| Problem Chosen | 2021 MCM/ICM Summary Sheet | Team Control Number |
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# "Climate Wars Episode V: The Drones Strike Back"- An economic analysis and optimization of type, quantity, and positioning of drones to combat Australian wildfires


**Summary Sheet**

As wildfires present an increasing threat to Victoria, Australia, firefighters must be equipped with two key tools: information and communication. The implementation of a drone system to support firefighting efforts employing two types of drones can provide firefighters with crucial surveillance data and increased communication ability.

We present a **linear optimization model** to determine the optimal quantity and combination of each of two types of drones for wildfires with various scopes and spreading risks. To determine these quantities, we characterize sub-regions of Victoria by their wildfire risk based on climate factors and topography, then estimate the scopes of average wildfires in those regions. Generalizing wildfire shapes as circular, a series of drone quantity related equations are linearly optimized to generate the necessary quantities of each type of drone. Using this model, we estimate the optimized drone needs of Victoria to be **180 communication enhancing drones and 133 surveillance drones**, accounting for both economic considerations and overall safety.

Considering the projected increase in wildfire duration and intensity over the next decade, we perform an external analysis and cost extrapolation of the situation to determine the resulting change in equipment needs and costs. Ultimately, the estimated increase in equipment costs due to climate volatility leading to more extreme fire events ranges from $2.2 million AUD to $3.3 million AUD. Over the next decade, Victoria will require at least another 69 communication enhancement and another 52 surveillance drones. This results from both an increase in the depreciation rate as well as an increased quantity demanded for total capital inventory.

We suggest a **total budget of $9.47 million AUD, distributed over the next decade**, in order to effectively implement a firefighting drone program and also provide adequate maintenance and replacement of drones to ensure the Victoria County Fire Authority personnel have sufficient drone support for the unforeseeable challenges of wildfires and climate volatility in the coming decade.

To determine the optimal placement of communication enhancement drones to maintain an unbroken chain of communication between frontline firefighting personnel and drone base sites for a given topographical region and fire size, we implement a modular **least-costs analysis model** between the fire perimeter and base camp to minimize topographical interference. We then form an unbroken semi-perimeter around the region of the fire being fought to ensure optimal firefighter-base camp communication.

# Contents



# 1 Introduction

In the battle against wildfires, information is as key a weapon as a hose or a fire extinguisher. Wildfires have been an increasingly severe issue for Australia, with the wildfires of last year (2020) being the worst since the 1974-5 season. Approximately 18 million hectares were burned in the fires with over $103 billion (AUD) in damages[8], with Victoria being one of the most highly affected regions. In an attempt to combat this worrying trend, Australian authorities have allocated more funds to wildfire prevention and control; these efforts include the federal government establishing a new fire brigade division known as Fire Rescue Victoria (FRV) with an annual operating budget of $126 million (AUD)[1]. To better prepare the Victoria County Fire Authority's new "Rapid Bushfire Response" (RBR) team, drones are crucial in gathering information to coordinate boots-on-the ground response. Two types of WilE 15.2X drones from Akme Corporation are used: **surveillance and situational awareness (SSA) drones**, which provide high-definition imaging and report data from front-line personnel, and **radio repeater (RR) drones**, which rebroadcast signals from front-line responders' two-way radios, dependent on distance and topography.

# 2 Problem Restatement

We determine the optimal number of SSA and RR drones necessary to combat a fire in any given region of Victoria, sensitive to the relative risk of that region due to factors such as topography, regional drought factor, humidity, temperature, and other climate information, by implementing a **linear optimization model**, while also remaining economically viable for the Victoria RBR. We assume that fires are fought on the perimeter, and therefore the drones, which provide information to support the frontline personnel, would also remain on the perimeter. Given the impact of climate change on the increasing likelihood of fire events, we **project the increased quantities and costs of drones and equipment needed for the RBR over a ten-year-period**, accounting for mechanical depreciation and increased wildfire intensity and frequency due to climate change. To determine the optimal placement of RR drones to maintain an unbroken chain of communication between frontline personnel and drone base sites for a given topographical region and fire size, we implement a **least-costs analysis model** between the fire perimeter and base camp, then, form an unbroken semi-perimeter around the region of the fire being fought.

# 3 Part I: Optimal Quantities of SSA and Radio Repeater Drones

## 3.1 Data Sources, Assumptions, and Overall Modeling Approach

### 3.1.1 FFDI

When analyzing the risk of a fire happening it is important to consider many different factors that will influence the inherent risk, such as temperature, relative humidity, and fuel availability to name a few. The McArthur Forest Fire Danger Index (FFDI) [9] is the most widely used metric to forecast the influence of weather on fire behavior specific to Australian forest fires. While in his original paper McArthur did not publish the original equations for calculating FFDI, others have derived an equation for FFDI using statistical methods. Noble et al. (1980) derived the main formula which is as follows:

$$\text{FFDI} = 2e^{(-0.45+0.987ln(DF)-0.0345RH+0.0338T+0.0234v)}$$

Where $RH$ is the relative humidity percentage, $T$ is temperature ($C$), $v$ is wind speed (km h$^{-1}$), and $DF$ is a number up to 800 and is a representation of the fuel availability for combustion, as the Drought Factor [7]. In using FFDI as a base for assessing fire risk, the model can more sensitively consider various factors influencing fire spread to calculate expected fire scopes. It is important to accurately predict fire scopes in order to accurately assess how many drones will be necessary in Victoria.

### 3.1.2 Assumptions

1. **Distance to Camp:** We assume a fixed distance $d$, 5 kilometers, from the Emergency Operations Center (EOC) where drones are launched to the perimeter of any fire. Although dispatch centers may be further away, firefighters will always require a local base camp; and this can be the point from which drones are launched.

2. **Circular Fires:** We assume fires to burn in a relatively circular shape without loss of generality. This is not necessarily unreasonable because the area of any shape can also be the area of a corresponding circle. Therefore, calculating one-third the circumference of the circle will give a good approximation for one-third the arc length of a fire of a given shape and size. These arc length calculations will be imperative for establishing estimates of surveillance perimeters.

3. **Firefighting Region**: Given that fires are fought largely at the perimeter, we focus both SSA and RR drones along the perimeter of the fire . Furthermore, we determined that approximately 1/3 of the fire would be fought from any given mobile EOC, considering that any more might require more EOCs.

4. **One Fire per EOC:** All fires considered are correlated with one EOC base camp. For larger fires, we will assume that the relationship between number of base camps and overall fire size is linear. Therefore, we can generalize and say that for a fire of size $n$ there will be one base camp; and for a fire of size $nk$, there will be $k$ corresponding base camps.

5. **Behavior of RR and SSA drones:** RR drones' only function is to establish an unbroken line of communication from all firefighters to the EOC. SSA drones provide visualizations over where the firefighters are currently fighting, not between the fire perimeter and EOC.

