READ 2024
RESEARCH & EDUCATION IN AIRCRAFT DESIGN
WARSAW, POLAND | 6-8 NOVEMBER 2024

IMPROVING AERIAL WILDFIRE FIGHTING EFFECTIVENESS USING FUTURE CLIMATE SENSITIVITIES AND NOVEL AIRCRAFT CONCEPTS

Nikolaos Kalliatakis[1], Nabih Naeem[1], Prajwal Shiva Prakasha[1] & Nagel Björn[1]

[1]German Aerospace Center (DLR), Institute of System Architectures in Aeronautics, Aviation System Design and Assessment, 21129 Hamburg, Germany

Abstract

Due to global warming, the prevalence and severity of wildfires is increasing, even outside of the wildfire season. If a fire is not controlled within the first few hours, the surrounding dry areas support rapid spread, giving rise to megafires, which contribute to 97% of the wildfire burnt area annually [1]. It is thereby essential to ensure a sufficient rapid response is maintained with the rising climate change impacts. EU initiatives such as the RescEU and projects like COLOSSUS aim to tackle this problem. The objective of this work is to aid in the solution approach by incorporating the evolving wildfire environment in the design and evaluation of an aerial wildfire fighting system of systems (SoS). Using an Agent Based Simulation with a Cellular-Automata wildfire model, a set of aircraft fleets will be examined in several scenarios with varying weather sensitivities, reflecting the potential changes to the climate. The goal of the study is to investigate how a given SoS can be evolved over time to meet the changing needs of the environment. In this regard, the TLAR of novel aircraft, and the fleet composition are varied to design an SoS with the future needs in mind. The fleet definitions and aircraft concepts are a combination of the EU natural disaster initiative (RescEU) fleet and the novel concepts from the COLOSSUS Project, consisting of seaplane and advanced air mobility (AAM) concepts. Thus, the research aims to answer two main research questions: 1) How do climate change forecasts impact the future of wildfire fighting in Europe 2) How can the corresponding SoS requirements be formulated to accommodate the changing wildfire environments?

Keywords: wildfire fighting, agent-based simulation, seaplane design, climate change

1 Introduction

Within the year of 2023, wildfire burnt area was record high, amounting to twice the area of Luxembourg [2]. Pairing this with the fact that the past 10 years in Europe have been the warmest recorded, with 2024 breaking the record the 11th time [3], it is evident that if left untreated, wildfire damage will become uncontrollable and deterministic on future European ecology and livelihood. Recent efforts by the EU have sought to contain wildfire developments, with the RescEU initiative acquiring 12 new Canadian DHC-515 water bombing aircraft [4], alongside countries like France and Greece bolstering their own aerial firefighting fleet. The importance of aerial firefighting becomes more apparent given the prevalence of wildfires on islands and mountainous regions, where land-based accessibility is restricted.

In a recent analysis funded by the EU COLOSSUS project, the composition of the ideal RescEU fleet was explored by considering two different firefighting scenarios based on historical events, one in Salamis Greece and one in Sardinia Italy [5]. The study revised the current RescEU fleet (composed mainly of DHC-515 water bombers and some helicopters) to include some seaplanes. The seaplanes are smaller than the water bomber, but due to reduced costs and hybrid electric architectures, seaplanes proved to function better and provide a reduced greenhouse emission index [5]. The goal of

this paper is to further develop the previous analysis- taking the best theoretical seaplane/ DHC-515 fleet configuration and evaluating its robustness given the future of climate trends. To do so, a set of theoretical but realistic weather variations will be created and applied to the prescribed scenarios in Salamis and Sardinia. The weather changes can give insight to the future of wildfire growth in Europe, but also provides a suitable sandbox for future aircraft design concepts to be tested operationally. In light of more severe weather scenarios, the ideal fleet composition, and seaplane design may be altered to better combat the wildfire developments. Additionally, the impact of operational activities such as the time between fire ignition and first response can be examined. Given the time horizons of the climate policies, up to the year 2050, the seaplane designs are quite conceptual, and thus the design variations explored will be focused on the top level requirements, like design payload, range and speed.
By considering future climate variations and exploring the design space of wildfire fighting seaplanes, this paper aims to answer two key research questions:

1. How do climate change forecasts impact the future of wildfire fighting in Europe?
2. How can the corresponding system of systems (SoS) requirements be formulated to accommodate the changing wildfire environments?

After discussing the modelling methods for the wildfire, aircraft performance and agent-based logic, the scenarios will be presented and the design of experiments used to evaluate the future aircraft changes and fleet combinations will be outlined. Following this, the analysis of obtained results and relevant conclusions to the research questions will be extrapolated.

2 Modelling and Simulation

To create wildfire scenarios and test aircraft and operational concepts, a DLR in-house simulation software is available, the System of Systems Inverse Design (SoSID) toolkit. SoSID is python based and was developed to simulate aerial wildfire fighting and urban air mobility use cases [6]. For wildfire simulation, there are 3 main components: wildfire modelling, suppression logic modelling and aircraft performance modelling. These are elaborated in subsection 2.1, subsection 2.2 and subsection 2.3 respectively.

2.1 Wildfire model

When it comes to wildfire simulation, there are several models possible, however SoSID utilizes the cellular automata model developed by Rui, X et al. [7]. The decision to use this model was due to its higher accuracy over map sizes which span several kilometers whilst giving a faster computation time. The model works by discretizing a a map region into a grid of equally sized boxes and assigning a set of values to each box to aid in fire progression. Each grid box has a combustibility which indicates the likelihood of fire spread to the region. Combustibility values are based on the terrain type of the box. For example, a box dominated by forests have a higher combustibility than a shrub area which has a greater combustibility compared to residential areas. As the simulation runs, a time step is applied where the spread and burning of fire is computed. Fire spread is affected by neighbor cell combustibility, elevation and slope alongside weather conditions; temperature, humidity, wind speed and direction have a significant role in determining fire spread to a neighboring cell. Once a cell is ignited, it burns for a period of time based on the same data that determined its spread likelihood. Each state of the fire burning is modelled, starting from early burning to extinction or suppression. The spread likelihood is also dependent on the fire state, where early and late burning has less spread chance. A depiction of how the fire progresses using its neighbouring cells each time step is shown in Figure 1

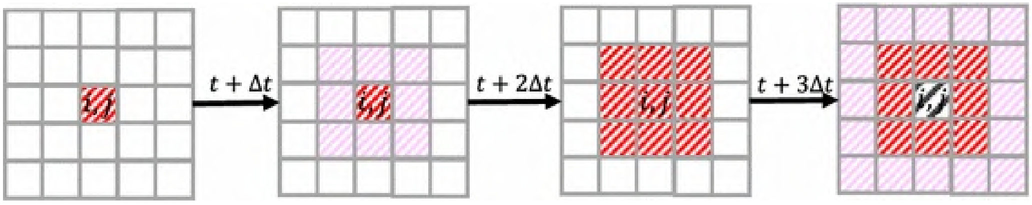


Figure 1 – Cellular automata fire spread to neighboring cells, appended from [7]. Fire spread takes into account previous time step fire states, weather conditions, and cell-specific data (elevation, terrain slope, and combustibility).

