D5.7 brief 1: Results and recommendations from a HAPS fleet simulation confronted to real risk and fire events data at South European level

www.fire-res.eu

fire-res@ctfc.cat

Project Acronym: FIRE-RES

Project name: Innovative technologies and socio-ecological-economic solutions for fire resilient territories in Europe

Call ID: H2020-LC-GD-1-1-2020 (Preventing and fighting extreme wildfires with the integration and demonstration of innovative means)

Work Package: WP5

Task Number: 5.2.3

Lead beneficiary: AIRBUS DS GEO SGSA

Contributing beneficiary(ies): AIRBUS DS GEO SGSA

This document was produced under the terms and conditions of Grant Agreement No. 101037419 of the European Commission. It does not necessarily reflect the view of the European Union and in no way anticipates the Commission's future policy in this area.

Publication

Publication date: 29/11/2024

Authors: Óscar Souto Lorenzo, Airbus; Francisco Javier Artero Basteiro, Airbus; Gal·la Farnós Solà, Airbus; Adrià Biel Simón, Airbus; Abel Grimaldos Pozo, Airbus; Samanta Simón Bernabeu, Airbus; Pol Llorca Felip, Airbus; Pere Roca Carles, Airbus

Abstract: This study simulates a fleet of High Altitude Pseudo-Satellites (HAPS) operating in Southern Europe. Utilizing historical fire and risk data, the simulation aims to demonstrate the fleet's capability to provide effective fire monitoring services. The results indicate that a combined approach, integrating both European and regional fleets, enhances response times and adaptability, particularly during seasonal fire peaks across various regions. This study highlights the potential of HAPS fleets to significantly improve fire monitoring and management, offering a strategic advantage in mitigating fire-related risks.

Key words: HAPS, EWE, Fires, Risks

Quote as: Souto-Lorenzo, O. et al. (2024) Results and recommendations from a HAPS fleet simulation confronted to real risk and fire events data at South European level. Deliverable D5.7 FIRE-RES project. 10.5281/zenodo.1418154

DOI: 10.5281/zenodo.1418154

Dissemination level

[X] PU- Public: must be available in the website

[ ] CO- Confidential: Only for members of the Consortium and the Commission Services

[ ] CI – Classified: As referred in to Commission Decision 2001/844/EC

Document history

Edition	Date	Status	Author
Version 1	29/10/2024	Draft 1	Óscar Souto Lorenzo, (Airbus), Francisco Javier Artero Basteiro (Airbus), Gal·la Farnós Solà (Airbus), Adrià Biel Simón (Airbus), Abel Grimaldos Pozo (Airbus), Samanta Simón Bernabeu (Airbus), Pol Llorca Felip (Airbus), Pere Roca Carles (Airbus)
Version 2	08/11/2024	Revision	Miguel Mendes (Technosylva), Adrián Jiménez Ruano (Technosylva)
Version 3	11/11/2024	Revision	Martín Senande Rivera (Mitiga)
Version 4	15/11/2024	Draft 2	Óscar Souto Lorenzo, (Airbus), Francisco Javier Artero Basteiro

Edition	Date	Status	Author
			(Airbus), Gal·la Farnós Solà (Airbus), Adrià Biel Simón (Airbus), Abel Grimaldos Pozo (Airbus), Samanta Simón Bernabeu (Airbus), Pol Llorca Felip (Airbus), Pere Roca Carles (Airbus)
Version 5	27/11/2024	Revision	Adrián Cardil (Technosylva), Pau Brunet (CTFC), Diana Bolopo (CTFC)
Version 6	29/11/2024	Final version	Óscar Souto Lorenzo, (Airbus), Francisco Javier Artero Basteiro (Airbus), Gal·la Farnós Solà (Airbus), Adrià Biel Simón (Airbus), Abel Grimaldos Pozo (Airbus), Samanta Simón Bernabeu (Airbus), Pol Llorca Felip (Airbus), Pere Roca Carles (Airbus)

Executive Summary

HAPS (High Altitude Platform Stations or High Altitude Pseudo-Satellites), operating at the stratosphere, are walking big steps towards becoming the third layer for Earth Observation and Communications between the space (satellites) and the troposphere (aircrafts, drones, ground facilities). The steps are both on technical and regulatory aspects. Thanks to its capacity to persist over the area of interest day and night for long periods without disturbing the airspace used by the firefighting aerial units, ESA and the HAPS community strongly believe that this technology will bring a significant value to the Forest Fires domain [RD-09].

In this document, Airbus is presenting a simulation exercise that helped transiting from this 'strong believe' to specific figures showing the performance of HAPS in the Forest Fires domain. The simulation confronted the HAPS – not just one, but a fleet – with real historical fire risk and fire events all over the south of the European continent. The results of the simulation are a tool for the firefighting community to assess the benefits of incorporating HAPS in their future operations and it enables Airbus to make recommendations on fleet size and fleet deployment. While satellite constellations sizing exercise is quite common in the industry, this is the first exercise in the HAPS and forest fires domain, so it represents a complete innovation that originated new methodologies and tools.

This document is focusing on the simulator and its results expressed as KPI. In order to provide context to the reader, it also includes a short overview of the HAPS technology and concept of operations, as well as its payloads, but these are more deeply explained in the document IA 5.6 brief 2: A high level definition of HAPS wildfire service. Examples of the simulator map views are also included in this second document. Finally, a third document is providing a roadmap for the EU institutions and national/regional forest fires stakeholders to adopt the HAPS solution: IA 5.6 brief 3: A roadmap for the implementation of the European HAPS-based wildfire service.

Defining the scope and inputs of the simulation required multiple trade-offs to make sure that the results are as representative of the reality as possible. In this regard, fixed-wing, heavier-than-air HAPS were selected leaving balloons and airships off the simulation because only the former have fully predictable trajectories. In consequence, the simulation playground was limited to south of parallel 44º N, to accommodate the current latitude limit of such platforms several months off the summer solstice. This capability is expected to improve in the next years. Nevertheless, countries below this latitude concentrate most large fire events in Europe. Complete and homogeneous fire events and fire risk datasets from the EFFIS component of the Copernicus Emergencies Program were selected, instead of gathering more granular but less coherent data from stakeholders at national or regional level. Only fires larger than a specific size or duration were selected. Finally, the simulation was limited to a season extending from May to September, including five years from 2018 to 2022 to smooth the intrinsic interannual variability of wildfires.

The development of the simulator required understanding the flight dynamics of fixed-wing HAPS in relation to the wind, which was achieved thanks to Airbus experience with

its record-breaking Zephyr aircraft. The authors created a dynamic lattice of wind speed and direction in the stratosphere from the ECMWF ERA5, Copernicus Climate Change Service (C3S). It was assumed that the HAPS could move freely in this lattice, following geodetic lines, with no regulatory/air traffic constraints.