### 3.1.3 Modelling Approach

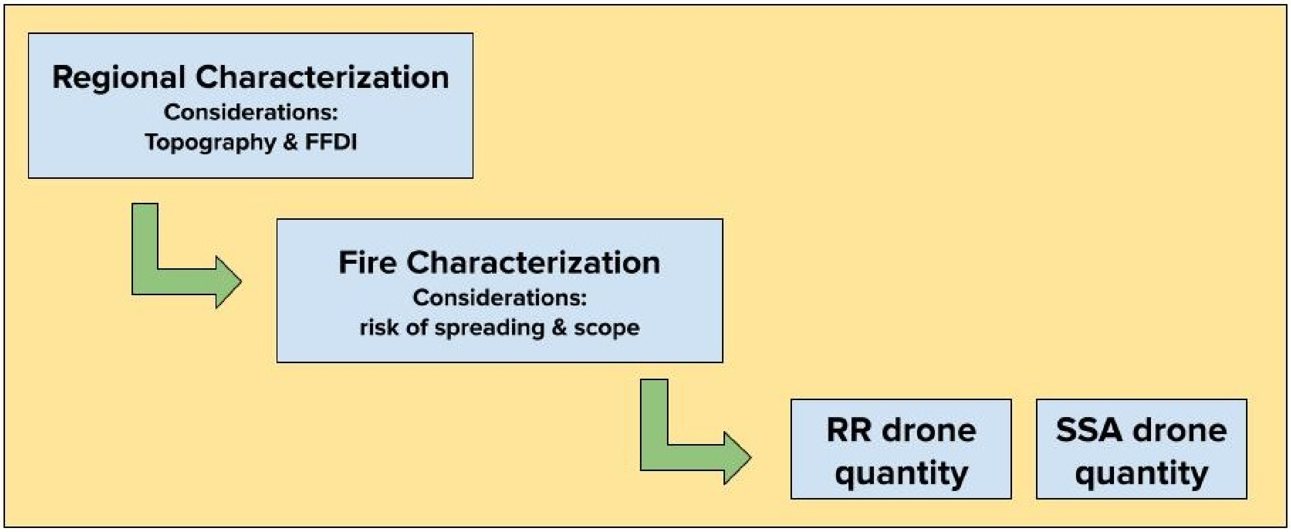


Figure 1: Description of the overall modelling approach, going from regional characteristics to drone quantities of each type necessary to fight a fire of a given scope

Taking into account regional characteristics such as topography and FFDI, we are able to calculate a regional risk of fire spread. As risk of fire spread directly correlates with area burned, we use this risk to determine a range of probable scopes of fires, which we define as the square kilometers of area burning. Based on the spread risk and scope of the fire, we are able to determine how many RR and SSA drones are necessary for fighting the fire from the perimeter, as visualized in Figure 1. We generate fires in each of five regions that form a representative sample and extrapolate the results to Victoria as a whole, accounting for how many regions may burn simultaneously and the personnel response capacity of the RBR team.

## 3.2 Model Parameters, Variables, and Equations

### 3.2.1 Parameters

The table explains the parameters of the model

Further Explanation of Parameters:

1. $\alpha$: Fire Scope Scaling Factor, 6*764: We identified 6 regions as described below using measurements from weather stations with approximate ranges of 764 square kilometers.

2. $\delta$: Fire Duration Scaling Factor, 10,000: this factor was determined experimentally, using historical data sets from prior Australian wildfires.

3. $\epsilon$: Fire Clustering Scaling Factor, 0.05: Fire scope and risk should both increase slightly, along with an exponential increase for number of previous fires in cluster.

Table 1: Model Parameters: Constants used in determining quantities of SSA/RR drones

| Parameter | Interpretation | Initial Value | Rationale |
|---|---|---|---|
| s | drone speed | 72 km/hr | Problem Statement |
| r | drone range | 20 km | Problem Statement |
| b | drone battery recharge | 1.75 hr | Problem Statement |
| t | drone maximum flight time | 2 hr | Problem Statement |
| $\alpha$ | scaling factor for fire scope | 4,584 | See further explanation |
| $\delta$ | scaling factor for fire duration | 100 | See further explanation |
| $\epsilon$ | scaling factor for fire clustering | 0.05 | See further explanation |
| f | FFDI of a given region | varies | Calculated w/ FFDI formula [9], climate data from [10] |
| n | No. fires in cluster | 1 | Assume a fire is the first |

### 3.2.2 Regional Characterization- FFDI

To characterize Victoria as a region, we selected a random sample of 5 weather stations from 285 weather stations in Victoria and named them by the closest landmark: Melbourne, Mt Buller, Kyabram, Mt. Buller, Bendigo, and Kilmore Gap. Assuming a relatively normal distribution of weather stations, and because the sample size of stations was sufficiently large, we can assume the sample is representative by the central limit theorem. Although wildfires themselves are not normally distributed across the region, the concentrations are themselves random - some areas are dense with fires or scarce, so the probability of getting a dense or scarce region is equivalent. This refers to a core notion in statistics that the random sampling distribution of non-normal distributions is itself a normal distribution. Therefore, the sampling method is reasonable.

We further considered each weather station to have an approximate area of 764 square kilometers, given that there are approximately 290 weather stations in Victoria, which contains 227,444 square kilometers. Although this may not be strictly true for all the measurements taken (temperature, humidity, drought index, etc), it is a necessary generalization when using the FFDI data calculated here for the purposes of measuring fire scope.

Using data from each weather station for each of the FFDI parameters (relative humidity, wind speed, drought factor, temperature), we were able to calculate the mean and maximum FFDIs during wildfire season (Nov-Feb) of 2019-2020, the peak season of the last decade. We used this data to extrapolate information about estimated fire scopes and incidence across all of Victoria to generate an estimated number of drones needed for the region at large.

Regions were also classified as 'flat' or 'jagged' depending on the overall physical and urban topography. This was necessary in estimating the RR drone quantities needed.

| Region | Topography | Mean FFDI | Max FFDI |
|---|---|---|---|
| Bendigo | Jagged | 11.82 | 80.00 |
| Melbourne | Jagged | 8.09 | 38.0945 |
| Mt Buller | Jagged | 3.03 | 2.96 |
| Kyabram | Flat | 10.819 | 67.65 |
| Kilmore | Flat | 4.798 | 16.77 |

Table 2: FFDI and topographical data for 5 regions, a representative sample of Victoria. FFDI calculated using climate statistics from weather stations [10]

#### 3.2.3 Fire Characterization

1. **Fire Risk:**

$$\frac{f_i}{\Sigma f}(1+\epsilon)^n$$

The risk of a particular region $i$ is the normalization of its FFDI, adjusted to account for the number of previous fires in its cluster, $n$, and a small constant of increase, $\epsilon$

2. **Fire Scope:**

$$\frac{f_i}{\Sigma f}(1+\epsilon)^n\alpha$$

The scope of a region is equivalent to its risk times the scaling factor for fire scope. In order to generate random fires within a region, we take a random variable power rule distribution centered on the regional FFDI as the FFDI, and multiply the overall scope by a random variable from a normal distribution from 0.5 to 2.0, to allow for both smaller and larger random fires. This is reasonable because a power law distribution most adequately captured the trends within the historical data.

3. **Fire Radius:**

$$\sqrt{\frac{f_s}{\pi}}$$

Assuming the fire is circular, and given the scope of the fire in square kilometers, we can use the area of a circle $\pi * r^2$ to calculate its radius in kilometers.

4. **Fire Duration:**

$$\delta f_r$$

The fire's duration is directly linked to the risk in its region (FFDI), therefore we scale the fire's risk by constant $\delta$.