The fire model allows for a quick casting of new scenarios, relying on user input for ignition location and map size, and time of day. The rest of the data (terrain information and weather conditions) are obtained from public data sources like OpenStreetMaps (OSM) and available weather API's. Should the user wish to adjust the obtained weather data, or simulate non-historical scenarios, they have the option to manually specify weather conditions. In this case a parametric weather model is used based on input distributions to the temperature, humidity, time of sunrise/ sunset, wind aspect variation and wind run. As the studies conducted in this paper are hypothetical situations based on future predictions, the parametric model will be used.

The fire model updates every time step until one of 3 conditions are met:

- The maximum simulation run-time is met, indicating **mission failure**
- The fire reaches the boundaries of the map, indicating **mission failure**
- The fire is completely suppressed or extinguishes, indicating **mission success**

2.2 Agent-based model

The goal of the agent-based model is to organize, instruct and operate the aircraft as the wildfire progresses. Since the fire progression is each time step, the aircraft must also assess and evaluate the best operation each time step. For this reason, the agent-based model proves beneficial as it enables the modelling of each aircraft as an agent which can determine its course of action when confronted with a change in environment. The benefit of this is the scalability for the system of systems (SoS); introducing new tactics, aircraft and ground agents like firefighters can be done easier with agent-based models [8].

Within SoSID, the aircraft agents are initialized upon the simulation start at user defined airbases. The aircraft hold at the airbase until a user defined response time is met. Upon response time termination, the agents determine their flight direction and goal which is based on the selected suppression tactic. The suppression tactics can vary from tracking and suppressing the fire at the front which maintains the highest spread rate, trying to eliminate it from spreading rapidly, to creating an elliptical fire block around the fire, trying to capture the fire in a zone to prevent prolonged burning. The choice of tactic impacts the agent logic as the aircraft seeks to choose the best suppression location which agrees with the tactic. Each agent operates independently, but they are aware of other agent actions, which ensures the agents select unique suppression points. After fire suppression, aircraft seek to refill their suppressant by going to water sources. Typically these water sources are grabbed with the aforementioned OSM data, but can be manually specified as well. Aircraft will continue to track their ideal suppression location, travel to said location, suppress and then resupply their suppressant until the mission is finished or the termination conditions are met (see subsection 2.1. The aircraft will also monitor their propellant consumption, returning to the nearest applicable airbase when necessary to refill.

2.3 Aircraft model

As the aircraft carry out their tasks of suppression, resupply and refueling, their flight segments are modelled. Taxi, take-off and landing are modelled as constant flight segments. Cruise climb, cruise and cruise descent are dependent on the take-off altitude, destination altitude and the great-circle distance between take-off and landing destinations. Each of these segments have a user defined vertical and horizontal speed alongside the associated power/ fuel consumption, which can be detailed for a set of aircraft masses or constant. Depending on the aircraft mass at each time step, interpolation may occur to determine the total propellant consumption along the flight.

When suppressing or resupplying at water sources, the aircraft will initiate a loitering phase, where they maintain a constant altitude and navigate towards the ideal fire front or water region for scooping. This step is necessary due to the potential advancement of the fire region with each time step. For water sources it is done to ensure that the aircraft approach the water source correctly considering the aircraft scooping capabilities. Water source width and length must be sufficient enough considering the aircraft span and required scooping length. Due to the uncertainty of loitering duration, reserve propellant may be used occasionally. Each resupply fulfills the aircraft's design payload, providing maximum suppression capability. Suppression patch sizing is modelled to be dependent on the amount of suppressant (aircraft payload) and the flow rate [m^3/s] [9].

To accommodate with the various performances across flight phases, suppression patch sizing and water source viability, aircraft requires several input variables when being defined in SoSID. The inputs are done via a '.json' file which contains top level and profile/ performance specific information. Maximum take-off mass (MTOM), operational empty mass (OEM), payload and propellant masses (usable and reserve) and other top level inputs like aircraft span are first required. After, one can define the range of power/ fuel consumptions for each flight phase, from taxi to landing and loiter. These performance inputs also include required scooping distance, refuel/ recharge times and even battery swapping capability for electric aircraft. Mission profile inputs deal with the aircraft horizontal and vertical speed for each flight phase, take-off, cruise and landing altitudes and taxi time. Aircraft agents can be defined as vertical take-off and landing (VTOL), where a transition and re-transition segment is included in the flight profile. In addition to this, aircraft can be specified to having water/ seaport landing capabilities, distinguishing seaplane aircraft capabilities from conventional aircraft.

2.4 DHC-515 and Seaplane creation

Based on the inputs possible with the SoSID toolkit, assimilating and creating new aircraft into SoSID is fairly straight-forward. That being said, it is reliant on having fairly accurate fuel/ power consumption data which is typically not available online.

For the seaplanes, this information is provided for from within the COLOSSUS project [10]- the conceptual design is carried out in a design loop with several design mission routes, upon which an optimal design is obtained [11]. As this study is a continuation of previous work, the seaplane data will be extrapolated from [5] which itself is outputted from the design loops of COLOSSUS. A sample geometry configuration of the seaplane used in this work is shown in Figure 2. Given the worsening future climate conditions, variations to the seaplane design will be made, specifically to the design payload, range and cruise speed. These variations are considering 2035-2050 technology levels which is why the variations considered are substantial (20% increase in payload/range/speed). The procedure under which these upgrades are obtained is not the focus of this study; rather the goal is to facilitate future requirement generation for aircraft design and operations. The baseline seaplane design used in this study is shown in Table 1. The hybridization is to promote fuel sustainability, with the battery power being primarily employed to reduce taxi, take-off and climb fuel usage when possible.

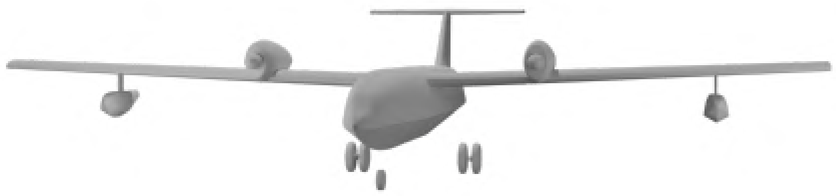


Figure 2 – Conceptual hybrid seaplane design, appended from [11]

The construction of each design is based on 2035 technology levels, where the base geometry and performance data is used to develop the further designs [10]. The change in design payload, range and speed result in an alteration to the aircraft's fuselage length to accommodate the payload changes and new lifting surfaces. The characteristic ratios of the aircraft, like aspect ratio, tail volumetric coefficient and other lifting surface sizes are maintained to maintain stability and control. For the aerodynamic specifications, semi-empirical relations from Roskam [12] and DATCOM manuals [13] were employed. After the sizing of the energy system is done, based on thrust/ power requirements. An assumed battery specific energy of 280 Wh/kg is used. The mass breakdown follows from semi-empirical Roskam and Torenbeek methods predominantly. Lastly mission analysis is employed using a point mass performance model and the aforementioned mass breakdown, aerodynamic and engine characteristic information. The flight segments are then solved for the fuel consumptions using simple differential equations. The end result is a new fuel mass estimation which then changes the estimated take-off mass, resulting in a re-iteration of the aircraft design. This is done until convergence is obtained between the fuel and take-off mass between iterations of 1%.

