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Multi-objective Planning of Fire Control Model Based on Terrain Factors and Electromagnetism

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Abstract: *Forest fires are a problem that every country has to face. Australia has encountered devastating wildfires in recent years. In order to control wildfires more effectively, two drones can be used for detection and communication, so as to control wildfires as effectively as possible. The purpose of this report is to establish a model that uses two different types of drones to control wildfires, to evaluate the cost of controlling wildfires and the degree of adaptation of the prediction model to future extreme conditions.*

Keywords: *Digital image processing, Electromagnetic wave propagation, Multi-index evaluation, Multi-objective Planning*

1. Introduction

1.1 Glossary

"Boots-on-the-ground" Forward Teams: The idiom "Boots on the ground" indicates personnel that are physically at the location of action. In firefighting, these are teams that are at the front

Lines of the efforts to control a fire event; they have immediate, critical knowledge of the rapidly changing situation.

Emergency Operations Center (EOC): The central command and control point for emergency related operations and activities, and for requests for activation and deployment of resources (personnel or equipment). A mobile EOC can be deployed near the site of an emergency.

Repeater: An unattended radio transceiver that automatically rebroadcasts a received signal at high power on a nearby frequency (±600kHz (0.6 MHz) for VHF & ±5MHz for UHF) or on an adjacent channel.

Transceiver: A radio that can both transmit and receive.

UHF: Ultra High Frequency, radio frequencies from 300 megahertz to 3,000 megahertz.

VHF: Very High Frequency, radio frequencies from 30 megahertz to 300 megahertz.

1.2 Background

Australia's 2019-2020 fire season has caused devastating wildfires in every state, with New South Wales and the Victoria hardest hit. Severe droughts and prolonged heat waves can cause wildfires, which are exacerbated by climate change.

In the face of wildfires, firefighters can use drones for surveillance and situational awareness (SSA) to help put out fires. SSA drones can monitor and report data from wearables for frontline personnel, enabling the emergency operations centre (EOC) to best guide active crew for optimal effectiveness and maximum security.

The EOC and "Boots-on-the-ground"forward teams can communicate by two-way radio. The personnel deployed carry handheld two-way radios operating in the VHF/UHF band with low power (usually a maximum of 5 watts) and a working range of 5 km in rural areas and 2 km in urban areas. The radio signal can be transmitted between the handheld radio and the EOC via a repeater. The repeater has

ISSN 2616-5872 Vol.3, Issue 1: 6-14, DOI: 10.25236/AJEE.2021.030102

a power of 10 watts and a working range of 20 km, and is assembled with the drones when working. The drone has a maximum speed of 20 meters per second, a maximum range of 30 km and a maximum flight time of 2.5 hours at a cost of $10,000.

1.3 Restatement of the Problem

Our team has been asked to establish a model considering the capability, safety, economy, mission requirement and terrain fire event size and frequency to determine the optimal number and combination of SSA drones and Radio Repeater drones. The model is used to guide Victoria’s proposed new division, “Rapid Bushfire Response”, of Victoria’s Country Fire Authority (CFA) to buy drones.

2. Cost Evaluation Model of drones Number Based on Safety Factor

In order to determine the combination and number of two different types of drones, the mission requirements of the two drones need to be considered. First, use the high-level image data of Australian altitude we found, combined with digital image processing and recognition technology to obtain terrain data of Victoria, Australia, and perform modeling to obtain key geographic location information. In order to determine the mission requirements that need to be met, digital image recognition is used to obtain the distribution of the fire scene, thereby determining the mission index.

Then, according to the electromagnetic signal two-path propagation model, combined with the drones cruising range, the relationship between the number of drones and the frontline personnel and EOC is established. In addition, in order to determine the number of monitoring drones, based on the sensor parameters carried by the man-machine determine its detection range, and combine the relationship between the charging time of the drone and the frequency of monitoring data refresh, thereby establishing a relationship with the distance between the EOC and the front line of the fire field. Finally, determine the number of monitoring drones and communication Radio Repeater drones.