#### 3.2.4 Drone Proportion and Quantity Determination

We determine a certain number of drones, then multiply that number by a constant of safety, allowing for a 25% reserve quantity of drones (to account for breakdowns of drone function. The overall desired behavior of the drones is as shown in Figure 2

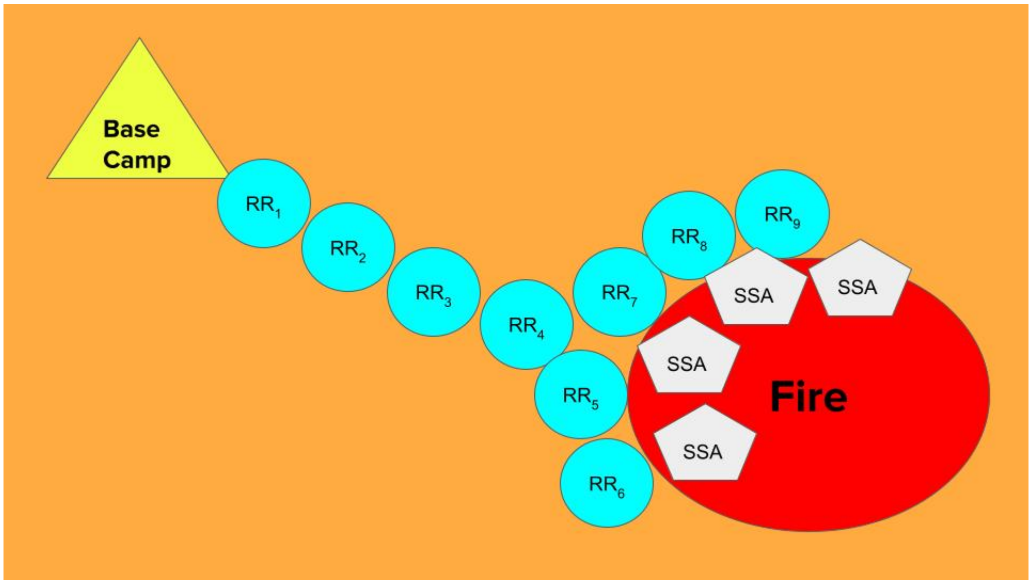


Figure 2: Representation of drone structure; RR drones form unbroken chain of communication, SSA drones monitor fire perimeter where boots-on-the-ground are deployed. Figure not to scale.

1. **RR Drone Range:**

$$a_c = \begin{cases} 2 & \text{Jagged terrain} \\ 5 & \text{Flat terrain} \end{cases}$$

   This is based on information given in the problem statement regarding the possible area covered for RR Drones in regions with different types of topography.

2. **Quantity of SSA Drones:**

$$\text{ssa} = \frac{9}{4} frac f_d d_f \frac{2\pi f_r}{s * d_f - 2d}$$

   Both types of drones must be within range of front-line personnel, who we determined to fight a maximum of 1/3rd of a fire around its perimeter. SSA drones fly from the EOC to a point on the perimeter of the fire, hover/fly within their range, then return to the EOC to recharge.

   We consider the fire to be circular in nature; therefore, we can derive the number of SSA drones needed by considering 1/3 of the fire's perimeter, the distance from base camp to the fire perimeter, and the scope of each SSA drone. The distance from EOC to fire perimeter constant for all SSA drones. To account for recharging the drones, as well as a 25 percent reserve to account for unexpected circumstances (equipment malfunction, unexpectedly jagged terrain, larger fires than predicted, dynamically shifting weather conditions, etc).

3. **Quantity of Radio Repeater (RR) Drones:**

$$\text{rr} = \frac{9}{4} \frac{d_f + 2\pi f_a}{a_c}$$

   The quantity of RR and SSA drones is similar, but RR drones also need to form an unbroken chain of communication from the fire to the EOC whereas SSA drones do not. The same considerations regarding firefighting region, and recharging/reserve quantity apply. The quantity of RR drones needed varies with topography, with jagged terrain reducing the range of each drone and requiring more drones per square kilometer of fire scope than flat terrain.

## 3.3 Model Results

### 3.3.1 Drones needed as a function of fire scope

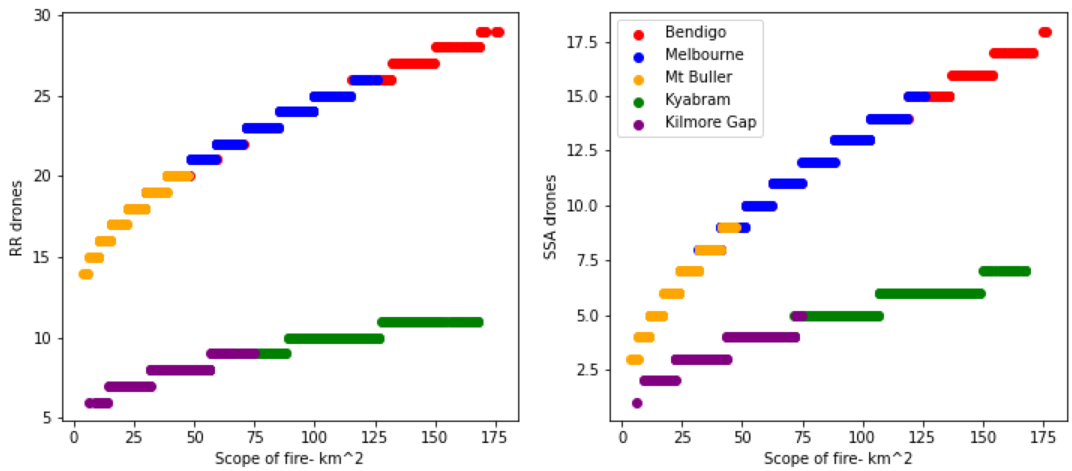


Figure 3: RR (left) and SSA (right) Drones needed varying with scope of fire for 5 regions of Victoria with different climates and topographies using **mean** FFDI of 2019-2020 bushfire season

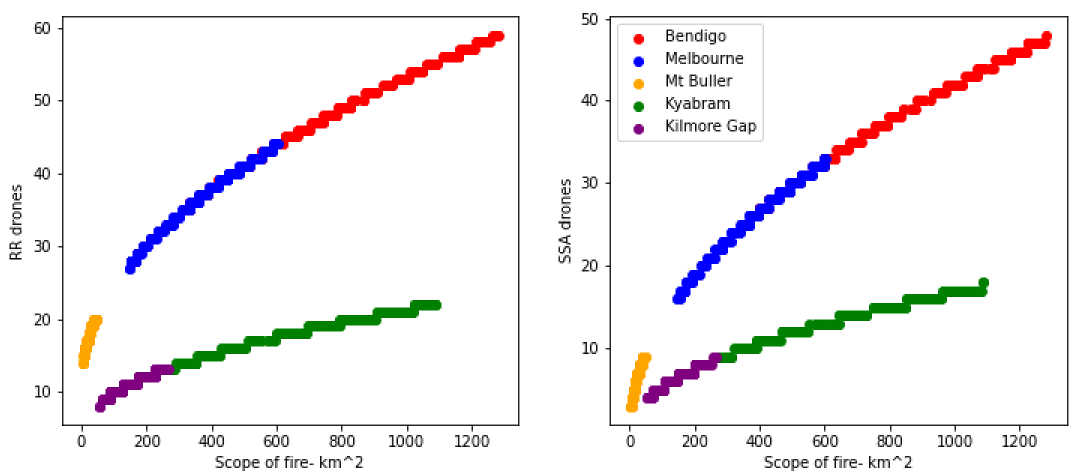


Figure 4: RR (left) and SSA (right) Drones needed, varying with scope of fire for 5 regions of Victoria with different climates and topographies using **max** FFDI of the 2019-2020 bushfire season

The number of drones needed naturally varies with fire scopes as a step function, given that drones can only be required in discrete quantities. Furthermore, it is evident that topography plays a heavy role in the necessity of drones - the flat regions (Kyabram, Kilmore Gap) require fewer RR drones than their jagged counterparts.