A significant effort was required to automate the individual HAPS assignation to fire risk peaks (fire detection) and to fire events (fire monitoring), emulating the human decision-making process. Geo-fencing was used to constrain some HAPS into specific countries or regions, while other were allowed to fly all over the playground. HAPS were also constrained in time, allowing some units enter and exit the game on specific dates. A complex structure of points of interest, fire weather index and fire burning ratio allowed to establish priorities and task the fleet on a 1-hour basis.

Multiple KPI were proposed and extracted from the raw output data of the simulator, both from the fire's perspective (i.e. percentage of burnt area monitored, average time from fire start to HAPS arrival, etc.) and from the HAPS perspective (i.e. percentage of time monitoring fires, percentage of time in fire detection, etc.). KPIs were assessed per month and per country/region. The most significant KPI were selected to drive the fleet sizing exercise.

Hundreds of simulations were launched with different input parameters and increasing the number of HAPS in the fleet. Two approaches were tested: 1) A single fleet covering the full area of simulation, 2) Multiple fleets each constrained to a countries or region (FIRE-RES Living Labs were used).

The results show that a high percentage of the burnt area is monitored with a relatively small fleet: 8 HAPS reach 90% of the burnt area, 14 HAPS reach 96% for both the full southern Europe simulation and the Living Labs simulation.

The Living Labs or regionalised approach offers higher reactivity, with HAPS reaching the fire in less than 3 hours. The pan-European approach shows an average of 6 hours, which is less reactive but still enough to cover the first night of a typical fire.

Almost two thirds of the fleet's flight time are dedicated to fire monitoring, including the travel time to fires. This is an excellent figure, which still leaves one third of the time for secondary use cases like fire detection or other emergency/security activities, in case the HAPS are shared with other users.

The study concludes proposing optimal fleet size for both the pan-European and the regionalised approaches on a monthly basis. Among other recommendations, the authors advocate for a mixed approach, with a baseline capability offered by European institutions complemented with regional deployments, where the authorities wish a more reactive premium service.

Table of contents

Acronyms

Table 1 Acronyms

Acronyms	Description
AoI	Area of Interest
AoS	Area of Simulation
BI	Burning Index
BUI	Build-up Index
CDS	Climate Data Store
CEMS	Copernicus Emergency Management Service
CONOPS	Concept of Operations
ECMWF	European Centre for Medium-Range Weather Forecasts
EFFIS	European Forest Fire Information System
EO	Earth Observation
ETA	Estimated Time of Arrival
EWDS	Early Warning Data Store
EWE	Extreme Wildfire Event
FDI	Fire Danger Index
FWI	Fire Weather Index
GIS	Geographic Information System
GS	Ground Speed
HAPS	High Altitude Pseudo-Satellite (or High Altitude Platform Station)
ISI	Initial Spread Index
KPI	Key Performance Indicator
LEO	Low Earth Orbit
PLOC	Payload Operations Centre
POC	Platform Operations Centre
PoI	Point of Interest
SatCom	Satellite Communications
TAS	True Air Speed

Reference Documents

[RD-01] Download real-time updated Burned Areas database (Shapefile) in https://forest-fire.emergency.copernicus.eu/applications/data-and-services

[RD-02] Copernicus Climate Change Service, Climate Data Store, (2019): Fire danger indices historical data from the Copernicus Emergency Management Service. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.0e89c522 (Accessed on 30-May-2024)

[RD-03] Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.bd0915c6 (Accessed on 30-May-2024)

[RD-04] The quest for the perfect fire danger index – article (https://predictia.es/en/news/en/fire-danger-index-correlation-data-viewer)

[RD-05] The quest for the perfect fire danger index – data viewer (https://showcase.predictia.es/global-fwi)

[RD-06] Los incendios forestales en España. Decenio 2006-2015 (Madrid 2019)

[RD-07] User Requirements Document (Oct 2018), Services enabled by High Altitude Pseudo Satellites (HAPS) complemented by satellites Project – Deliverable 1

[RD-08] Services and System Definition (Feb 2019), Services enabled by High Altitude Pseudo Satellites (HAPS) complemented by satellites Project – Deliverable 2

[RD-09] Viability Assessment (Feb 2019), Services enabled by High Altitude Pseudo Satellites (HAPS) complemented by satellites Project – Deliverable 3

[RD-10] Roadmap and Recommendations (Jun 2019), Services enabled by High Altitude Pseudo Satellites (HAPS) complemented by satellites Project – Deliverable 4

[RD-11] Outline Proposal for IAP Demonstration Project (Mar 2019), Services enabled by High Altitude Pseudo Satellites (HAPS) complemented by satellites Project – Deliverable 5

[RD-12] Deliverable 1 (Technical Note 1): HAPS Flight Campaign Conception - European HAPS Campaign Preparation Study 2023 (AIRBUS, ESA)

[RD-13] Fire Danger Forecast (https://forest-fire.emergency.copernicus.eu/about-effis/technical-background/fire-danger-forecast)

[RD-14] Copernicus Emergency Management Service Fire Danger Rating https://effis-gwis-cms.s3.eu-west-1.amazonaws.com/effis/applications/effis.viewer/userguide.pdf

[RD-15] Canadian Forest Fire Weather Index (FWI) https://cwfis.cfs.nrcan.gc.ca/background/summary/fwi

[RD-16] National Fire Danger Rating System (United States) https://www.fs.usda.gov/detail/cibola/landmanagement/resourcemanagement/?cid=stelprdb5368839

[RD-17] McArthur Forest Fire Danger Index (Australia) https://www.bushfirecrc.com/sites/default/files/managed/resource/ctr_010_0.pdf

[RD-18] [RD-13] Annex G – Technology readiness levels (TRL), HORIZON 2020 Work Programme 2018-2020, General Annexes

1. INTRODUCTION

FIRE-RES is a 4-year project (2021-2025) led by the Forest Science and Technology Centre of Catalonia in Spain and funded under the European Union's H2020 research and innovation programme. It aims to promote the implementation of an Integrated Fire Management approach and support the transition towards more resilient landscapes and communities to Extreme Wildfire Events in Europe. For this, FIRE-RES is developing more than 30 Innovation Actions intended to move toward an integrated model for Extreme Wildfire Events' management.

The Innovation Action 5.6 is included in the Working Package 5 "Advanced technologies, equipment and decision support systems", and it is dedicated to exploring the potential of a fire-fighting monitoring service provided by a fleet of High-Altitude Pseudo-Satellites (HAPS).

