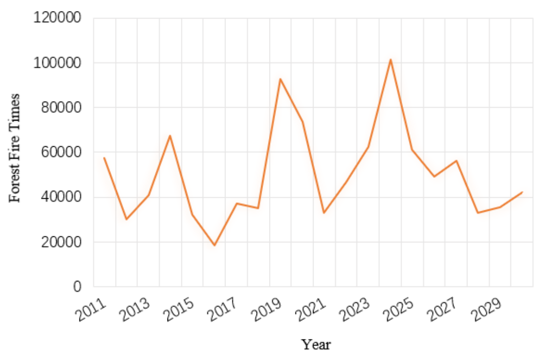

Fig. 7. Fire projections for the next 10 years

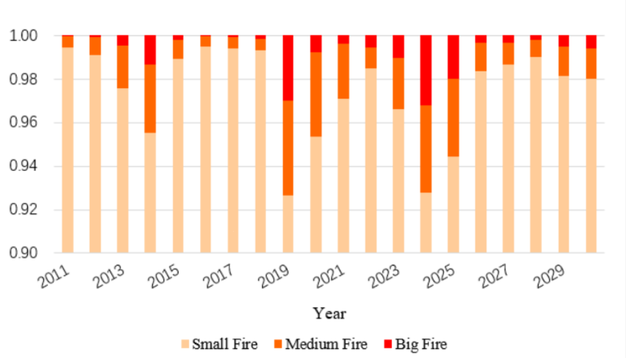

Fig. 8. Fire frequency forecast for the next 10 years

5.2.4 Model accuracy analysis

We use the residual qualified model to test, and take the original sequence of the total number of fires as an example for calculation. We get the relative error sequence Δ :

Table 4. Error sequence table

$\bar{\Delta}_1$	$\bar{\Delta}_2$	$\bar{\Delta}_3$	$\bar{\Delta}_4$
0.05	0.07	0.09	0.07

It can be seen that the average relative error is less than 0.1 and the accuracy level is higher than the third level. It means the prediction has a high credibility, so we believe that the forecast results are credible.

5.2.5 Equipment Cost Change Forecast

Assuming that the cost of the drone system is constant, the remaining equipment cost at this time mainly includes the EOC construction cost, the cost of wearable equipment, etc. The figure below forecasts the Victorian government's spending on equipment.(Use Victoria's spending on equipment in 2019 as a baseline value 1).

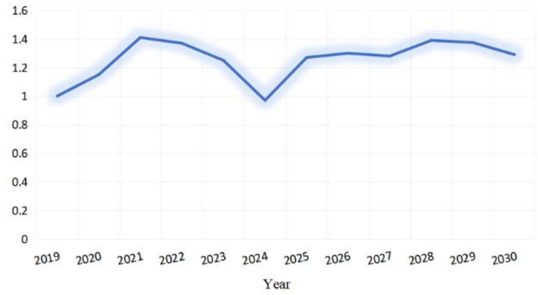

Fig. 9. Equipment cost forecast in the next 10 years

6. Network Grid Optimization Model Based On Cellular Automata

6.1 Additional Assumption

1. The RR drones moves horizontally at a certain altitude without any change of coordinates in the vertical direction.
2. The obstruction of trees to signal transmission is not considered, only the obstruction of mountain and terrain to signal is considered.

6.2 Basic Statement

Based on the above analysis, we have established the joint control model of Drones. In order to achieve the balance among safety, economy and situation monitoring effect, we obtained the optimal solution of the number and combination of drones through model analysis.

Now, in order to optimize the position of the RR drones on the basis of the above model, we have established a brand new model, which can be tested to optimize the position of the RR drones in different geographical locations and fire situations. In particular, we put forward the new RR drones cruise strategy in the model, establishing credibility and related indicators, while guaranteeing the reliability of the data validity and situational monitoring sharply reduce the number of the RR drones, significantly reduce the cost of government purchase of RR drones, and realizing the simultaneous optimization of safety, economy and fire situation detection effect.

