2021 MCM Problem B: Fighting Wildfires

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1 Abstract

The objective of this project was to create a model to determine the optimal number of Surveillance and Situational Awareness (SSA) and Radio Repeater drones for the new division, “Rapid Bushfire Response,” of CFA Victoria, Australia. The varying topographies have to be taken into account when determining the quantity of drones needed to cover the necessary area and to report back to front line personnel when bushfire observation occurs. Another objective was to discuss the projection of bushfires over the next 10 year and how it relates to the model. A formal Budget Request from CFA to the Victoria State Government was created based on the quantity of drones determined by the model created.

Assumptions and simplifications were made to determine the best way to utilize the two types of drones to observe bushfires for a more rapid and efficient response. The model created is based on a geometric perspective, where the average area of a fire is taken into account as well as the coverage area of the SSA and Repeater drones. Next, the frequency of fires per day along with the different terrains in Victoria are considered as multipliers in the model to determine the optimal number of the two drones. The 2019-2020 wildfire season in Victoria, Australia was found to be an extreme when compared to previous seasons. The data from this season was used in the model to create an estimate of the number of SSA and Repeater drones needed in preparation for the 2020-2021 season. Based on data from the 2007-2008 up to the 2019-2020 season the frequency of fires is predicted to decrease from the 2019-2020 season.

2 Introduction

The country of Australia has experienced an extremely devastating number of wildfires in the 2019-2020 bushfire season. Historically, Australia is one of the most at risk countries when it comes to wildfires. The intense bushfire season of 2019-2020 raised global awareness of Australia’s situation and climate-change as a leading factor in the increase in fire frequency. It became apparent that in order to lower the severity of the bushfires the response time of front line workers needed to improve.

With new advancements in unmanned aerial vehicles (UAV), also known as drones, the front line personnel will receive and transmit information with the Emergency Operations Center (EOC) at a quicker rate. The first responders have handheld radios which communicate with the EOC to keep the status of the bushfire updated. The two drones being considered are Surveillance and Situational Awareness (SSA) drones and Radio Repeater drones. SSA drones, which obtain thermal imaging, have a transceiving range of 5km over flat ground and 2 km over urban areas.[3] Repeater drones are much more powerful and resend signals at a higher power. Repeater drones have a range of 20 km. [3] Using these two drones a model can be created to minimize bushfire response time and thus decreasing the damage done.

3 Assumptions and Notations

3.1 Assumptions

Due to the lack of necessary data, we make the following assumptions:

1. We assume that while flying, no drones will have accidents or become lost. The cost of buying new drones is high and recovering lost drones or fixing fallen drones can be difficult. We decided that to circumvent this problem, we assume that no drones are hit or fly outside of fire areas and the EOC.
2. We assume that all drones can be charged as soon as they land at charging stations, as staff is always available there. This helps optimize the time that drones are monitoring.
3. We assume that the given drone ranges in the problem are circular, i.e. a range of 5 kilometers means a circular range with radius 5 kilometers.
4. We assume that the lifespan of a drone is unbounded, so as long as its batteries are being changed.
5. We assume that while one set of drones is charging, another set is out hovering and monitoring, and this process switches once the other set needs charging. We do not adopt an optimization of the battery or charging times, as we felt it would make our model easier to work with.
6. We assume that the 2020-2021 Victoria bushfire season will be similar in magnitude and frequency to the 2019-2020 Victoria bushfire season.

3.2 Notations

The notations used in this paper are as follows:

Table 1: Notations Used in Model Construction

Notation	Meaning
C_f	Circle representing a single fire f
r_f	Radius of the circle C_f representing a single fire f
A_f	Area of the circle C_f representing the fire f
P_f	Circumference of the circle C_f representing the fire f
F_d	Average number of fires started per day
N_{f_s}	Number of SSA drones required per fire f

N_{f_r}	Number of repeater drones per fire f
$N_{s_{FG}}$	Number of SSA drones required for fires on flat ground per bushfire season
$N_{s_{UA}}$	Number of SSA drones required for fires in urban areas per bushfire season
N_s	Total number of SSA drones required per bushfire season
N_f	Total number of repeater drones required per bushfire season
R_{FG}	Ratio of fires that are on flat ground
R_{UA}	Ratio of fires that are in urban areas

4 Model Construction

4.1 Simplifications

Before we construct our model, we first make some simplifications. First, we assume that each fire is in the shape of a circle C_f. Fires in real life have very complex shapes, and we have decided to consider each fire a circle in order to make the modeling process easier. This has allowed us to turn this problem of wildfires into a problem of geometry.

Furthermore, we assume that each fire is stationary and unmoving. In other words, we assume each fire has a fixed size. We realized that the scale and frequency of fires is evolving, and it was going to be very difficult to consider fires in their natural, dynamic state. Using our first simplification, this translates to each fire having a fixed circular area.

Also, we assume that a single fire either totally covers flat, unobstructed ground or totally covers urban areas. We decided that accounting for the complexity of Victoria's topography would have been a difficult problem, so to circumvent this difficulty, we have decided to simplify the problem of topography into 2 types of land: fully flat ground and fully urban area. Thus, fires are either on flat ground or in urban areas.

4.2 Rationale

4.2.1 Drone Formation

We know that the surveillance and situational awareness (SSA) drones "monitor and report data from wearable devices on front-line personnel", and repeater drones "automatically rebroadcast signals at higher powers." Since the SSA drones report data from devices on front-line personnel, we thought it was optimal for them to hover as close to the front-line personnel as possible. Considering that it is the safest for front-line personnel to be outside the fire, we have decided that our model would place the SSA drones over the perimeter of the fire in order to monitor the evolving situation.

Further, we know that the repeater drones "automatically rebroadcast signals at higher powers." Because of their ability to fly at higher altitudes and report data at longer ranges, we have decided that our model would place the repeater drones inside the area of the fire.

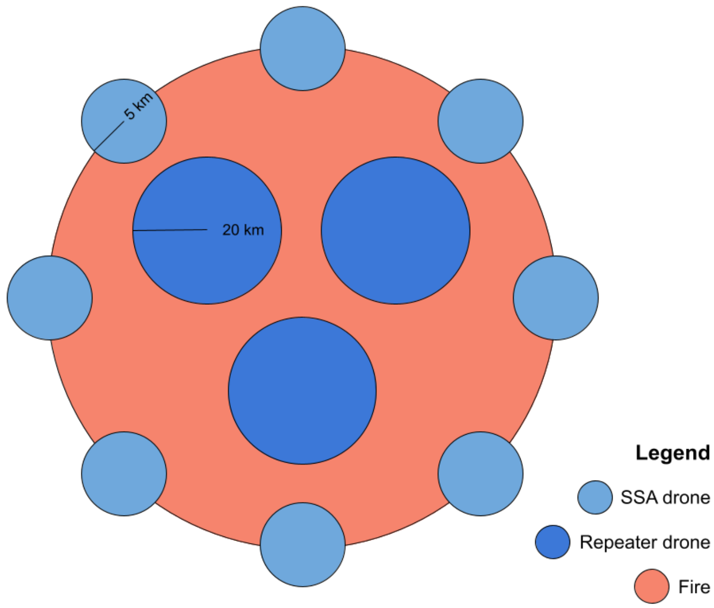

Figure 1: Modeling the Drone Formation

4.2.2 Drone Quantity

Since it is crucial that the SSA drones monitor as much of the fire as possible from the outside, it is important that the formation of SSA drones is enough to fill the perimeter of the fire. Thus, the quantity of SSA drones is dependent on the circumference of C_f. Each SSA drone covers an arc of C_f, and we approximate each arc by a line.