To achieve representative and actionable results, a comprehensive simulation was conducted, utilizing historical fire and risk event data across Southern Europe. The first deliverable D5.7 of this Innovation Action 5.6 is centred on the results and recommendations of the simulation. This document will be followed by deliverable D5.8, that will provide a high-level definition of HAPS wildfire services. Lastly, deliverable D5.9 will propose a roadmap for implementing the service.

The first chapter of this document serves as an introduction to the HAPS platforms, Earth Observation payloads, and the concept of operations of the services they can provide. This foundational context is crucial for understanding the subsequent simulation design and its implications.

Following the introduction, the document delves into the specifics of the simulation design and the input data required. This section includes an assessment of the types of data needed and an examination of the pre-processing steps necessary to ensure integration and coherence within the overall model. To accurately represent reality in a simplified manner, several models were developed. These models include representations of fire events, HAPS platforms, and the criteria for prioritization and assignment of the HAPS fleet.

The simulation strategy is then outlined, detailing the main requirements that drive the sizing of the fleet. This strategy involves executing multiple simulations aimed at obtaining results that are relevant for understanding the performance of the service. The simulations are conducted at two different scales: European and regional, with the latter focusing on the Living Labs of Southern Europe. This dual-scale approach allows for a comprehensive analysis of the fleet's capabilities and adaptability.

The results obtained from these simulations are analysed to understand the impact of the fleet size and the deployment strategies. With the outcome of this analysis, the HAPS fleets configurations are enhanced with the aim to improve the performance of the service.

The final chapter of the document is dedicated to presenting the conclusions and recommendations derived from the simulations. This section synthesizes the findings and offers strategic insights for future implementations. Additionally, an annex is included, which details the requirements used in the design of the simulation, providing a comprehensive reference for the methodologies and tools developed during this innovative exercise.

This document represents a significant advancement in the field of fire monitoring and management, showcasing the potential of HAPS fleets to enhance response times and adaptability, particularly during seasonal fire peaks.

1.1. Scope

The objective of this document is to provide conclusions and recommendations about the implementation of a fire monitoring service provided by a HAPS fleet deployed in Southern Europe. Two different types of simulations have been conducted: European scale, and regional scale (based on Living Labs).

The simulations are based on the period 2018 – 2022, and make use of historical data of fires, risks and wind. This input data is pre-processed for integration and serves to model some realities like the fire behaviour or the flight dynamics of the HAPS platforms.

Based on the results of the simulations, the optimal HAPS fleet has been refined for the European and regional scale, and the main conclusions and recommendations have been elaborated.

2. HAPS INTRODUCTION

The stratosphere, the second lowest layer of the atmosphere located at an altitude between 12 and 50 km, offers an environment of low air density, where the drag is reduced and the lift can be maintained equal to the aircraft weight, without wind turbulence and generally free of obstacles (above commercial air transportation). These conditions allow the aircraft flight to last longer than in tropospheric conditions.

Long endurance flights at the stratosphere have been studied since at least 1938, but currently it has become one of the main focuses for technology development due to its great potential for a diversity of applications, like Earth Observation (EO) and communications.

In particular, the stratosphere offers the following advantages regarding EO (including fire detection and monitoring):

- Observation from a strategic position from above clouds, commercial aviation and drones and below the crowded layers of the Low Earth Orbits (LEO).
- Unique perspective from which images of Earth surface can be captured with higher resolution than satellite images and downlinked in real-time.
- More operational flexibility than satellites thanks to the flight persistence and real-time commanding, answering faster to specific events/emergencies and changing necessities.

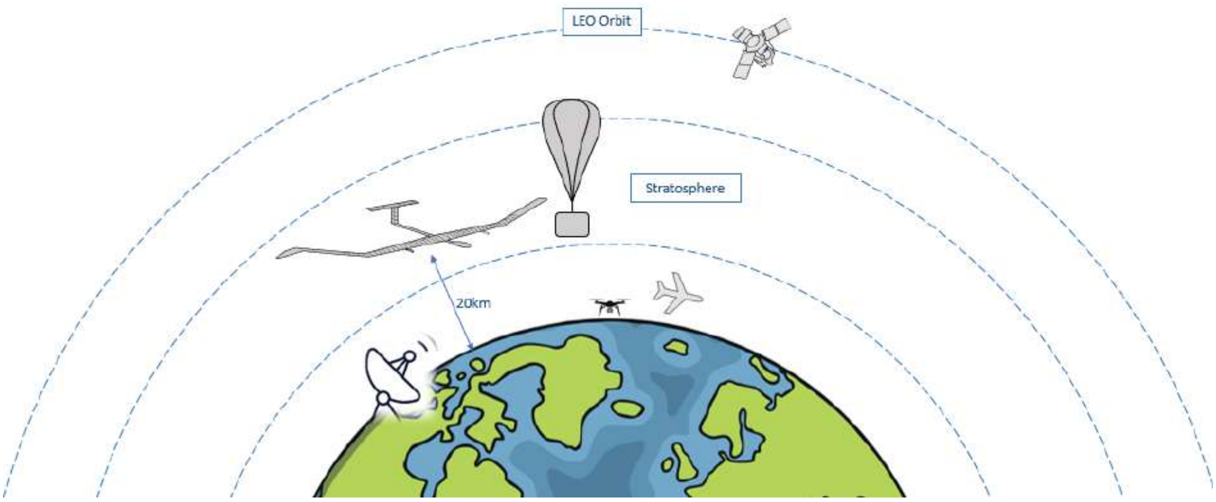


Figure 1 Commercial aircraft, HAPS and LEO satellites (not at scale)

The HAPS, High Altitude Pseudo-Satellite (a.k.a. High-Altitude Platform System), are unmanned platforms designed to host payloads and bring them safely to the stratosphere, at an average altitude of 20 km, from where they can be operated remotely to fulfil their objectives.

These stratospheric platforms can be of two main types: aerodynamics (fixed-wing like aircrafts) or aerostatics (like balloons).

2.1. Aircraft HAPS

There are many aircraft-type HAPS under development, however, none of them is as advanced as Zephyr (from AALTO HAPS), which has achieved the following objectives:

- It has performed many long duration flights, in particular, in 2022 performed a 64 days flight without refuelling.
- FAA has provided approvals for flying over air traffic.
- It has performed international flights

Figure 2 Zephyr HAPS

Zephyr flies at an average altitude of 20 km, reaching the stratosphere within 12-24h. Thanks to the stratospheric conditions together with the light and aerodynamic design of Zephyr, it can reach any area of the World in maximum 10 days.

Its proven manoeuvrability allows the pilots to drive the aircraft with precision to the target point of interest and remain in the desired area for extended times, providing persistence for detection and/or observation in real-time.

