SENSITIVITY ANALYSIS OF AERIAL WILDFIRE FIGHTING TACTICS WITH HETEROGENEOUS FLEETS USING A SYSTEM OF SYSTEMS SIMULATION FRAMEWORK

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Abstract

The rise in the average global surface temperature has caused wildfire seasons to expand leading to more incidents with severe intensities causing a significant increase in suppression expenditures, losses, and casualties. In addition, the larger number of wildfire incidents gives rise to higher carbon release that stays in the atmosphere, therefore, further intensifying global warming. Fire incidents vary substantially in complexity from the point of view of required and available firefighting means which makes for a challenging multi-level complex problem. System of Systems (SoS) approach can be used to investigate such problems taking into accounts various factors such as response time, firefighting tactics, fleet composition, available agents, and resources. This study uses a SoS simulation framework for overall wildfire suppression mission modeling. It builds upon the research previously performed by the authors by introducing:

1. An extensive analysis for the effect of wildfire environment parameters on fire spread.
2. Multiple suppression tactics which open the door to new solutions for wildfire fighting in addition to revealing nuanced trends at the system of systems level by using SoS framework.
3. A heterogeneous fleet composed of various suppression drones with different airframe configurations, payload capacity, flight velocity, and powertrain architecture.

Keywords

Wildfire Suppression Tactics; Aerial Firefighting; Agent-Based Simulation; System of Systems

1. INTRODUCTION

In recent years, forest fires have been causing both environmental and socio-economic damage due to the increase in fire frequency, fire intensity, season length, area burnt , carbon emissions and suppression expenditures as the global average temperature has peaked due to climate change. Based on recent anomalies and historical global temperature data, the Global Climate report [1] predicts that the year 2022 has a 99.7% probability of being the peak of the last decade. The catastrophic combination of rising global surface temperature combined with poor air quality, dry vegetation and slow forest regeneration is creating a severe warming cycle. Temperature rise is one of the main reasons for the upward trend in wildfires, leading to increased Greenhouse Gas (GHG) emissions associated with wildfires. Recent studies [2] show that carbon emissions associated with wildfires are no longer considered part of the carbon-neutral cycle, with 10% of carbon emissions remaining in the atmosphere, exacerbating climate change impacts. Moreover, the growth of forest-urban interfaces not only increases the number of human-caused fire incidents, but also puts human lives at great risk.

The forest fire in Portugal (2017), a fire-prone country, not only burnt more than 500,000 hectares, but also caused the death of many firefighters and civilians [3]. This shows that forest fire preparedness is of primary importance for suppressing forest fires and controlling the severity of fire damages. However, the fact that the fire incident in Sweden (2018) resulted in the burning of more than 23,000 hectares shows that providing more resources for firefighting does not necessarily provide the optimal solution, as the firefighting assistance for this incident was the largest civil protection operation in Europe [3]. Furthermore, as Sweden is not considered a fire-prone country, the fact that areas with low fire proneness can also cause severe and intractable damage suggests that the phenomenon of wildfires should be thoroughly investigated to discover the reasons behind these damages and prevent them in the future.

Previous research by the authors has provided an overview of the fire model and containment methodology for wildfire incidents but has been limited to capturing the impact of heterogeneous fleet composition as well as using different containment methodologies for wildfire suppression. This study aims to reveal the effects of heterogeneous fleet compositions as well as the suppression strategies used in wildfire suppression missions. Furthermore, the authors investigate the effects of environmental parameters by providing an environmental sensitivity study for the wildfire phenomenon. This paper extends the previous research conducted by the authors by first presenting a brief literature review on current wildland firefighting equipment and methodologies used in suppression missions. Then, the System of Systems (SoS) framework is introduced as an agent-based simulation and data analysis environment, including aircraft design, wildfire, suppression, and cost modeling. Next, a use case is shown for an overall sensitivity analysis of wildfire and suppression model parameters. Finally, the results of the sensitivity analysis of each model are presented and the paper concludes with overall outcome and future work.

2. WILDFIRE LANDSCAPE

2.1. General Wildfire Fighting Equipment

The main resources used by fire management agencies can be categorized into three groups: fire crews, ground, and aerial vehicles. Fire crews mainly consist of trained personnel on long-term or seasonal contracts, such as hand crews and smokejumpers, civil service staff and volunteer firefighters, equipped with hand tools, hoses, pumps, personal protective equipment and other means for fire management and containment. Ground vehicles are mainly different types of fire engines and heavy equipment, varying according to terrain and fire type, and are mainly used for retardant delivery, vegetation removal, fire line construction, fire suppression and fire crew transportation. Finally, aircraft are used for crew, equipment, and fire-retardant transportation as well as fire retardant dropping for suppression. The suppression mission assessment for aircraft is divided into five groups: reducing fire intensity, delaying fire spread, protecting risk areas, building fire lines, and extinguishing the fire.

The deployment of available and required assets varies from one country to another, depending on reserves and fire proneness. However, European Union (EU) member states and other participating states provide international assistance when national resources are not sufficient for wildfire incidents. In 2019, the EU introduced a new component for the EU Civil Protection Mechanism, rescEU, which provides a fleet of aerial firefighting vehicles [4]. Currently, the rescEU reserve consists of 11 firefighting airplanes and 6 firefighting helicopters from 6 EU Member States in emergency situations. Depending on the fire proneness and topography, aerial suppression may not be necessary, as in the Netherlands in 2020, where 1830 fire engines and 652 water trucks were deployed, and aircraft were deployed only for thermal imaging. On the other hand, in some incidents all firefighting means can be used, such as in Greece in 2020, where 3,459 ground vehicles and 64 aircraft are deployed alongside 18,419 people, including permanent and seasonal staff, civil service personnel and volunteer firefighters. There are also other incidents where all firefighting means are needed but state reserves are not sufficient or available and international assistance is needed, such as in the case of Italy in 2020, where 2 aircraft of the National Fire Service were deployed on the basis of a government agreement and the assistance of the EU Civil Protection was not available [3].

Overall, most fire incidents requiring only the deployment of fire crews and ground agents can be contained with available resources. However, for large fire incidents requiring all firefighting means or only aircraft, when the life of the fire crew is endangered or ground agents are inoperable, firefighting means may not be sufficient or available, depending on the number of aircraft and aircraft type.

2.2. Wildfire Suppression Strategies and Tactics

There are three main plans or directions that can be chosen to control fires: direct control, perimeter control and prescription control. **Direct control** is applied to relatively small fires which can be fully suppressed. **Perimeter control** is a strategy that aims to contain active fire zones which are responsible for the fire spread. Even though, this strategy slows down the fire spread, it does not necessarily lead fully containment. Finally, **prescription control** follows a strategy that allows the fire to burn within a set of geographical boundaries and predetermined combustion characteristics [5].

Depending on the chosen strategy, initial attack tactics can be determined as the next step. The initial attack tactics for a fire containment and control vary from one incident to another. These tactics can be analyzed under five categories: direct attack, parallel attack, indirect attack, hot spotting and mop up [5]. A **direct attack** is considered to be any treatment applied directly to burning fuel. A direct attack can be obtained by following a flank side originating from an anchor point or attacking the fire from every location (head, back, left, and right flank) at the same time. The corresponding locations are indicated in FIGURE 1. As the name suggests, **parallel attack** is a method of firefighting in which the fire line is built approximately parallel to the edge of the fire and far enough away to allow firefighters and equipment to operate effectively. The risk of fire escape can be reduced by using parallel attack. **Indirect attack** is a method of suppression where the control line is located at a considerable distance from the active edge of the fire. This method is preferable when a direct attack is not applicable, or it is not secure enough. **Hot spotting** is controlling the spread of fire at points where it spreads more rapidly or poses a particular threat. It is often the first step in rapid control, emphasizing first priorities. This method is necessary when fire escapes due to convective heat transfer and creates multiple spots. **Mop up** is extinguishing or removing burning material near control lines to increase the fire safety and reduce residual smoke. This method is crucial to ensure that fire line construction is carried out effectively [6].

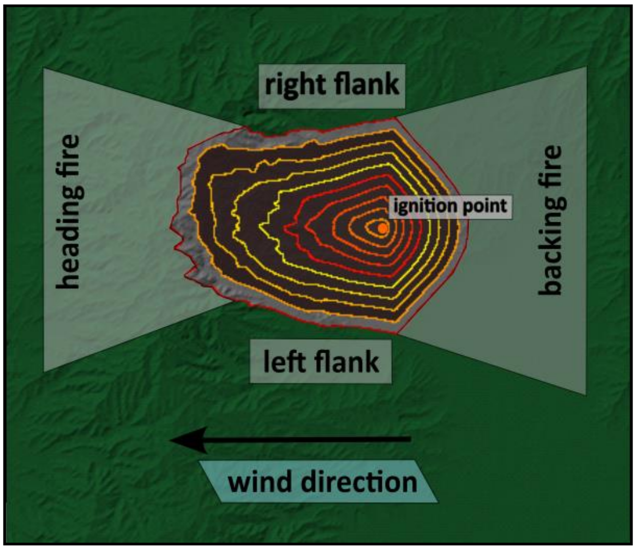


FIGURE 1. Illustration of different fire segments ignited from a point source

In this study, the authors demonstrate the impact of both direct and indirect attack tactics on the burnt area and the number of successful fire containment.