Furthermore, it is crucial that the repeater drones monitor as much of the fire as possible from the inside. Hence, it is important that the formation of repeater drones is enough to fill the area of the fire. Thus, the quantity of repeater drones is dependent on the area of C_f. Each repeater drone covers a sub-area of C_f.

4.3 Model

4.3.1 Parameters

The parameters of our model are area per fire in square kilometers A_f (fire event size), average number of fires per day F_d (frequency), ratio of fires that are on flat ground R_{FG}, and ratio of fires that are in urban areas R_{UA}.

4.3.2 SSA Drones

Our model aims to fully cover the perimeter of the fire with SSA drones. Hence, the number of SSA drones is dependent on the circumference P_f of the fire C_f. Suppose we have a single fire C_f of radius r_f. Then the area of the fire A_f is $A_f = \pi r_f^{\ 2}$ square kilometers, so $r_f = \sqrt{A_f/\pi}$ kilometers. Hence, the circumference of the fire P_f is

$$P_f = 2\pi r_f = 2\pi\sqrt{A_f/\pi} = 2\sqrt{\pi \times A_f} \text{ kilometers.}$$

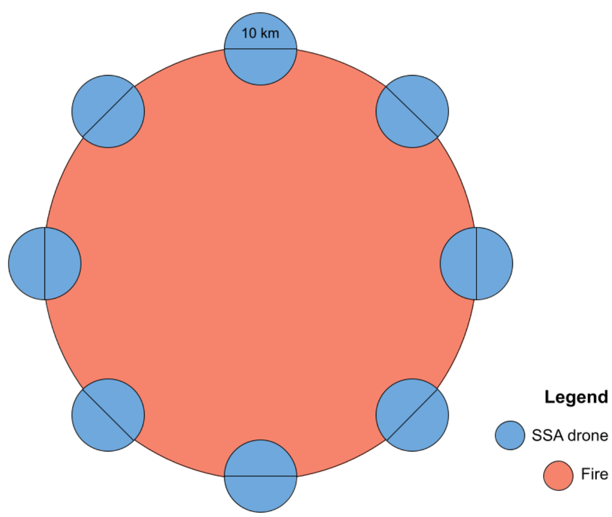

Figure 2: Approximating Each Part of the Perimeter Covered by a Drone as a Straight Line

Now, we will approximate each arc covered by a drone as a straight line. Each arc will be covered by the diameter of a single drone. The total range of the SSA drones must equal the total circumference P_f of the fire f. Thus, the number of SSA drones needed for a single set of monitoring and reporting per fire f is found by dividing the total circumference P_f of the fire f by the diameter of a single SSA drone. We take the ceiling to ensure an integer number of SSA drones. Since two sets are needed per fire to account for battery and charging times, the total number of SSA drones required per fire is twice the ceiling of the ratio of the total circumference P_f of the fire f to the diameter of a single SSA drone.

On flat ground, SSA drones have a range of 5 kilometers, so each SSA drone covers 10 kilometers on the perimeter of the fire. In urban areas, SSA drones have a range of 2 kilometers, so each SSA drone covers 4 kilometers on the perimeter of the fire. Thus, the number of SSA drones required per fire f is

$$N_{f_s} = 2 \times ceil\left(P_f \times \frac{1}{10}\right) = 2 \times ceil\left(\frac{1}{5}\sqrt{\pi \times A_f}\right) \qquad \text{if } f \text{ is on flat ground}$$

$$N_{f_s} = 2 \times \left(P_f \times \frac{1}{4}\right) = 2 \times ceil\left(\frac{1}{2}\sqrt{\pi \times A_f}\right) \qquad \text{if } f \text{ is in urban area}$$

Now we consider the fire frequency and the ratios of fires happening on flat ground and in urban areas. Suppose that there are F_d fires started per day in a given bushfire season. Suppose further that the ratio of fires on flat ground is R_{FG} and that the ratio of fires in urban areas is R_{UA}. Then the number of SSA drones $N_{s_{FG}}$ required for fires on flat ground per bushfire season is found by multiplying the ratio of fires on flat ground R_{FG}, the number of fires F_d started per day, and the number of SSA drones N_{f_s} required per fire f. Likewise, the number of SSA drones $N_{s_{UA}}$ required for fires in urban areas per bushfire season is found by multiplying the ratio of fires in urban areas R_{UA}, the number of fires F_d started per day, and the number of SSA drones N_{f_s} required per fire f. Hence, we have

$$N_{s_{FG}} = R_{FG} \times F_d \times N_{f_s} = 2 \times R_{FG} \times F_d \times ceil\left(\frac{1}{5}\sqrt{\pi \times A_f}\right)$$

$$N_{s_{UA}} = R_{UA} \times F_d \times N_{f_s} = 2 \times R_{UA} \times F_d \times ceil\left(\frac{1}{2}\sqrt{\pi \times A_f}\right).$$

Thus, the total number of SSA drones N_s required per bushfire season is

$$N_s = N_{s_{FG}} + N_{s_{UA}} = 2F_d\left[\left(R_{FG} \times ceil\left(\frac{1}{5}\sqrt{\pi \times A_f}\right)\right) + \left(R_{UA} \times ceil\left(\frac{1}{2}\sqrt{\pi \times A_f}\right)\right)\right].$$

4.3.3 Repeater Drones

Our model aims to fully cover the area of the fire with repeater drones. Hence, the number of repeater drones is dependent on the area A_f of the fire C_f. The total range of the repeater drones must equal the total area A_f of the fire f. Thus, the number of repeater drones needed for a single set of monitoring and reporting per fire f is found by dividing the total area A_f of the fire f by the area of a single repeater drone. We take the ceiling to ensure an integer number of repeater drones. Since two sets are needed per fire to account for battery and charging times, the total number of repeater drones required per fire is twice the ratio of the total area A_f of the fire f to the area of a single repeater drone. Since the area of the range of a single repeater drone is $\pi \times 20^2 = 400\pi$, the total number of repeater drones required per fire is

$$N_{f_r} = 2 \times ceil\left(A_f \times \frac{1}{400\pi}\right).$$

Now we consider the fire frequency. Suppose that there are F_d fires started per day in a given bushfire season. Then the total number of repeater drones N_r required per bushfire season is found by multiplying the number of fires F_d started per day by the total number of repeater drones N_{f_r} required per fire. Thus, the total number of repeater drones N_r required per bushfire season is $N_r = F_d \times N_{f_r} = 2F_d \times ceil\left(A_f \times \frac{1}{400\pi}\right)$.