According to *the Australian McArthur statistical model [1]*, the speed of wildfire spread is determined, combined with the transfer time of EOC and the distance between EOC and the line of fire, to establish a safety evaluation system. Then establish the relationship between economic loss and safety factor based on the data obtained from the reference.

Finally, the number of drones and the safety factor are combined to construct a cost evaluation model for the number of drones based on the safety factor, and the number of drones is determined by the principle of least money spent.

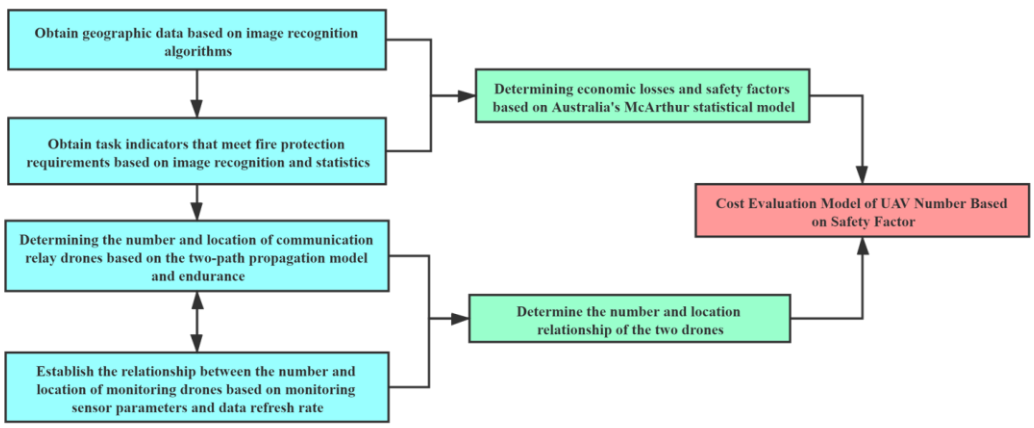

Figure 1: The structure of our model in question 1

2.1 Geography of Victoria

First obtain the geographic data of Australia from the Australian Government Meteorological Administration and the National Aeronautics and Space Administration resource management system, and then use the characteristics of each pixel in the geographic picture to establish a relationship with the geographic location such as altitude and slope, and finally obtain the required information data.