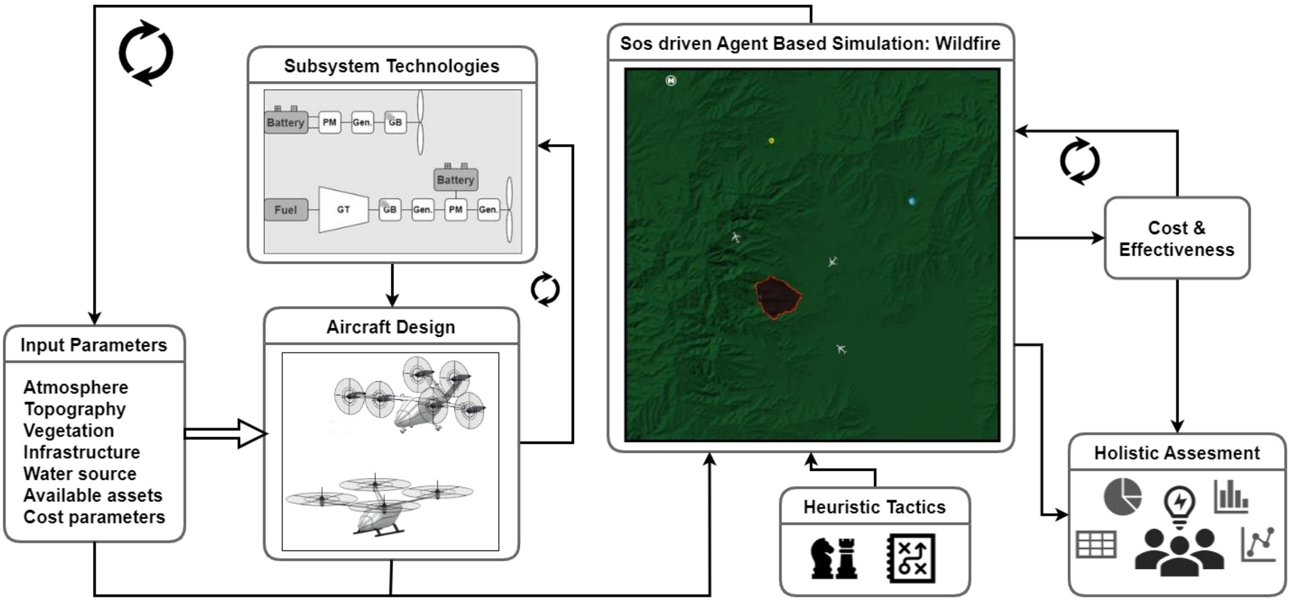


FIGURE 2. System of Systems driven multi agent-based simulation framework

3. SYSTEM OF SYSTEMS DRIVEN AGENT BASED SIMULATION FRAMEWORK

3.1. Overview of the Framework

In order to represent the phenomenon of aerial wildfire suppression; subsystem, system, and system of systems definitions need to be established. In the framework, subsystem definitions such as fleet composition are fed into the simulation as input parameters. System definitions, such as aircraft or fire, are created using object-oriented programming paradigm to define system properties and behaviors and to enable interactivity between component systems. An agent-based simulation model is preferred to be able to capture synergies between constituent systems.

The framework receives the environmental conditions, fleet composition and cost parameters to be fed to fire model, aircraft model and cost model respectively. Depending on the heuristic logic implemented, the suppression mission is simulated in the framework, and mission responses are obtained for post-processing in order to complete overall analysis and evaluation based on several evaluation metrics such as total cost of operation (see FIGURE 2). A detailed description of the framework can be found in the authors' previous works [7].

3.2. Heterogeneous Fleet Composition

The fleet composition selected for the forest fire suppression mission consists of 6 different aircraft types. Two different electric vertical take-off and landing (eVTOL) configurations, multirotor and tiltrotor, and three powertrain architectures, all-electric and serial hybrid-electric, are sized by constraining with respect to the payload. The details of the setup are described in TABLE 1.The aircraft types are chosen such that the payload capacity, flight velocity and power train architecture comparison can be done between different compositions. The details of the design process of the fleet are presented at [8] and explained in [9].

Based on various powertrain architectures, each aircraft is limited to provide a certain amount of energy. The available/usable energy is one of the key parameters for the requirement of reenergization during the wildfire mission.

	Small Capacity Electric Multirotor	Small Capacity Hybrid Multirotor	Large Capacity Hybrid Multirotor	Medium Capacity Electric Tiltrotor	Medium Capacity Hybrid Tiltrotor	Large Capacity Hybrid Tiltrotor
Configurations	Multirotor	Multirotor	Multirotor	Tiltrotor	Tiltrotor	Tiltrotor
Powertrain Architecture	Electric	Hybrid	Hybrid	Electric	Hybrid	Hybrid
Payload [kg]	360	360	720	540	540	720
Flight velocity [m/s]	~40	~40	~40	~65	~65	~65
Usable energy [MJ]	0.71	0.86	1.1	0.78	0.84	0.97
MTOM [kg]	~2400	~1500	~3000	~3400	~2200	~2600
Cruise Power [kW]	196	212	289	225	283	317
Hover Power [kW]	317	325	472	622	711	846

TABLE 1. Aircraft details for fleet composition

3.2.1. Top Level Aircraft Requirements

Since there are operational constraints for aircraft to operate in wildfire fighting mission, these constraints must be taken into account before sizing the aircraft to achieve the expected performance. The mission requirements and operational constraints are described below:

1) Operational wind speed should not pass 25 knots.
2) Aircraft must cross the ridges at least 1,000 ft above the ridge altitude.
3) The payload capacities must be fixed to 360, 540 and 720 kg for each configurtions.
4) Powertrain should be all-electric or serial hybrid-electric.
5) Reserve time must be set to 20 mins.
6) Range requirement is 100 km for each aircraft.

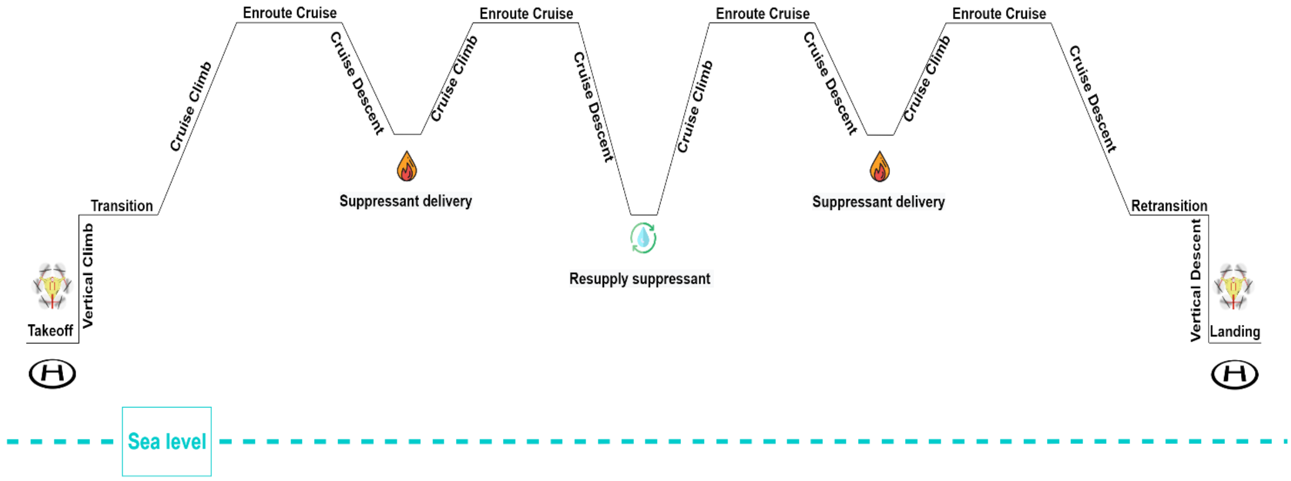


FIGURE 3. Mission profile representing suppressant delivery and replenishment

3.2.2. Mission Profile

The mission profile is implemented into the simulation framework via the suppression logic to capture the aircraft suppression mission accurately. The mission profile consists of two legs to represent both the drop task and resupplying task. In FIGURE 3, the mission profile followed in the simulation is presented. The logical implementation of mission segments into the agent task sequence is demonstrated in FIGURE 4.

3.3. Suppression Tactics

In a multi-agent simulation framework, all agents (fleet composition) are subjected to a set of rules (behavior) to contain the fire. Depending on the heuristic algorithm given to the agents, the dynamics of the suppression task is expected to change. Therefore, this study extends the tactics given to agents to explore the importance of tactics in the overall suppression task. The task sequence of the agents is updated by four different algorithms.

The first tactic is a direct attack approach by following the fire front with a highest spread rate. The choice of a fire front is made by minimizing the distance of an agent to the fire as well as maximizing the distance of the fire to predefined protection locations such as urban areas. If a location is already assigned to an agent, the next agent selects another location following the same logic. Once the fire front is selected, the Moore neighborhood within a radius of the selected location is examined and the neighbor with the maximum spread rate is selected for suppression. The spread rate of each position is calculated by a mathematical model formulated in [10]. The fire spread rate is estimated by considering vegatation combustibility, the slope of the location, terrain elevation, wind speed, wind direction, relative humidity, and temperature. The studies done by authors demonstrated that the terrain slope is one of the most essential parameters which is determining the rate of fire spread. Considering the slope effect, the second tactic implemented to the simulation follows the same logic as the previous tactic, taking into account the slope of the fire position that is being examined.

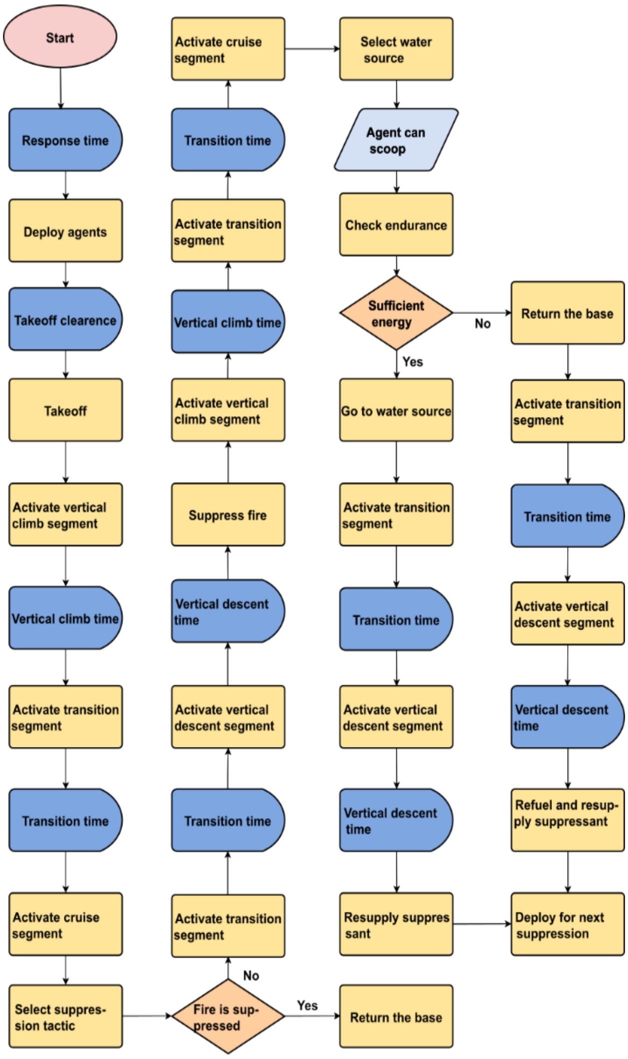


FIGURE 4. Agent task sequence logic with the implementation of the mission profile

The choice of the firefront is done by minimizing three cost parameters: the distance of the aircraft from the fire, the distance of the fire from the protection locations, and the mean slope of the Moore neighborhood (Radius=1) of the fire position. As it can be seen in FIGURE 5 (left), each fire drop is influenced by the terrain slope.