4.3.4 Full Model

We now state our complete model. The parameters of our model are area per fire in square kilometers A_f (fire event size), average number of fires per day F_d (frequency), ratio of fires that are on flat ground R_{FG}, and ratio of fires that are in urban areas R_{UA}. The total number of SSA drones N_s and repeater drones N_r required per bushfire season are

$$N_s = 2F_d\left[\left(R_{FG} \times ceil\left(\frac{1}{5}\sqrt{\pi \times A_f}\right)\right) + \left(R_{UA} \times ceil\left(\frac{1}{2}\sqrt{\pi \times A_f}\right)\right)\right],$$

$$N_r = 2F_d \times ceil\left(A_f \times \frac{1}{400\pi}\right).$$

4.3.5 Applying the Model to Victoria's CFA's Rapid Bushfire Response

Now we will determine the number of drones to purchase for Victoria's Country Fire Authority's new Rapid Bushfire Response division for the 2020-2021 Victoria bushfire season. As mentioned in section 3.1, we will be assuming that the 2020-2021 Victoria bushfire season will be similar in magnitude and frequency to the 2019-2020 Victoria bushfire season. Thus, all parameters will be based on the data from the 2019-2020 Victoria bushfire season.

In the 2019-2020 Victoria bushfire season, more than 3500 fires burned more 1.5 million hectares across 98 days [2]. Since we do not have exact data, we will assume that exactly 3500 fires burned exactly 1.5 million hectares, or 15,000 square kilometers, across 98 days. Assuming that fires always burned new land, this amounts to $\frac{15000}{3500} = 4\,\frac{2}{7}$ square kilometers per fire and $\frac{3500}{98} = 35\,\frac{5}{7}$ fires per day. We figured that we would round these figures up to the nearest integer, as we believe it is better to overshoot rather than undershoot for the virtue of safety (although we recognize that overshooting comes at the expense of total cost). Thus, we have that in the 2020-2021 Victoria bushfire season, each fire will have an area of 5 square kilometers and there will be 36 fires per day.

Also, 92% of the area burned in Victoria in the 2019-2020 bushfire season was forested [5]. We believe it is reasonable to assume that this forested area is flat ground. Furthermore, because we are not given the amount of area burned that was urban, we would like to assume that the rest of the burned area from 2019-2020, 8% of it, is urban area. Knowing that more SSA drones are needed in urban areas because of their shorter range in higher grounds, this estimation of 8% being urban area means that we will always either have an accurate ratio or overshoot the ratio, and never undershoot it. Since more drones means more ensured safety and communications needs (at the expense of total cost), we believe this is a safe assumption. Thus, we have that in the 2020-2021 Victoria bushfire season, $R_{FG} = 0.92$ and $R_{UA} = 0.08$.

With these parameters, we have

$$N_s = 2F_d\left[\left(R_{FG} \times ceil\left(\frac{1}{5}\sqrt{\pi \times A_f}\right)\right) + \left(R_{UA} \times ceil\left(\frac{1}{2}\sqrt{\pi \times A_f}\right)\right)\right] =$$

$$2 \times 36 \times \left[\left(0.92 \times ceil\left(\frac{1}{5}\sqrt{\pi \times 5}\right)\right) + \left(0.08 \times ceil\left(\frac{1}{2}\sqrt{\pi \times 5}\right)\right)\right] = 77.76$$

$$N_r = 2F_d \times ceil\left(A_f \times \frac{1}{400\pi}\right) = 2 \times 36 \times ceil\left(5 \times \frac{1}{400\pi}\right) = 72$$

Taking the ceiling of N_s, we have that $N_s = 78$ and $N_r = 72$. Thus, the 2020-2021 Victoria bushfire season will require a total number of 78 SSA drones and 72 repeater drones.

5 Adaptation of the Model to the Next Decade

5.1 Model is Not Self Adapting

Before discussing how the sizes and frequency of fires affect the model for the next decade, we will discuss that the model is not self adapting. This means given some information about the number of fires they are in a year we cannot determine how many fires and how big they are in the subsequent year. This would surely determine how many drones we would need each year and it is important information that is needed to predict how many drones are needed. This is due to a few factors, one being that the number of fires Victoria, Australia faces each year is relatively consistent during the last decade except for a couple of years where they had an astronomically higher number of fires. Because of this it is hard to predict how many fires we have with a line of best fit because we either have a normal level of fires or we have 2 to 3 times as many fires. Below is a graph that shows this problem:

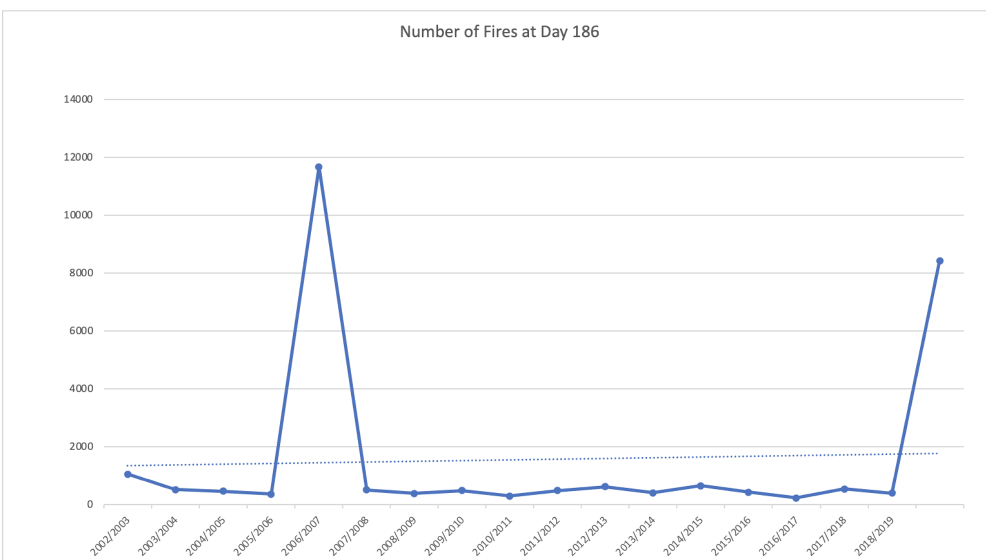

Chart 1: This is data collected by the Global Fire Emissions Database [100]

This is information about the number of fires up to the 186th day of the bushfire season which starts in July and ends in June. The reason why this data is constrained to the 186th day is because for the 2019/2020 season the data collection ended on day 186. As previously mentioned, we can see that the number of fires in the past 18 years is very bivariented and makes it difficult to make a prediction of what the 2020/2021 year will look like as far as the number of bushfires that will occur.