The establishment of the model is similar to the idea of cellular automata. In order to describe the information of different dimensions such as geographical location and fire distribution in a unified model, we set up a data discretization model -- network grid model. A series of grid points can be obtained by meshing the actual two-dimensional map. The more rows and columns are segmented vertically and horizontally, the closer the network grid model is to the real and continuous situation. The schematic diagram of this model is shown in Figure .10.

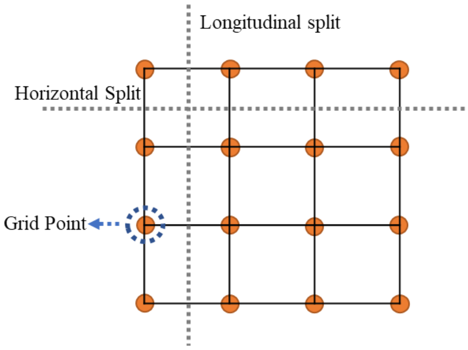

Fig. 10. Schematic Diagram of Network Grid Model

Each grid is like a container with variables, and the key to building the model is to determine what information each grid carries. A series of key problems involved in this model can be solved by describing these information. The information each node contains is mainly represented by the following variables:

- (X, Y) -- Indicating the coordinates of the grid's position on the horizontal plane, corresponding to longitude and latitude;
- Z_1 -- Representing the height of the grid point in three-dimensional space, corresponding to the actual altitude;
- Z_2 -- Indicating the severity of the fire occurring at the grid point;
  If $Z_2 = 0$, it means that there is no fire at this point;
  If $Z_2 = i(i = 1, 2, 3...)$, then indicates that there is a fire at this point, and the value of i from small to large indicates that the corresponding fire event is more and more serious;
- Z_3 -- Indicating whether a grid point was observed (we'll define what "observed" means later);
  If $Z_3 = 0$, that means it was not observed;
  If $Z_3 = 1$,that means it was observed;
- Z_4 -- Indicating how much time has elapsed since the last update of the grid status;
- Z_5 -- Indicating how many fires have occurred at this grid point.

To facilitate representation, we define all variables except coordinates (X, Y) as a data set, represented by Z_Σ , which contains the following elements:

$$Z_\Sigma = \{Z_1, Z_2, Z_3, Z_4, Z_5\} \tag{22}$$

Based on the above description of basic variables, we will then describe the principle of this model. SSA drones and frontline personnel work in a constant position, like surveillance towers around fire incidents. But different from the model mentioned above, our RR drone does not hover at a fixed working position, but is always in constant motion, receiving and sending information in a cruising way. Assuming that the RR drone moves between two EOCs on a broken course and paths are planned with as few turning points as possible, then in the process of straight flight, a slot-like mobile communication area (Mobile Communication Area for MCA) can be obtained, as shown in Figure.11. The arrow represents the movement direction of the drone, p_{t1}, p_{t2}, p_{t3} represents the position of the drone at time t_1, t_2, t_3 , and S_{t1}, S_{t2}, S_{t3} represents the communication area(Communication Area for CA) of the drone at the corresponding position.

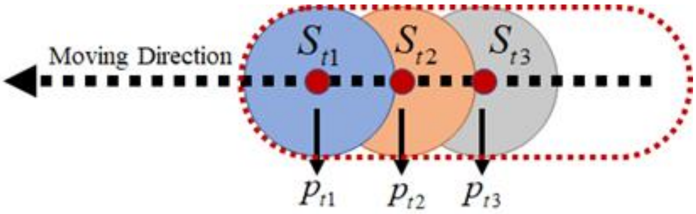

Fig.11. Slot Communication Area Diagram

During the cruise of the drone, SSA drones and frontline personnel kept measuring the data of the fire, but the measured data could not be returned to EOC all the time through the RR drone. However, only when SSA drones and frontline personnel enter the slot communication range, the RR drone can detect the measured data of SSA drone within a certain period of time and complete the update of the corresponding grid data. As shown in Fig. 12, after the drone moves to p_{t2} ,the grid point to be updated enters its communication range, and the drone can receive the corresponding measurement data of the grid point and complete the data update of the grid point; When the drone moves to p_{t1} ,the grid point to be updated leaves its communication range, and the drone cannot receive the signal of the grid point. For the grid point, period $t_2 \sim t_1$ is the period during which the measured data of the grid point can be transmitted to the EOC through the RR drone, and also the period during which the data of the grid point can be updated.