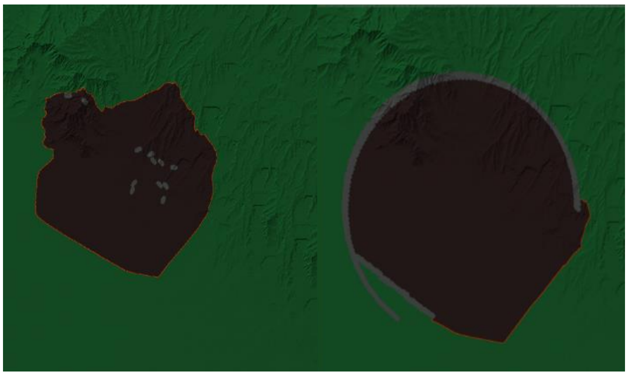


FIGURE 5. Elliptic fire line construction followed by fire front tracking with terrain slope

Encircling a fire is considered as a well-established approach to take the fire under control, especially if the fire is large. There are several ways to encircle a fire both with direct and indirect attack methods as described in section 2.2. Attacks can be made by building continuous fire lines or by suppressing different locations as in, hot spotting. Encircling approach is implemented to the simulation in a way that agents prioritize the distance of the fire locations from the boundaries of the area of interest. First, the logic receives the information of the ignition center. Then, it creates an area of interest around the ignition center by placing an imaginary polygon, by default four corners are considered for the polygon size. Then, the agents search for the fire position closest to each center of the polygon edge. If the position is already followed by another agent, the agent chooses the second position closest to the polygon to suppress. If all the corners of the polygon are taken, agent chooses the closest fire position to suppress. If any fire position reaches any location on the border of area of interest, the imaginary polygon size is extended. This process is done until the boundary of area of interest reaches the boundary of the real map considered in the fire incident. The purpose of this method is to contain the fire by attacking from various positions on each side and not allowing it to expand in a particular direction, which could lead the fire to spread faster. In addition, the tactic is capable of capturing spot fires.

As in parallel attack and indirect attack, attacking a fire from a distance by constructing a fire line, is considered the safest way to contain a fire, especially if the fire is large and the fire crew is involved. Therefore, the last method, elliptic fire line construction, is chosen to combine both indirect and direct attacks sequentially. Previous studies [11] show that fire growth can be represented by a wave propagation model based on the assumption that the fire shape can be formulated by a closed shape, a combination of elliptical fire particles. It is therefore advantageous to construct the fire line in an elliptical shape to contain the fire. The implementation of the indirect attack logic is initiated by drawing an imaginary predefined ellipse around the ignition center. Then, pre-defined ellipse is rotated along the wind direction since fire spread is more likely to follow the wind direction based on the environmental study conducted in section 5.2. Since the ellipse size does not change during the simulation, the center of the ellipse is shifted towards the possible fire growth direction to reduce the risk of fire spread before the fire line is constructed. Once the agents have completed the fire line construction, they continue the mission with a direct attack, tracking the fire front. However, if the fire exceeds the pre-defined ellipse boundaries, the indirect suppression is to be cancelled and the tracking fire front is activated (see FIGURE 5, right).

The logic behind the implementation of each tactic can be seen in FIGURE 6. The strategy of using direct attack and indirect attack becomes a very powerful choice when the fire is challenging and difficult to take under control. To increase the effectiveness of the indirect attack, fire line can be built dynamically by monitoring the fire and as in parallel attack, fire line can be built from a distance based on the active fire positions. However, there is also the need to investigate whether applying both direct attack and indirect attack simultaneously by dividing the fleet based on pre-assigned tasks or performing both types of attack sequentially (as in elliptic fire line construction) is more advantageous. Another issue is that it is not possible to determine which tactic is the most appropriate or whether there is an optimal tactic, as the phenomenon of wildfire is non-linear. Suppression tactics will vary in their effectiveness not only depending on the number of aircraft used in the mission, but also on the different combinations of the fleet.

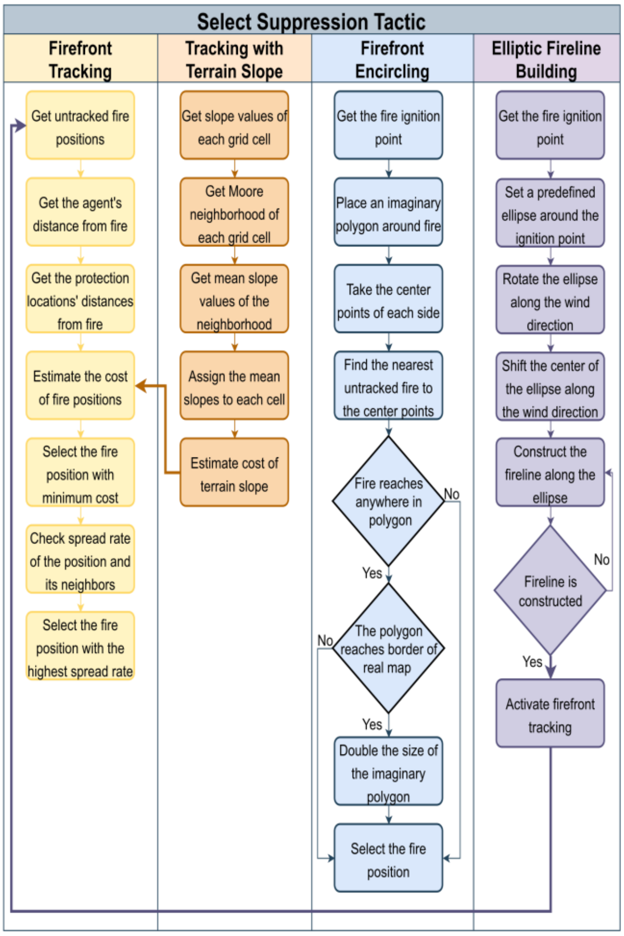


FIGURE 6. The logic implementation of each tactic to suppress fire

3.4. Cost Model

The cost model of the aerial firefighting mission consists of the acquisition cost of the fleet composition and total cost of operation per mission. The total cost of operation per mission is calculated as a sum of capital expenses and operational expenses. The details of the cost model distribution are shown in FIGURE 7. The mathematical model used in the cost estimation can be found in [12]

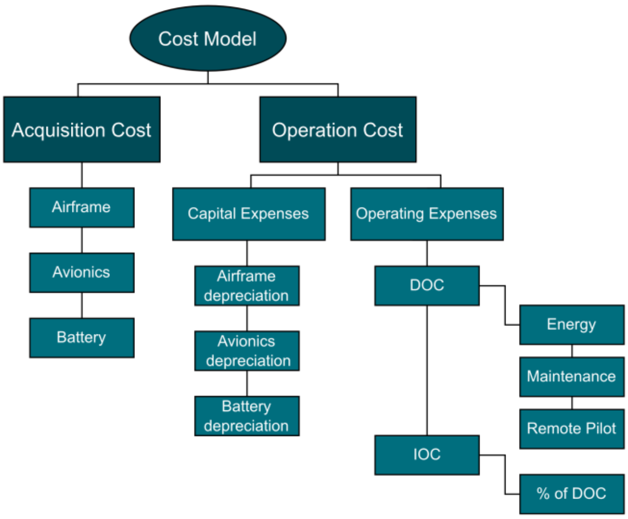


FIGURE 7. Cost model structure for aerial firefighting

Since the cost estimation is estimated per mission, a general breakdown for operational cost does not apply to wildfire suppression mission. Due to the limited number of use of aircraft assets, it is expected that ownership cost of aircraft dominates the other cost components as observed in the authors' previous work [12].

The capital expenses do not include finance cost with the assumption that the loan will not be necessary for such humanitarian project. Similarly, insurance cost is neglected with the assumption that the private liabilities will not be required. The residual value of aircraft, value of the assets after its useful life, is neglected.

The direct operating cost does not include the ground crew cost, route cost and infrastructure cost for simplicity. The indirect operation cost is calculated as a constant fraction of direct operating cost. The capital expenses are separated from the direct operation cost so that the domination of the capital expenses can be avoided.

The energy cost of fleet is calculated by receiving the energy consumption of the fleet for both electric and hybrid fleet compositions. Autonomous flight conditions are assumed for aerial firefighting. A remote pilot is assigned to all fleet to operate. The maintenance cost is calculated similarly for all aircraft type irrespective of their sizes. The maintenance cost difference emerging from aircraft size is neglected. The details of methodology and the parameter assumptions for the cost estimations can be found in TABLE 2.

Cost Components	**Methodology**	**Assumptions**		
		Cost Parameter	**Value**	**Unit**
Capital Expenses	Capital expenses are estimated as the sum of airframe, avionics and battery depreciation costs. Airframe and avionics depreciation is estimated as an exponential decay over time. Battery depreciation is estimated by allocating the unit price of the battery to on-mission consumption. Insurance cost and finance cost are not included in capital expenditures for the wildfire suppression mission.	Airframe price	1,102	USD/kg
		Avionics price	100,000	USD
		Depreciation rate	7.5	%
		Aircraft life time	15	years
		Number of missions	60	1/years
		Battery specific energy	250	Wh/kg
		Battery capacity specific cost	300	USD/kWh
		Battery life cycle	500	-
Energy Cost	Estimated as a summation of fuel cost and electricity cost per mission.	Electricity price	0.2	USD/kWh
		Fuel price	3.3	USD/kg
Maintenance Cost	Estimated by multiplying the mechanic wrap rate and ratio of maintenance man-hours to flight hours.	Mechanic wrap rate	75	USD/hour
		MMH/FH	0.6	-
Remote Pilot Cost	Estimated by multiplying pilot's hourly rate and mission time. The remote pilot is assumed to be responsible for all the fleet.	Pilot wrap rate	150	USD/hour
		Number of aircraft assigned to pilot	Fleet size	-
Indirect Operating Cost (IOC)	Assumed to be constant fraction of direct operating cost.	Fraction	20	%

TABLE 2. Assumptions for estimation of total cost of operation [12]

4. CASE STUDY

4.1. Setup

A challenging mission was created for the fire model to conduct the sensitivity study so that the impact of heterogeneous fleet composition and various suppression tactics can be captured. The fire is initiated around a mountainous area with challenging weather conditions to capture the transition between successful and unsuccessful missions. The details of infrastructure and fire setup can be seen in FIGURE 8. For the tactical evaluation, the simulation was run for both homogeneous and heterogeneous fleet. The study is conducted using full factorial design by distributing 0, 4, and 8 aircraft to each base equally. Two different aircraft configurations were selected for the tactical evaluation: multirotor and tiltrotor configuration with large payload capacity. For the heterogeneous fleet assessment, the details of the fleet are described in section 3.2.1. Next, the environmental parameter study is set up separately from the suppression model. Initially, the study was set up for three different values: low, medium and high. Then, depending on the impact of the parameters, the range covered is increased to capture the effects more precisely. The environmental parameters considered for this study are wind speed, wind direction, temperature, relative humidity and maximum elevation.