ISSN 2616-5872 Vol.3, Issue 1: 6-14, DOI: 10.25236/AJEE.2021.030102

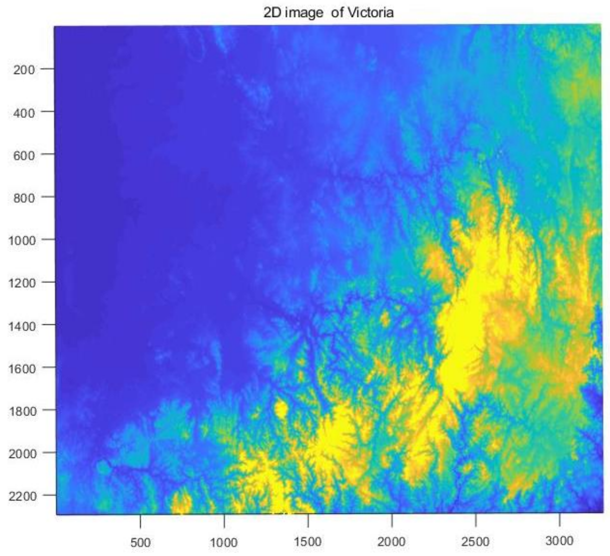

Figure 2: Satellite raw image of Victoria

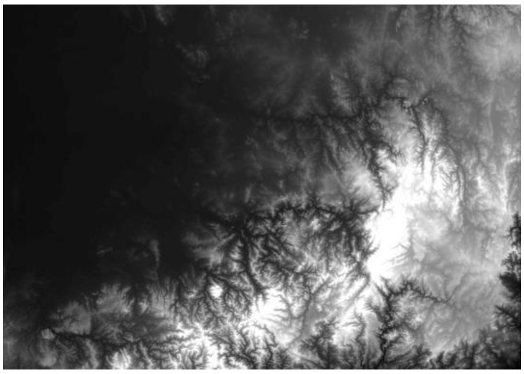

Figure 3: 2D image of Victoria after processing

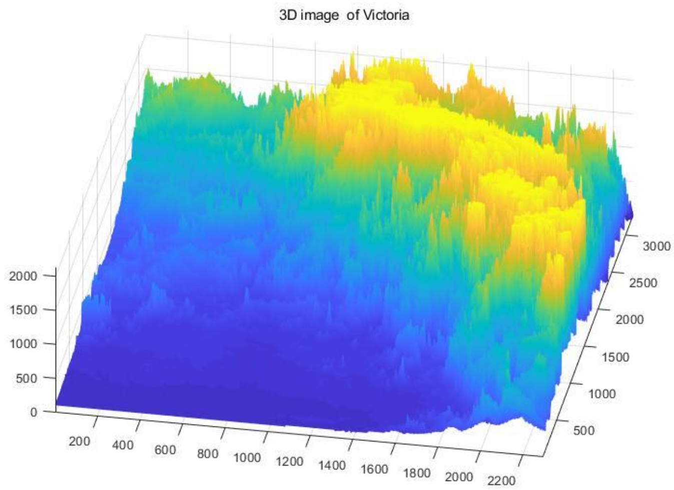

Figure 4: 3D image of Victoria after processing

Because for the Satellite raw image of Victoria, the value of each pixel represents the average altitude of the area, so we can convert the value of each pixel to its corresponding altitude, and then find the average value of the image matrix The average altitude can be obtained, and then the degree of dispersion of the altitude data is obtained, that is, the standard deviation is obtained, and the value is normalized, and finally the Terrain factor can be obtained as follows:

ISSN 2616-5872 Vol.3, Issue 1: 6-14, DOI: 10.25236/AJEE.2021.030102

$$\text{for}: P(X=x_i, Y=y_i) = p_{ij}, i,j = 1,2,3,...,$$

$$Z = g(X,Y)$$

$$E(Z) = E(g(X,Y)) = \sum_{i=1}^{+\infty}\sum_{j=1}^{+\infty} g(x_i, y_i)\, p_{ij}$$

Table 1: Geographic data

Average altitude	780m
Terrain factor	0.3718

2.2 Determination of the number of Radio Repeater drones and SSA drones

2.2.1 Two-path propagation model

The reflection of electromagnetic waves occurs on the interfaces of different objects. These interfaces may be regular or irregular, smooth or rough. For simplification, we consider that the reflective surface is smooth, also called the ideal medium surface. The electromagnetic wave is reflected after passing through the surface of the ideal medium, and the energy of the electromagnetic wave is reflected back in full wave. The propagation environment of wireless communication is very complicated. In fact, due to the existence of numerous reflected waves, what the receiving end receives is the superposition of a large number of multipath signals. [2] In order to simplify the problem, it is assumed that signal propagation obeys two-path propagation.

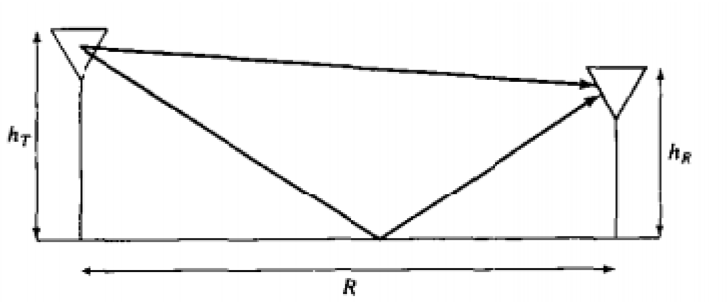

Figure 5: Two-path propagation model

The following expression exists in the two-path propagation model:

$$P_r = P_t G_t G_r \left[\frac{h_t h_r}{d^2}\right]^2$$

Pr and Pt represent received power and transmit power, and Gr and Gt represent antenna gains of base stations and mobile stations. Express it in decibel form:

$$P_r(dB) = P_t(dB) + 10\lg G_t + 10\lg G_r + 20\lg(h_t h_r) - 40\lg d$$

It can be seen from the above formula that when the distance d is large, the received power decays with the 4th power of the distance, much faster than the loss in free space. At this time, the received power and path loss are independent of frequency (wavelength). The path loss of the two-path model can be expressed as:

$$\mathrm{L(dB)} = 40\lg \mathrm{d} - (10\lg \mathrm{G_t} + 10\lg\mathrm{G_r} + 20\lg\mathrm{h_t} + 20\lg\mathrm{h_r})$$

According to the conditions given in the question, it is known that the longest distance of the handheld radio signal is 5 kilometers, and the shortest distance is 2 kilometers. So it can be known that the transmit power and the received power of the signal transmission can be kept unchanged in the two cases. However, considering the influence of terrain and other factors in the transmission process, an attenuation factor can be introduced, which is related to the unevenness of the terrain. Finally establish the distance established when the drone communicates with the ground:

ISSN 2616-5872 Vol.3, Issue 1: 6-14, DOI: 10.25236/AJEE.2021.030102

$$L1 = \beta * \left(ha^\wedge 2/d^\wedge 2\right)^\wedge 2$$

2.2.2 Determination of the working mode and quantity of the two drones

The detection range of the SSA drones is related to the sensor parameters mounted below it, and the determined monitoring angle can be obtained by referring to the relationship table between the angle and the focal length. To establish a working model of the SSA drones.

APS-C (DX) 23,7 x 15,6 mm (3:2) 1,5 x	APS-C 22,5 x 15,0 mm (3:2) 1,6 x	MFT 17,3 x 13,0 mm (4:3) 2 x	1" 13,2 x 8,8 mm (3:2) 2,7 x	2/3" 8,8 x 6,6 mm (4:3) 3,9 x
13 mm	12,5 mm	10 mm	7 mm	5 mm
16 mm	15 mm	12 mm	9 mm	6 mm
19 mm	17,5 mm	14 mm	10 mm	7 mm
23 mm	22 mm	17,5 mm	13 mm	9 mm
33 mm	31 mm	25 mm	18,5 mm	13 mm
57 mm	53 mm	42,5 mm	31,5 mm	22 mm
90 mm	84 mm	67,5 mm	50 mm	35 mm
133 mm	125 mm	100 mm	74 mm	51 mm
200 mm	187,5 mm	150 mm	111 mm	77 mm
400 mm	375 mm	300 mm	222 mm	154 mm
800 mm	750 mm	600 mm	444 mm	308 mm

Figure 6: The relationship between focal length and angle

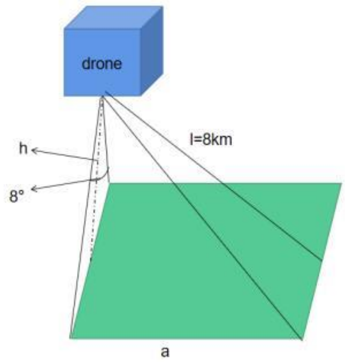

Figure 7: SSA drones working mode

The angle is related to the drone's scan width as follows:

$$W1 = 2 * h_a * \tan(\Theta)$$

An analysis of Australian fire data shows that the majority of the fires are in the following shapes:

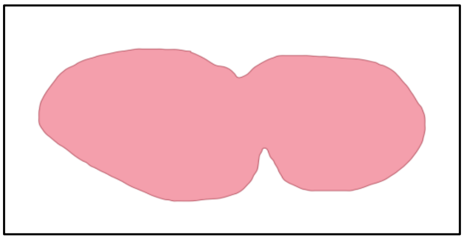

Figure 8: "8" shape fireground

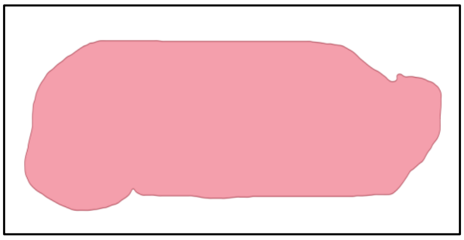

Figure 9: Strip fireground

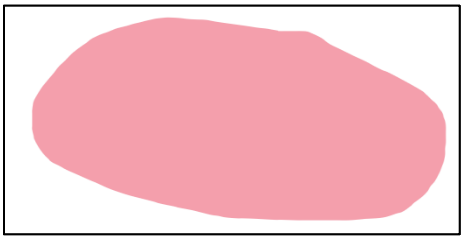

Figure 10: Circular fireground

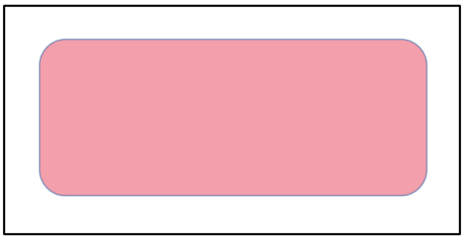

Figure 11: Rectangular fireground

Because firefighters are always distributed on the edge of the fire field, the fire line can always be stretched into a straight line. Therefore, the number of the two types of drones is related to the total length of the fire line and the length of the fire line that needs to be deeply detected. From the perspective of considering the endurance and communication distance of the drones, the aircraft paths of the two drones can be assumed as shown in the following picture:

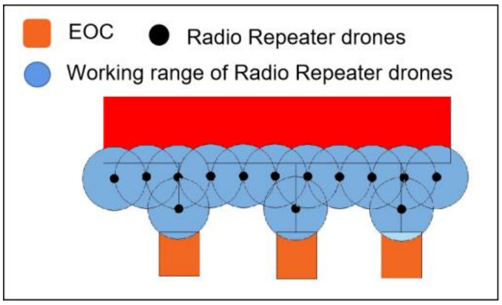

Figure 12: SSA drones flight path

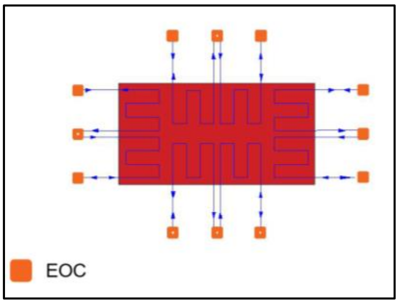

Figure 13: Radio Repeater drones flight path

In order to take into account the factors of charge recovery and data update frequency, the following relationship can be established according to the analysis of its internal mechanism:

$$f1 = T1*10/\left(9000 - \sqrt{(0.5*W1)^2 + (L4 - L1)^2}\right)$$

$$N1 = ((L2*L3)/S1)*(1500 + T1)*f$$

$$N2 = (L4/20000) + (((L4 - L1)/20000)*f1)$$

The relationship between the total numbers of drones that can be obtained from the above expression is shown in the following figure:

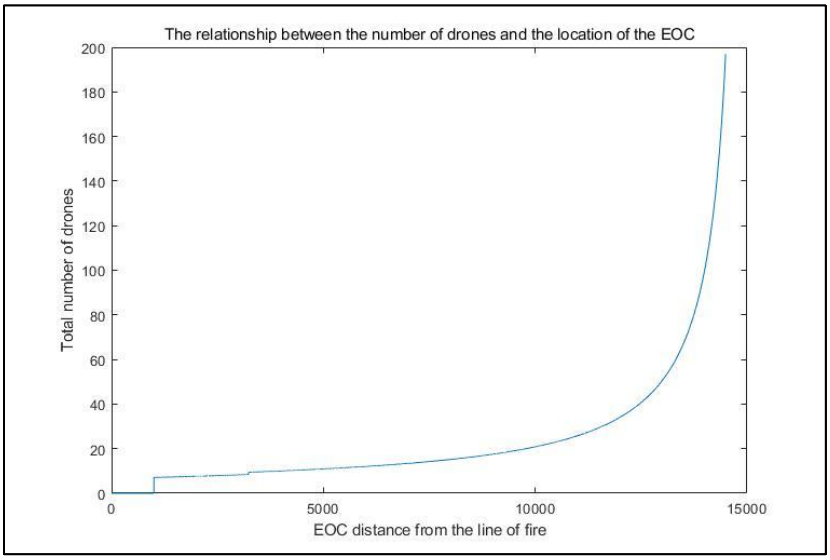

Figure 14: The relationship between the number of drones and the location of the EOC

You can see that the number of drones is positively correlated with the L 4s, and accordingly, the total cost of drones has increased.

2.3 Establishment of safety evaluation system

Because in Australia's wildfires, the speed of fire spread often determines people's escape time, so the distance from the EOC to the fire site can be used as a safety indicator. First, establish a fire spread model based on the Australian McArthur statistical model:

R—The spread speed of forest fire, the unit is km/h

F—Fire Spread Index

W—load of combustible material (t/hm2)

M—The moisture content of combustibles (%)

V—average wind speed 10m above the ground (m/min)

According to Mcarthur’s statistical model:

ISSN 2616-5872 Vol.3, Issue 1: 6-14, DOI: 10.25236/AJEE.2021.030102

$$R = 0.13F$$

When M<18.6%:

$$F = 3.35We^{-0.0897M+0.0403V}$$

When 18.6%<M<30%:

$$F = 0.299We^{(-1.686+0.0403V)+(30-M)}$$

The fire spread model established according to the Australian McArthur statistical model can find the relationship between the fire spread speed and the water content of combustible material and load of combustible material.

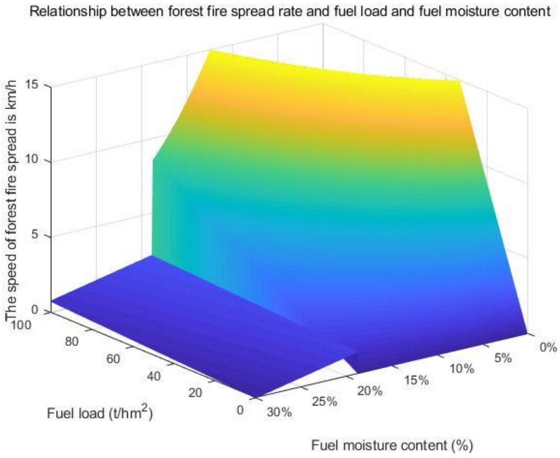

Figure 15: Relationship between forest fires spread rate and fuel load and fuel moisture content

According to the Australian Bureau of Statistics website, Australia's forests are dominated by Eucalyptus (78%, moisture M1 = 65%), followed by Acacia (7%, moisture 12%) and Melaleuca (5%, moisture 16%) [3, 4]. The actual forest litter per hectare is estimated to be 0.35-10.98 t/hm^2 per hectare using the amount of litter generated by eucalyptus per hectare. The fuel load W and water content M can be calculated.

Table 2: Data of combustibles in Australia forest

W	152.035t/hm ²
M	25.42%
V	1.1m/s

The following relationships are then established based on the intrinsic relationship between the speed of fire spread and the distance travelled:

$$A = R*(-\ln(10000/L4)*T2+3)$$

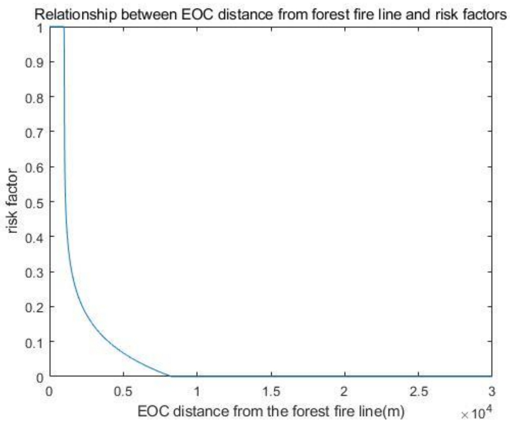

Figure 16: Relationship between EOC distance from forest fire line and risk factors