5.2 Increasing Size of Fires

One of the inputs for our model is the size of each fire and how that affects how many drones we need for each circular group. In order to be sure that we rarely would underestimate the size of each of the fires we chose a period of time where there was a significant amount of land being burned and made our model accordingly to this fire. The fires we decided to use were the 2019/2020 season specifically from November 2019 to January 2020 which seems to be in an extreme time period where more than 1.5 Hectares burn over the course of more than 3500 fires [2]. Fire sizes are a very difficult parameter to get information on because most of the statistics we have come across only discuss how many fires occur and how much land those fires burned. So as previously mentioned we decided the average fire size by checking how much land was burned and divided it with the number of fires to determine the fire sizes. We are making the assumption in this model that most of the land that burns only burns once and not multiple times in a year. This part of the model should be adaptable to the next decade given that the case we have considered is an outlier case and we are compensating for a worse case scenario instead of an average one.

5.3 Increase of the Number of Fires

The change in the number of fires over the last 18 years has been pretty stagnant over the last couple of years. Before discussing what the projected changes are within the next decade, we will look at the same data, one with outliers in the chart and one without the outliers. Below is the chart of data that included the years 2002/2003 and 2006/2007. As previously mentioned in section 5.1 because the outliers are so far out of the norm it isn't feasible to make predictions with the data including them. The chart below includes the outlier data with the line of best fit indicating the projection:

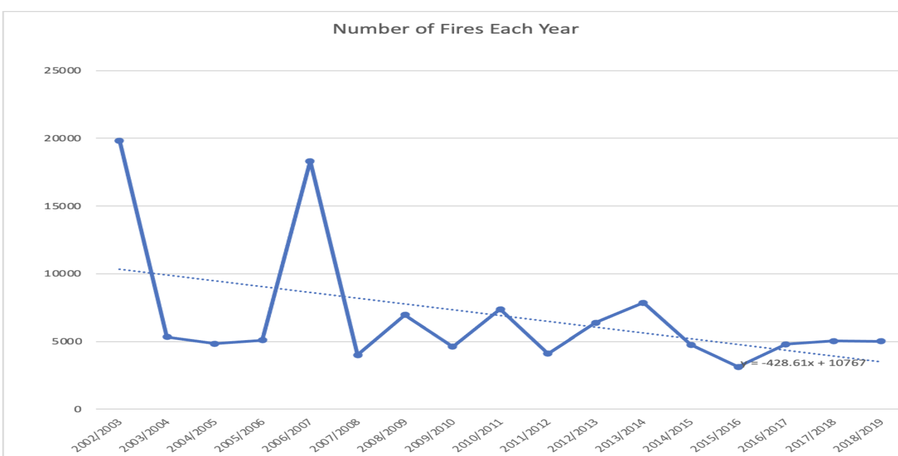

Chart 2: This is data collected by the Global Fire Emissions Database with outliers [1]

In the data above it gives the impression that the number of wildfires each year is reducing about 428 wildfires each year where the truth of the matter is that the number of fires has not changed that much in the last 5 years. But to have a relatively reliable set of data we will go based off of 2007/2008 and onwards for the prediction of the next decade. The chart below will reflect those changes:

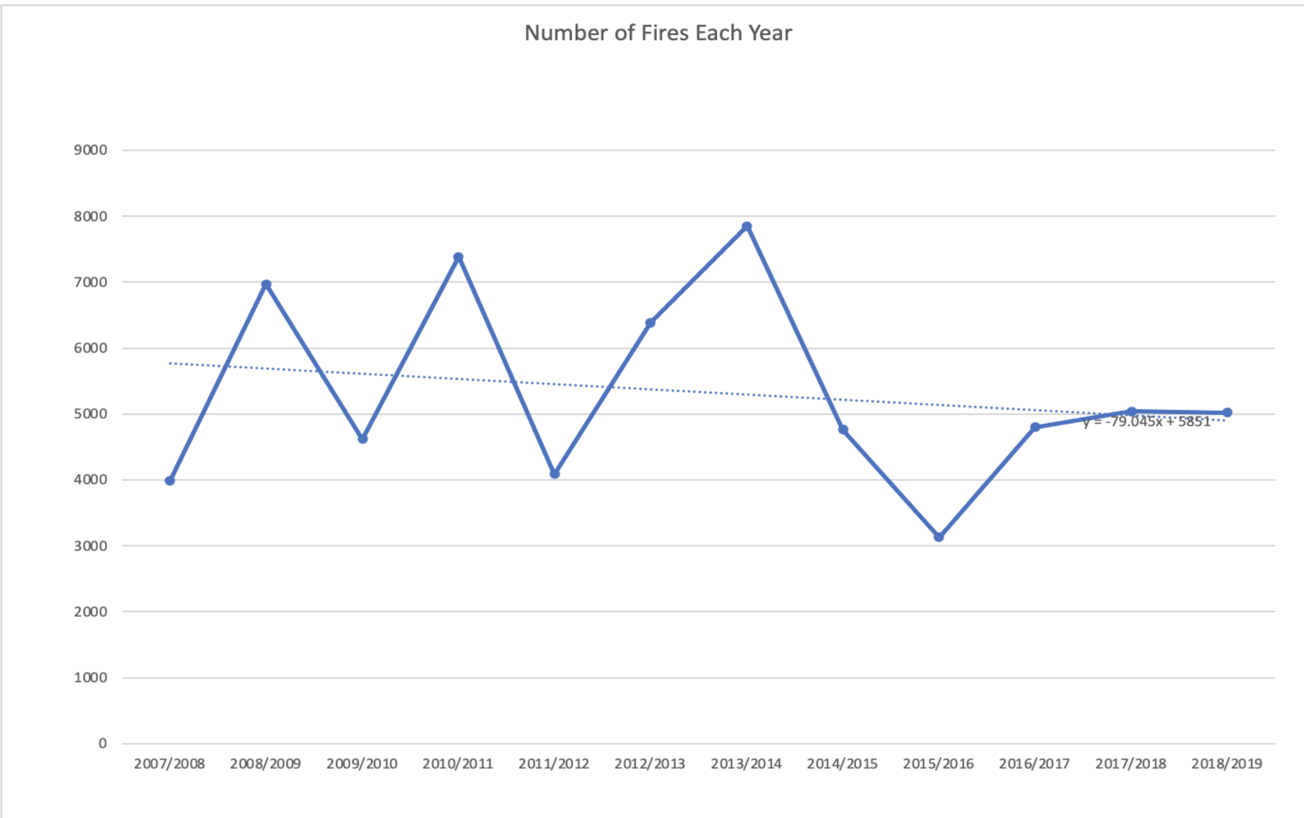

Chart 3: This is data collected by the Global Fire Emissions Database with no Outliers[1]

This data is probably more accurate to work off of and it projects that the number of fires every year in the next decade may not be that different. This could mean the model itself may not need to change very much outside of adding or subtracting a couple dozen circular groups. That being said, this stagnant number of fires, should not be a sign that we will not have another bad season in the state of Victoria, Australia. There needs to be a concerted effort to combat climate change as well as implementing controlled fires over the areas that are more likely to have bushfires. According to the Parliament of Australia's article "2019–20 Australian bushfires" lightning accounts for 50% of fires [4] that are started so the country needs to reduce the potential of fire starting in at risk areas by performing prescribed fires.

