The Systematical Solutions About Victoria's "Fire Emergency Drones" Quantity and Location Solutions

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Abstract. For more than a year, there have been severe fires in almost all Australian states, with the eastern state of Victoria in particular. This paper aims to address three specific problems in "fighting wildfires" with three mathematical models. On the basis of analyzing the data, Model 1 obtains the specific fire situation of more than 5 months at the end of 2019. Since the occurrence of fire follows Poisson distribution, we use Monte Carlo method to generate random numbers that meet such distribution for simulation. Finally, the entropy weight method + Topsis method was used to determine the optimal combination: 13 SSA UAVs and 19 repeater UAVs, and the cost was $242,000. Model 2 needs to consider how equipment increases under extreme fires. To get the worst fire scenario in 10 years, we used cellular automata to simulate the occurrence, spread and extinction of fires. For Model 3, We use the improved genetic algorithm, by means of crossover, combination mutation, position mutation and displacement mutation of genes are carried out to select a certain number of excellent individuals. The algorithm balances the performance and accuracy, and finally obtains that the layout of the UAV should be concentrated in the east side of Victoria State as far as possible. In addition, we also analyzed the robustness and sensitivity of the model, it turns out that the model is robust.

Keywords: Monte Carlo, Cellular automaton, poisson's distribution, Genetic algorithm, Forest fires.

1. Introduction

1.1. Problem Background

In 2019-2020, Australia experienced severe wildfires, in order to take quick action on the fires, firefighters used drones to monitor and sense the situation, while hand-held two-way radios could transmit the signals back to the EOC. However, such devices had a very limited travel range. So, the hovering UAV with repeater is used to greatly expand the infinitely low transmission range, but such UAV is expensive, how to balance the use of the two types of UAV, as well as the specific distribution of the situation, has become the problem before us. The scope of our research this time is focused on the state of Victoria in the southeast of Australia.
1.2. Assumptions
To simplify the problem, we make the following basic assumptions, each of which is properly justified.

- **Assumption 1**: SSA drones perform surveillance missions with frontline personnel, approximately in the same location.
- **Assumption 2**: A repeater transmits only one fire at a time, even though some fires are very close together.
- **Assumption 3**: Frontline personnel performing their missions shall not be more distant from the nearest EOC, repeater drone, or other frontline personnel than the maximum distance that a handheld two-way radio can radiate.
- **Assumption 4**: The repeater drone will fly at an altitude of 100 meters in normal operation.

2. Model I Optimal combination model of UAV

2.1. Data Description
First, we collected fire data for the entire state of Australia from August 2019 to early 2020 at https://www.kaggle.com/ and source files from the NASA website. Because the dividing line between Victoria State and other regions is relatively complex, in order to facilitate data processing, we used spherical coordinates to represent points on the data set. To get the true distance relationship on the map, we approximate the state of Victoria as a plane quadrilateral with latitude \( \lambda \) and longitude \( \lambda \).

2.2. The Establishment of Model 1

2.2.1. Two schemes. SSA UAV can monitor the front changing circumstances, handheld two-way radios will be the front line of transmission back to the EOC, so can be concluded that firefighters extinguishing action basically has the following two options.

| Scheme one | Scheme two |
|------------|------------|
| SSA UAV + Hand held two-way radio | A UAV with a repeater + Hand held two-way radio |
| The transmission range is near (the range of the radio) | The transmission range is far (the repeater's range) |
| The cost of SSA UAV | The cost of Repeater UAV |

2.2.2. Safety. For plan a, in order to let the EOC can accept the information sent back to the handheld wireless devices, EOC and SSA unmanned aerial vehicle (uav) is not greater than the range of the radio transmission range. So, we need to differentiate between fires with different intensity ranges in order to be applicable to different scenarios.

Every fire has its corresponding flame radiation power (frq), and this index is used as the criterion of fire intensity. After consulting the [1] literature, it can be assumed that when frq=35, it is regarded as a small fire. Option one can be used at the time. When frq>35, it is necessary to use a repeater drone with a longer transmission range to detect and transmit the fire situation, which is the second option. This ensures the safety of the model to a large extent.