Zephyr rellies fully in solar power, which not only makes it more sustainable than airplanes and satellites, but also allows it to fly during long periods without needing to land for refuelling. It currently holds an endurance record without refuelling for a heavier than air platform of 64 days. The manufacturer AALTO targets 180 days of autonomy.

2.2. Balloon HAPS

Stratospheric balloons are typically filled with helium or hydrogen and can reach altitudes between 18 and 21km.

They have higher payload capacity than aerodynamic HAPS and are more cost-efficient. Their launch and recovery are usually simpler than aircraft HAPS and currently, they have more flight endurance in the stratosphere (flights up to 200 days have been carried out).

However, current balloons manoeuvrability is very limited and highly linked to winds. Although they can be launched nearby the area of interest and reach the area in short time, their travelling times between points of interest are longer and highly dependable of wind direction and speed. Therefore, to persistently cover an area of interest, more than 1 balloon might be needed. It is noted though, that manoeuvrable stratospheric balloons are under development.

Google Loon designed and launched stratospheric balloons with some level of manoeuvrability. By adjusting the volume and density of the internal gas, the balloon could be place at the most desirable altitude with winds compatible with the target direction. However, in 2021 the project was shut down.

Figure 3 Loon stratospheric balloon (Christchurch, NZ, June 2013)

Since then, some other companies are developing manoeuvrable stratospheric balloons, e.g. Hemeria. It is expected that in the following years, manoeuvrable balloon HAPS are available in the market.

Figure 4 HEMERIA stratospheric balloon

2.3. Selection of HAPS platform

The fire monitoring service requires a high level of reactivity and responsiveness. Once a fire is detected, it is key to understand the scope and situation of the event as soon as possible. For that, the imagery obtained with HAPS is a very useful tool to improve the situational awareness of the fire fighters. This requires a platform with high manoeuvrability and flexibility to go to the area of interest in the shortest time possible, and the capability to keep the position once arrived. With the current state of the art, this requirement discards the possibility of using balloons, due to their lack of agility to head to the target destination or to keep the position, in case of windy conditions in the stratosphere. Thus, the simulation will be based on a fleet of HAPS fixed-wing platforms covering Southern Europe. Due to its many advantages respect other current market HAPS, Zephyr has been selected to be used for the HAPS model in this project. The main features of Zephyr are set out below:

- Name and Version: Zephyr Z8B.

- Type: heavier-than-air (fixed-wing) HAPS.
- Manufacturer and operator: AALTO HAPS.
- Physical characteristics:
  - Propulsion: two propellers driven by electric motors.
  - Energy: solar panels and batteries (no fuel used).
  - Wingspan: 25 m.
  - Weight: 75 kg.
- Operating altitude:
  - Minimum: 60,000 ft (18 km).
  - Maximum: 75,000 ft (23 km).
- Speed over ground:
  - Average speed during operations of 60 km/h.
  - Zephyr can reach any part of the Globe in about 10 days.
- Manoeuvrability: near 100% manoeuvrability is guaranteed in summer at most latitudes (the wind speed in the stratosphere is lower than Zephyr's navigation limit).
- Autonomy:
  - Demonstrated to date: continuous flight of 64 days.
  - Target: 6 months.
  - During daylight it acquires enough solar energy to operate and charge the batteries, which are used at night to keep Zephyr in the air.
- Operation latitudes limited based on several constraints:
  - The total amount of sun-light hours per day shall be enough to charge the batteries to hold during night hours. Flying above some latitudes where the incidence of the sunlight is lower or flying outside summer months when the daylight hours are decreased implies not reaching these minimum hours of sunlight. It is expected that this limitation will be improved with subsequent versions of the aircraft.
  - Winds above the allowed limit: high latitudes during winter period statistically present some days with winds above the limit that ensures a good manoeuvrability of the aircraft.
- Based on this, flight is limited to summer season beyond the tropics.

2.4. Earth Observation payloads

The integration of advanced payload technologies is a big step forward in the field of Earth Observation. Payloads can significantly enhance forest fire risk management, by themselves or combined with satellites. The use of this technology leads to more effective prevention, detection, and response strategies.

Payloads oriented to forest fires purposes should include certain requirements to appeal to the interest of forest fire management communities. One of the key requirements is the capability of capturing high quality imagery during day and night. Quickly acquisition of data is key during forest fire events, providing imagery of the overall forest fire situation before the arrival of firefighters would highly benefit planning forest fire extinguish activities more efficiently.

Sensors included in the payload should encompass visible and infrared spectrum, especially Medium Wave Infrared (MWIR) which displays a significant contrast between hot and cold elements. Smoke and clouds can constraint heavily Earth Observation activities by blocking partially or completely the area to be monitored. Payloads must be prepared with sensors that pierce through clouds and smoke, as much as possible, to obtain valuable information. Ideally, sensors should include a 360º steerable camera during detection operations to look for angles with best visibility. In addition, sensors using an oblique pointing to the horizon can be key for detecting smoke columns from a much further distance than sensors pointing to nadir.

Since the payload can be either used for monitoring (image acquisition steerable from Nadir) or for detection (view range up to the horizon), the sensors must be stable and equipped with a steering system to provide flexibility to the operation. This is achievable through the installation of a gimbal or a mirror attached to a rotation system.

The acquired footprint depends on the two operational modes, detection or monitoring. Considering the current Airbus stratospheric payload as a reference, the footprint in monitoring mode should be in the order of 1 km^2 for a high-resolution camera (0.18 m) steerable over a field of regard of 20 km x 40 km, and 70 km^2 for a medium-resolution camera (2 m) at Nadir. It is noted that the acquired area is also increased along the flight direction thanks to the movement of the platform. In terms of format, the images resulting from the acquisition must be georeferenced to allow an easy integration in GIS, with processing software to identify flame fronts and hotspots. The system should also allow the mosaic of images to allow a better situation awareness offering a comprehensive aerial view of the area in situations where multiple hotspots are dispersed.

Payloads with live-stream imagery enable keeping track of the forest fire evolution and beware of sudden changes of the fire behaviour. Though live-stream imagery is desirable, its assumable that there are certain situations where live-stream is not available. For those situations, the process of downloading images from the payload to a ground station and its post-processing should be carried out quickly enough to deliver information recurrently at least every 60 minutes. Once the data is downloaded on ground, the payload imagery should be processed to extract clear shots of the flame front and hot spots, while also enhancing the quality of the image.

3. CONOPS DESCRIPTION

The concept of operations (CONOPS) will be described and explained in detail in the deliverable D5.8 IA 5.6 brief 2: High-level definition of HAPS wildfire services. In this document however, a general introduction is presented to help understand the design of the simulation and the overall results.