5.4 What will this all look like in a decade?

As mentioned previously we do not have the full number of fires for the year but we will extrapolate that by finding an average of fires per day for the 2019/2020 season and use that number to find how many fires will occur that year. This is by no means as accurate as we would like it to be but it will give us an idea of what we are looking at to extrapolate future trends for the next 10 years. After calculating the average number of fires per day in 2019/2020 we got approximately 45 fires per day and that resulted in a projected 16537 fires for the whole year. With that number we have the resulting graph excluding previous outliers to be:

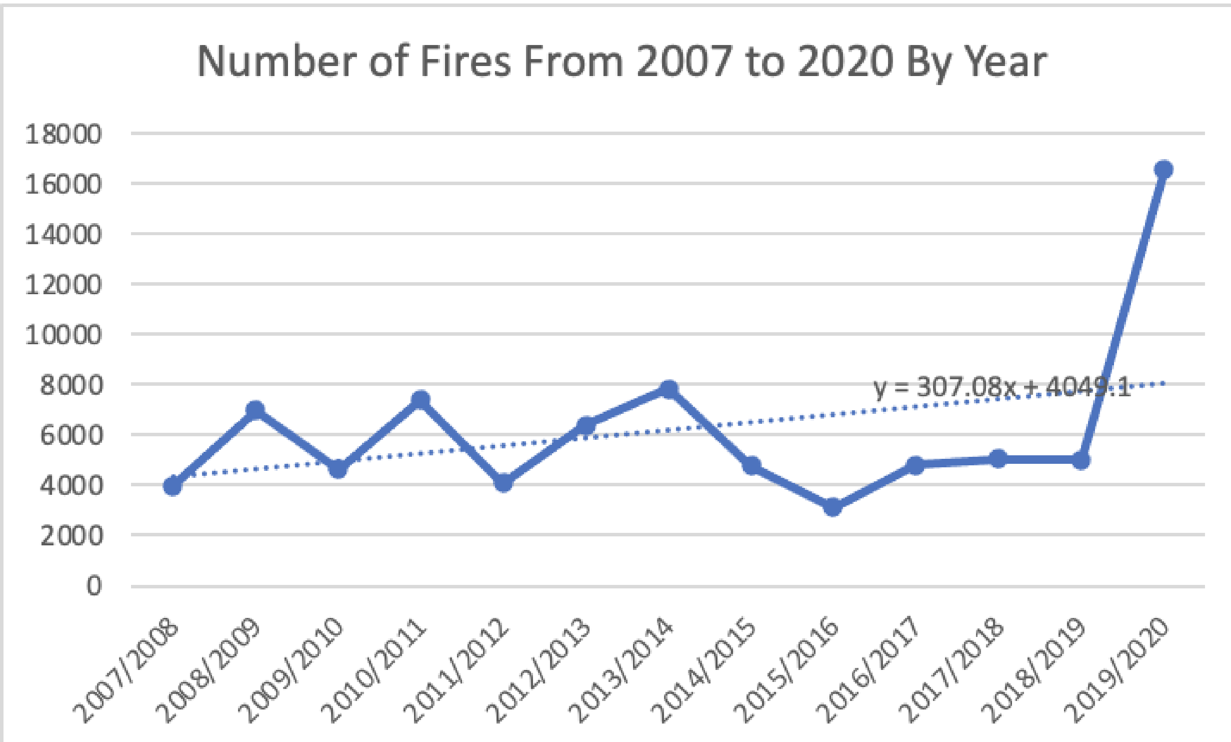

Chart 4: This is data collected by the Global Fire Emissions Database with an extrapolation for the year 2019/2020 [100]

We will display two predictions for the next decade, one with the trend line based off of chart 3 that does not include any outliers and one that uses the trendline in chart 4 which includes recent outliers in 2019/2020. The reason why we are doing this is for chart 3 the data seems to be pretty stable for a whole decade where for chart 4 we want to account for future extreme fire seasons since 2019/2020 may just be the beginning of a series of bad seasons. Another assumption being made is that the fire sizes are going to be consistent with the value we calculated before because we believe fire sizes will not deviate too much from our original calculation; this value will be 5km . Both charts will use 2018/2019 as the base number of fires which is 5018 fires and we will use the trend slot for both to predict the next decade. The two graphs are as follows