## 3.4 Parameter Variations

1. *Topography:* As shown in Figure 6, given a region with the same FFDI, varying the topography from flat to jagged dramatically changes the number of drones necessitated. For both types of drones, this is because the risk of fire spread is higher in topologically jagged regions; but and especially affects RR drones whose range is reduced by a factor of 0.4 in jagged terrain compared to flat.

2. *Clustering:* Wildfires can appear in a short period of time, one after another, a phenomenon observed most keenly in human-started fires but also present in wildfires, particularly in regions as prone as Victoria [5]. Given a region with the same FFDI, the first, second, and third fire in a cluster in that region demand different responses, as seen in Figure 6. As the incidence number of the fire in the cluster increases, the regional risk does too, explaining why fires that are higher order in a cluster have different predicted scopes. The model starts to break down beyond 3 fires in a cluster, where could recommend over 1000 drones for a single fire, as in reality, the fires would likely converge to one larger fire at that point.

### 3.4.1 Total drones needed for Victoria Bushfire Rapid Response Team

Realistically, considering the area burned by wildfires in the 2019-2020 season, and knowing that the effects of climate change mean longer, more intense wildfire seasons for the decades to come, it is more apt to view the data from the maximum FFDIs collected from regions of Victoria. Annual mean temperatures have been continuously increasing, and humidity, rainfall, and soil water availability have all been decreasing as well - all factors that dramatically increase risks of wildfire [2].

Therefore, in order to recommend a reasonable number of drones needed for the Victoria Bushfire Rapid Response team that will be useful in wildfire firefighting, it is reasonable to use the maximum FFDIs observed during wildfire season in a random sampling of Victoria.

Calculating 40 randomly generated samples of weather stations in Australia, we observe the average number of RR and SSA drones needed for the average fire scope in each region's maximum FFDI observed in the last bushfire season, yielding a calculation of **180 RR drones and 133 SSA drones**. Given that we have built into the model a 25 percent reserve into the resultant quantity needed for each drone already, these numbers do not need further reserve accommodations.

## 3.5 Strengths and Weaknesses of the Model

### 3.5.1 Strengths

1. *Sensitivity to Long-term Regional Risk:* By incorporating FFDI into our regional characterization, we holistically consider each region's climate and elevation factors in a way that directly correlates with its risk for wildfire and wildfire spread. Therefore, we are able to generate fires with more reasonable scopes and risks of spreading depending on a region's risk factors. By better

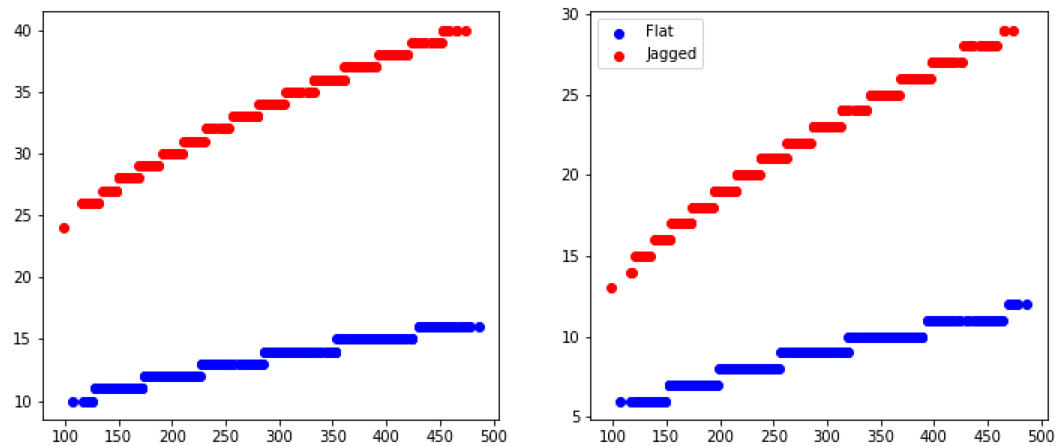


Figure 5: Given a region with FFDI 16.08 (the mean FFDI of the whole of Victoria during wildfire season), **changing the topography** from flat (blue) to jagged (red) causes a marked increase in RR drones(left) and SSA drones(right) needed at each fire scope.

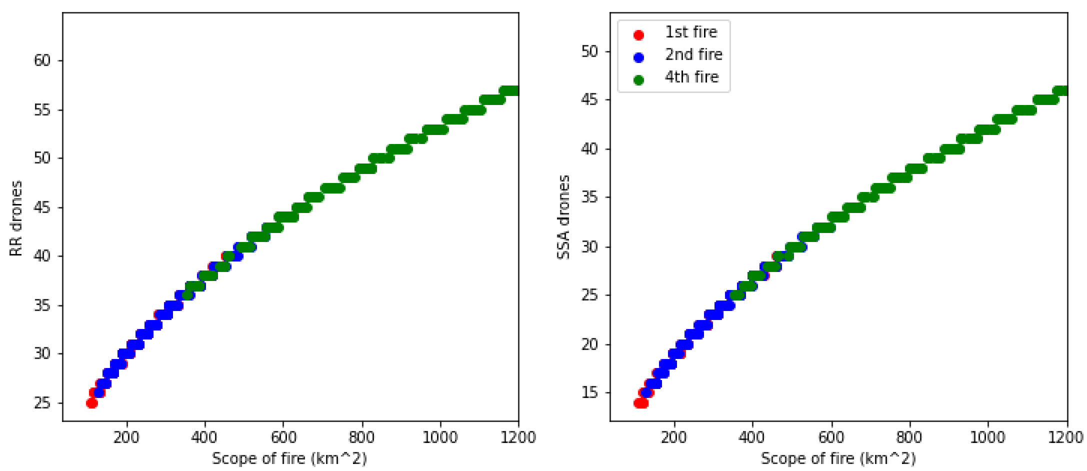


Figure 6: RR (left) and SSA (right) Drones needed for a fire in a flat region with FFDI 16.08, as the **1st, 2nd, or 3rd fire in a cluster**

characterizing the fire in terms of its scope and risk, we are able to more accurately calculate how many drones are strictly necessary.

2. *Differing Drone Needs:* Each drone has different behavior as determined by the function it needs to perform. Our model takes this into account when calculating how many drones of each type are necessary. Furthermore, because each drone performs an entirely different function with relation to firefighting, each drone is independently considered. For the RR drones, the model considers topography in its calculation, given the limiting effect of jagged topography on RR drone capability.

3. *Clustering:* Our model allows for the examining of fires as the nth fire in a cluster, allowing us to observe changes in drone needs for fires that occur in sequence. By considering the fact that prior fires in the cluster indicate an elevated level of risk and increased chance of spread, the drone needs are accordingly adjusted.

### 3.5.2 Weaknesses

1. *Static Fires:* Fires are examined with respect to an unchanging scope and risk factor, whereas fires in real life may dynamically grow and shrink through climate factors, wind speed and direction, firefighting efforts, and so on. However, by ignoring these factors and providing a generally applicable number of RR and SSA drones, we are able to provide a general estimate, leaving small adjustment to on-site personnel. Furthermore, the case of higher drones is accounted for in our 25 percent reserve quantity, so we consider these factors accounted for in our analysis.