Table 1 – Baseline seaplane data

Attribute	**Value**
Powertrain Architecture	Hybrid Electric
Takeoff/Landing Type	Water
Payload Capacity (kg)	1235
Design Cruise Speed (m/s)	93
OEM (kg)	4464
MTOM (kg)	6297
Design Range (km)	450
Can Scoop	True
Suppressant Flow Rate (l/s)	1.2
Scooping Distance (m)	200
Span (m)	18.7
Take-off Power(MTOM) [W]	697
Cruise Climb Power (MTOM) [W]	618
Cruise Power (MTOM)[W]	425
Cruise Descent Power (MTOM) [W]	580
Landing Power (MTOM) [W]	580
Loiter Power (MTOM) [W]	294
Charging Power (kW)	359
Total Mission Usable Propellant Energy (kJ)	516988
Reserve Energy (kJ)	146396
Battery Swap Enabled	True
Battery Swap Time (s)	300.0

Take-off Fuel Consumption (MTOM) [kg/s]	0.0293
Cruise Climb Fuel Consumption (MTOM) [kg/s]	0.0435
Cruise Fuel Consumption (MTOM) [kg/s]	0.0227
Cruise Descent Fuel Consumption (MTOM) [kg/s]	0.0335
Landing Fuel Consumption (MTOM) [kg/s]	0.0335
Loiter Fuel Consumption (MTOM) [kg/s]	0.0208
Total Mission Usable Propellant Fuel (kg)	203
Reserve Fuel (kg)	91
Refuel Rate (kg/s)	15.14
Hybridization Ratio	0.163

Unlike the seaplane, the DHC-515 is modelled based on online data where available. Absence of fuel consumption data meant a method for obtaining fair approximations for the different flight phases was required. To do so, the DHC-515 was modelled in a DLR in-house conceptual design tool called OpenAD [14]. OpenAD utilizes a set of empirical equations based on Raymer and other methods to model aircraft based on user given requirements and design mission profiles. OpenAD outputs a finalized design of the aircraft according to MTOM convergence (<0.5% change in MTOM through iteration). To get more detailed fuel consumption data, the mission profile input of OpenAD is further analyzed with the output detailed design of the aircraft. Fuel consumption evaluation may result in engine re-sizing which results in a re-iteration of the OpenAD design, causing a linked design loop between OpenAD and the fuel analysis.

The input design mission has a large impact on the output design, significantly affecting converged fuel and empty masses. To get a more accurate design, the design mission was altered to give values design range and fuel consumption values that were consistent with online data [15]. The converged DHC-515 design that is used in SoSID to represent the RescEU fleet is given in Table 2. Even though the DHC-515 is classified as a water bomber, it typically takes off from standard airports due to its larger size inhibiting its water take-off performance [15]. Scooping capabilities are maintained however.

Table 2 – DHC-515 SoSID data

Attribute	**Value**
Powertrain Architecture	Conventional Fuel
Takeoff/Landing Type	Airport
Payload Capacity (kg)	6200
Design Cruise Speed (m/s)	96
OEM (kg)	12217
MTOM (kg)	20547
Design Range (km)	1000
Can Scoop	True
Suppressant Flow Rate (l/s)	1.2
Scooping Distance (m)	410
Span (m)	28.4
Take-off Fuel Consumption (MTOM) [kg/s]	0.495
Cruise Climb Fuel Consumption (MTOM) [kg/s]	0.426
Cruise Fuel Consumption (MTOM) [kg/s]	0.232
Cruise Descent Fuel Consumption (MTOM) [kg/s]	0.056
Landing Fuel Consumption (MTOM) [kg/s]	0.159
Loiter Fuel Consumption (MTOM) [kg/s]	0.208
Total Mission Usable Propellant Fuel (kg)	4608
Reserve Fuel (kg)	655
Refuel Rate (kg/s)	15.4

In most aspects, the DHC-515 is dominant to the COLOSSUS seaplane. Yet when acquisition and operational costs are considered this is no longer the case. For the DHC-515 acquisition cost is based on the RescEU contract, where 12 DHC-515's are being acquired for €600 million, giving an average cost per DHC-515 of €50 million [4]. The operational cost is based on the fuel consumption, base cost of use ($42000) and cost per flight hour ($13500/ hour) [16].

Because the seaplanes are still conceptual designs, their acquisition and operational costs are based largely on empirical relations and models. The seaplane acquisition cost modelling is based on an empirical relation of similar seaplanes and a function of OEM, shown in Equation 1. The operational cost for the seaplane is then modelled as a sum of capital, crew, energy and maintenance costs, as shown in Equation 2. Capital cost is dependent on the acquisition cost and assumed flight hours per year of 1500 [17]. Crew cost is based on a two person crew and a €40/ hr salary. Energy cost is dependent on the total fuel and energy consumed through the mission, and maintenance costs are modelled using an empirical relation which is a function of the acquisition cost and energy consumption.

$$\text{Acquisition Cost [M€]} = 1.84e^{-6} * OEM + 3.591 \tag{1}$$

$$\text{Operational Cost [€/hr]} = \text{Capital} + \text{Crew} + \text{Energy} + \text{Maintenance} \tag{2}$$

3 Experimental Setup

The experimental setup section details the different scenarios, including the future weather definitions, alongside the simulation operational setup for the various analyses. The future climate and environmental scenarios are defined in subsection 3.1 and the operational setup and variations to fleet, seaplane design and operational considerations is outlined in subsection 3.2.

3.1 Future climate scenarios

There are two environmental scenarios considered in this study, one on the Greek island of Salamis and the other in Italy's Sardinia. Both of these regions have a history of wildfire affliction during the Summer over the past decades. The choice of these specific destinations was due to the uncontrollable nature of their spread, taking several days to eventually contain. The fact both of the fires occurred on islands gives credence to the potential utility of seaplanes, as they may be more opportunely located than having to haul a heavy water bomber from a main airport. The fire ignitions in these regions are commonly due to dry conditions, arsonists and smoking negligence [18].