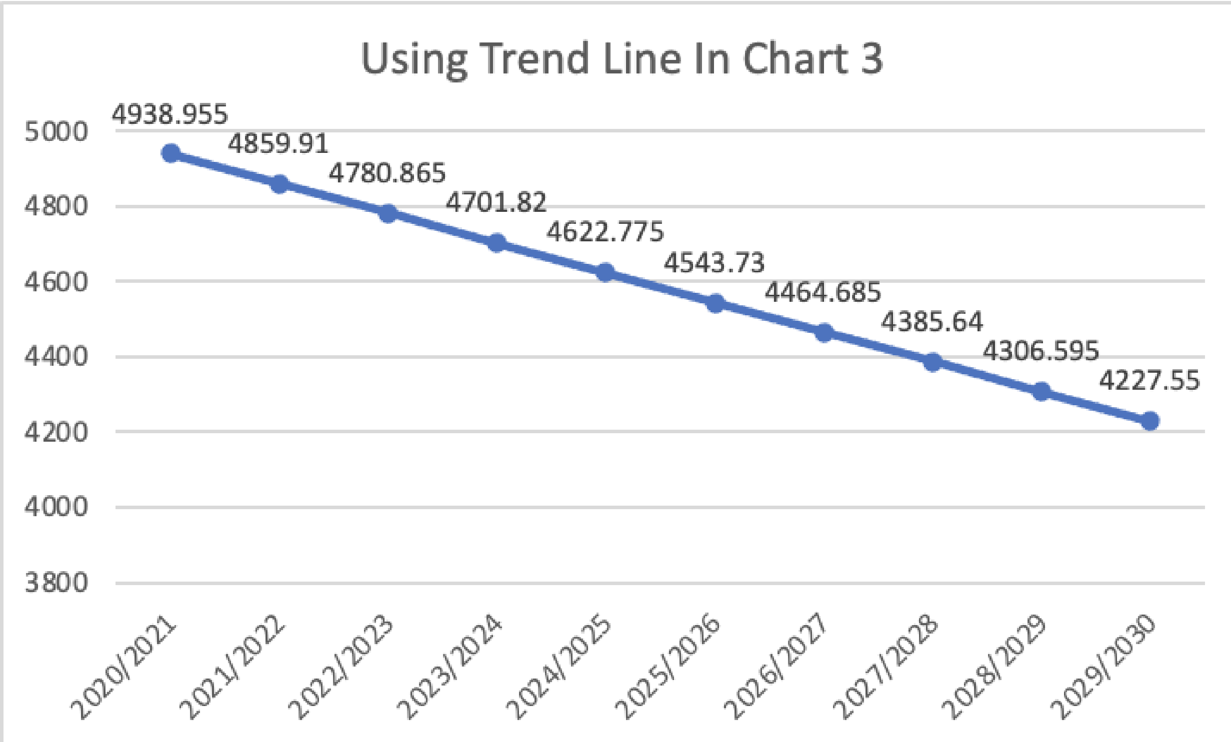

Chart 5 : Using trendline with a slope of m=-79.045

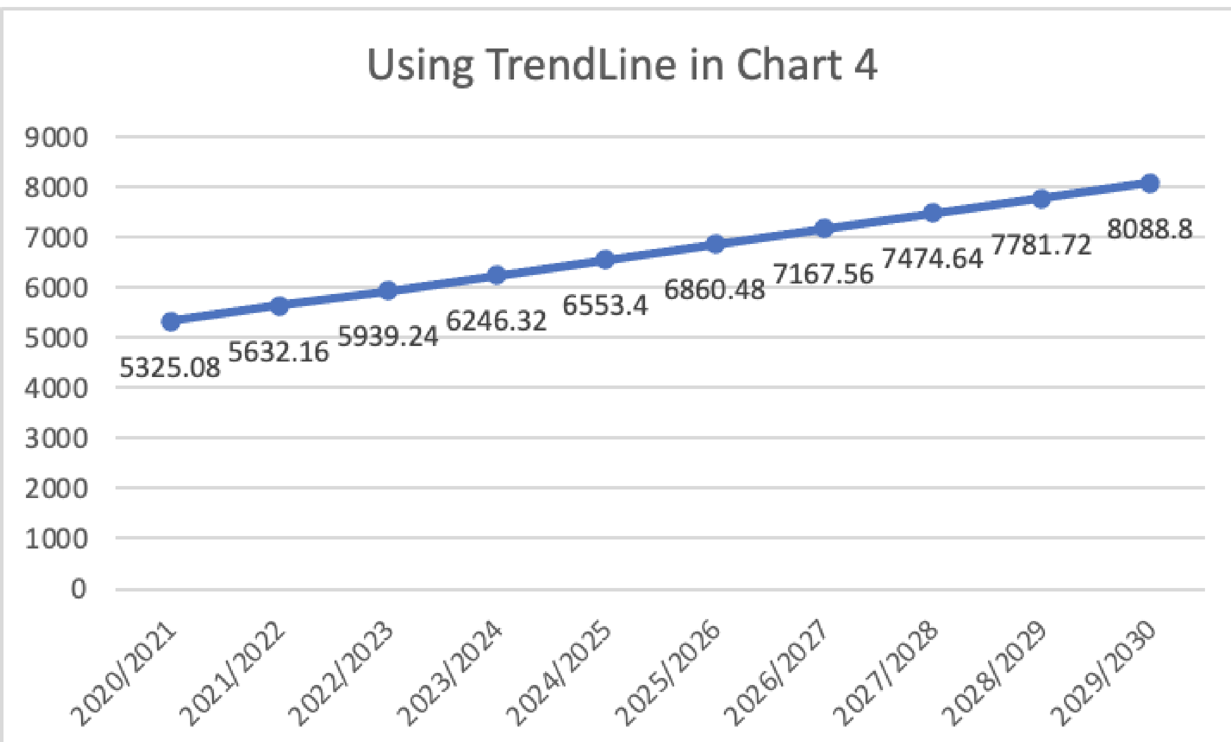

Chart 6 : Using trendline with a slope of m=307.08

The cost of drones over the next decade is dependent on how many fires are in the worst projected year. For chart 5, the worst year is projected to be 2020/2021 and the number of fires that year would be about 4939 fires for the year. By using the equation in section 4 we would have

$$N_s = 2 \times 14 \times \left[\left(0.92 \times ceil\left(\frac{1}{5}\sqrt{\pi \times 5}\right)\right) + \left(0.08 \times ceil\left(\frac{1}{2}\sqrt{\pi \times 5}\right)\right)\right] = 31$$

$$N_r = 2 \times 14 \times ceil\left(5 \times \frac{1}{400\pi}\right) = 28$$

These calculations for chart 6 do relatively the same thing but the worst cast is at the end of the decade with 8008 fires. The number of drones we would need of each would be as follows:

$$N_s = 2 \times 22 \times \left[\left(0.92 \times ceil\left(\frac{1}{5}\sqrt{\pi \times 5}\right)\right) + \left(0.08 \times ceil\left(\frac{1}{2}\sqrt{\pi \times 5}\right)\right)\right] = 48$$

$$N_r = 2 \times 22 \times ceil\left(5 \times \frac{1}{400\pi}\right) = 44$$

These extrapolations are much lower then the budget request for the 2020/2021 proposal because we are extrapolating from what we consider as “normal” data which uses everything from 2007/2008 to 2018/2019 season which are relatively tame compared to the 2019/2020 year where we had a huge outbreak of fires. The only difference between the two proposals is the slope that we will use, one that is based with outlier data and one that is based on our “normal” years data. Now we will discuss the assumptions that we are making when calculating the budget for the next decade. We are assuming that the ratio between different terrain over the next decade. This ratio wouldn’t affect the number of drones very much anyways since it plays a very small role in calculating the total drones. We are assuming the size of fires are not changing very much from year to year but we do take in account fire frequency which does in fact change a lot. Lastly, we are assuming that these drones will last throughout the decade and will not need to be replaced. These estimations also do not take into account an astronomical outlier that may occur in the next decade but the second chart calculation is more friendly to outliers than the first. Given that it will cost $590,000(AUD) for data in chart 5 and $920,000 for the data in chart 6 for all the drones for the decade.

6 Adaptation of the Model to Different Terrains

This section only serves as an extension of the work in section 4. We have determined that the optimal location for the drones is to have the SSA drones hover over the perimeter of the fire because of their range and for the safety of the front-line personnel, and the repeater drones hover over the inside area of the fire because of their long range and better broadcasting powers. Furthermore, because the SSA drones have shorter range in urban areas, the model will require more of them for fires in urban areas, assuming fires have the same area.