The goal of the service is to provide imagery of the fires of interest to improve the situational awareness of the firefighting units. The key factors for the service are:

- to arrive to the fires as quick as possible.
- to provide imagery of the fires with a good frequency to allow the monitoring of the fire.

For that, a HAPS fleet would be deployed in the European stratosphere. These HAPS platforms would be flying in the European sky, at around 20 km of altitude, way above the commercial aircraft airspace, and they will be available to provide a fire monitoring service. Upon requests of the end users, the HAPS would be tasked to go to specific fires and to provide imagery for the local firefighting units.

The command and control of the HAPS fleet would be done by the Ground Segment via Satcom, guaranteeing global coverage. This Ground Segment would be composed of two main elements:

- Platform Operations Centre (POC): responsible of the control and tasking of the HAPS fleet.
- Payload Operations Centre (PLOC): responsible of the control and command of the payloads to acquire the imagery, and point of contact with the end users. This centre is also the responsible of the request for tasking the HAPS fleet to the Platform Operations Centre. Lastly, they provide and control the infrastructure for the acquisition, processing and delivery of the imagery to the end users via the cloud for remote access.

Once a fire has been detected and under the criteria of the local firefighting department, a request will be made to command the HAPS in the area of interest to provide imagery that helps to visualize the extent of the fire. The initial information on the location of the fire can be varied depending on the previous knowledge available. With the first warning of the sighting of fire or smoke, the initial data could be a reference to a particular road or municipality. Over time, as more information is available, specific geographical coordinates could be available to indicate where the fire is.

When the HAPS platform has reached the site provided by the fire brigade, the PLOC will task the payload to capture imagery/video from the area of interest to capture the fire and its surroundings. For this coverage, the HAPS platform will execute the most suitable trajectory to facilitate the acquisition. In case the fire is not visible at the provided location, the HAPS platform will be able to execute a particular trajectory in order to locate the flame front and capture the images/videos.

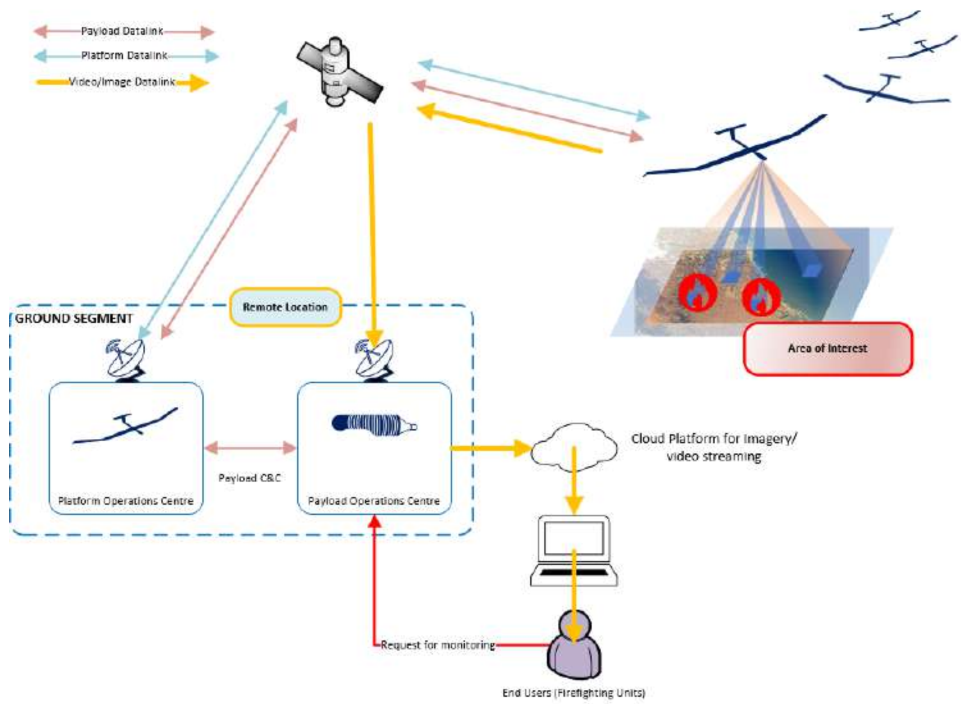


Figure 5 Dataflow diagram in HAPS Firefighting CONOPS

The imagery/video data capture will be transferred via Satcom to the PLOC. From there, they will be uploaded to the cloud platform, making them accessible to the end users. This monitoring service will keep providing imagery for as long as the firefighting units consider it. Eventually, when another fire becomes more important or the current one is extinguished or under control, the HAPS will be tasked to another activity upon criteria of the end users.

When there are two fires close enough to allow the same HAPS to go-and-return providing imagery on an hourly basis of both, the HAPS will multi-monitor these fires. In this scenario, the usage of the HAPS platform is being maximised.

On the other hand, in the case that there are no fires happening at a given moment, the HAPS could be tasked to be in detection mode in the areas of higher risk of fire. Another possibility would be to task the HAPS to provide other Earth observation services to other users.

The HAPS monitoring service would be provided during the summer season, where there are more fires. Based on the current operational range of the state-of-the-art HAPS platform, this period could go from May until September.

4. SIMULATION DESCRIPTION

4.1. Area of simulation: where and when

The simulation will be bounded in time and space. The limitations are based on the geographical location of Europe, and the operational range of the fixed-wing HAPS fleet. These platforms are solar-powered, and hence their capability to persist in the stratosphere depends on the solar intensity, linked to the angle of incidence, and daylight duration. Due to this, HAPS are limited to certain latitude and season. For mid/high latitudes like Europe, the viable season is the summer period, when the solar incidence angle is higher and the day is longer. For this study, the assumption is that the HAPS can fly over Europe from May until September, both included, in the area contained in the following coordinates:

- North (N): 44º
- South (S): 35º
- West (W): -10º
- East (E): 29º

Notice that higher latitudes are achievable for shorter seasons around summer solstice. Also, it is expected that new versions of Zephyr or similar HAPS will provide extended latitude/season capability. However, the team in charge of this study prefers to be consistent with current capabilities and to keep the simulation playground stable along the months simulated.

Figure 6 shows the Area of Simulation and the months of the year. In this area, the last 5 years will be simulated, from 2018-2022, in the months of May-September. This period has been defined according to the scope of the Innovation Action, and based on the data that was available during the development of the action (some input data of 2023 was not available at the time).