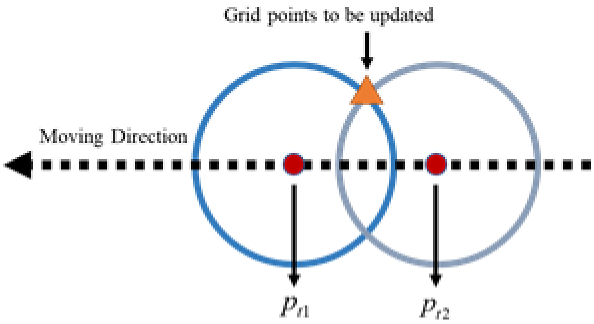

Fig. 12. Grid Communication Range to be Updated

If the location of the fire event is regarded as a simple two-dimensional distribution, the communication range of the RR drone at a certain moment is a circle with a radius of 20km. However, in the process of modeling, we also took into account the influence of altitude, and optimized and modified the model. Different drones communicate in the form of electromagnetic waves. The equiphase surface of the electromagnetic wave is a sphere, which diffuses and propagates to the periphery with the location of the drone as the center of the sphere in the three-dimensional space. Considering the local terrain, it is appropriate to set the drone at an altitude of $H_r = 2km$. Therefore, when we investigate the influence brought by altitude, the communication distance of 20km of the RR drone is no longer the horizontal distance on the two-dimensional plane, but the hypotenuse of the right triangle as shown in Fig. 13. At this time, the horizontal distance is as follows:

$$R_{mod-1max} = \sqrt{R_{1max}{}^2 - \Delta H^2} \tag{23}$$

$$R_{1\max} = 20km \tag{24}$$

$$\Delta H = \left|2000 - Z_1\right| \tag{25}$$

Where, $R_{\text{mod}-1\max}$ is the corrected communication range and the absolute value of the altitude difference between the RR drone and the grid point to be measured.

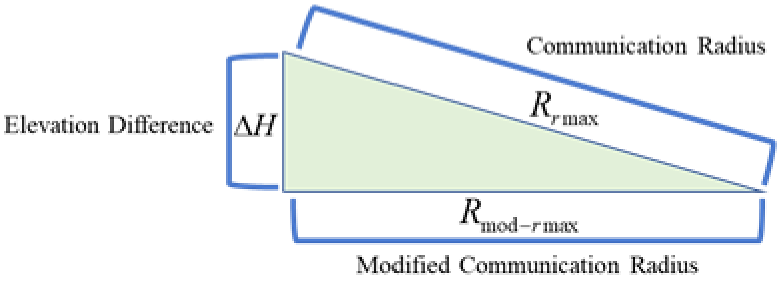

Fig. 13. Modified Map of Communication Range Considering the Tffect of Altitude

Then the communication area of the RR drone on the two-dimensional plane is no longer a standard circle. Instead, the projection on the horizontal plane of the intersection line between the ground and the sphere with the radius of the maximum communication distance $R_{r\max}$ and the RR drone as the ball center.

6.3 Model application mode

6.3.1 Determination of the EOC Location

The RR drone collects data in a cruising way and updates grid data. Its basic movement mode is to start from one EOC and move to another EOC for charging. The location of EOC should meet the following three requirements:

- The RR drone shall not be separated from the maximum communication radius $R_{E\max}$ of a single EOC during its endurance, $R_{E\max} = 30km$;
- The distance of one movement shall not exceed the maximum flight distance of a single charge $D_{E\max}$, $D_{E\max} = v_{\max} t_{endurance} = 180km$;
- The mobile communication area of the relay drone should contain all the fire prone area S_{fire}, which represents the collection of all fires that occurred in East Victoria from 1 October 2019 to 7 January 2020. This condition can ensure that the total mobile communication area of the RR drone can include all the fire events regardless of the distribution of the fire events under the very high probability.