Operational parameter setup

Number of bases: 4
Number of water sources: 4
Response time: 20 mins
Min. distance between base and fire: 30 km
Min. distance between water source and fire distance: 10 km

Environmental parameter setup

Wind speed: 5 m/s
Wind aspect: 90°
Temperature: 30 °C
Relative humidity: 30%
Max. elevation: 100 m

FIGURE 8. Simulation set up for aerial firefighting mission

4.2. Assumptions & Limitations

The heterogenous fleet consists of various aircraft with different powertrain architectures. It is expected that the turnaround time for the aircraft slightly differs from each other due to battery recharging. The difference between the turnaround time is neglected in the current setup. Moreover, it is assumed that the fleet composition does not include any large airtankers, therefore, leading airplane in the fleet composition for fire line construction is not considered.

The simulation terminates when any fire position reaches any border of the map. Therefore, mission success is highly dependent on the proximity of the ignition center to the border. The ignition center chosen for this study is towards the center of the map to prevent premature termination of the simulation by giving the fleet the most time to suppress and contain the fire. In addition, information on the exact location, shape and time of the fire is assumed to be obtained through Global Positioning System (GPS) services. Another key point to mention is that the area to be suppressed in the simulation is determined probabilistically to cope with different resolutions. However, this method also introduces a source of uncertainty on the response. To avoid the uncertainty, the simulation is run with 2 m resolution. Even though, improving resolution increases the efficiency of the fire model, the simulation accuracy decreases by solely decreasing the cell size [10]. Therefore, the time step is lowered to 0.05 as well for this study.

5. RESULTS AND DISCUSSIONS

5.1. SoS Level Analysis

In this section an SoS level analysis and evaluation is demonstrated to shed light on research points shown as following:

1) The impact of environmental conditions on wildfire
2) The impact of different tactics used in the wildfire suppression mission
3) The impact of heterogeneous fleet composition with different payload, flight velocity and powertrain architecture on the wildfire suppression mission

The achievement of the objective is assessed by total operating cost and total burnt area. The measure of effectiveness of each design point is calculated as the averaged and normalized summation of these two functions meaning a lower overall value implies a more effective fleet.

5.2. Environmental Impact Study

5.2.1. Overview

The spread of forest fires is significantly affected by environmental conditions. This study aims to reveal the influence of weather conditions and topography on the rate of fire spread. The parameters to be studied are wind speed, wind direction, temperature, relative humidity, and maximum elevation.

5.2.2. Wind Speed

The effect of wind speed on fire spread is analyzed from no wind to a wind speed of 10 m/s. FIGURE 9 shows the total area burnt in terms of football fields over three and a half hours where one football field corresponds to approximately 5500 m^2.

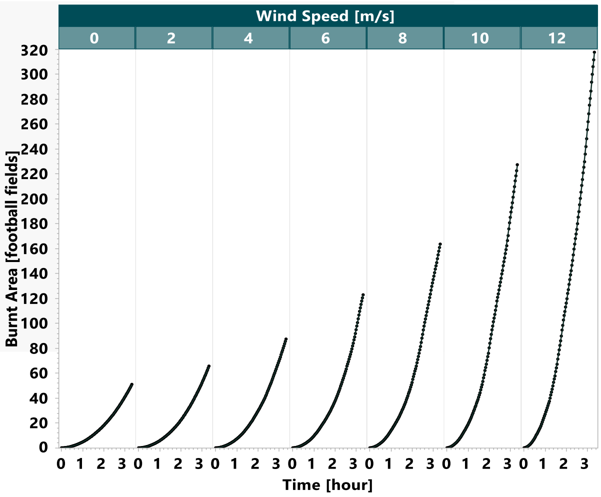


FIGURE 9. Total burnt area in football fields with respect to different wind speed values

As it is seen in the FIGURE 9, the slope of the curve gets steeper when the wind speed increases as expected. However, it is seen that the change in the steepness (the rate of the fire spread) differs in each segment. To be able quantify the change in the spread rate, one-way ANOVA (Analysis of Variance) analysis is done by applying the least significant difference (LSD) test and connecting letters. One-way ANOVA analysis is a statistical test used to investigate the relationship between the means of more than two groups by using a single independent variable. Therefore, it can be used in the environmental factor investigation by comparing the means of each level with respect to a single response (total burnt area). The positive values in the LSD test implies significant difference between the levels. The connecting letters are used to classify each significantly different level. The details of the analysis are out of the scope of this research.

	LSD Threshold Matrix						
LEVEL	12	10	8	6	4	2	0
12	-14.44	15.81	37.71	53.42	62.84	69.77	74.16
10	15.81	-14.44	7.45	23.16	32.59	39.51	43.90
8	37.71	7.45	-14.44	1.27	10.69	17.62	22.01
6	53.42	23.16	1.27	-14.44	-5.02	1.91	6.30
4	62.84	32.59	10.69	-5.02	-14.44	-7.52	-3.13
2	69.77	39.51	17.62	1.91	-7.52	-14.44	-10.05
0	74.16	43.90	22.01	6.30	-3.13	-10.05	-14.44
Connecting letters	A	B	C	D	D - E	E	E
Means [ff]	105.64	75.38	53.49	37.78	28.35	21.43	17.04

TABLE 3. The least significant difference test based on total burnt area by factor wind speed

In TABLE 3, the lower triangular shows the positive relations when the wind speed levels are significantly different. This indicates when the wind speed values are higher than 6 m/s, the burnt area is highly sensitive to the wind speed. On the right-hand side, the negative relations in the wind levels indicate that the effect of each level has similar effect on total burnt area. It can be easily seen that the wind speed level 6 m/s is the threshold value for the impact level of wind speed in this scenario.

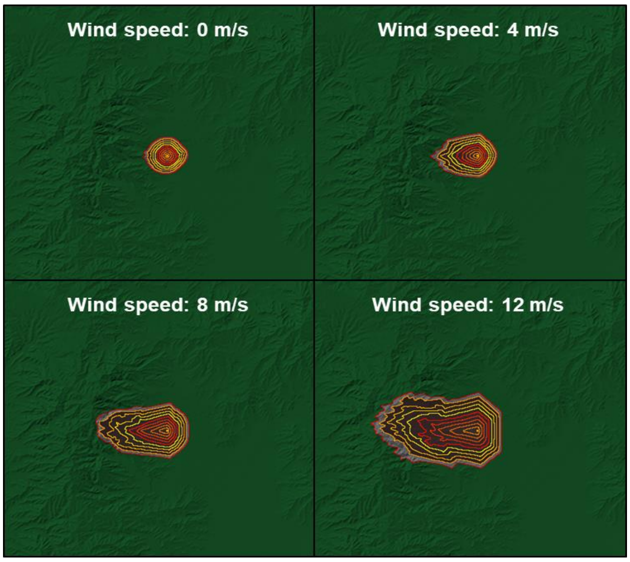


FIGURE 10. Wildfire behavior with respect to different wind speed values

However, the drastic difference between the mean value of the burnt area does not solely emerge from the wind speed level. FIGURE 10 shows that when the wind speed is higher, the fire spreads towards the mountainous area, therefore the fire spread is affected by the change in the topography as well. On account of this, the significance of the elevation changes on the total burnt area to be investigated next.

5.2.3. Elevation

The rate of fire spread varies depending on different terrain slopes. The steepness of the terrain slope is directly related to the maximum elevation of the topography.

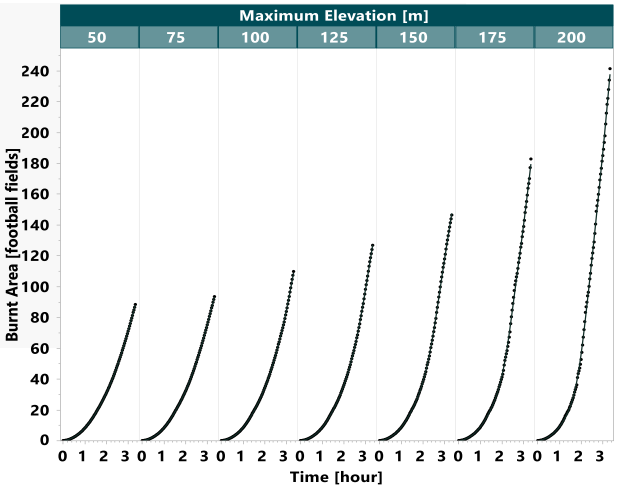


FIGURE 11. Total burnt area in football fields with respect to different maximum elevation values

As shown in FIGURE 11, fire spreads faster on steeper slopes than on gentler slopes. Due to the feasibility of maximum elevation value consideration, the study does not include any value above 200 m. It is observed that the steepness of the fitting curve does not increase drastically as in wind speed effect. However, as the elevation value increases, the rate of difference in the total burnt area increases as in the wind speed evaluation.

	LSD Threshold Matrix						
LEVEL	200	175	150	125	100	75	50
200	-12.40	3.24	10.70	16.30	19.99	22.90	24.31
175	3.24	-12.40	-4.93	0.66	4.35	7.26	8.67
150	10.70	-4.93	-12.40	-6.81	-3.12	-0.20	1.20
125	16.30	0.66	-6.81	-12.40	-8.71	-5.80	-4.39
100	19.99	4.35	-3.12	-8.71	-12.40	-9.49	-8.08
75	22.90	7.26	-0.20	-5.80	-9.49	-12.40	-11.00
50	24.31	8.67	1.20	-4.39	-8.08	-11.00	-12.40
Connecting letters	A	B	B - C	C - D	C - D	C - D	D
Means [ff]	66.16	50.52	43.05	37.46	33.77	30.85	29.45

TABLE 4. The least significant difference test based on total burnt area by factor maximum elevation

The LSD test results in similar behavior in the elevation values up to 150 m (see TABLE 4). As it is seen form the connecting letters, the threshold value for elevation impact can be considered as 150 m. The transition occurs between 125 and 150 m and 150 m to 175 m. Then the elevation value starts to impact the spread rate significantly. It is also seen that 25 m increment is suitable for capturing the transitions between elevation levels.

As it is seen in the FIGURE 12, as the elevation value increases, the fire reaches the mountainous area where the slope of the terrain is higher and much irregular. The increase in the slope value amplifies the impact of the maximum elevation significantly due to direct correlation. Therefore, it is important to investigate the effect of the direction of the fire growth in a specific set up as the next step.