7 Sensitivity Analysis

Here, we will adjust the parameters of the model and observe their effects on the total number of SSA and repeater drones. We will adjust the parameters from the 2020-2021 Victoria bushfire season to conduct the sensitivity analysis.

7.1 Adjusting the Area Per Fire

Fixing the parameters of the number of fires per day, $F_d = 36$, and the ratios of burned land that is flat, $R_{FG} = 0.92$, and that is urban, $R_{UA} = 0.08$, we will adjust the parameter of the area per fire, $A_f = 5$. We know that before taking the ceiling, $N_s(A_f) = 77.76$ and $N_r(A_f) = 72$.

Given ϵ, we calculate $N_s(A_f \pm \epsilon)$ and $N_r(A_f \pm \epsilon)$. The results are as follows:

ϵ	$N_s(A_f + \epsilon)$	$N_s(A_f - \epsilon)$	$N_r(A_f + \epsilon)$	$N_r(A_f - \epsilon)$
1	83.52	77.76	72	72
0.1	83.52	77.76	72	72
0.01	77.76	77.76	72	72
0.001	77.76	77.76	72	72
0.0001	77.76	77.76	72	72
0.00001	77.76	77.76	72	72

Table 1: Sensitivity Analysis of A_f

We observe that the only change occurs in the number of SSA drones when the original parameter A_f is increased by $\epsilon = 1$ and $\epsilon = 0.01$. The relative difference in both cases is $\frac{83.52-77.76}{77.76} \times 100 = 7.41\%$, which is relatively small. We conclude that the model is mostly insensitive to adjusting the area per fire. Note that these results are based on ϵ, which is 20%, 2%, 0.2%, 0.02%, 0.002%, and 0.0002%, respectively, of the original parameter, $A_f = 5$.

7.2 Adjusting the Number of Fires Per Day

Fixing the parameters of the area per fire $A_f = 5$ and the ratios of burned land that is flat, $R_{FG} = 0.92$, and that is urban, $R_{UA} = 0.08$, we will adjust the parameter of the number of fires per day, $F_d = 36$. We know that before taking the ceiling, $N_s(F_d) = 77.76$ and $N_r(F_d) = 72$.

Given ϵ, we calculate $N_s(F_d \pm \epsilon)$ and $N_r(F_d \pm \epsilon)$. The results are as follows:

ϵ	$N_s(F_d + \epsilon)$	$N_s(F_d - \epsilon)$	$N_r(F_d + \epsilon)$	$N_r(F_d - \epsilon)$
7.2	93.312	62.208	86.4	57.6
0.72	79.3152	76.2048	73.44	70.56
0.072	77.91552	77.60448	72.144	71.856
0.0072	77.775552	77.744448	72.0144	71.9856
0.00072	77.7615552	77.75884448	72.00144	71.99856
0.000072	77.76015552	77.75984448	72.000144	71.999856

Table 2: Sensitivity Analysis of F_d

We observe that there are changes across all changes ϵ. The greatest amount of relative change in the number of SSA drones is $\frac{93.312-77.76}{77.76} \times 100 = -\frac{62.208-77.76}{77.76} \times 100 = 20\%$, which is equal to the change ϵ. The greatest amount of relative change in the number of repeater drones is $\frac{86.4-72}{72} \times 100 = -\frac{57.6-72}{72} \times 100 = 20\%$, which is also equal to the change ϵ. All of the other differences are magnitudes are also equal to the change ϵ. We conclude that the model is sensitive an amount proportional to the change ϵ. Looking at the equations for N_s and N_r, this makes sense: F_d is a multiplier in both of them. Note that these results are based on ϵ, which is 20%, 2%, 0.2%, 0.02%, 0.002%, 0.0002%, respectively, of the original parameter, $F_d = 36$.

7.3 Adjusting the Ratios of Flat and Urban Land

Fixing the parameters of the area per fire $A_f = 5$ and the number of fires per day, we will adjust the ratios of burned land that is flat, $R_{FG} = 0.92$, and that is urban, $R_{UA} = 0.08$. Since these two parameters have a constant sum of 1, adjusting one adjusts the other, so we will consider only one of them, namely R_{FG}. We know that before taking the ceiling, $N_s(R_{FG}) = 77.76$ and $N_r(R_{FG}) = 72$. Also note that only N_s is dependent on R_{FG}, so we only conduct a sensitivity analysis for N_s.

Given ϵ, we calculate $N_s(R_{FG} \pm \epsilon)$. The results are as follows:

ϵ	$N_s(R_{FG} + \epsilon)$	$N_s(R_{FG} - \epsilon)$
0.184	—	91.008
0.0184	76.4352	79.0848
0.00184	77.62752	77.89248
0.000184	77.746752	77.773248
0.0000184	77.7586752	77.7613248
0.00000184	77.75986752	77.76013248

Table 3: Sensitivity Analysis of R_{FG}

We observe that there are changes across all changes ϵ. The greatest amount of relative change in the number of SSA drones is $\frac{91.008-77.76}{77.76} \times 100 = 17.07\%$, which is relatively large. The next greatest amount of relative change is $\frac{79.0848-77.76}{77.76} \times 100 = 1.71\%$, which is relatively small. All of the other differences are even smaller. We conclude that, barring a change ϵ that is 20% of the original parameter, R_{FG}, the model is minimally sensitive to adjusting the ratio of the burned land that is flat and that is urban. Note that these results are based on ϵ, which is 20%, 2%, 0.2%, 0.02%, 0.002%, 0.0002%, respectively, of the original parameter, $R_{FG} = 0.92$.

8 Conclusion

In conclusion, we decided to base our model on a geometrical approach, treating a single fire as a circle, C_f. Because of safety and communication needs, we found it optimal to place the SSA drones along the perimeter of the fire and have the repeater drones placed in the area of C_f.

The model found to determine the optimal quantity of SSA drones and Repeater drones was found to be

$$N_s = 2F_d\left[\left(R_{FG} \times ceil\left(\frac{1}{5}\sqrt{\pi \times A_f}\right)\right) + \left(R_{UA} \times ceil\left(\frac{1}{2}\sqrt{\pi \times A_f}\right)\right)\right],$$
$$N_r = 2F_d \times ceil\left(A_f \times \frac{1}{400\pi}\right).$$

where N_s and N_r represent the number of SSA and repeater drones required per bushfire season, respectively.