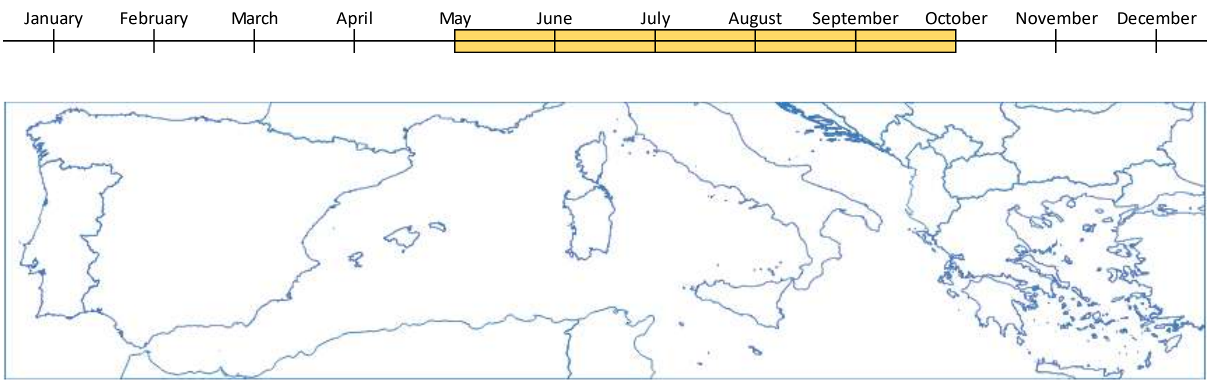


Figure 6 Area and time window for the simulation

4.2. Simulation model

In this section the simulation model is explained. In general terms, the purpose has been to reproduce in the best way possible the concept of operations with the historical real risk and fire data available. Nonetheless, some assumptions have been made for simplification.

The simulation will model a fleet of HAPS monitoring the historic fires in the European territory. During the simulation, the HAPS will be assigned to monitor the most important fires happening in every specific moment. Once assigned, they will fly to the target destination in a geodesic trajectory, that is the shortest distance between two points on Earth. The speed at which the HAPS platforms will move will depend on the intensity and direction of the winds in the stratosphere.

The criteria to select which fires are monitored or not is modelled in this simulation. This has been a complex topic in the development of the project, due to the difficulty to parametrize the subjective decision-making of the firefighting authorities. This type of decisions is based on experience and a lot of information about the fire, like the meteorology, the local terrain orography and type of vegetation, etc. For this simulation, due to the large quantity of fires, the amount of data used to model each fire has been limited. The prioritization criteria for the fires has been based on this data, and standardized for all fires in the simulation.

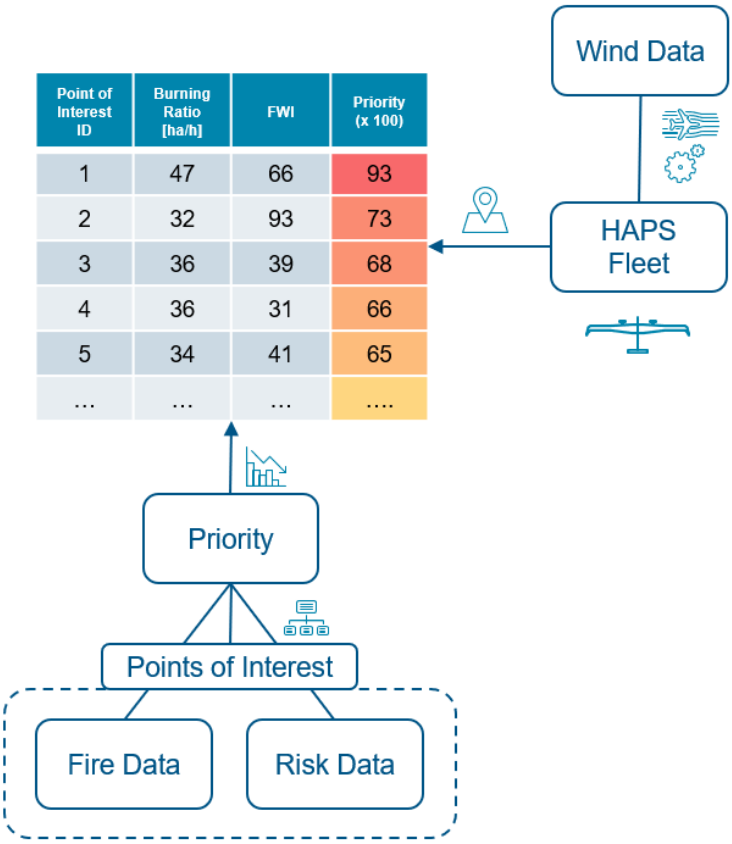
The assignation of the HAPS to the fires will be based on a priority value, that is a function of the current burning ratio of the fires, and the Fire Weather Index of the area where the fire is located. This function is explained in detail in section 5.5. The Fire Weather Index (FWI) is a risk indicator that serves as a secondary parameter to discern about the prioritization of the fires. In the case that there are no fires happening on a certain moment, the HAPS will be assigned to the centroids of the areas with higher FWI to work on detection mode. In addition, this strategy will serve as a pre-position of the HAPS to reduce the times of arrival to the fires in case they appear.

The steps of the simulation will be on an hourly basis, updating the status of the fires, the assignation of the HAPS to the fires, and their movement based on the current winds.

Another assumption in the simulation is the communication process for the request of the monitoring. The simulation is focused on the fires and the HAPS platforms, and this communication process has no effect on the results. Once a HAPS is assigned to monitor a fire, it will be targeted towards the location automatically.

With respect to the provision of imagery and videos, the simulator will consider that the provision of imagery is instantaneous after having arrived at the fire. With this, once the HAPS platform reaches the fire, the monitoring time will start to count.

Once in the destination, the trajectories performed by the HAPS for the monitoring are not simulated. This is because the duration of each step of the simulation is 1 hour, and these trajectories have an order of magnitude in time below that threshold.



Point of Interest ID	Burning Ratio [ha/h]	FWI	Priority (x 100)
1	47	66	93
2	32	93	73
3	36	39	68
4	36	31	66
5	34	41	65
...	...	...	....

Figure 7 General architecture of the simulator

4.3. Input data selection

Based on the previous explanation, to build this model several data are needed. First, a database of the historical fires in Europe along 5 years (2018-2022). For the construction of the priority value, apart from the fire data, the Fire Weather Index is needed. From the HAPS side, the representation of the flight dynamics of the platforms requires the data of the winds at the stratospheric at flight level.

Next, the different data needed for the simulation is explained in more detail, together with their source.