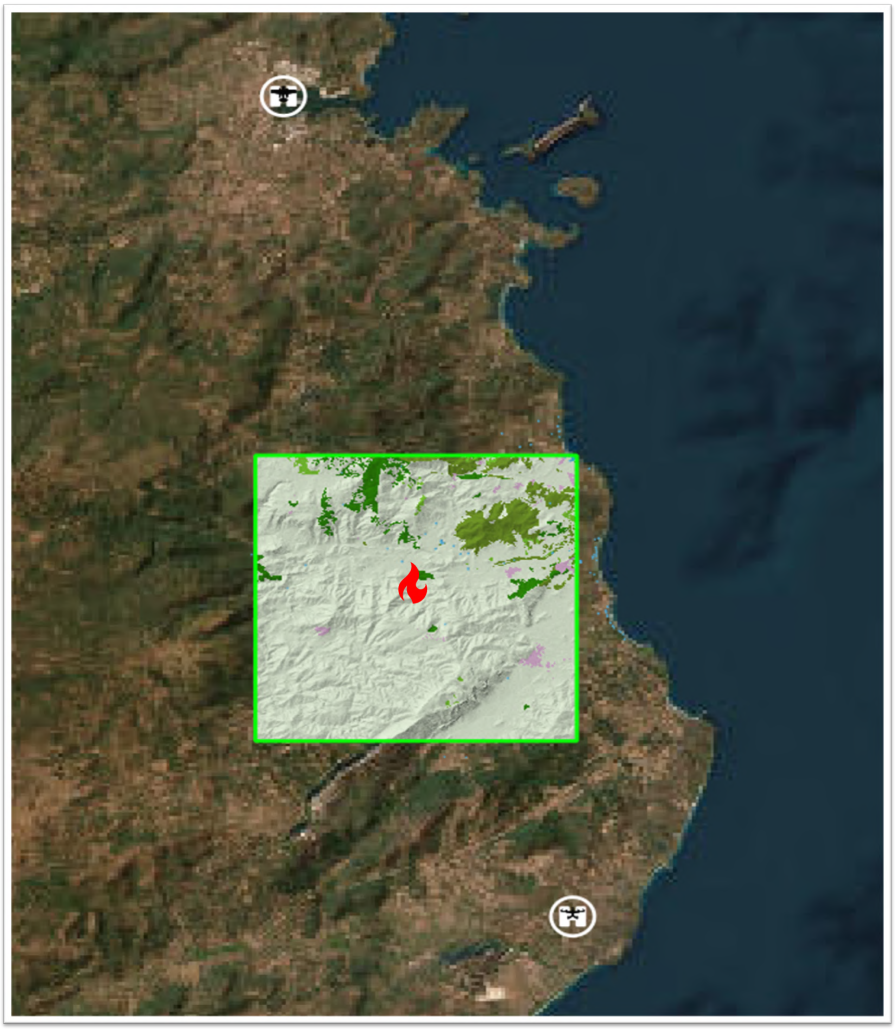


Figure 3 – Sardinia wildfire scenario in SoSID

SoSID can simulate these scenarios effectively by defining the bounding box of the fire region to be simulated alongside any airports or seaports of consideration. The end result is a map which contains the user inputted ignition center and the surrounding terrain and operational information. The maps for Sardinia and Salamis outputted and used by SoSID are shown in Figure 3 and Figure 4 respectively. On each map there is a dedicated seaport for the seaplanes and dedicated airport for which the DHC-515 is deployed. The cell size for the maps is 5 m and due to the larger terrain region of Sardinia, the map size is 3000x3000 cells compared to Salamis which is 2000x2000 cells. For the original scenarios, the fire starts on the 6th of August 2023 at 8:39 AM in Sardinia and the 17th of July 2023 at 3:59 PM in Salamis.

Figure 4 – Salamis wildfire scenario in SoSID

For each scenario, 3 weather variations will be assessed. The original weather conditions matching to the date of ignition, the most severe weather condition around the same time period of the fire ignition and a future, severe weather condition applying the 2050 policies for estimated climate change effects.
In Sardinia the most severe weather was obtained on the 24th of July, almost two weeks before the original fire ignition, with peak temperatures reaching 44℃ [19]. For Salamis the most severe weather condition was obtained on a similar date to Sardinia, on the 23rd of July, with peak temperatures also reaching 44℃ [19]. The distinction in weather from the original dates is due to the occurrence of the fires being from arsonists, but also due to the prevalence of heat waves in Southern Europe through the Summer periods [20]. Thus it is not unrealistic to hypothesize a situation in which a wildfire starts during these hot days, with the consequences of such a propagation being a concern for study. The last weather scenario established is in applying the projected temperature of the European region by the policies set for 2050, which indicate a stated an increase in global median surface temperature of 2℃ by 2050 [21].
Considering that the severe scenarios are typically within heat waves, it is important to understand the future of heat waves by the year 2050 as well. It is estimated that with a 1.5℃ increase in global mean temperature, the mean duration of a heatwave can increase by 6 days [20] and the frequency of heat waves per year also increases per degree by 1.5-2 [22]. During heat waves, the maximum temperature of the day exceeds the 90th percentile of the historical period, which gives indication that the true temperature change for heat wave days in 2050 may be more than the 2050 stated policies [22]. A study which analyzed the future temperature changes over Italian agricultural areas concluded that between the 2021-2050 period, the median minimum temperature of the day is expected to increase by around 1.5-2℃ with upper values of the distribution (90 percentile) being around 3-4.5℃. The same study indicated median maximum temperature increases of around 2-2.5℃ with upper values being 4-6℃ [23]. As the weather scenarios are dealing with severe conditions, aligned with heat waves, the upper band of values will be used to construct the 3rd weather scenario for the Salamis and Sardinia use cases. Thus, the last scenario will implement a 3.5℃ increase in the minimum temperature and a 5℃ increase in the maximum temperature of the 2nd weather scenario.

The summarized weather conditions for the hypothetical scenarios are shown in Table 3. The dew point is unchanged in the future extreme scenarios, which will reflect a drop in humidity given the higher temperature values.

Table 3 – Weather scenario definitions

	Sardinia			**Salamis**		
	Standard	Extreme	Future Extreme	Standard	Extreme	Future Extreme
Min Temp. [℃]	22	23	26.5	28	30	33.5
Max Temp. [℃]	30	44	49	37	44	49
Mean Dew Point [℃]	10	16	16	12	13	13
Mean Wind Speed [m/s]	4.4	4.5	4.5	5.2	5.4	5.4
Mean Wind Aspect (North = 0°)	0	240	240	0	180	180

3.2 Design of Experiments

The outcome of previous analysis highlighted strong benefits for a heterogenous aircraft fleet which is composed of at least two DHC-515's and at around 4 smaller seaplanes [5]. The purpose of the design of experiments (DoE) is to test the robustness of such a fleet composition, evaluating its performance in extreme scenarios (outlined in Table 3) and determining potential drawbacks and improvements. To explore the design space of the fleet, operations and seaplane design, iterations on these variables will be made relative to a baseline setup. The baseline in this case is the outcome of the previous analysis. The DoE design variations are shown in Table 4.

Table 4 – Aircraft, fleet and operational design variations per weather scenario

		Aircraft Design			Fleet Design	Operational Design
		Payload	Range	Speed	# of Seaplanes	Response Time [hrs]
	[Min, Max]	[-20%, 20%]	[-20%, 20%]	[-20%, 20%]	[2,6]	[2, 4]
	Step	10%	10%	10%	1	2
Aircraft Design	Payload	■	x	x	x	x
	Range	x	■	x	x	x
	Speed	x	x	■	x	x
Fleet Design	# Seaplanes	x	x	x	■	x
Operational Design	Response Time	x	x	x	x	■

The DoE will be applied to each weather scenario in each use case, totaling 7440 setups. It should be noted that there are several further operational and fleet considerations that could be explored, such as aircraft initialization and positioning, night time operations and choice of suppression tactic. For this study these values will be fixed to resemble as much as possible the previous study and the scenarios described in subsection 3.1. Night time operations will be allowed to prevent result complication and the suppression tactic used by the aircraft will be indirect attack, where a fire line is created around the fire before directly suppressing the fire fronts, shown in Figure 5. The indirect suppression tactic was found to be better in performance compared to more direct strategies, yielding less burnt area and a higher mission success for the given use cases [5].