2. *Uniform Topography:* We uniformly consider regions with fires to be topographically jagged or flat for the purpose of calculating the number of needed RR drones. Of course, real-world terrains may have heterogeneity of elevation and jaggedness which influence RR drone range. Underestimating the number of necessary drones could lead to a fatal breakdown in communication, so we instead choose to conservatively classify regions with mixed topography as uniformly jagged. This may lead to more RR drones being recommended than strictly necessary.

3. *Fire Scope:* We assume fires are circular, and assume constant distance between the EOC and fire perimeter. This may cause discrepancies as the real distance may vary for various drones along the boundary of the fire, however we assume this distance will be both shorter and longer for some drones, limiting the overall impact. Furthermore, we account for a 25 percent reserve, which should alleviate stress in the situation where the number of drones is too small. We also assume that 1/3 of a fire can be fought, which may be too small or too large of a fighting range depending on the size of the fire; however, since our overall goal is to calculate the number of drones needed for the region as a whole, this has less impact.

# 4 Part II: Projected expenses in a ten-year period

## 4.1 Adjusting the Model to Account for Climate Change

By the most conservative estimates, wildfires will increase in area burned by a minimum of 30 percent over the next decade [12], meaning that the risk of fire in every region will increase, corresponding to increased average fire scopes and a need for larger quantities of drones. Estimates vary from 30 percent to 400 percent increases in area burned, but for the purposes of determining costs over the next year, we will examine several cases ranging from a 30-45 percent increase in wildfire area burned.

The current operating budget for Fire Rescue Victoria is 127 million dollars, a quantity which will presumably increase as the wildfires increase in scope and intensity over the next decade [1]. With the drones required immediately, based on data extrapolated from the 2019-2020 bushfire season, requires an initial investment of approximately 3.5 million dollars (AUD), as shown in Table 3. Although the initial investment in drones seems proportionally large, the return on investment for the Australian government makes it worth funding, given that wildfires cause an estimated 3-4 billion dollars (AUD) in economic damage annually [4]. However, taking into consideration future damage due to climate change and depreciation, the current figures will likely change.

As the climate in Australia becomes drier and more risk-prone for wildfires, the FFDIs of any given sub-region of Victoria will also increase, since factors like humidity will decrease and temperature/drough index will increase. Furthermore, as long as the strategy for using drones in wildfire fighting remains relatively constant, the methods of optimization for the purposes of the model remain unchanged. Assuming a scalar increase in land area burned, we can assume a linear relationship between the increase in land area burned and drones of each type needed to fight fires overall in Victoria. Although this assumption is simplifying, it captures increased projected areas of wildfires and increased spread risk for wildfires, both of which require additional drones per fire.

| | SSA | RR | Maintenance | Repair Personnel | Charging Stations | |
|---|---|---|---|---|---|---|
| Quantity | 133 | 180 | 3 | 3 | 313 | |
| Price/Unit | 10,000 | 10,000 | 1,000 | 70,000 | 500 | |
| Net Cost | 1,330,000 | 1,800,000 | 3,000 | 210,000 | 156,000 | 3,499,500 |

Table 3: Case I: Current net cost estimate based on model estimates for numbers of drones needed (AUD)

## 4.2 Cost Extrapolation

Here we extrapolate how the overall cost of the drones will vary as time goes on. Using the following variables:

- $(D_1, P_1)$: quantity, cost of SSA drones
- $(D_2, P_2)$: quantity, cost of RR drones
- $(S, P_3)$: quantity, cost of drone charging stations
- $(R, P_4)$: quantity, cost of repair persons and corresponding equipment
- $\delta$: the rate of depreciation

- $n$: the number of years

We can model the cost equation for a given region's fire unit response as follows:

$$\text{Costs} = \text{Fixed} + \text{Variable} = (\text{Initial Equipment Cost}) + (\text{Replacement Equipment})$$

$$F = D_1 * P_1 + D_2 * P_2 + S * P_3 + R * P_4$$
$$V = [D_1 * P_1 + D_2 * P_2 + S * P_3 + R * P_4](1 - \delta)^n$$
$$C = F + (F - V)$$

Or, written more generally with K as the unit of capital and $p$ as the price of unit $K$:

$$C = \Sigma(K) + (K - (K)(1 - \delta)^n)$$

The overall cost includes both a fixed cost, the initial drones and equipment, as well as the variable cost, the annual cost of replacing equipment. Let $f$ denote the random variable representing fire frequency in a region and $s$ denote a random variable capturing fire scope in a given region. Then the rate of depreciation has the following relationship by the following relationship:

$$\delta \propto E[f] * E[s]$$

As extreme fire events—denoted by a higher regional fire frequency and a larger average scope—increase over the next decade, the rate of depreciation will increase proportionately. In addition to the cost of additional drones, charging stations, and repair personnel, as the frequency and scope of fires increase, the increasing rate of depreciation will cause the equipment to deteriorate quicker and require more frequent replacements. These factors will all contribute considerably to the final cost assessment and analysis.

## 4.3 Estimated Costs

Taking into consideration 5 potential cases for increased area burned by wildfire over the next ten years, we propose five associated combinations of drones. As more area burns, presumably either the scope of each fire will increase or the number of fires will increase. In either case, the quantity of drones necessary should increase along with the increase in area burned; we approximate this using a linear relationship between growth in fire area burned and drones required.
With unit prices for goods associated with drone program implementation as showing in Table 5, the initial investment, maintenance, depreciation, and annual maintenance funding can be determined.

For each of these cases, using the above guiding assumptions regarding cost extrapolation, we can then assess the initial drone implementation costs along with their projected future maintenance costs. Depreciation grows linearly with fire growth as previously described.

In order to project a budget for the Victoria County Fire Authority, we select Case IV as the optimum case. With Australia's climate changing rapidly beyond expectation each year, it is highly likely that the most conservative estimates for wildfire growth will be surpassed; however, over-purchasing drones may not be an efficient allocation of funding for the Victoria County Fire Authority. A yearly re-analysis of current drone capabilities with respect to wildfire growth and actual depreciation of equipment would likely be necessary.

| | Fire Growth | Quantity of SSA drones | Quantity of VHF drones | Maintenance Supply Sets | Drone Repair Persons |
|---|---|---|---|---|---|
| Case I | N/A | 184 | 184 | 3 | 3 |
| Case II | 30% | 240 | 240 | 4 | 4 |
| Case III | 34% | 247 | 247 | 5 | 5 |
| Case IV | 38% | 254 | 254 | 5 | 5 |
| Case V | 42% | 262 | 262 | 5 | 5 |
| Case VI | 45% | 267 | 267 | 5 | 5 |

Table 4: Equipment Inventories for 6 cases of fire growth from 30-45 percent over the next 10 year period

| | SSA Drones | RR Drones | Maintenance Cost | Repair Personnel | Charging Stations | Net Cost |
|---|---|---|---|---|---|---|
| Price/Unit | 10,000 | 10,000 | 1,000 | 70,000 | 500 | |
| Source | Problem Statement | Problem Statement | Estimate | Ave salary [11] | Ave charger [3] | |

Table 5: Costs for drones and associated goods/services necessary for implementation (AUD)

# 5 Part III: Determining Ideal Locations for RR Drones

## 5.1 Modelling Approach

We determine a model for optimizing for optimizing RR drone placement for a given topographical region and size of fire. Our modular process will have three components, wherein the first part can be implemented independently from the other two:

1. *Construction of a least cost path:* Defining drone locations from the EOC to the fire considering regional topographical heterogeneity. Jagged regions are more costly to fly over because they reduce the range of a RR drone, so these are avoided.