4.3.1. Fire maps

This is the most important dataset of the simulation. The main objective of the HAPS is to monitor the fires happening in a specific moment. For that, historical data of real fire events is needed. The European Forest Fire Information System (EFFIS) [RD-01] offers a service to access historical real-time updated burned areas database. The result of this request is a shapefile that contains polygons that represent the fires, with several attributes with the related information. The time series starts in the year 2000 and continues to be updated at present. The most relevant attributes of the polygons are described below, with their assumed understanding:

- FIREDATE: Start date and time of the fire observed.
- LASTUPDATE: End date and time of the fire observed.

- COUNTRY: Code of the country where the fire has happened.
- AREA_HA: Total area burned of the fire.

Fire Source

Source: European Forest Fire Information System (EFFIS) [RD-01].

Download Parameters:

- Product: Download real-time updated Burned Areas database → Shapefile.
- Filtering Criteria:
  - Fire date ≥ 2018.
  - Last update ≤ 2022.

Figure 8 represents the shapefile with the fires downloaded for the period 2018-2022. The green box identifies the Area of Simulation.

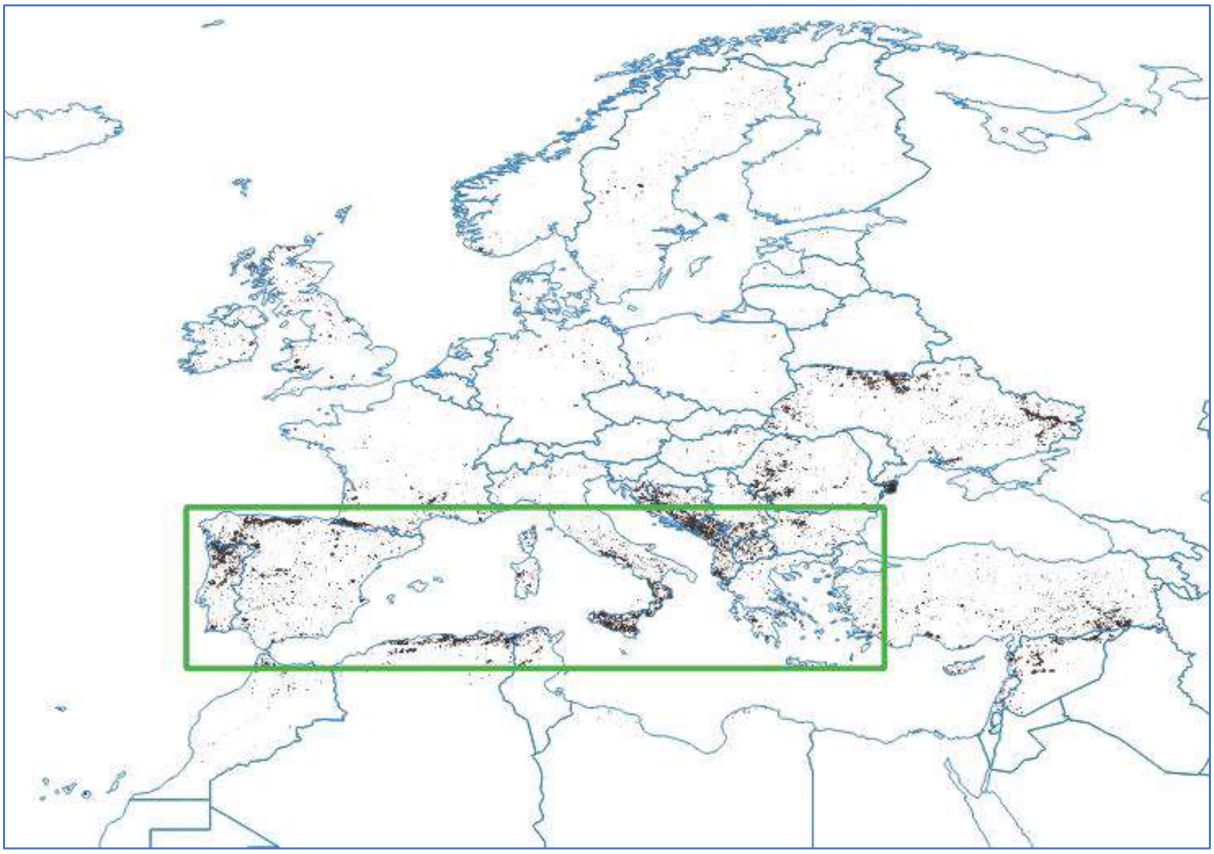


Figure 8 EFFIS fires shapefile representation (2018-2022)

4.3.2. Fire Weather Index (FWI)

Rationale: The main factor to determine the assignation of the HAPS is the current status of the fires, more specifically, the current burning ratio. But there are certain situations where the current burning ratio alone is not enough information to assign the HAPS. This can be the case of two fires with the same burning ratio for which there is only one HAPS to be assigned. In reality, these decisions are done by the firefighters based on their experience and knowledge of the terrain, forecast wind in the area and the threat they suppose to the people living around, in case there is any. All these variables are not included in the simulator due to the complexity to build such a model, and because that is not the main objective of this simulator, that is focused on the HAPS fleet. Instead, an index that represents the risk of the fire spread has been selected. For this selection, several indexes were available:

- The Fire Weather index (FWI) from the Canadian Forest Service Fire Weather Index Rating System. ([RD-15])
- The Burning Index (BI) from the National Fire Danger Rating System (NFDRS) (United States). ([RD-16])
- The Fire Danger Index (FDI) from the McArthur's Fire Danger Rating System (Australia). ([RD-17])

All three indexes were available in the Copernicus Climate Change Service [RD-02]. The selection of them has been based on their representativeness in Europe. *Predictia*, a spin-off company from the University of Cantabria, analysed the three different indexes and their relationship with the total burned area observed in an article called "The quest for the perfect fire danger index" [RD-04].

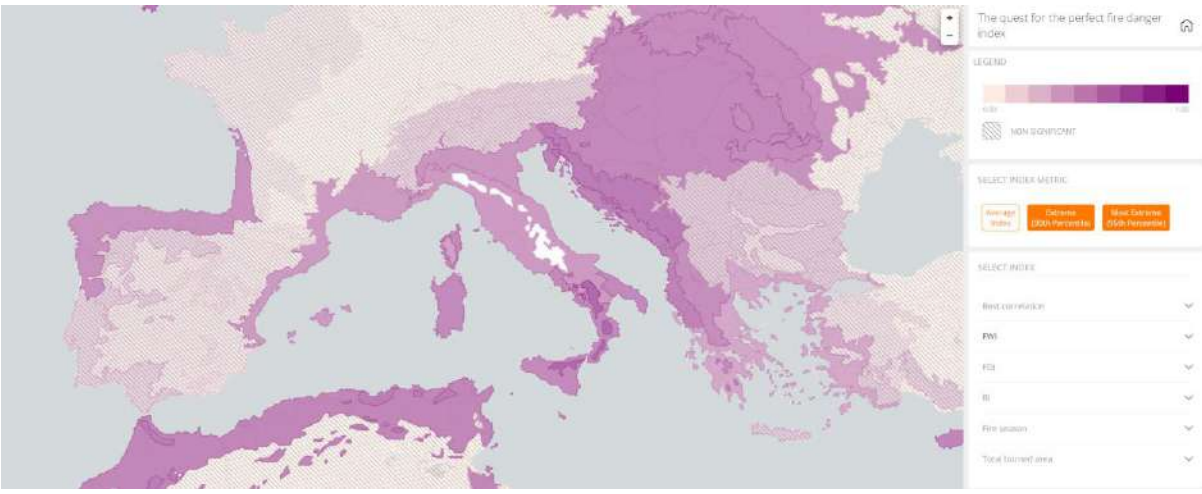


Figure 9 Capture of the data viewer of Predictia [RD-05]