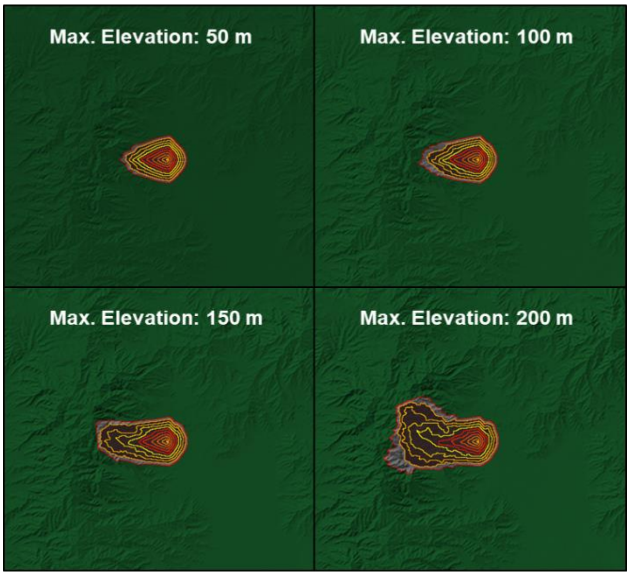


FIGURE 12. Wildfire behavior with respect to different maximum elevation values

5.2.4. Wind Aspect

The fire growth is indirectly related to the wind aspect because it varies from one location to another. If the wind direction is towards an area with a high slope, the wind speed impact is amplified by the terrain slope impact on fire.

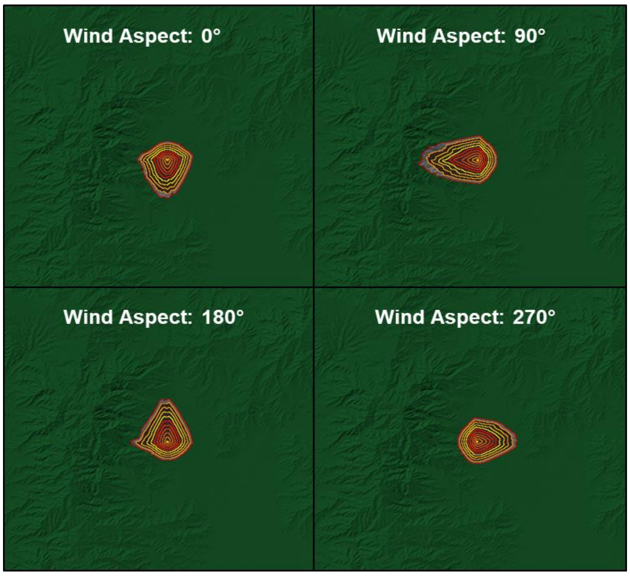


FIGURE 13. Wildfire behavior with respect to different wind direction values

As it is seen in FIGURE 13, the burnt area varies considerably if only the wind direction is towards a terrain with high slope values. The difference between the 90° (east) and 270° (west) shows that the wind direction can be an advantage or disadvantage based on the area of interest.

5.2.5. Temperature

The weather temperature is one of the most important factors affecting the rate of fire spread. As can be seen in FIGURE 14, the total burnt area is very sensitive to changes in each segment and its influence on fire spread increases substantially as the temperature rises. As the temperature changes from 10 °C to 40 °C, the steepness of the curve rises significantly, especially after 30 °C.

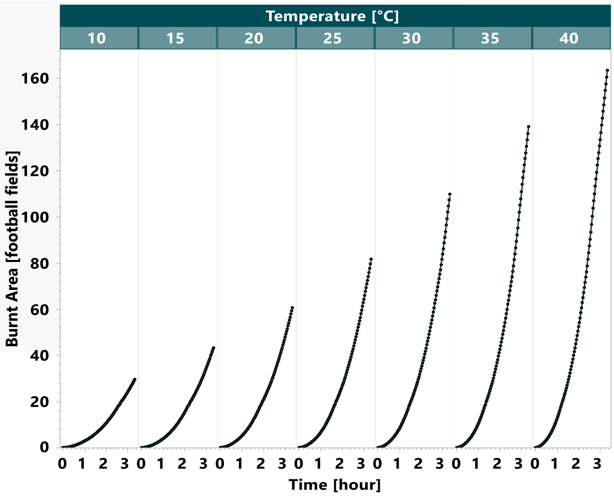
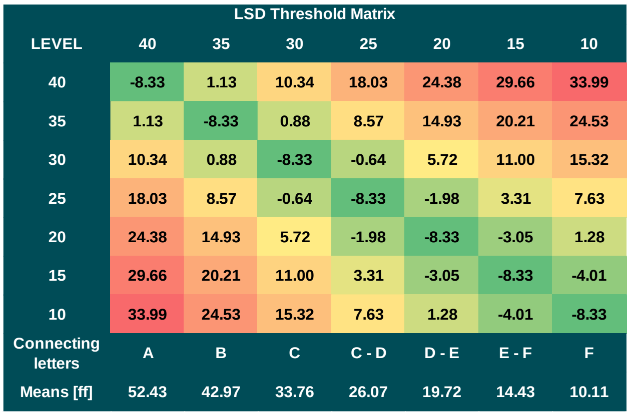


FIGURE 14. Total burnt are in football fields with respect to different temperature value

In TABLE 5, the difference in the effect of temperature in each segment can be seen quantitatively. Most of the temperature levels are significantly different from each other. As shown in the lower or upper triangular of the table, there is a clear distinction between the values before and after 25 °C, and after 30 °C, any temperature change significantly affects the spreading rate, as indicated by the connecting letters. Therefore, the increment of 5 °C is not sufficient to categorize the temperature values in one segment for the high temperature values.



LSD Threshold Matrix							
LEVEL	40	35	30	25	20	15	10
40	-8.33	1.13	10.34	18.03	24.38	29.66	33.99
35	1.13	-8.33	0.88	8.57	14.93	20.21	24.53
30	10.34	0.88	-8.33	-0.64	5.72	11.00	15.32
25	18.03	8.57	-0.64	-8.33	-1.98	3.31	7.63
20	24.38	14.93	5.72	-1.98	-8.33	-3.05	1.28
15	29.66	20.21	11.00	3.31	-3.05	-8.33	-4.01
10	33.99	24.53	15.32	7.63	1.28	-4.01	-8.33
Connecting letters	A	B	C	C - D	D - E	E - F	F
Means [ff]	52.43	42.97	33.76	26.07	19.72	14.43	10.11

TABLE 5. Total burnt are in football fields with respect to different temperature values

Moreover, this drastic impact can be considered as isolated from the topography effect. The FIGURE 15 shows that even at the highest possible temperature value, the fire does not only spread towards the mountainous area but rather it spreads from every direction.

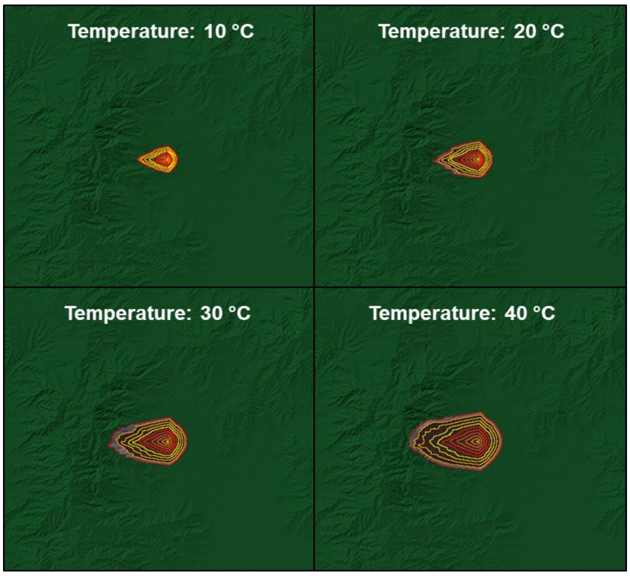


FIGURE 15. Wildfire behavior with respect to different temperature values

5.2.6. Relative Humidity

In principle, lower humidity and higher temperature lead to a reduction in fuel moisture. The decrease in fuel moisture results in more intense growth of the fire. However, in contrast to the temperature sensitivities, the change in the growth of the fire in each segment has a smoother transition, as seen in FIGURE 16.

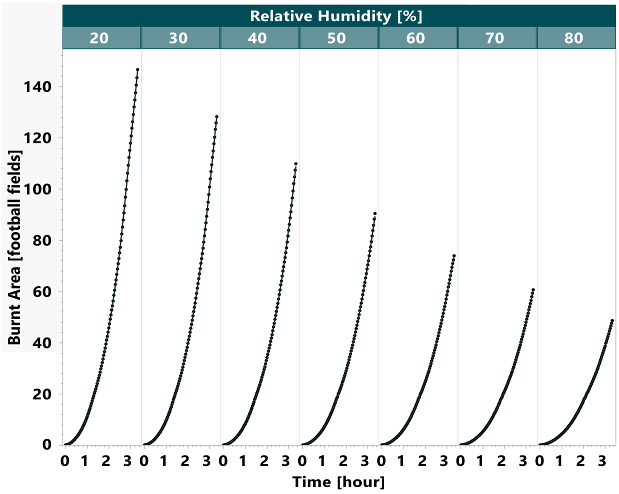
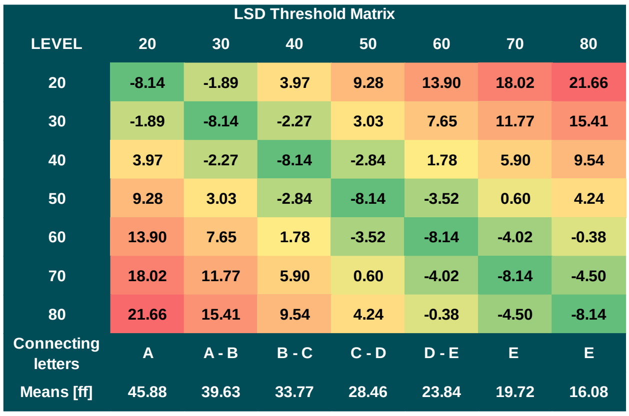


FIGURE 16. Total burnt are in football fields with respect to different relative humidity values

The LSD test in TABLE 6 demonstrates that the humidity levels have similar effect on the fire growth when the humidity is higher as it was in the case of low temperature. However, overall matrix shows that 20% change in the relative humidity can capture the transition between different labels.



LSD Threshold Matrix

LEVEL	20	30	40	50	60	70	80
20	-8.14	-1.89	3.97	9.28	13.90	18.02	21.66
30	-1.89	-8.14	-2.27	3.03	7.65	11.77	15.41
40	3.97	-2.27	-8.14	-2.84	1.78	5.90	9.54
50	9.28	3.03	-2.84	-8.14	-3.52	0.60	4.24
60	13.90	7.65	1.78	-3.52	-8.14	-4.02	-0.38
70	18.02	11.77	5.90	0.60	-4.02	-8.14	-4.50
80	21.66	15.41	9.54	4.24	-0.38	-4.50	-8.14
Connecting letters	A	A - B	B - C	C - D	D - E	E	E
Means [ff]	45.88	39.63	33.77	28.46	23.84	19.72	16.08

TABLE 6. The least significant difference test based on total burnt area by factor relative humidity

The mean values of the burnt area show that relative humidity has less influence on fire growth compared to other environmental parameters FIGURE 17 shows that the relative humidity was not much affected by the topography changes in the fire, as the fire did not reach the mountainous area as in the previous cases.