2.2.3. Topography. The occurrence of fire can be regarded as a Poisson distribution with a parameter of \( \lambda \), and we need to use data to determine the parameter.

First of all, we need to count the total number of fires from August to December 2019. By averaging the number of fires of the two types, we can get an average of 66.98 and 73.60 fires of the two types.
per day. It can be seen from the topic data that each UAV can be used for 2.5 hours continuously and charged for 1.75 hours each time, and it takes about 3 hours to extinguish the fire each time. Therefore, we set a cycle of 4 hours, and about 6 cycles occur in a day. The intensity of the two types of fire is respectively.

\[
\lambda_1 = 66.98 / 6 = 11.1633 \\
\lambda_2 = 73.60 / 6 = 12.2667
\]  

Let \( X_1 \) and \( X_2 \) respectively represent the number of small fires and large fires, the occurrence of small fires obeys the Poisson distribution with an intensity of \( \lambda_1 \), and the occurrence of large fires obeys the Poisson distribution with an intensity of \( \lambda_2 \), so:

\[
P(X_1 = k) = \frac{\lambda_1^k}{k!} e^{-\lambda_1} \quad (k = 0, 1, 2 \cdots) \\
P(X_2 = k) = \frac{\lambda_2^k}{k!} e^{-\lambda_2} \quad (k = 0, 1, 2 \cdots)
\]  

The range of radio transmission over different terrain (5 km in open areas (such as rural areas) and down to 2 km in obstructed areas (such as urban areas)) indicates that terrain can have a significant impact on fire control. Through the data statistics can be obtained, plains and mountains, respectively, 64% and 36% of the state of Victoria.

Since the transmission range of Scheme I is attenuated to two kilometers in mountainous areas, the fires with a spread range of more than two kilometers in Category I fire cases cannot be handled by SSA UAV in some cases. Similarly, for the Scheme II, the transmission distance of the repeater in the mountain area will also be shortened, so the original "repeater UAV + radio" scheme cannot cover the original range, so we need to introduce a third scheme: increase the number of repeater UAV to 2.

We use the area ratio of plain and area ratio of mountain to weight small and large fires respectively. At the same time, it is considered that the combustion condition in mountain area is better than that in plain area, so the above numbers need to be continued to be weighted.

2.2.4. Capacity. Let \( x_1 \) and \( x_2 \) respectively be the number of purchased SSA drones and repeater drones. What is the confidence interval within which the fire can be solved? This is the ability problem of the final solution. The ability parameter is set as \( \mu \). The stipulation is:

\[
0.80 \ll \mu \ll 0.99
\]  

There are several situations where drones are not able to meet fire-fighting needs:

\[
A: \lambda_3' + \lambda_4' + 2\lambda_1' > x_2 \\
B: \lambda_2' + \lambda_3' + 2\lambda_4' = x_2, \quad \lambda_1' > x_1 \\
C: \lambda_2' + \lambda_3' + 2\lambda_4' < x_2, \quad \lambda_1' + \lambda_2' + \lambda_3' + 2\lambda_4' > x_1 + x_2
\]  

That is:

\[
P(A) + P(B) + P(C) \leq 1 - \mu
\]  

2.2.5. Economics. The price of the SSA UAV is $4,000, and the price of the repeater integrated UAV is $10,000, so the total cost is

\[
Y = 4000*x_1 + 10000*x_2
\]
2.3. The Solution of Model 1

After the parameter $\lambda$ of Poisson distribution is known, 1,000,000 random Poisson distribution numbers can be generated by [2] Monte Carlo method. The probability distribution curve of Poisson distribution is shown in the figure.

![Figure. 1 Probability density curve](image1)

![Figure. 2 Poisson distribution histogram](image2)

After traversing different values of $\mu$, find out the case where $Y$ is the smallest, in order to obtain the overall optimal combination, we can use entropy weight method to impose certain weight on the ability factor and economic factor, and finally get the weight of 0.6933 and 0.3067 respectively. After that, we can use Topsis evaluation method to get the score of each group. Therefore, we obtained the final optimal combination of 13 SSA drones and 19 repeater drones. This solution, which balances capability, security and economy, and takes into account the requirements and terrain of observation and communication missions, is the optimal solution. The purchase cost of this program is: 234000 dollars.