2. *Fire Perimeter:* Defines drone locations to form an unbroken semi-perimeter around the segment of the fire being fought.

3. *Changing of the Guard:* Drones have a battery life of 2.5 hours, so they are replaced in the most optimal fashion in a "changing of the guard" for charging purposes.

## 5.2 Assumptions

1. The EOC unit sets up a base camp some distance from the fire. The ideal path between the EOC and the fire perimeter $d$ will be determined by Dijkstra's algorithm taking into account regional topography.

| | Fire Growth | Current Equipment Value | Depreciation Rate | Future Equipment Value | Maintenance/ Replacement | Net Cost |
|---|---|---|---|---|---|---|
| Case I | N/A | 3,499,500 | 0.2 | 375,756 | 3,123,744 | 6,623,344 |
| Case II | 30% | 4,549,350 | 0.26 | 230,902 | 4,318,448 | 8,867,798 |
| Case III | 34% | 4,689,330 | 0.268 | 207,119 | 4,482,210 | 9,171,540 |
| Case IV | 38% | 4,830,500 | 0.276 | 191,152 | 4,639,348 | 9,469,848 |
| Case V | 42% | 4,969,290 | 0.284 | 175,964 | 4,793,325 | 9,762,615 |
| Case VI | 45% | 5,074,275 | 0.29 | 165,245 | 4,909,030 | 9,983,394 |

Table 6: Net Costs for 6 cases of fire growth from 30-45 percent over the next 10 year period

2. *Firefighting Region:* The EOC unit then sets up some unbroken perimeter along an arc of the fire's circumference; for this example, we will assume that the EOC unit covers one-third of the perimeter without loss of generality for any alternative strategies. As the fire size is reduced, the scope of the perimeter will naturally continue until the fire is extinguished. Thus, in general terms, the drones will cover $\frac{1}{k^{th}}$ the arc length of the fire. $k$ will typically progress sequentially along the sequence $k$ = 3, 2, 1 as the fire decreases in size.

3. *Manageable Fires:* We consider for this example a "manageable fire," such that this fire is discrete and of a reasonable size such that it can be combated by one EOC base camp. For larger fires, we will assume that the relationship between number of base camps and overall fire size is linear; so that we can generalize the manageable fire to the $n^{th}$ degree to optimize a solution for any fire size.

4. *Drone Behavior:* The radio repeater drones have a single function: to form an unbroken line of communication from base camp all the way to the furthest extent of the EOC team's established perimeter to ensure communication is never lost between any squadron.

Without loss of generality, assume that the Radio Repeater drones have a circular range. Therefore, the optimum string of drones will be the minimum number of drones required to extend the signal from base camp to the furthest established perimeter. We know from the first principles of calculus that the optimal configuration will occur with a string of circles all tangent to each other and tangent to the fire's perimeter. If the terrain is jagged, the signal will be less effective, but ultimately the same principle applies: place a series of drones from base camp to the furthest perimeter so that each drone's range is tangent to the range of the drone in front of it and behind it. The only difference is that the quantity of drones required will be greater in jagged terrain.

## 5.3 Least Cost Path

For a given region with a fire and a corresponding base camp, we can break the region down into an $MxN$ grid. Each square will be assigned either smooth or jagged and also a corresponding cost for each. Let $C_{smooth}$ be 2, let $C_{Jagged}$ be 5, and let $C_{fire}$ be 25. Each segment's cost represents the opportunity cost of the adjacent option; because drones have a range of 5 km in smooth terrain, the cost of jagged terrain is 5; similarly, drones have a range of 2 km in jagged terrain, so the cost of smooth terrain is 2; and the cost of traveling into the fire is chosen to be arbitrarily large so it never occurs.

Then we can implement Dijkstra's algorithm [6] to determine the lowest cost path from the base camp, $(0,0)$ to the top point of the fire, $(i, j)$ along a grid, as show in in figure 7. Once the cost has been

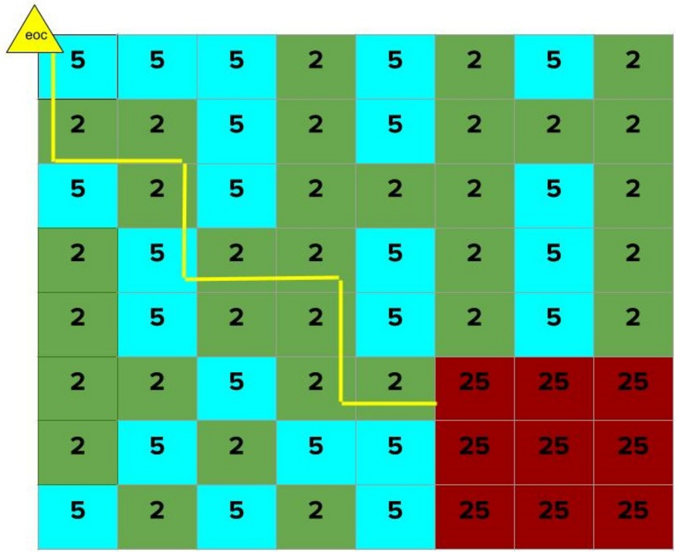


Figure 7: A visual representation of the least-cost path from the EOC (yellow triangle) to the fire perimeter for a region with highly heterogeneous topography. 'Jagged' regions (blue) have a higher cost than 'flat' regions (green) due to the effect of topography on RR drone range

calculated via Dijkstra's Algorithm, the least cost path can be deduced algebraically by the following equation:

$$C_{min} = 2 * s + 5 * t$$

Where $C_{min}$ is the minimum cost path and $s$ and $t$ are positive integers that represent a unique permutation of squares. The algorithm to determine $s$ and $t$ is trivial. For example, if $C_{min}$ is 18, then $s = 5$ and $t = 2$, representing the permutation of squares $P = \{2, 2, 2, 2, 2, 5, 5\}$. Because this is a unique path, the optimal path is clear and can be derived from the set of permutations of adjacent squares of size 7.

## 5.4 Fire Perimeter

Once we have established the least cost path, we need to establish a perimeter of VHF drones such that the drones encompass one-third the arc length of the fire. More generally, we can now say that, for some function G which maps a given region's topology and fire size, G must map to a set D of $n$ drones as follows:

$$G(T, F) :\rightarrow D = \{d_1, d_2, d_3, \dots, d_n\}$$

such that the following properties must hold for some fire object, $F$, its corresponding arc length $||F||$, and $\forall d_i, d_j D$ :

1. $range(d_i) = range(d_j)$

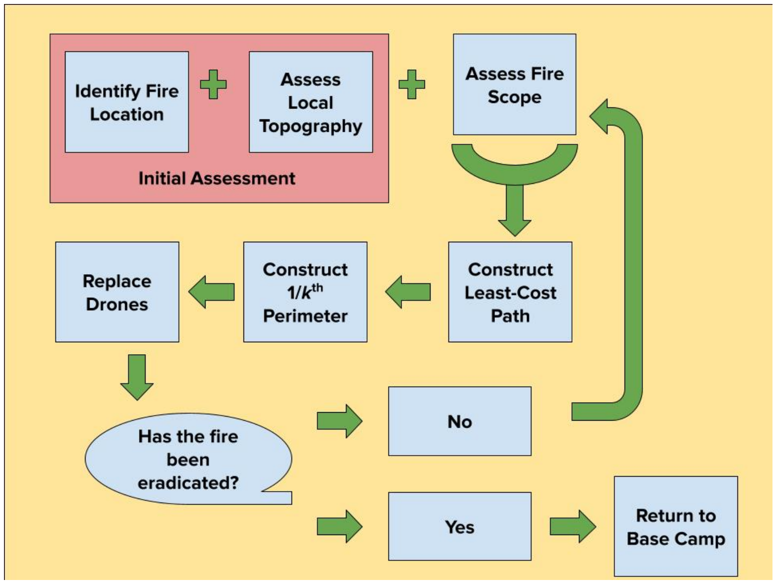


Figure 8: Drone Positioning Routine: after an initial assessment of regional characteristics and topography, the fire scope is assessed and a least-cost path is constructed from the EOC to the fire perimeter, where a perimeter is constructed for the 1/kth proportion of the fire being fought. As drones lose battery, they are replaced in a 'changing of the guard'. The process repeats while the fire is still being fought.