6.3.2 Update of Data

We take ten minutes as the data update cycle, that is, every ten minutes the RR drone will send all the measured data in its communication area to EOS for processing, so as to complete the data update of the corresponding grid point.

For ease of presentation, we define the update of the data as the update of all elements in the data set Z_{Σ}.

6.3.3 Introduction of Credibility

Since our data is not updated in real time, when the grid is outside the RR drone communication area, the variables stored by our grid may be the state of one or several cycles ago, and the reliability of the data decreases accordingly. We need a variable to measure whether this data is reliable, so we introduce the concept of credibility β , which is directly related to Z_4, and its expression is:

$$\beta=\frac{K_\beta}{\sqrt[\frac{1}{3}]{Z_4}} \qquad (K_\beta < 1) \tag{26}$$

K_β is the credibility factor.

6.3.4 Nine-Grids Criterion

In order to judge the size and occurrence of fire easily and accurately, we propose a nine-grids criterion based on network grid model.

In order to prevent errors in the results caused by equipment failure or measurement error and to accurately reflect the size of the fire by using this model, we take Z_2 values of ten cycles for accumulation, namely:

$$Z_{2\Sigma}{}^{j}=\sum_{i=1}^{10} Z_{2i} \tag{27}$$

In order to consider the influence of the surrounding grid points on the grid point and make the spread of the fire in the model more smooth, we take the nine grid points centered on the grid point for weighted average processing, and get the variable $\overline{Z}_{2\Sigma}$ that can accurately reflect the size of the fire. The weight λ_j is represented by the credibility of each node. The expression of the above variables is as follows:

$$\overline{Z}_{2\Sigma}=\sum_j \lambda_j Z_{2\Sigma}{}^{j} \tag{28}$$

$$\lambda_j=\frac{\beta_j}{\sum_k \beta_k} \tag{29}$$

Using the same method to calculate the weighted average, we can judge whether there is a fire at this grid point to prevent the occurrence of misjudgment. The expression is as follows:

$$\overline{Z}_{3\Sigma}=\sum_j \lambda_j Z_{3\Sigma}{}^{j} \tag{30}$$

$$\lambda_j=\frac{\beta_j}{\sum_k \beta_k} \tag{31}$$

If $\overline{Z}_{3\Sigma} < 0.3$, then there is no fire at the grid point, and $\overline{Z}_{2\Sigma}=0$ satisfies at this time. If $\overline{Z}_{3\Sigma} > 0.3$, then the grid has a fire.

6.3.5 Corrections that Take into Account Terrain Effects

After screening and analysis, the influence of terrain mainly includes the following two aspects. In view of the problems raised, we have made corresponding corrections and optimization to the model.

Due to the very complex terrain in mountainous areas, there is local subsidence near some fire sites, which may lead to poor communication quality between SSA drones and RR drones .If seven or more of the eight grid points around the nine grids are higher than the altitude of the central grid point, it is considered that there is topography depression (as shown in Fig. 14), and the communication quality declines.

In order to represent the decline of communication quality, we propose the modified formula of reliability as follows:

$$\beta' = K_{sink}\beta \tag{32}$$

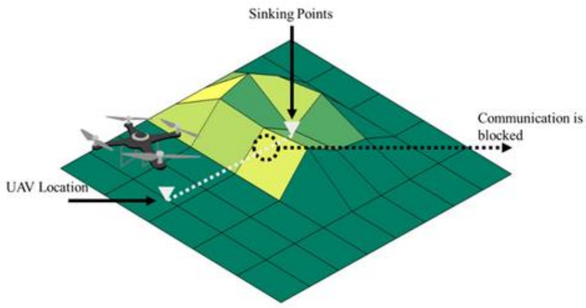

Fig. 14. Diagram of Subsidence Terrain

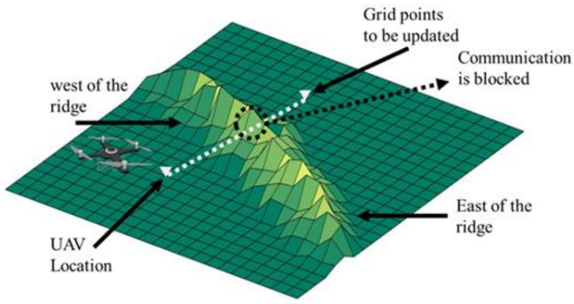

Fig. 15. Diagram of Ridge Topography

Where, β' represents the reliability after correction, and K_{sink} represents the local terrain correction coefficient.