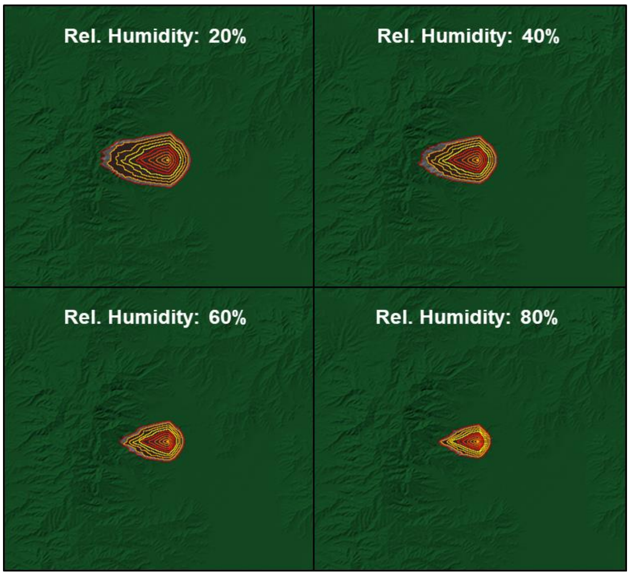


FIGURE 17. Wildfire behavior with respect to different relative humidity values

The environmental study conducted above shows that the fire growth is considerably influenced by the wind speed and the elevation of the fire area. As the wind speed changes, the fire growth rate changes more comparably and the combined influence of high slope and high wind speed causes drastic changes in the total burnt area. It is also seen that the wind direction is very important as it can direct the fire growth in a challenging topography. The temperature and the relative humidity have similar influence on the fire growth; however, the temperature values are much more sensitive to any changes. Due to high sensitivity of the fire in environmental parameters, dynamic changes in the weather conditions must be considered during fire incidents as shown in [13].

5.2.7. Suppression Tactic Sensitivities

Three measures of dispersion are used to interpret variability in the design of experiments: range, variance, and standard deviation. FIGURE 18 shows the total burnt area with respect to the fleet size by using 4 different tactics. The tactics on the right-hand side are ordered in the descending order with respect to the burnt area. A major difference is in the mission success is observed when the fleet size is relatively small (indicated in orange color box). It can be seen that the mission success is significantly affected by the suppression tactic when the available assets are limited. It is also observed that mission success is not directly related to the total area burnt. In order to see the impact of the tactics on the area burnt, a design point was tracked (labeled and shown in orange). It can be seen that changing the suppression tactic can cause up to 86% change in the total area burnt.

On the top right of FIGURE 18, the dispersion metrics are shown. The figure demonstrates the elliptic fire line building and fire front encircling tactics lead to relatively more successful missions. Comparisons are made with respect to the fire front tracking tactic which is assumed to be the default tactic in the simulation. The elliptic fire line building increases the number of successful missions by surrounding the fire before applying direct attack on the fire. However, since the fire is allowed to burn during fire line construction, the successive application of indirect and direct attack results in an increase in the area burnt even for the successful missions. Similarly, fire front encircling tactic improves the number of successful missions compared to the fire front tracking. This is expected due to the fact that the fire is always controlled by prioritizing the four leading edges. Therefore, the fire is restricted for expanding in a specific direction. Moreover, it is observed that using encircling tactic results in reduction in the total burnt area. This is due to the fact that even though the information of terrain slope or spread rate is not delivered to the agents, the location of the leading edge is informed to the agents. By using this approach, the agents leverage observation instead of causation of the fire. Therefore, dispersion metrics for fire front encircling are considerably lower than the other suppression tactics. The design point traced shows that following the fire front, considering the slope of the fire front area, decreases the mean total burnt area. However, suppression by tracking with terrain slope also decreases the total number of successful missions. As the transition design points (the points where the mission success is under risk) are failed missions for fire front tracking with terrain slope; dispersion metrics are not entirely reliable for this scenario.

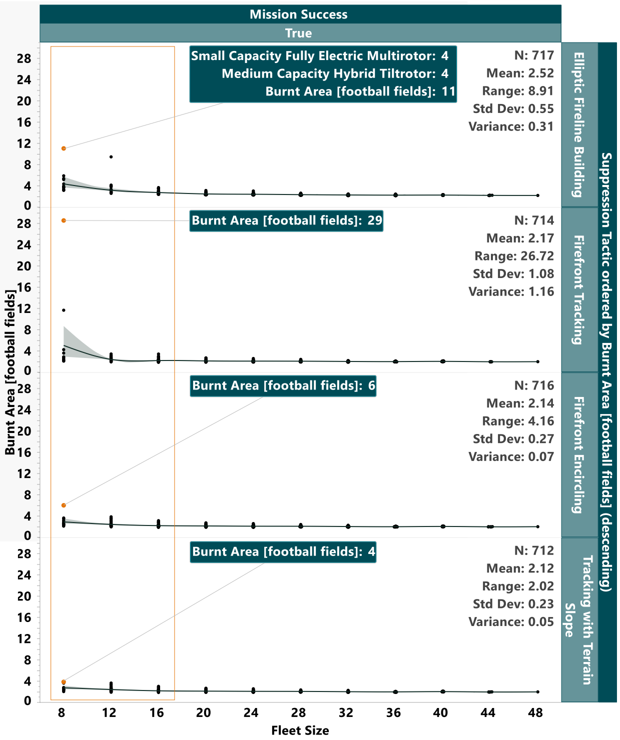


FIGURE 18. Total burnt area for heterogeneous fleet compositions with various suppression tactics

As the dynamicity is relatively higher for the small fleet sizes, it is needed to zoom in to these design points. FIGURE 19 indicates that the elliptic fire line building has the highest number of successful missions followed by fire front encircling. As both tactics are aimed to surround the fire using different methods (direct and indirect attack), increase in the mission success is expected. However, it must be noted that indirect attack followed by a direct attack, results in higher success rate compared to solely direct attack. Another point to note is that a decrease in the mean of total burnt area for a fleet size of 8 aircraft, is observed by tracking the fire front with terrain slope. This decrease emerges from the fact that the number of successful missions was decreased as well. Therefore, the dispersion metrics are not reliable due to the considerable reduction in the data points. The reason behind the reduction in successful missions can be explained by considering the implementation of the tactic logic. Since the terrain slope tactic implementation considers only the surrounding locations with Moore neighborhood Radius=1, the irregularities of the terrain may mislead the real value of the target location. Therefore, tracking with terrain slope results in a smaller number of successful missions.

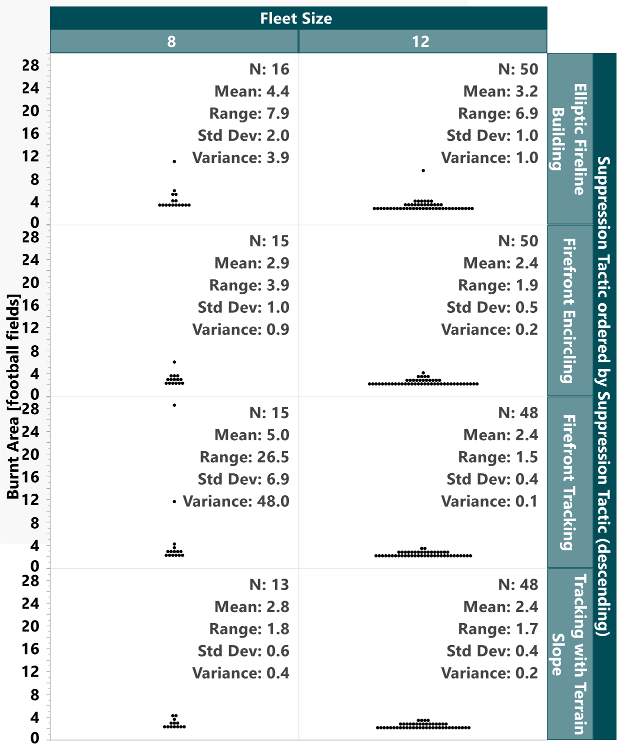


FIGURE 19. Total burnt area with dispersion metrics with respect to different suppression tactics for smaller fleet sizes

For a more precise understanding of the tactics on the total burnt area, two homogeneous fleets are shown in FIGURE 20. As it can be seen, when the fleet size is large enough; the effect that has been previously observed is relatively smaller. By having the highest total burnt area, it is shown that the elliptic fire line building loses its advantages for the relatively less challenging missions as the fire line construction becomes unnecessary. When the fleet size is large enough to be able to suppress the fire with direct attack, using an indirect attack followed by a direct attack does not improve the mission effectiveness. On the contrary, the burnt area increases due to the fact that aerial assets were not used to suppress the fire initially, instead being deployed to build a fire line at a distance from the fire encircling a larger area than would have burnt had a direct attack tactic been used. Especially, when the fleet has relatively lower flight velocity (multirotor composition), losing time in the fire line construction delays the mission completion and therefore increases the total burnt area considerably. Although the burnt area may be higher, since the number of successful missions is slightly higher for the indirect attack for a fleet of 8, it can be considered to be more robust.

As the effectiveness of each tactic changes based on different fleet sizes and fleet compositions, FIGURE 21, shows that using a different fleet can affect the selection of tactic to be used. For a fleet size of 8 aircraft, using a homogeneous fleet with medium capacity fully electric tiltrotor configuration (design set 2, colored in red) performs significantly better than using a heterogeneous fleet with small capacity hybrid multirotor and medium capacity fully electric tiltrotor (design set 1, colored in orange) with the fire front tracking tactic. While the fire front tracking tactic performs poorly for the selected heterogeneous tactic, shifting the fleet composition by keeping the fleet size constant, makes fire front tracking tactic as one of the best performing tactic on the fire. This implies that improving the fleet with respect to payload capacity and flight velocity will change the ideal tactic to be applied on the fire. FIGURE 21 also shows that the influence of the tactic selection becomes insignificant when the fleet size is doubled for heterogeneous composition (design set 3, colored in green).