Figure 5 – Indirect suppression in Salamis

4 Analysis & Discussion

With the experimental setup defined, the next step is to answer the research questions posed in section 1. The impact of climate effects will be dealt with in subsection 4.1 whilst the second research question dealing with the SoS evolution in correspondence to the climate effects is discussed in subsection 4.2.

4.1 Climate effects

The impact of the weather conditions is reflected in the fire model by increasing the spread rate of the fire, with hotter and drier conditions promoting a faster spread. As the extreme and future extreme weather scenarios have higher temperatures and reduced humidities, these scenarios have a higher burnt area for the same burn time compared to the standard.

For Salamis, the wildfire in the standard scenario without any firefighting efforts burns 17.0 ha of land after 4 hours. In the extreme scenario, at this same time, the wildfire burnt area is more than double, at 36.1 ha. Further increasing the temperature and reducing humidity for the future extreme scenario gives a burnt area of 41.7 ha. The increase in temperature compared to the standard scenario greatly hastens the wildfire's growth rate in the early stages of burning (<4 hr), to which at some point further weather extremities have a diminishing effect. After 12 hours of un-restrained burning, the standard scenario achieves a burnt area of 121.8 ha. The extreme scenario at this time has a burnt area of 147.8 ha, which is only slightly more than the original difference in burnt area, evidencing the diminishing effect of weather once a large enough fire front is obtained within Salamis. The future extreme scenario obtains a burnt area of 166.8 ha. The exact comparison in burning area is not always conclusive to the impact of weather as in mountainous environments with rich terrain diversity (woodlands, residential areas, shrubs, etc.) the fire spread in complex. In Salamis, fire spread becomes very rapid once the fire reaches the greener regions (which indicate woodlands) of the images shown in Figure 6. This explains why all 3 weather scenarios see a substantial and somewhat even increase in burnt area between 4 hr and 12 hr.


(a) Standard (b) Extreme (c) Future extreme

Figure 6 – Salamis Wildfire- 4 hr Comparison


(a) Standard (b) Extreme (c) Future extreme

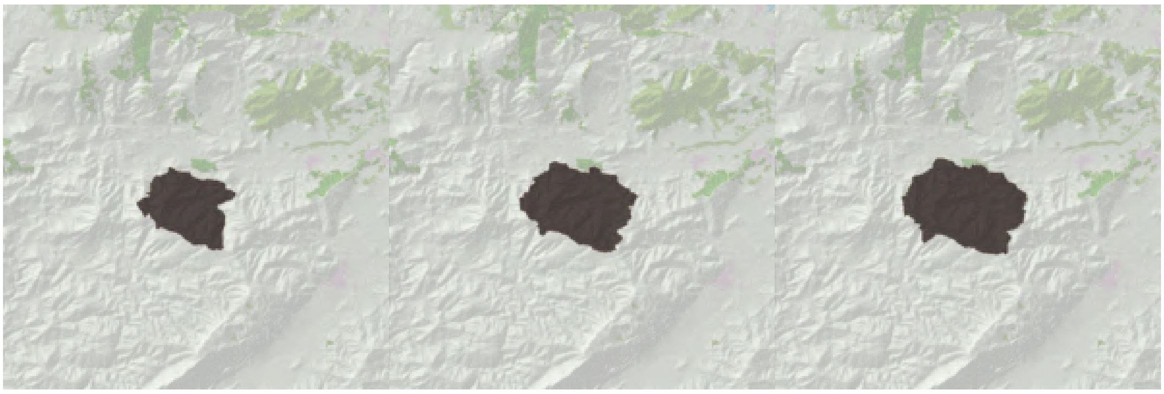
Figure 7 – Salamis Wildfire- 12 hr Comparison

The weather scenarios in Sardinia are slightly more mild compared to Salamis, with a generally lower temperature, humidity and wind speed. The same comparison between the weather scenarios is shown in Figure 8 and Figure 9. Sardinia's map is larger than Salamis' because the airbases are not as closely positioned, and thus the map needs to be large enough to accommodate for early fire growth before aircraft suppression. For the 4 hour comparison, the standard scenario has 13.3 ha of burnt area, the extreme has 25.7 ha and the future extreme 32.9 ha. All of these are less than the first stages of burning in Salamis, which corroborates the idea that the weather severity has a large impact on the initial stages of burning. At 12 hours of burning, the standard scenario reaches 131.4 ha, with the extreme having 185.6 ha and the future extreme 221.0 ha. These numbers are much larger than compared to Salamis despite the same burn time and reduced weather conditions. This is likely attributed to the terrain and environment of Sardinia, having more consistent terrain and reduced water boundaries. As a result of this, the 12 hour comparison highlights the significance of weather variations over a sustained period, with the peak temperatures giving a much larger burnt area. Compared to Salamis, the weather effects are most prominent in the later stages of fire burn (>4 hr). The ignition time is coinciding with this revelation as the fire ignition in Sardinia is in the morning compared to the afternoon in Salamis. Thus the weather impacts are greater portrayed when the fire ignition is early in the day as the most severe conditions (those which promote fire growth) are typically experienced at noon to the afternoon.

In regards to wildfire suppression capabilities, when analyzing the suppressive capabilities of the initial RescEU fleet (four baseline seaplanes and two DHC-515's) in each scenario, the graphs of

(a) Standard (b) Extreme (c) Future extreme

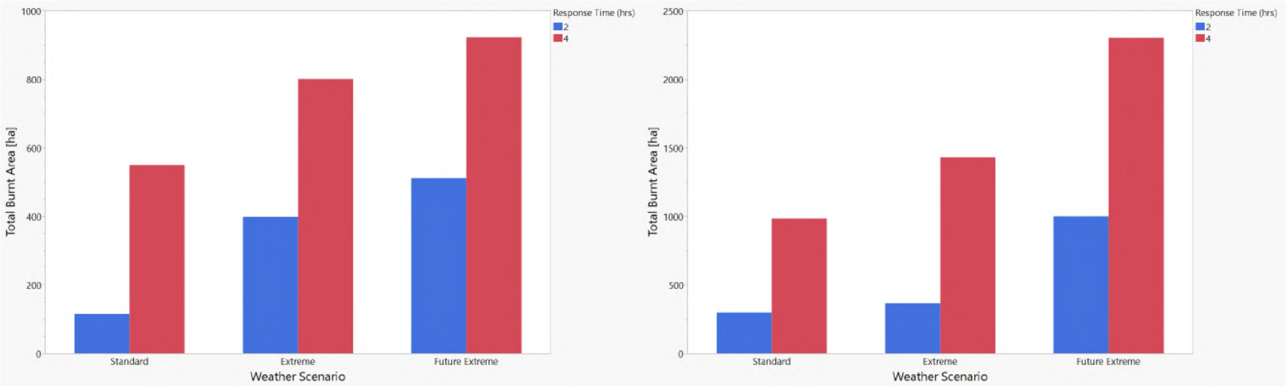
Figure 8 – Sardinia Wildfire- 4 hr Comparison