As shown in Fig. 15, the topographic map drawn from elevation data shows that there are ridges in mountainous areas. If the location of the fire event, namely the grid to be updated and the location of the RR drone, are on both sides of the ridges, then the ridges will obstruct the transmission of electromagnetic signals and degrade the communication quality. In order to represent the decline of communication quality, we propose the modified formula of reliability as follows:

$$\beta' = K_{ridge}\beta \tag{33}$$

Where, β' represents the reliability after correction, and K_{ridge} represents the terrain correction coefficient of the ridge.

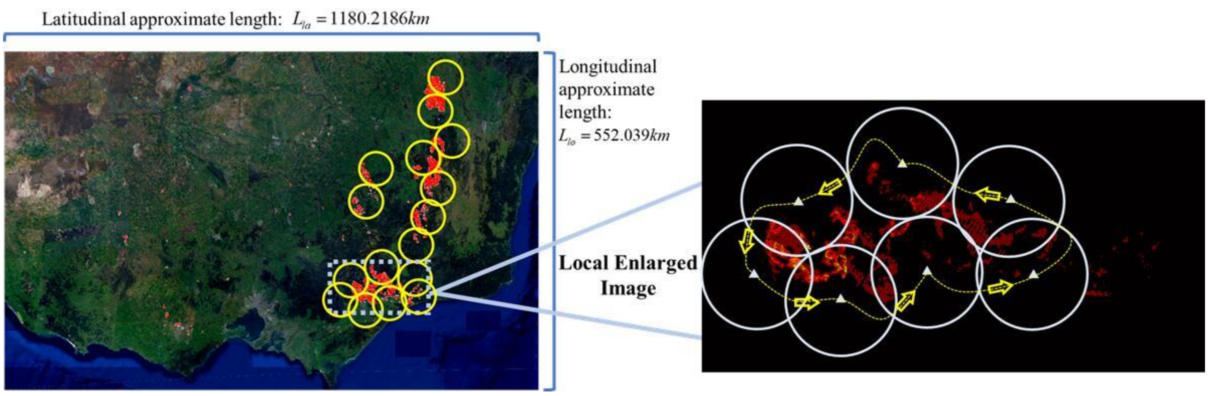

Fig.16. RR drones cruise strategy schematic diagram

7. Model Testing

We use the multi objective programming approach, consider the safety, economy and other factors, build the Joint Control Model of Drones which can efficiently and reasonably monitor the fire, and use the cellular automata algorithm to optimize the RR drone position. Monte Carlo method is adopted in the modeling, and a large number of random and uncertain fire situations are taken into comprehensive consideration. Therefore, no matter we add some fire data to the model or delete some data from the model, the model results will not fluctuate greatly, indicating that our model has good stability.

When the weight coefficient β in multi-objective programming changes in a small range, Monte Carlo method can also use a large number of experiments to eliminate its fluctuation effect, so the model has weak sensitivity.

Based on the above stability and sensitivity analysis, we believe that the model is robust.

8. Strengths and Further Improvements

Strengths ：

- Applying interdisciplinary ideas to solve problems, and using knowledge of mathematics, geography, economics and other disciplines to build the model;
- Weak correlation variables are ignored in the process of model establishment to make the model simple.
- We performed stability and sensitivity tests to make the results more convincing;
- The graphics are depicted accurately and vividly, making the results easy to understand;
- We put forward the network grid optimization model and efficient drone cruise strategy, which provides a new idea for the establishment of Drone Surveillance System;
- The model structure is rigorous and reasonable, suitable for solving practical problems. It also retains enough interfaces to make the model universal and extensible;

Some Improvements :