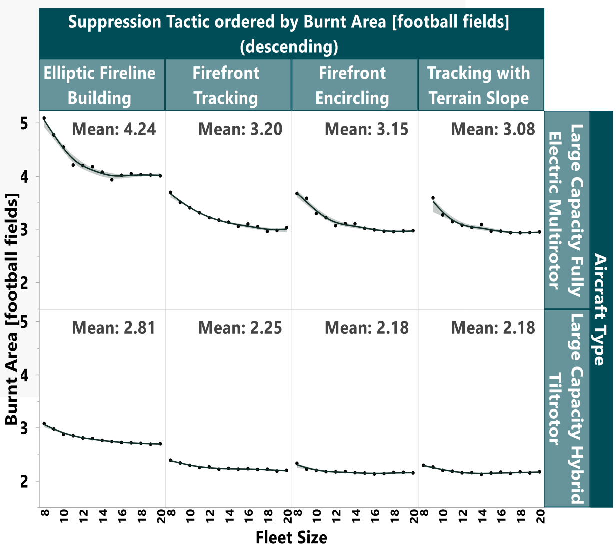


FIGURE 20. Different suppression tactic response with two different homogeneous fleet

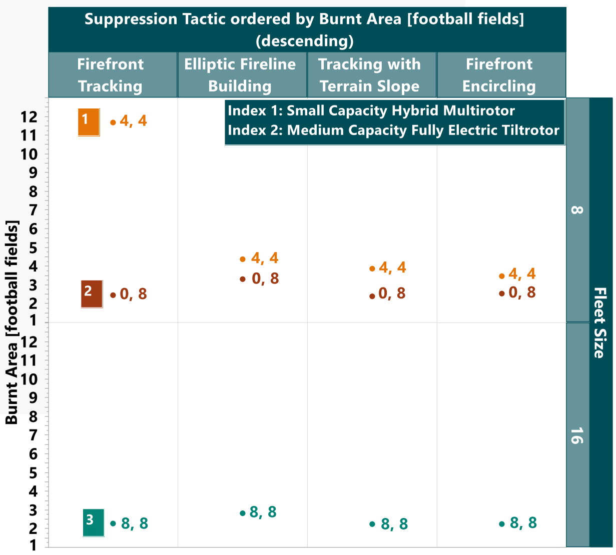
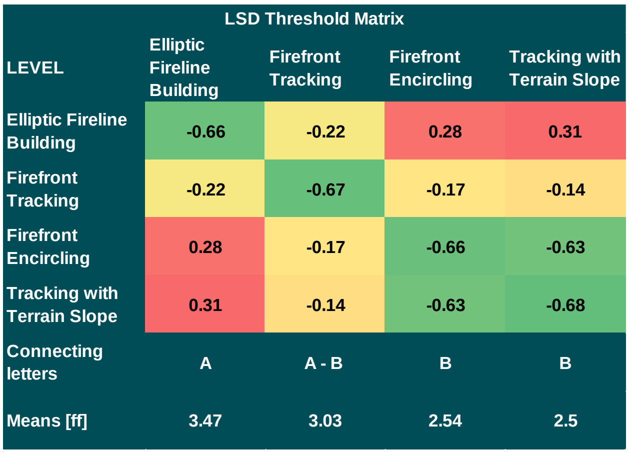


FIGURE 21. Suppression tactic influence on the total burnt area using different fleet sizes and compositions

One-way ANOVA analysis is done by applying LSD test and connecting letters to quantify the impact of each suppression tactic on the total area burnt. In TABLE 7, the positive values indicate the significance of the difference on the burnt area means. The connecting letters label the different levels of tactic considering the overall mean values of the total burnt area. The table consists of only successful missions with 8 and 12 fleet sizes. The connection letters demonstrates that ercircling the fire and supressing with slope consideration improves the total burnt area similarly. As expected, fire line construction differs from other methods due to delay in the direct suppression time. However, LSD test values show that the impacts of all the tactics are not very distinctive from each other.



LSD Threshold Matrix				
LEVEL	Elliptic Fireline Building	Firefront Tracking	Firefront Encircling	Tracking with Terrain Slope
Elliptic Fireline Building	-0.66	-0.22	0.28	0.31
Firefront Tracking	-0.22	-0.67	-0.17	-0.14
Firefront Encircling	0.28	-0.17	-0.66	-0.63
Tracking with Terrain Slope	0.31	-0.14	-0.63	-0.68
Connecting letters	A	A - B	B	B
Means [ff]	3.47	3.03	2.54	2.5

TABLE 7. The least significant difference test based on total burnt area

5.2.8. Heterogeneous Fleet Sensitivities

The heterogeneous fleet with different payloads, flight velocities and powertrain architectures can influence the mission success, fire growth rate and the total burnt area significantly. To evaluate the overall system response, measure of effectiveness is formulated combining both total burnt area and cost of operation. Both responses are normalized by the maximum values reached in the successful missions and averaged summation is subtracted from one, therefore the overall evaluation aims to increase the value of measure of effectiveness estimation. FIGURE 22 demonstrates that the measure of effectiveness is highly driven by the total burnt area when the number of aerial assets is limited as indicated by the orange box. As the fleet size increases, measure of effectiveness is dominated by the total cost of operation due to the strong correlation between the operating cost and the fleet size and insignificant changes in the total burnt area.

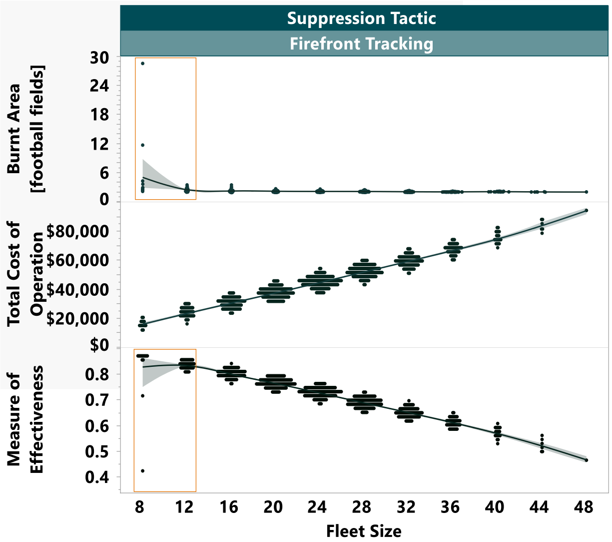


FIGURE 22. Overall evaluation of wildfire suppression with different fleet compositions with respect to fleet size

Noting that all the heterogeneous fleet investigations are done with the tactic fire front tracking, the highest dynamicity is observed when there are 8 suppression aerial assets. In FIGURE 23, it is observed that doubling the payload capacity and increasing the flight velocity of half of the fleet can improve the total burnt area by 83% (see design point 1 and 2). As it is seen, design point 3 is an outlier for the dataset implying that this point is one of the transition design points from mission success to mission failure.

The variance in total burnt area when the fleet size is 8 indicates that this fleet size has a high potential to be the transition threshold between successful and unsuccessful missions. Therefore, the unsuccessful missions are also to be investigated for further understanding. The outlier design point 3 in FIGURE 23 and design point 1 in FIGURE 24 demonstrates that changing the fleet composition from hybrid tiltrotor to electric tiltrotor leads mission to fail due to the change in the usable energy of each configuration. As indicated in section 3.2, as the usable energy increases for hybrid tiltrotor, active fire suppression is not delayed. Since firefighting success depends significantly on early intervention, when the fleet needs to be re-energized early, the fire becomes much more difficult to suppress when the fleet returns to active suppression. Moreover, FIGURE 24 shows that the combined impact of high payload capacity, flight velocity and usable energy decreases the fire growth rate significantly even though the missions fail (see design point 2 and 3).

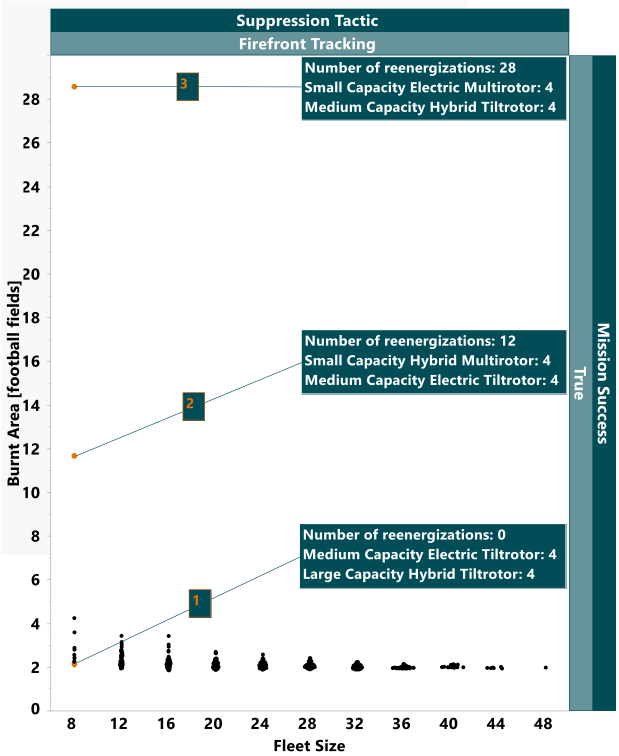


FIGURE 23. Change in the total burnt area with different fleet compositions for successful suppressions

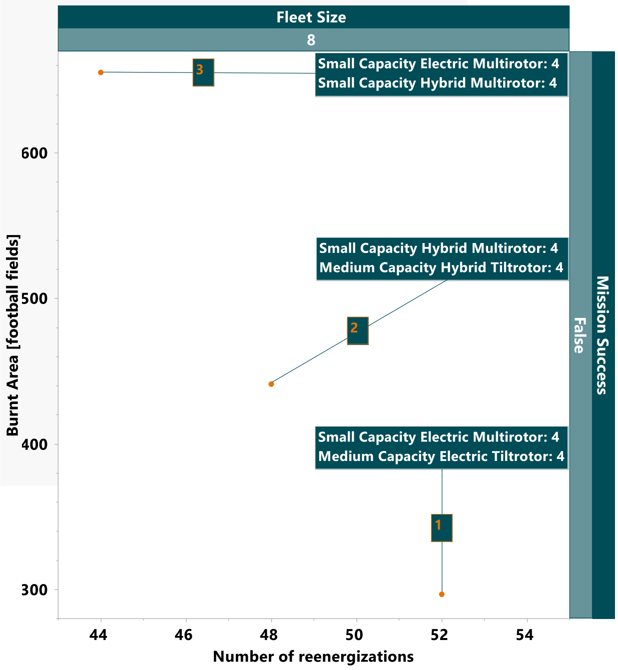


FIGURE 24. Failed missions for fleet size 8 with different fleet compositions

Another question to be answered is that whether the variation in the fleet improves the fire suppression mission. In FIGURE 25, instead of using 8 small capacity and slower fleet, improving the fleet composition with medium capacity and faster fleet (see design point 2 and 3) not only leads mission to success but also improves operational cost.