ISSN 2616-5872 Vol.3, Issue 1: 6-14, DOI: 10.25236/AJEE.2021.030102

2.4 Result

According to the safety evaluation index, the relationship between distance and economic loss can be constructed, that is, when the distance between the EOC and the fire field is within a safe distance, the loss increases rapidly as the distance decreases. However, in the relationship between the EOC distance from the fire site and the number of drones, the cost is positively correlated with the distance, but in the safety evaluation system, the economic loss is negatively correlated, so the distance from the EOC to the frontline fire site can be The above two models are linked together to find the optimal solution under the conditions of the task. The result is shown below

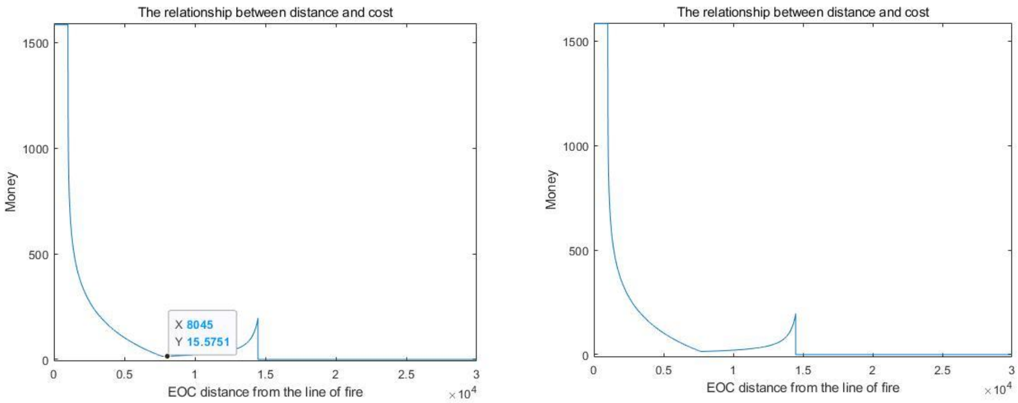

Figure 17: Result of question 1

It can be seen from the data in the figure that under the average firefighting mission requirements of Victoria, Australia, only 15 drones are needed to meet the requirements. Among them, there are 6 Radio Repeater drones used for signal relay for dynamic the number of drones monitored is 9 and the closest safe distance between EOC and the fire site is about 8 kilometers.

3. Budget Request for Drone Purchase

3.1 Project Description

Victoria's Country Fire Authority (CFA) create a new department named Rapid Bushfire Response. The obligation of this department is to get to the fireground as soon as possible and start to put out the fire. We want to purchase some drones to enhance the ability to detect the burning situation and communication ability between the *Emergency Operations Center (EOC)*and active crews.

3.2 Cost Elements

3.2.1 Equipment

Table 3: Equipment budget

Name	Unit Price	Number	Total Price
SSA drones	$10,000	6	$60,000
Radio Repeater drones	$10,000	12	$120,000

Justification: SSA drones allow the EOC to get the real-time burning situation and come up with a plan to put out the fire. Radio Repeater drones increased the communication distance between active crews and EOC. With the Radio Repeater drones, the range of communication can up-to 25km. The numbers and proportion of two kinds of drones is the optimal choice deceived from the model we established.

3.2.2 Other Expenses

According to the model we established, the mathematical expectation of increase in equipment costs is in the following table.

ISSN 2616-5872 Vol.3, Issue 1: 6-14, DOI: 10.25236/AJEE.2021.030102

Table 4: Other expenses budget

Name	Price
SSA drones	$443,000
Radio Repeater drones	$519,000
Total	$962,000

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