2. $d_i \perp d_j$
3. If $d_i$ is a limit point on $F$, then $F \perp d_i$
4. $\forall d_i$ satisfying Property 3, $\frac{1}{3}x||F|| \leq \Sigma(d_i)$

Then following graphic depicts the model representation described above in general terms:

## 5.5 Changing of the Guard

In order to ensure the drones do not run out of battery, they must be replaced every 2.5 hours. Given a distance of 5 km from the base camp, drones can reasonably replace one another on approximately 5 minute centers (determined by the distance from base camp multiplied by the drone's speed). The drones will be replaced in the following manner:

Running 5-minute centers, new drones will replace old drones from either perimeter; as new drones replace the perimeter drones, the drones move inwards up the queue with each drone taking the spot of the drone before it. This process repeats iteratively until the drone closest to base camp moves into base camp for recharging and a new drone departs to replace the furthest drone on the opposite side. This process repeats itself until the fire is extinguished or the drones are no longer needed, as shown in figure 9. Assuming the drones exist in a linear queue which is $n$ drones long and has $n + 1$ total length including the base camp, it takes $n$ steps until the $n^{th}$ drone returns to the base camp. Therefore, the drones can exist in the queue only as long as their battery life is not zero. Because we already determined drones can be replaced every five minutes, this implies the drone battery life divided by the

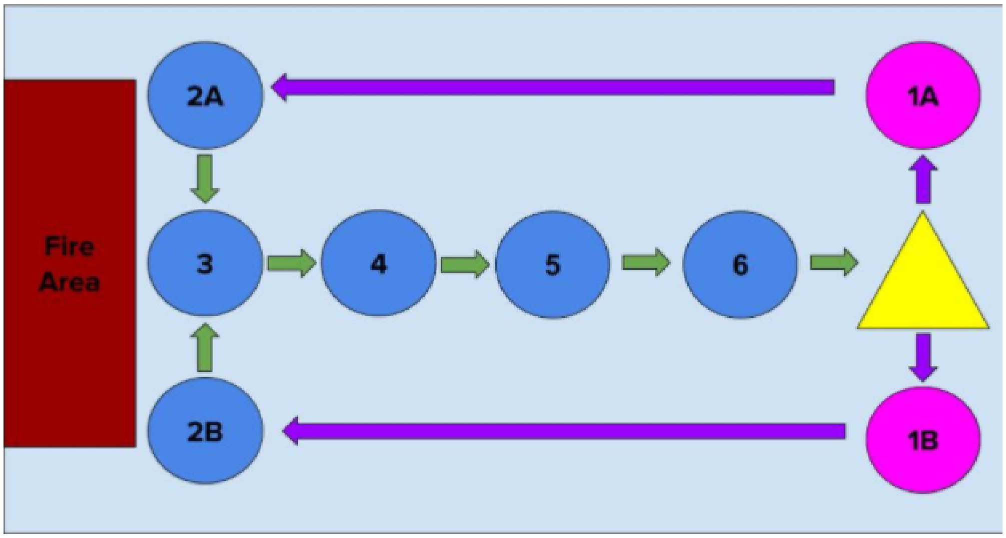


Figure 9: Changing of the Guard: Drones begin at the EOC (yellow triangle) and fly either to its right or left, denoted by 1a or 1b at the fire perimeter. They start at the outmost position (2a, 2b) and fly inward (3). Many drones can be between position 2a/2b and 3 in an unbroken chain. The drone with the lower battery will always be in position 6. Drones are recharged and replaced from the EOC.

number of drones can never be less than 5 minutes. In symbols:

$$\frac{150 \text{ Minutes}}{n} = 5 \text{ minutes per drone}$$

Therefore, the maximum number of drones per base camp can never exceed 30. If a fire needs 31 or more VHF drones, there must be multiple base camps combating the fire.

## 5.6 Strengths and Weaknesses

### 5.6.1 Strengths

1. *Segmented Approach:* The segmentation of the method offers flexibility in real-world implementation; for example, given different average distances between the base camp and fire perimeter, or drones with different battery life, the approach can be modified. Its modular implementation offers the ability for implementation in parts, as well; the placement of RR drones from the base camp to the fire perimeter can be used without necessarily using the fire perimeter and changing of the guard methods.

2. *Clear and Comprehensible:* Offers a diagrammatic solution to the problem of optimizing drone placement within a given region and directly maps the drones to the region.The clarity and generalized nature of the problem allows researchers to easily understand and implement the solution.

3. *Sensitive to Topography:* The method is sensitive for regions with heterogeneous topography; for instance, the implementation shown in Figure 7 displays a case with extremely heterogeneous topography. This allows for implementation of the method across any type of region.

### 5.6.2 Weaknesses

1. *Abstracted Solution:* We generalize fire shapes and overall desired drone behavior to offer an abstract solution. Furthermore, we did not incorporate real-world data into the model; we believed that generality and abstraction from specific cases would be far more powerful and allow firefighting support personnel to understand the high-level problem without muddling in the details of any specific region—thus not missing the forest for the trees.

2. *Limitation of EOCs:* In the solution we offer, a maximum of 30 drones can be maintained per base camp based on pure logistics (availability and timing of charging, etc). However, our model from Part I suggests that fires requiring 31+ RR drones can range from 300-1200 km$^2$ in scope depending on the fire's risk of spreading. For such a large scope, is not unreasonable to assume that in the case of a fire that requires 30 drones, firefighters would require more than one EOC to offer entry into the fire perimeter.

# 6 Conclusion

Drones offer a powerful tool to support firefighters in their efforts to calm the unprecedented wildfires in Victoria, Australia. To offer a comprehensive plan for implementation of drone support, this paper outlines the optimal quantities of RR and SSA drones needed to fight wildfires in Victoria, along with a model for determining the ideal positioning of RR drones, as well as the estimated cost for implementation on a ten-year scale, accounting for changes due to mechanical depreciation and the climate crisis.

In Part I, we modeled the optimal quantities needed of RR and SSA drones required for the surveillance and communication needs of boots-on-the-ground firefighting units as a function of wildfire scope. We constructed a linear optimization model which characterized sub-regions of Victoria using their topography and their FFDI, an index calculated from climate factors (humidity, temperature, drought index, etc) directly correlated to wildfire scope and risk of spreading. Given the risk of fire is directly correlated with the size and spread of fires in a given region, we simulated a range of fires with varying scopes, and optimized drone quantities using a set of linear equations assuming the fires had a relatively circular shape. The resulting outputs enabled us to estimate the optimal drone response while remaining within the constraint of economic efficiency for a given fire. Generalizing a random representative sample of Victoria's regions and examining their maximum FFDIs during last season's bushfires, we determined the optimal quantity of drones needed to be 180 RR and 133 SSA drones. Though the model may not accurately reflect drones needed for a given fire due to dynamically shifting conditions, such as weather and wind, the estimate provides a strong base number which can be adjusted.