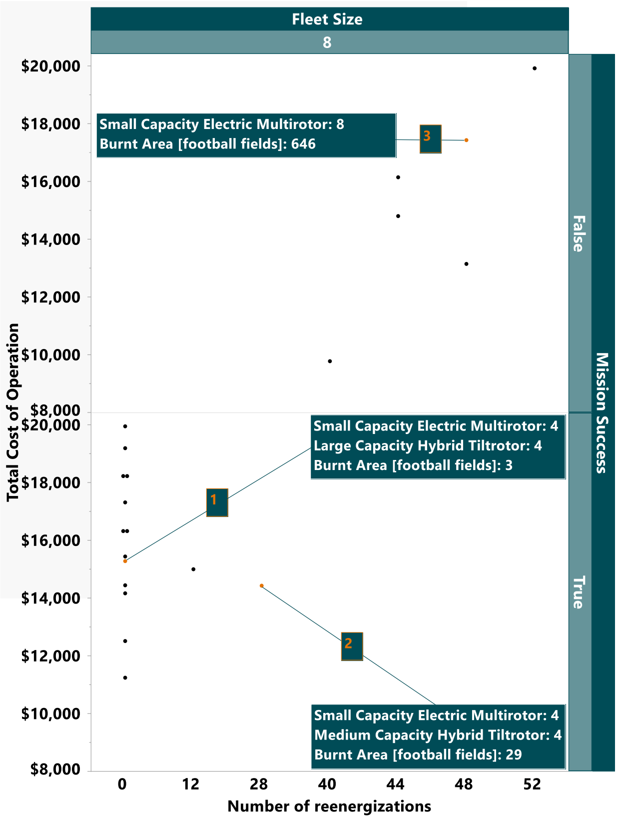


FIGURE 25. The impact of transition between homogeneous and heterogeneous fleet

Even though the multirotor and tiltrotor composition (design point 1) has heavier composition than homogeneous multirotor composition (design point 3), leading increase in the capital expenses, the operating expenses become more considerable when the fleet size is constant, and containment is not achieved over the given time constraint (design point 3). FIGURE 25 also suggests that changing half of the fleet from medium to large capacity (design point 2 to 1) can result in an 90% improvement in total area burnt, with a 6% increase in total operating cost. As expected, the capital expense impact becomes more prominent when fire suppression is not coercive.

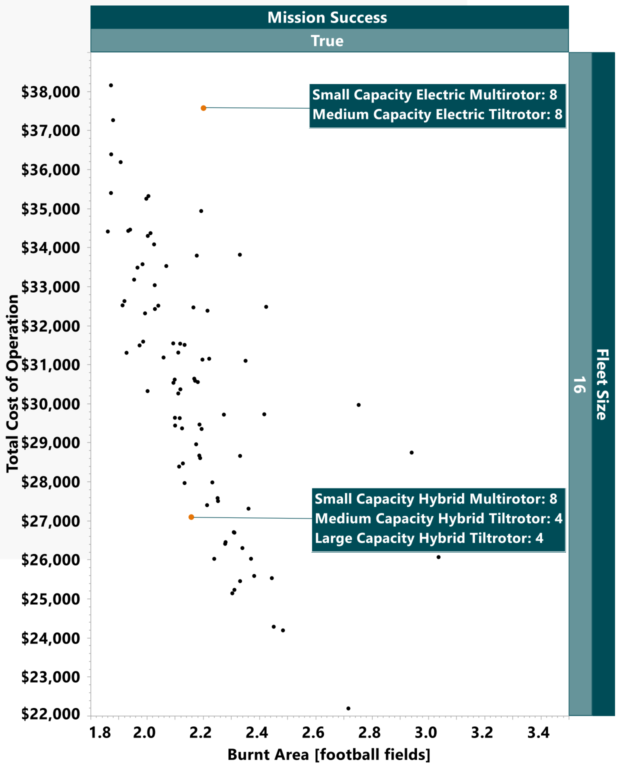


FIGURE 26. Change in the total cost of operation with respect to the fleet composition for similar total burnt area

The influence of the capital expenses plays a significant role for finding an optimal fleet composition. In FIGURE 26, the total burnt area does not vary significantly for 16 aerial assets. The indicated two points results in the same burnt area response with 40% difference in the total cost of operation. When the number of available assets is sufficient, the decrease in the MTOM and the power architecture, improve the airframe and battery cost significantly. Therefore, the assessment of the aerial assets based on the fire risk value is the key element for optimizing the fleet compositions.

For further investigation of the impact of heterogeneity, FIGURE 27 demonstrate multiple design points with respect to total burnt area and total cost of operation for both homogeneous and heterogeneous fleet compositions. The first design point corresponds to a homogeneous fleet with large capacity hybrid multirotor configuration in FIGURE 27. As it is seen, this fleet has the highest total burnt area compared to both homogeneous and heterogeneous fleet compositions. Even though the fleet has high payload capacity (720 kg), low flight velocity (40 m/s) of the fleet becomes dominant for small fleet size and therefore, total burnt area increases. However, due to its airframe configuration and powertrain architecture, this fleet composition has the lowest total cost of operation with low capital expense and battery cost as can be seen in the horizontal axis. Therefore, the measure of effectiveness (MoE) is still in the similar range (0.87) with other fleet compositions. Since the homogeneous fleet with multirotor response was highly dominated by the flight velocity (40 m/s), the fleet composition is not a reliable candidate for comparison between homogeneous and heterogeneous fleet. Therefore, medium capacity fully electric tiltrotor (design point 4) and large capacity hybrid tiltrotor (design point 6) are selected for reliable comparison. The design point 4 consists of 8 medium capacity (540 kg) fully electric tiltrotor. On the other hand, the design point 5 is composed of 4 medium capacity fully electric tiltrotor and 4 medium capacity hybrid tiltrotor. It is seen that even though the total burnt area is improved slightly from design point 5 to 4, the major impact is seen in the total cost of operation by using heterogeneous fleet. The homogeneous fleet composition is relatively heavier than the heterogeneous fleet due to change in the powertrain architecture (see TABLE 1). Moreover, the battery cost is also higher for the homogeneous fleet. Therefore, the design point 4 has the highest operational cost leading the measure of effectiveness to the highest (0.85) in the overall comparison which is the least effective design point considering the overall comparison.

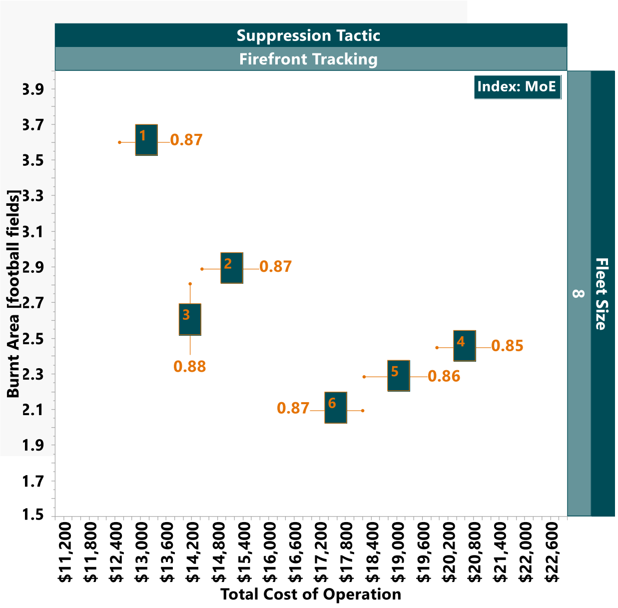


FIGURE 27. Cross comparison of total burnt area and total cost of operation between design points for a fleet size of 8 aircraft

The next comparison can be done between design point 6 and design point 3. While the design point 6 is composed of 8 large capacity (720 kg) hybrid tiltrotor configurations, the design point 3 has 4 small capacity hybrid multirotor (360 kg) and 4 large capacity hybrid tiltrotor configurations. As expected, due to lower flight velocity and payload capacity of multirotor, the homogeneous fleet improves the total burnt area more. In fact, due to the high flight velocity and payload capacity, the design point 6 has the most significant impact on decreasing the burnt area. However, the influence of using a lighter aircraft in design point 3 can be seen in the significant reduction in the total cost of operation. Since the operational cost decreases significantly, the measure of effectiveness hits the best value in the overall comparison.

Lastly, a comparison can be done between two heterogeneous fleet: design point 2 and 3. The design point 2 consists of 4 large capacity hybrid multirotor and 4 medium capacity hybrid tiltrotor. Even though, the total payload capacity of the fleet is higher in the design point 2, the flight velocity of the fleet becomes more dominant in the mission. Therefore, using large capacity with faster aircraft in design point 3, improves the total burnt area more than using large capacity with slower aircraft.

6. CONCLUSION AND FUTURE WORK

In this study, an SoS evaluation is done by applying a sensitivity study on an aerial wildfire suppression use case. The sensitivity analysis was conducted based on different fleet compositions considering payload capacity, flight velocity and powertrain architecture for the containment of an exemplary wildfire scenario.

It was found that the fleet composition chosen for a suppression mission influences not only the total burnt area but also the mission success. It was observed that using heterogeneous fleets can decrease the total burnt area while decreasing the cost of operations as long as the fleet composition selection is done by considering payload capacity, flight velocity and the endurance of the fleet.

In addition, the sensitivity of the suppression mission is evaluated based on various suppression techniques considering both direct and indirect attack tactics. It was found that the suppression tactic can impact the total burnt area significantly as well as the number of successful missions. Moreover, it was observed that indirect attack may result in higher burnt area when the missions are considerably less challenging. Therefore, it does not necessarily contribute positively to SoS performance. However, it contributes to increase in the possibility of containment by partially surrounding the fire. It was also seen that suppressing the highest spread rate does not always lead to the optimal results. Providing the information of the fire locations and the terrain information of the fire location to the suppression agents can improve the total burnt area significantly.

Lastly, environmental impact on fire growth was investigated considering atmospheric conditions and topologies. The studies showed that the fire growth is highly sensitive to the wind speed and topology. It was seen that the wind direction influences the fire growth depending on the location of the fire incident and therefore it indirectly affects the fire growth through topographic properties. The variance analysis in the environmental studies showed that change in the environment temperature highly influences the total burnt area and fire growth is very sensitive to any changes in the temperature. Moreover, the nonlinear impact of the combination of high wind speed and high terrain slope was captured by indicating that the fire growth rate rises drastically. These results indicate the need for a simulation informed approach for the forest fire containment.

Moreover, the results indicate that the fleet assessment must be done considering the available number assets by maximizing the payload capacity and flight velocity, and it is also observed that compositions are also highly dependent on the infrastructure. Based on the available water resources and the base locations around the fire, the power requirement from the fleet must be estimated considering the need of reenergizations of the fleet so that the powertrain architecture can be assigned to the composition precisely. In addition, it was seen that the way of applying indirect attack is very crucial for challenging fire containment missions. Building connected fire lines and dynamically following the fire growth can improve the fire containment. Since the response of chosen suppression strategies rely on every decision that is taken significantly, finding an optimal strategy for each fire incident is a challenging problem where machine learning algorithms for decision making can provide a solution for. Lastly, since the environmental conditions are the driving force for the fire growth, a suppression strategy must be directly linked to the risk of the fire growth.

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