3. Extreme fire simulation models

3.1. Establishment of Model 2

In order to cope with the extreme fire situation that will occur in the next decade, we need to further build a simulation model of real fire.

At present, [3] the establishment of cellular automata model is a common method of fire simulation. August to December 2019, as the outbreak period of fire in Australia, can be used to simulate the situation of the high fire incidence period in Victoria in the next decade. After taking into account the complexity of processing data and the actual situation as much as possible, we set 1 $KM^2$ as the area of a grid, so that the state of Victoria can be divided into 1177*358 cells. We only consider two cases of large fires here, and we assume that all small fires will be solved within an iteration period, and no large spread will occur. For large fires occurring in the mountains and the original said, the two cases corresponding to the intensity of the Poisson distribution is not the same, need to be expressed separately.

Based on the results, we assume that, for the cellular space, the probability of producing 20 fires and the probability of producing 12 fires in an iterative cycle on the plain is 0.6 and 0.4. Mountains and so on. And in the cellular automaton iteration process, the intensity $\lambda$ is changed at random at a time point, and then restored to the original value after a period of time, to observe the changes in the fire.

In a cellular automaton, we select the brightness temperature of I-4, the brightness temperature of I-5, the confidence level, and the flame radiation power Four are used as evaluation indicators, and the hazard coefficient $\gamma$ of each fire occurrence point is obtained through the entropy method + Topsis...
evaluation method. Suppose that for point \( a \), its hazard coefficient is \( \gamma_a \), and there are \( n \) points on fire among its 8 neighbors, the probability of point \( a \) being spread to fire is:

\[
P_a = \frac{\sum_{i=1}^{n} \gamma(\text{fire})}{\sum_{i=1}^{8} \gamma(\text{neighbor}) + \gamma_a}
\]  

(8)

For each point, the more dangerous it is, the more likely it is to spread. This in turn depends on the state and risk of its neighbors, and this is a reasonable quantification of the probability of this abstraction.

Since all the fires simulated at present are large ones, we can guarantee to solve the problem within 84% confidence interval after solving the first question. Let's suppose that for every fire generated in the current iteration period, 84% of the fire will be extinguished in the next cycle, while only the remaining 16% will continue to spread. And so on, and so on, and so forth.

3.2. The Solution of the model II

Use MATLAB to write related procedures to solve the above problems. The result is shown in the figure. The reason for this phenomenon is that the growth cycle of the tree is too short. After checking, it turns out that because these points have a value of 0, they are not considered divisors. However, when we replace the value of 0 with a very small value, the result is still problematic.

Instead of thinking of hazard zero as a data miss point, hazard zero would mean almost no spread and no natural fire, so the points where natural fire can occur would be: (1) no zero value and (2) the presence of trees. After revising the model, we can get a more realistic result.

![Large error result](image1)

![The final result](image2)

Since all of our analysis objects are big fires, we can see from Model 1 that big fires need the solution of "repeater UAV + radio". Repeater's propagation distances in mountains and plains are very different, and they correspond to Scheme 2 and Scheme 3 in Model 1 respectively. Let's assume that the probabilities of these two scenarios are again based on the probabilities of the total area of the two terrains. Therefore, the number of schemes two is \( 233 \times 0.64 = 149 \), and that of scheme three is \( 233 \times 0.36 = 84 \). The total number of Repeaters required is 317, an increase of 298 over Model 1. It can be concluded that the additional cost is $2.928 million.
4. Model III: UAVs distribution optimization model

4.1. Efficiency of multi-repeater UAVs

In order to optimize the location distribution of UAVs, we need to make clear that the signal radiation range of UAVs is affected by different terrain. However, due to complex terrain factors, there is still no single optimal fitting model to predict path loss. Nowadays, path loss models of radio are mostly given by experience, such as Itorin, CCIR, Cost 231, HATA, Davidson model, etc.