(a) Standard (b) Extreme (c) Future extreme

Figure 9 – Salamis Wildfire- 12 hr Comparison

Figure 10 are generated. The impact of response time is shown alongside. For Salamis, the fleet typically manages to suppress the fire quickly, with average burnt areas being half that of Sardinia. This is due to the terrain in Sardinia being more restrictive to wildfire spread and the opportune location being close to the sea and nearby airbases. If the fire is given the opportunity to spread to the nearby forests, either through increased fire spread rate through a more severe weather or an increase in response time, the burnt area increases substantially. The future extreme scenario with a 2 hr response time results in a similar burnt area compared to the standard scenario with a 4 hr response time, evidencing the importance of response times and weather. Sardinia sees a similar effect, with the 2hr response time in the future extreme scenario performing similar to the standard scenario's 4 hr response time. Unlike Salamis, the impact of response time does not diminish with more severe weather conditions. The 2 hr difference in response time for the extreme scenario leads to almost +250% burnt area, whereas in Salamis this was less than +100%. For the future extreme scenario in Sardinia, the difference is >+100%, and in Salamis, it is less than +80%. This information can be useful for tailoring future wildfire fighting efforts, as a greater understanding of the terrain environment can help operators determine how rapid their reaction forces should be, especially given future climate predictions.



(a) Salamis (b) Sardinia

Figure 10 – Burnt area and weather condition comparison

Of all the missions with the baseline seaplane design, mission success (fire extinction) was obtained in all scenarios except for the future extreme scenario of Sardinia, especially with the 4 hr response time. In this case, the fire reached the boundaries of the map, halting the simulation. It was only with a fleet of 6 seaplanes (2 more than the standard) and two DHC-515 that mission success was achievable, with the distinction in burnt area being less than 10%.

4.2 Evolving the SoS

Navigating through the multitude of scenarios can be difficult and troublesome with all the DoE variations. To overcome this, a measure of effectiveness (MoE) can be defined which tries to attribute the key outputs of a simulation in a conclusive manner to better gauge the performance of a SoS design. In this study, the MoE is defined as in Equation 3, where the attributes shown are all normalized with respect to the maximum value obtained across all simulations. The burnt area emissions are typically orders of magnitude higher than the fuel burn emissions but the inclusion of fuel burn emissions is to better distinguish operations with similar burnt area and slight differences in operational efficiency (less fuel burn). The terms for fleet acquisition and operational cost in the MoE are without the DHC-515 inclusion since this aircraft is already procured and the desired insights are regarding the prospective of future seaplane integration.

$$\begin{aligned}\textbf{MoE} =& (1-\widehat{TotalBurntArea})*0.25+(1-\widehat{FleetAcquisitionCost})*0.25+(1-\widehat{FleetOperationalCost})*0.25\\ &+(1-(\widehat{BurntAreaEmissions}+\widehat{FuelBurnEmissions}))*0.25\end{aligned} \tag{3}$$

The MoE is created for each environment, one for Sardinia and one for Salamis, and a final MoE is then determined by averaging the MoE's of the two use cases together. Aircraft design exploration can be done through a heatmap, with the aircraft design payload, design range and design cruise speed variations on different axes and the combined MoE as the color. From the aircraft design section, 124 of the 125 aircraft design configurations are present, but the configuration matching to a +10% increase in design payload and design cruise speed with the baseline range was non-convergent (non-feasible), which is why there are no results for that configuration. Figure 11 highlights seaplane designs across all scenarios, response times and fleet sizes and their corresponding effectiveness. The seaplane designs which offer the greatest effectiveness, considering cost and operational effectiveness are those which are smaller than the baseline, with reduced payload, range and speed capabilities. More specifically, the ideal design across all scenarios is a seaplane with a -10% design speed and range and a -20% design payload relative to the baseline data of Table 1.
Albeit initially unexpected, this conclusion can be explained with several reasons. First, the seaplane design iteration loop, and the outputted take-off and empty weight, are more sensitive to design payload variations than design range or speed variations. This means that for the same percentage

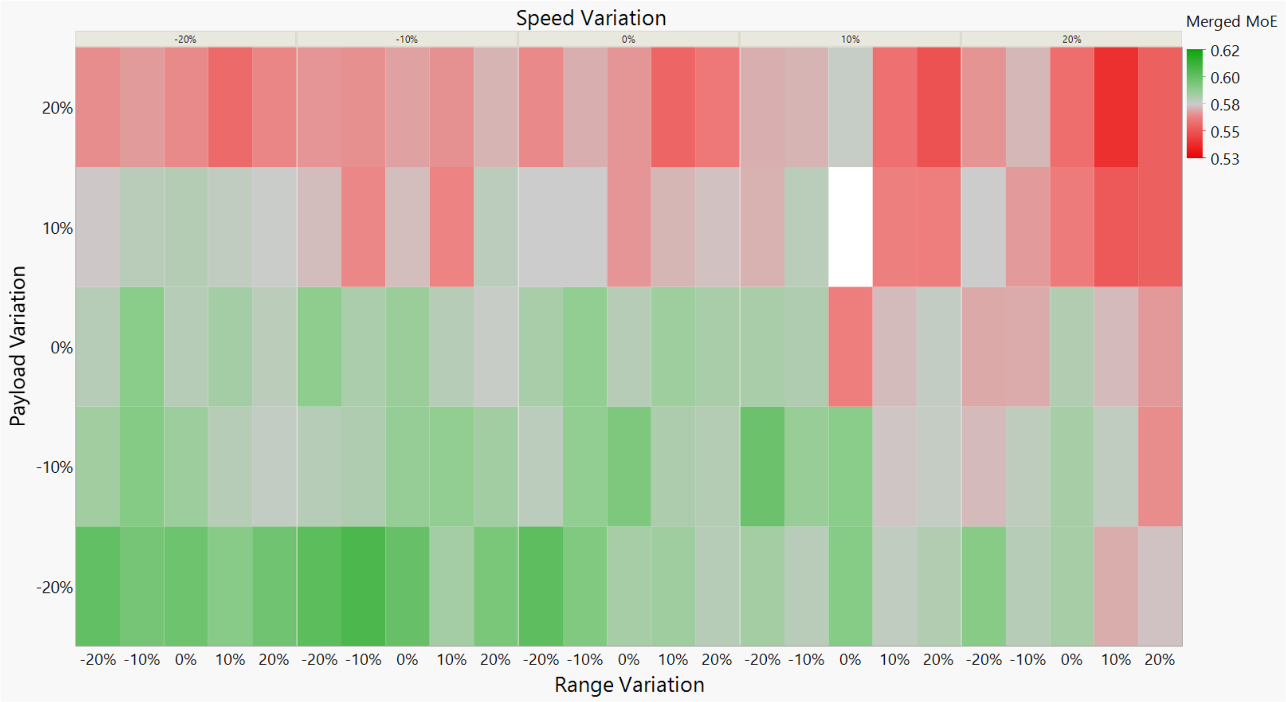


Figure 11 – Seaplane design exploration based on total scenario effectiveness

increase in design payload, the fuel consumption and production and therefore acquisition and operational cost increase more so than an increase in design range or speed. As a result, sustained fire fighting capability is reduced. The increased payload does lead to the greatest suppressive performance compared to the other two parameters, as the suppressant patch used to extinguish the fire is dependent on the payload capacity. This would typically justify the increased costs, however in the scenarios presented, the contribution of the seaplanes suppression relative to the DHC-515's is much weaker, establishing the seaplane as a supportive role to the fire suppression. In subsequent, the optimized MoE will be more tending to designing seaplanes that are more cost effective whilst ensuring their contribution is still impactful. In this case, seaplane impact is reflected in a longer sustained effort in staying close to the fire and dropping smaller fire patches to fill any holes in the fire block. This conclusion is not too dissimilar from previous research [5], where even though fleets with more DHC-515's were shown to be the most effective in wildfire suppression, the costs of operation and acquisition made the ideal fleets be composed of smaller seaplanes where every two seaplanes would be similar in price to one DHC-515.