However, we acknowledge that the probability of extreme fire events occurring over the next 10 years will likely increase, as other wildfire projections suggest at minimum a 30% increase in land burned over the coming decade. Therefore, we adjusted our previous model by factor scaling FFDI values based off of projections of fire activity for the next 10 years. Budget estimates were increased to account for depreciation attributed to fire damage and wear/tear. We scaled the rate of depreciation by a factor proportional to the increased frequency of fires associated with higher FFDI values. This approach allowed us to simulate drone inventory requirements for the future. Striking a balance between the conservative and pessimistic camps, it is the judgement of this firm that there will likely be an approximate 38% increase in land burned over the coming decade. Due to increased equipment needs and greater rates of depreciation, this report suggests increasing the quantity of drones be increased to 249 VHF drones and 184 SSA drones for the coming decade. These adjusted numbers will ensure Victoria County Fire Rescue personnel will have adequate air support to maintain reliable communication and surveillance channels.

An iterative approach was further implemented to optimize the positions of RR drones to ensure that firefighting teams never lose communication with the EOC. The approach involves determining a least-cost path from a given base camp to the apex of a fire, establishing a semi-perimeter of drones roughly equal to one-third the arc length of the fire's perimeter, and rotating the drones on 5-minute centers to ensure communication channels are never broken while still ensuring drones never run out of battery. Additionally, this report determined that any given EOC camp can only reasonably support 30 drones with two given allocated sets of drones to ensure full rotational capabilities to balance communication networks with this consistent recharging process. Therefore, if a fire demands a greater quantity of drones, the number of base camps or drones per base camp must increase proportionately.

Finally, the paper recommends to the CFA that the Victoria government allocate $9.47 million AUD to effectively implement and support this drone program over the next decade. Given the severity of this problem, this team postulates that this is a relatively low-cost solution to a grave and imminent danger to all who reside within Victoria. The return-on-investment for this program is immeasurable, with regards to both dollars saved to the Australian taxpayer as well as lives saved by providing firefighters with much-needed tools to enhance visibility and communication on the front lines of the battle to save the planet from the deleterious effects of climate change. As these first responders straddle the line between imminent danger and an unknowable future, every second matters; so every additional drone will serve an irreplaceable role as an augmentation and extension for the firefighters at the edge of chaos.

# 7 Budget Request

For the Consideration of the Victoria State Government:

## 7.1 Budget Summary

With the recent rapid increase of wildfires across Victoria, it is more crucial than ever to equip firefighters with every possible weapon. Two of the most crucial assets in firefighting, information and communication, are enhanced significantly through the use of drones. This budget provides an outline for a firefighting drone program to enhance current firefighting efforts. Based on the most conservative estimates, it is believed that wildfires will grow about 30% over the next decade; contingent on worsening conditions, it is the judgement of this consultancy that the region of **Victoria should prepare for 38% growth in wildfires**. Using our proprietary model, we have estimated the necessary quantities of various types of drones and determined that an **initial budget of $4.83 million AUD** should be allocated to initially implement the program; furthermore, there should be an **annual budget of $515,482 AUD allocated over each of the remaining nine years** to ensure equipment remains at the highest standard possible to enable Fire Response Victoria to most effectively perform their tasks and keep Victoria safe from this national emergency. Ultimately, **a total cost of $9.47 million AUD** over the next ten years should be allocated to most effectively combat this threat.

## 7.2 Budget Categories

The following items are included in this budget request:

1. **SSA Drones:** survey and situational awareness (SSA) drones equipped with HD cameras spread themselves along the perimeter of the fire

2. **RR Drones:** Radio repeater (RR) drones optimize communication between firefighting coordinators and firefighters. Their range is limited by topography

3. **Maintenance Tools:** tools associated with drone repair/maintenance

4. **Drone Maintenance Personnel:** It is estimated that one drone maintenance personnel can be responsible for up to 75 drones.[11]

5. **Charging Stations:** Mobile charging stations for efficient transportation.[3]

## 7.3 Drone Quantity Prediction using Evidence-Based Optimization Model

To estimate the necessary quantities of situational awareness (SSA) and radio repeater (RR) drones necessary, we characterized sub-regions of Victoria by their risk for fire using their topography and 2019-2020 weather data regarding humidity, drought index, temperature, etc. Given the correlation between increased fire risk and increased fire spread, we were able to predict average wildfire scopes across Victoria and assess how many of each type of drone would be necessary for a given size of wildfire. The quantity of SSA drones was determined based on the expected value of the size of a given fire's perimeter. The quantity of RR drones was determined based on the number of drones necessary to form a continuous least-cost path from the base camp to the fire, as well as expected value of the size of a given fire's perimeter.

## 7.4 Budget Estimations

Given the most conservative estimates put increased area burned in wildfires over the next ten years at 30 percent, but it may likely be higher, we calculate price estimates for five cases ranging from a 30-45 percent increase in wildfire area burned, based on our estimates for the current drone need. For each of these cases, and taking into account the depreciation for the drones, we estimate net initial costs as shown in Table 7.

| | Fire Growth | Current Equipment Value | Depreciation Rate | Future Equipment Value | Maintenance Tools | Net Cost |
|---|---|---|---|---|---|---|
| Case I | N/A | 3,499,500 | 0.2 | 375,756 | 3,123,744 | 6,623,344 |
| Case II | 30% | 4,549,350 | 0.26 | 230,902 | 4,318,448 | 8,867,798 |
| Case III | 34% | 4,689,330 | 0.268 | 207,119 | 4,482,210 | 9,171,540 |
| Case IV | 38% | 4,830,500 | 0.276 | 191,152 | 4,639,348 | 9,469,848 |
| Case V | 42% | 4,969,290 | 0.284 | 175,964 | 4,793,325 | 9,762,615 |
| Case VI | 45% | 5,074,275 | 0.29 | 165,245 | 4,909,030 | 9,983,394 |

Table 7: Net Costs for 5 cases of fire growth from 30-45 percent over the next 10 year period

Given the strong influence of climate change and the increasingly hotter, drier Australian climate, there is incentive to prepare for significant wildfire growth. In accordance with this, we recommend preparing for Case IV, a 38 percent increase in wildfire area burned over the next ten years. A further breakdown of the budget is included in Table 8.

| | SSA Drones | RR Drones | Maintenance Cost | Repair Personnel | Charging Stations | Net Cost |
|---|---|---|---|---|---|---|
| Quantity | 184 | 249 | 4 | 4 | 433 | |
| Price/Unit | 10,000 | 10,000 | 1,000 | 70,000 | 500 | |
| Net Cost | 1,840,000 | 2,490,000 | 4,000 | 280,000 | 216,500 | 4,830,500 |

Table 8: Case IV: Current net cost estimate based on model estimates for numbers of drones needed (AUD)

With an initial investment of $4.8 million AUD, along with an annual investment of approximately $515,482 AUD for maintenance, and to get the best value from the initial investment, the Rapid Bushfire Response division will be able to more efficiently and effectively respond to bushfires in the 2020-21 season and for the next decade.

Return of the Drones Modeling Agency
in support of the Victoria County Fire Authority

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