We substituted 1m into Hb and Hm, and 5km and 2km into HATA model expressions in rural and urban environments respectively, and took different values of frequencies from small to large to calculate the path losses of the two. When the difference between the two path losses reaches the minimum, the transmission frequency at this time is closest to the frequency at the time of measurement. Using this method, we calculate that the radio works at 83MHz.

We assume that the repeater drone flies at an altitude of 100m, operates at 83MHz, and has a measured propagation distance of 20km in the open area, and then the maximum propagation distance between the repeater UAV and hand-held radio can be obtained by substituting the cut-off loss into the expression of the HATA model in rural and urban environments. This distance reflects the drone's true signal coverage and changes in real time depending on where it is.

4.2. The fitness function of genetic algorithm

In order to reflect the ability to respond to fires of different sizes in the optimal position distribution of the SSA and the repeater UAV, the hazard factor is used.

We define the control index as a measure of the ability of the UAV to prevent and control fires when it is positioned at a certain location. Namely

\[ C = \eta \cdot \gamma \sum \]

(9)

The mean overlapping area is the mean of the overlapping area of the signal radiation range between two pairs of UAVs. Its expression is as follows:

\[ A = \frac{\sum_{i=1}^{n} S_i}{n} \]

(10)

To sum up, the fitness function is designed as

\[ f(C, A) = \ln \frac{C}{A} \]

(11)

Where, C is the sum of the prevention and control indexes of an individual, and A is its average overlapping area. In this way, the balance between the optimal location distribution and the control index and the average overlapping area can be reached.

4.3. An improved genetic algorithm for two-dimensional search

In order to cope with the extremely large solution space faced in this problem, we adopted a packaged chromosome coding approach. [4] This ensures that the length of the chromosomes is only related to the number of drones, reducing the size of the chromosomes by 40,000 times compared to normal coding methods.

Because the solution space of this problem is too large and the feasible solution domain is relatively small, it is difficult to use the random generation method to generate the initial population whose fitness is greater than zero. Therefore, we use the following generation and competition method to generate a better initial population.
In the crossover stage, the population was first sorted according to fitness, and the individuals with similar fitness were matched. Then, a single dot crossover was performed on the genes generated at the crossover position to obtain new progeny chromosomes. Since the search space of the problem is two-dimensional, we adopt a special variation method. First, a chromosome is randomly selected according to a certain probability, according to the mutation gene address generated by the crossover stage, the chromosome mutation is carried out, and a new position is directly generated randomly on the mutation gene, and the offspring population of the location mutation is obtained.

After the mutation, in order to protect the optimal individuals, all the parent individuals and the offspring individuals generated through crossover and mutation were merged into a preparatory population. Then, the population was ranked according to fitness, and the individuals with lower fitness were directly eliminated, only a fixed number of better individuals were retained, and an evolution was completed.

After tens of thousands of iterations, the algorithm can give a relatively stable optimal solution. When the number of iterations reaches the number of times, the algorithm has generated a relatively stable optimal solution.

### 5. Conclusion

This paper aims to address three specific problems in "fighting wildfires" with Monte Carlo, Cellular automaton and Genetic algorithm models. In this paper, the data matches the actual situation and the introduction of the risk coefficient parameter takes into account the different probability of fire occurrence at each point more specifically, which makes the occurrence and spread of fire accord with the actual situation. What's more, make updated rules for cellular automata that take into account the reality of the situation, rather than just using a very simplified general model. In order to solve the search problem in two-dimensional space, we use an improved genetic algorithm, which gives consideration to both performance and convergence precision, and finally can give the optimal solution in a relatively short time. Therefore, this model has good robustness and can better adapt to the situation in Victoria. Even though, there are still some weaknesses, such as the consideration of terrain is relatively rough, only roughly divided into mountains and plains, considering their influence on radio transmission, but the actual terrain situation is much more complicated. And the scheme in the first model is not very general, not all fires can be solved by these three schemes, and for some cases, one SSA can monitor several fires.

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