- We can make the model closer to the real situation. We put forward many assumptions and simplified the actual situation when building the model, but these assumptions will cause some errors.
- We did not properly consider the influence of tree distribution on signal communication range in mountainous terrain;
- The differences in fire awareness and firefighting ability of personnel in different regions are not scientifically considered in our model, that is, human factors are not sufficiently considered;

Budget Request

1. Project Details

Date Submitted: 2021.2.8

Project Name: Purchase of forest fire prevention and control equipment

Project Originator: Country Fire Authority

2. Project Description

In recent years, the frequent occurrence of forest fires in Victoria State has caused huge losses to the local ecological environment and economy.In 2019 alone. For example, there were nearly 100,000 fires, large and small, in Victoria state. And this issue really needs to be taken seriously by the state government. Australia has a large area and few people, and there are few forces to mobilize. Traditional forest fire fighting methods can not effectively detect fires in some areas, and fire information is difficult to be effectively transmitted in weak signal areas, which will make it impossible for the command center to give accurate guidance based on the disaster situation in time, affecting fire rescue and further aggravating the disaster. A new forest fire fighting and fire monitoring system is urgently needed, with the "Super Wildfires" occurring in 2019~2020 being the most powerful wake-up call.

Among the existing schemes, the drone system has become one of the most potential fire research projects with its flexible Over-the-Horizon (OTH) and excellent communication ability, which can well solve the problems of wide fire distribution area and limited manpower mobilization. Therefore, in order to deal with fires more scientifically and efficiently, the damage caused by forest fires should be reduced to a minimum. I would like to apply to you for funds to purchase a batch of drones (including SSA drones and RR drones) and wearable devices carried by fire personnel. SSA drones and firefighters carrying equipment can effectively obtain fire information, and the signal transfer function of RR drone can expand the range of information transmission, so that EOC can obtain real-time disaster information, and then achieve the effect of efficient fire suppression and suppression of fire disaster development.

After comprehensive comparison of different drone models, we chose WiLeE-15.2X hybrid drone as the device carrier. In order to obtain the optimal drone purchase strategy, we established the joint control model of SSA drone and RR drone and obtained our optimal quantity and combination according to the data of previous years:

1128 SSA drones;715 RR drones;3,384 sets of wearable fire fighting equipment.

Fire events can not be generalized, according to the size of the fire will be divided into large, medium and small three types of fire. According to the characteristics of different communication range of drone in different terrain, the terrain is divided into three categories: complex, ordinary and flat, and the occurrence frequency of different types of fire under different terrain conditions is divided into three categories: low, medium and high. In order to balance expenditure and loss, we comprehensively considered the equipment purchase cost and the equivalent economic loss of the disaster, and worked out the economic benefits and other indicators. Finally, we combined the economic benefit index, the firefighter's safety index and the information value index to develop a comprehensive evaluation index, and obtained the total amount of equipment purchase by Monte Carlo method through several experiments.

In addition, we predict the number and size of fires in Victoria over the next decade, based on future temperature and rainfall changes. After substituting for the number of equipment we have purchased, it can perfectly meet the needs of fires except for 2024. The prediction results show that in 2024 we are going to have a slight shortage of equipment, but there are still 0.97 according to the comprehensive evaluation index to judge the score, thus this also demonstrates that our equipment purchases are still well positioned to respond to the 2024 fire scenario. Therefore, it can be seen that our model and corresponding calculation results are suitable for solving practical problems, and can meet the needs of effective monitoring of fire situation in a period of ten years or even longer, and have a strong adaptability to the change and development of fire situation.

3. Project Cost Estimate

Equipment Cost

Item	Amount	Cost $\times 10^3$ \$
SSA drone	1128	11280
RR drone	715	7150
Equipment	3384	10152

Total $\times 10^6$ \$: 28.582

Annual Operating Cost

Maintenance Costs $\times 10^3$	500
Energy Costs $\times 10^3$	10

Total $\times 10^6$ \$: 0.51

4. Declaration

Capital project funds may only be used for purchases approved by commission. When a capital project is completed an Office or Department cannot automatically transfer appropriated funds left over to another project or purchase without commission’s approval.

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