The equation to determine N_s was found by deriving P_f (the circumference of C_f) from the parameter A_f (the area of C_f). We found P_f to be $2\sqrt{\pi \times A_f}$. To accommodate the differing ranges for flat ground and urban area, the equation is broken down into a sum of the number of SSA drones needed for each topography. For flat ground, SSA drones have a range of 5 kilometers and therefore a diameter of 10 kilometers. Taking P_f and dividing it by the diameter of a SSA drone on flat ground, we get $\frac{1}{5}\sqrt{\pi \times A_f}$. The ceiling of this function is then taken to determine the number of SSA drones needed per fire on flat ground. This is then multiplied by the ratio of fires per season on flat ground, R_{FG}. The same process is conducted for urban areas, where a SSA drone has a range of 2 kilometers and therefore a diameter of 4 kilometers. Dividing P_f by a diameter of 4km yields $\frac{1}{2}\sqrt{\pi \times A_f}$. The ceiling is then taken and multiplied by R_{UA}, ratio of fires per season over urban areas, to find the number of SSA drones needed per fire over urban areas. The sum of the number of SSA drones needed for the two topographies results in the total number of SSA drones needed per fire.

The equation to determine N_r was found by taking A_f and dividing it by the area covered by one Repeater drone (400π) and rounding up to a whole integer, to give the number of Repeater drones needed per fire.

Both the number of SSA drones and Repeater drones needed per fire is multiplied by 2, to account for a second fleet when charging, and by F_d, average number of fires per day, to ensure every fire is observed by the drones.

To determine the desired number of SSA and repeater drones for the 2020-2021 Victoria bushfire season, we used data from the 2019-2020 Victoria bushfire season. We found that the average fire size that season was $4\frac{2}{7}$ square kilometers per fire and the frequency of fires was $35\frac{5}{7}$ fires per day. We decided to round these numbers up to $A_f = 5$ square kilometers and $F_d = 36$ fires per day. Also based on the 2019-2020 season $R_{FG} = 0.92$ and $R_{UA} = 0.08$. Plugging these variables into the model we got $N_s = 78$ and $N_r = 72$ for the 2020-2021 season.

In the past decade the number of fires per season has remained fairly consistent besides the 2006-2007 and 2019-2020 seasons. This makes it difficult to predict future seasons, causing us to keep a non self adapting model. By using data from the extreme 2019-2020 bushfire season our model should be sufficient for the next decade, in regards to bushfire size. We assumed fire size and ratio of flat ground and urban area burned would remain constant.

First we considered data from the 2007-2008 season to the 2018-2019 as it excluded outliers, such as the 2019-2020 season. This data resulted in a trendline of $y = -79.045x + 5851$ where x is the bushfire season and y represents the number of fires each season. Using this linear regression to predict the next year we get an overall decrease in fire frequency with an estimate of 4228 fires in the 2029-2030 season. This results in about 14 fires per day. Plugging in $F_d = 14$, $A_f = 5$, $R_{FG} = 0.92$ and $R_{UA} = 0.08$ to the model we get $N_s = 31$ and $N_r = 28$.

Next we decided to include the 2019-2020 bushfire season which resulted in a trendline of $y = 307.08x + 4049.1$ and predicts an increase in fire frequency over the next decade. This linear regression anticipates 8089 fires in the 2029-2030 season, resulting in approximately 22 fires per day. Plugging in $F_d = 22$, $A_f = 5$, $R_{FG} = 0.92$ and $R_{UA} = 0.08$ to the model we get $N_s = 48$ and $N_r = 44$.

Both predictions for the 2029-2030 season result in a decrease in the number of SSA and Repeater drones needed. By using the data from the 2019-2020 season, we are accounting for more severe wildfire seasons. Having enough drones for such an extreme season ensures that if another anomaly season were to happen the CFA of Victoria would be well prepared.

8.1 Shortcomings and Future Studies

Here, we would like to shortly address the shortcomings of our model and what further considerations can be made. First, we were not able to find data for fire event sizes to do an analysis of how the model adapts over the next decade. It was necessary, then, to make the assumption that fire event size would stay constant over the next decade.

A common simplification throughout the model construction was that of shapes. In this model, we assume all fires are circles in order to simplify the analysis. In future studies, ellipses and more complex shapes may be considered, or even a more general analysis of fire growth that is irrespective of a general shape. We also approximated the coverage of each SSA drone on the perimeter of a fire as a straight line for simplicity. In future studies, arc lengths may be calculated for a more precise measurement of the number of SSA drones.

We also made assumptions about the life of a drone, namely that its lifespan is unbounded and that it does not encounter any accidents or becomes lost. These assumptions allowed for simplicity; however, future studies may consider limited lifespans of drones or take into account the possibility of a drone encountering accidents or becoming lost. These are very realistic possibilities and must be considered for any bushfire response division.

Other common assumptions were those concerning the nature of the fires, namely that each fire is stationary and unmoving, and that each fire either totally covers flat, unobstructed ground or totally covers urban areas. This was because we realized it was going to be very difficult to consider fires in their natural, dynamic state, as well as over more complex, varying topographies. It is more realistic to consider fires as evolving and dynamic situations, and models that take this nature into consideration will be more optimal for future bushfire seasons.

9 Budget Request

Project Name : Rapid Bushfire Response for Victoria, Australia
Date Submitted : Tuesday the 27th of April 2021

The associated cost and justification for the project “Rapid Bushfire Response for Victoria, Australia” is presented in this Budget Request. The proposed budget below provides an itemization of the cost and materials that make up the requested budget.

9.1 Justification

Victoria, Australia has had a long history of bushfires resulting in negative effects on the economy as a result of property damage, as well as the loss of numerous lives. With advancement in drone technology the CFA of Victoria, Australia has created a new division titled “Rapid Bushfire Response.” This new division is working with drone technology to improve the response time for bush fires in the state of Victoria.

The CFA of Victoria, Australia is requesting this budget to fund the “Rapid Bushfire Response” division in purchasing both SSA and Radio Repeater drones. These drones will aid the front line personnel in minimizing their response time to any bushfires detected by the drones.

9.2 Summary of Estimated Costs

Below is an itemized list of the budget requested by the CFA

Item	Quantity	Cost per unit (AUD)	Overall Cost (AUD)
SSA drone	78	$10,000	$780,000
Radio Repeater drone	72	$10,000	$720,000

Total Budget Requested	$ 1,500,000 (AUD)

This Budget Request was created by CFA of Victoria, Australia and presented to the Victoria State Government. This proposal displays the most accurate appraisal cost based on the data and research conducted by the “Rapid Bushfire Response” division of CFA.

Country Fire Authority, Victoria, Australia

10 References

[1] “2019-20 Australian bushfire season”
https://globalfiredata.org/pages/2020/01/03/2019-20-australian-bushfires/

[2] “Final significant fire contained in Victoria”
https://news.cfa.vic.gov.au/-/final-significant-fire-contained-in-victoria

[3] “2021 MCM Problem B: Fighting Wildfires”
http://www.immchallenge.org/mcm/2021_MCM_Problem_B.pdf

[4] “2019–20 Australian bushfires”
https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/rp/rp1920/Quick_Guides/AustralianBushfires

[5] “Forest fire data”
https://www.agriculture.gov.au/abares/forestsaustralia/forest-data-maps-and-tools/fire-data#fire-area-and-area-of-forest-in-fire-area-by-jurisdiction