In terms of fleet size, the desire to have a reduced cost of seaplanes is highlighted again in Figure 12. The more severe weather conditions result in a lower MoE due to the increased burnt area and operational costs in suppression. Increasing the fleet size does decrease the burnt area, as shown in Figure 13, but the increased operational (and acquisition costs) are greater, which concludes in a overall reduction in MoE. Since the seaplanes are used in these scenarios to delay fire progression compared to completely nullify its presence, even larger fleets designed with greater payload, range and speed capabilities tended to perform similar or only slightly better than smaller fleets. Smaller fleets of 2-3 seaplanes, designed with smaller payloads and better fuel and cost efficiency, were able to fulfill the supportive role sufficiently in most scenarios, with only the future extreme case in Sardinia proving to be insufficient. If a complete, oppressive force is required, one that can deal with further severe conditions, either seaplanes need to be designed with a similar payload and fuel economy of the DHC-515, which comes at a great cost burden, or the rapid reaction capabilities must be exploited. The latter point is promising, especially given the operational environment being Southern Europe and the Mediterranean, areas with naturally high seaplane density.

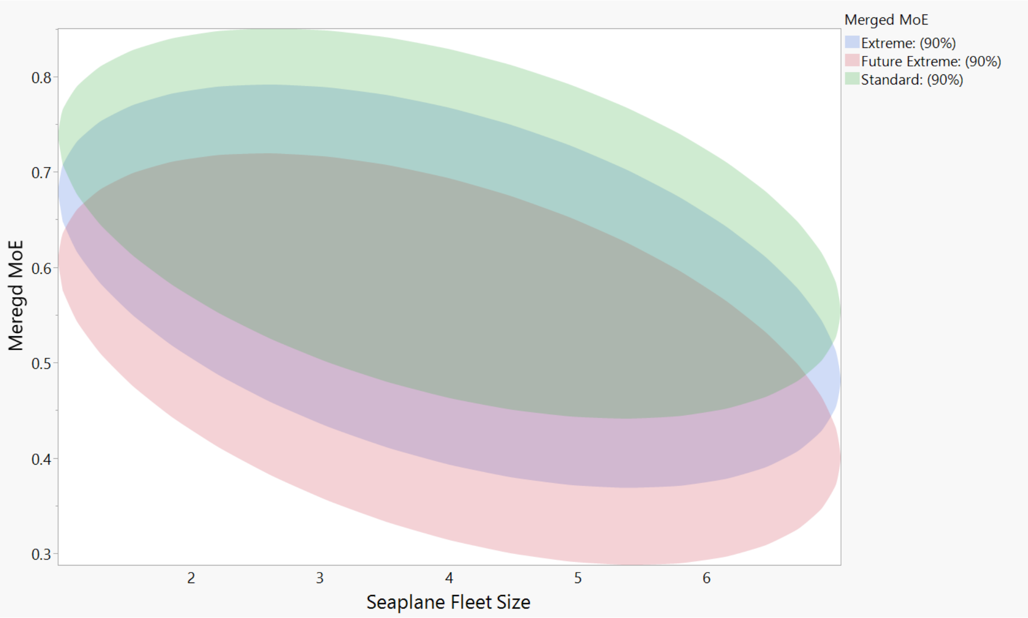


Figure 12 – Fleet size and weather scenario impact

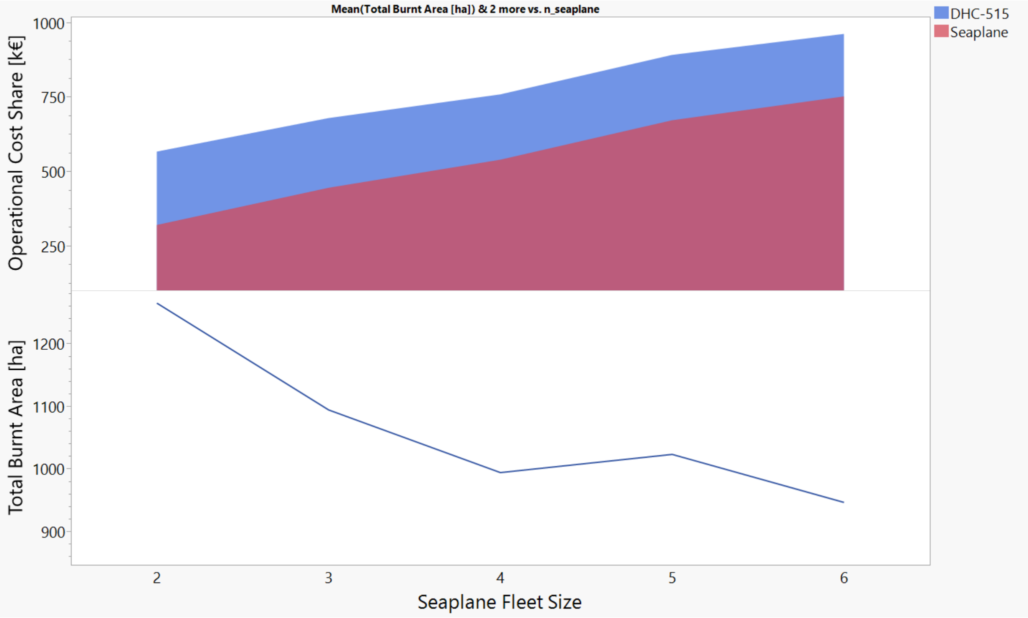


Figure 13 – Seaplane operational cost and burnt area comparison

5 Conclusion

The purpose of this research was two-fold: to attempt to understand how future climate change predictions can affect wildfire and wildfire fighting in Europe, and to explore how future aerial wildfire fighting in in response to the increase in wildfire severity could be evolved using seaplane designs. This was achieved through a simulation tool which employs a cellular automata wildfire model and an agent-based model to simulate aerial wildfire fighting aircraft agents. Based on future 2050 prediction policies and historical data, several weather scenarios were created and simulated on two different environments in the Mediterranean. Compared to current conditions, future severe weather predictions result in 50-100% increases wildfire burnt area. The location of the ignition center and the weather conditions determine the phase of burning through which fire propagation is extreme. The response time of wildfire fighting forces is key in such scenarios, with a 4 hr response time resulting

in up to +250% more burnt area compared to a 2 hr response time. Aside from operational considerations, a continued research on the integration of seaplane vehicles in a future fleet with large water bombers like the DHC-515 was explored. The seaplanes employ a supportive role in such a configuration, impeding the increasing wildfire spread rate whilst larger bombers conduct the larger suppression. Based on the cost effectiveness, smaller seaplanes with a reduced payload, range and speed are found to be ideal. If seaplanes are to be designed with similar size capabilities as large water bombers or operation and production costs are reduced, future analysis could indicate their benefit. Even so, the implied availability of seaplanes during Summer months in common wildfire areas, like the Mediterranean, justify their prospective inclusion in future fleets.
Improvements to this study can be done through running larger, more varied (inland) scenarios as current computational and time capabilities impaired map sizes to be 20x20 and 30x30 km. Ground agents are still be explored in coincidence with aerial wildfire fighting, even if their ability is diminished due to the restrictive scenarios analyzed. This paper is not intended to provide a definitive answer to how to design future wildfire fighting systems or the exact replication or forecasting of wildfires in Europe. Rather the researched conducted hopes to service future exploration into seaplane design for aerial wildfire fighting and provide awareness for the growing trends in wildfires in Southern Europe.

6 Acknowledgements

The research presented in this paper has been performed in the framework of the COLOSSUS project (Collaborative System of Systems Exploration of Aviation Products, Services and Business Models) and has received funding from the European Union Horizon Europe program under grant agreement No. 101097120. The Swiss participation in the Colossus project is supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 22.00609.

7 Copyright Statement

References

[1] Garroussi, S. E., Giuseppe, F. D., Barnard, C., and Wetterhall, F., “Europe faces up to tenfold increase in extreme fires in a warming climate,” *npj Climate and Atmospheric Science*, 2024. URL `https://api.semanticscholar.org/CorpusID:267359783`.

[2] “Wildfires: 2023 among the worst in the EU in this century,” , 4 2024. URL `https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/wildfires-2023-among-worst-eu-century-2024-04-10_en`.

[3] Frost, R., “Hottest summer ever? Experts reveal what could be in store for Europe in the next few months,” 2024. URL `https://www.euronews.com/green/2024/06/18/hottest-summer-ever-experts-reveal-what-could-be-in-store-for-europe-in-the-next-few-`

[4] (CCC), T. C. C. C., “CCC, France sign contract for DHC-515 FIREFIGHTER™ aircraft - Canadian Commercial Corporation (CCC),” , 10 2024. URL `https://www.ccc.ca/en/announcements/ccc-france-sign-contract-for-dhc-515-firefighter-aircraft/`.

[5] Shiva Prakasha, P., Naeem, N., Kalliatakis, N., and Björn, N., “A System of systems approach to evaluate potential of wildfire fighting seaplanes in future RESCEU fleet designs,” 14th International EASN Conference, 2024.

[6] Kilkis, S., Prakasha, P. S., Naeem, N., and Nagel, B., "A Python Modelling and Simulation toolkit for rapid development of System of Systems Inverse Design (SOSID) case studies," *AIAA AVIATION 2021 FORUM*, 2021. https://doi.org/10.2514/6.2021-3000, URL https://doi.org/10.2514/6.2021-3000.

[7] Rui, X., Hui, S., Yu, X., Zhang, G., and Wu, B., "Forest fire spread simulation algorithm based on cellular automata," *Natural Hazards*, Vol. 91, No. 1, 2017, pp. 309–319. https://doi.org/10.1007/s11069-017-3127-5, URL https://doi.org/10.1007/s11069-017-3127-5.

[8] McDonald, G. W., and Osgood, N. D., *Agent-Based Modeling and Its Trade-Offs: An Introduction and Examples*, Springer International Publishing, Cham, 2023, pp. 209–242. https://doi.org/10.1007/978-3-031-40805-2_9, URL https://doi.org/10.1007/978-3-031-40805-2_9.

[9] Legendre, D., Becker, R., Alméras, E., and Chassagne, A., "Air tanker drop patterns," *International Journal of Wildland Fire*, Vol. 23, No. 2, 2013, p. 272. https://doi.org/10.1071/wf13029, URL https://doi.org/10.1071/wf13029.

[10] COLOSSUS, "Deliverable D4.2 Conceptual Seaplane & UAM Aircraft Design Set for SoS Analysis (design loop 1)," Tech. rep., 4 2024.

[11] "MULTIDISCIPLINARY PRELIMINARY DESIGN PROCESS OF HYBRID-ELECTRIC SEAPLANE," 2023. URL https://www.icas.org/ICAS_ARCHIVE/ICAS2024/data/preview/ICAS2024_0470.htm.

[12] Roskam, J., *Preliminary sizing of airplanes*, DARcorporation, 2015.

[13] Vukelich, S. R., Stoy, S., Burns, K. A., Castillo, J. A., and Moore, M., *Missile Datcom*, 1988.

[14] Wöhler, S., Atanasov, G., Silberhorn, D., Fröhler, B. M. H. J., and Zill, T., "PRELIMINARY AIRCAFT DESIGN WITHIN A MULTIDISCIPLINARY AND MULTIFIDELITY DESIGN ENVIRONMENT," 2020. URL https://api.semanticscholar.org/CorpusID:235679112.

[15] of Canada, D. H. A., "De Havilland Canadair 515 - De Havilland Canada," , 10 2024. URL https://dehavilland.com/de-havilland-canadair-515/.

[16] Acarter, "The most economical solution," , 2020. URL https://www.firebossllc.com/cost-comparison/.

[17] Ioannidis, S., "Firefighting planes flight hours up by 1260to last year," 2024. URL https://www.ekathimerini.com/news/1242871/firefighting-planes-flight-hours-up-by-1260-compared-to-last-year/.

[18] Carbonaro, G., "Wildfires: Hundreds evacuated in Italy's Sardinia as fires rage in Portugal and Cyprus," 2023. URL https://www.euronews.com/2023/08/07/more-than-600-people-evacuated-as-wildfires-rage-across-italys-sardinia.

[19] "The weather year round anywhere on Earth - Weather Spark," , 2024. URL https://weatherspark.com/.

[20] Wong, T., "What Would Cities Look Like With 3 Degrees C of Warming vs. 1.5? Far More Hazardous and Vastly Unequal," , 09 2024. URL https://www.wri.org/insights/climate-change-effects-cities-15-vs-3-degrees-C.

[21] International Energy Agency, *World Energy Outlook 2021*, IEA, Paris, 2021. URL https://www.iea.org/reports/world-energy-outlook-2021.

[22] Domeisen, D. I. V., Eltahir, E. A. B., Fischer, E. M., Knutti, R., Perkins-Kirkpatrick, S. E., Schär, C., Seneviratne, S. I., Weisheimer, A., and Wernli, H., "Prediction and projection of heatwaves," *Nature Reviews Earth & Environment*, Vol. 4, No. 1, 2022, pp. 36–50. https://doi.org/10.1038/s43017-022-00371-z, URL https://doi.org/10.1038/s43017-022-00371-z.

[23] Tomozeiu, R., Pasqui, M., and Quaresima, S., "Future changes of air temperature over Italian agricultural areas: a statistical downscaling technique applied to 2021–2050 and 2071–2100 periods," *Meteorology and Atmospheric Physics*, Vol. 130, No. 5, 2017, pp. 543–563. https://doi.org/10.1007/s00703-017-0536-7, URL https://doi.org/10.1007/s00703-017-0536-7.