This study compared the three indexes with the total burned area over time, and the results were shown by ecoregion. For the purpose of this document, only the area of Europe has been considered to assess the representativeness of the indexes. For instance, the time series of the indexes against the area burned in the ecoregion Northeast Spain and Southern France Mediterranean Forests is shown in Figure 10 .

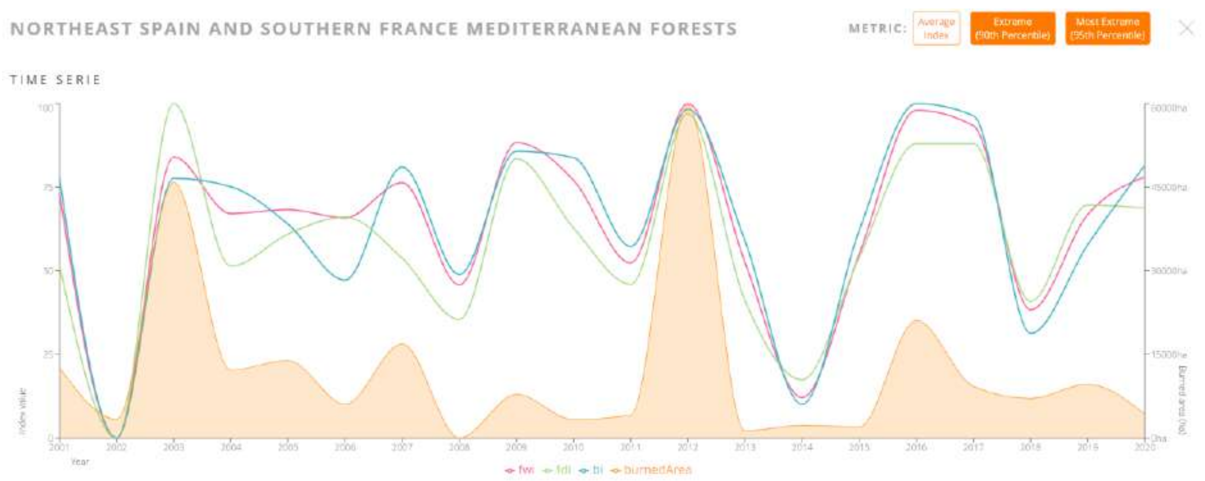


Figure 10 Time series in the ecoregion Northeast Spain and Southern France Mediterranean [RD-05]

However, after analysing the correlations in the different ecoregions of Europe, there was no index that stood out with respect to the others in the territory. Each index had the best correlation in a certain ecoregion but provided higher representativeness with respect to the other.

In view of this lack of evidence to select a specific index, the FWI has been chosen because the EFFIS network had adopted it as the method to assess the fire danger level in a harmonized way throughout Europe.

The values of this index go from 0 upwards, and can be stratified in 7 different classes according to their range (Table 2). The 7 levels have been based on the 6 levels of the EFFIS FWI Classification (from low to very extreme) ([RD-13]), and the addition of the very low level used by the Copernicus Emergency Management Service (CEMS) Early Warning Data Store (EWDS) ([RD-14]).

Table 2 Fire Weather Index Classes

Fire Danger Classes	FWI
Very Low	< 5.2
Low	5.2 - 11.2
Moderate	11.2 - 21.3
High	21.3 - 38.0
Very High	38.0 - 50.0
Extreme	50.0 - 70.0
Very Extreme	> 70.0

Fire Weather Index Source

Source: Copernicus Climate Change Service [RD-02].

Definition from CDS: The FWI is a combination of Initial spread index (ISI) and Build-up index (BUI) being a numerical rating of the potential frontal fire intensity. In effect, it indicates fire intensity by combining the rate of fire spread with the amount of fuel being consumed. FWI values are not upper bounded, however, a value of 50 is considered as extreme in many places. The FWI is used for general public information about fire danger conditions.

Download Parameters:

- Product Type: Reanalysis.
- Variable: Canadian Forest Service Fire Weather Index Rating System: Fire Weather Index.
- Dataset type: Consolidated dataset.
- System version: 4.1.
- Year: 2018, 2019, 2020, 2021, 2022.
- Month: all.
- Day: all.
- Geographical area: N:44º / S:35º / W: -10º / E: 29º.
- Grid: 0.25º x 0.25º (interpolated) (degrees).
- Format: NetCDF.

4.3.3. Wind data

Rationale: The HAPS platform will have a constant speed with respect to the air (TAS, True Air Speed) of 60 km/h. Their speed with respect to the ground (GS, Ground Speed), though, will be affected by the speed of the air in which the HAPS is flying. So, the determination of the trajectories and estimated times of arrival of the HAPS to their target destinations needs to know the values of the wind speeds and directions in the Area of Simulation.

The winds included in the model have been extracted from the ERA5 Copernicus Climate Change Service (C3S) [RD-03][RD-03]. ERA5 is the fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for the global climate and weather for the past 8 decades. Data is available from 1940 onwards. This climate reanalysis provides time data on many atmospheric, terrestrial and sea state parameters, together with uncertain estimates. Climate reanalysis combines past observations with models to generate consistent time series of multiple climatic variables.

Winds are determined by atmospheric pressure. In this case, the pressure selected has been the pressure at the operational altitude of Zephyr. For an altitude of 20,000 m, according to the *International Standard Atmosphere (1976)*, the pressure is 54.74 hPa. This value coincides with that provided by other atmospheric models such as the *ICAO Standard Atmosphere* (54.70 hPa), or the *U.S Standard Atmosphere* (54.75 hPa). As pressure decreases with the altitude, the criteria has been to select the lower limit of operational altitude, which represents an upper limit in pressure.

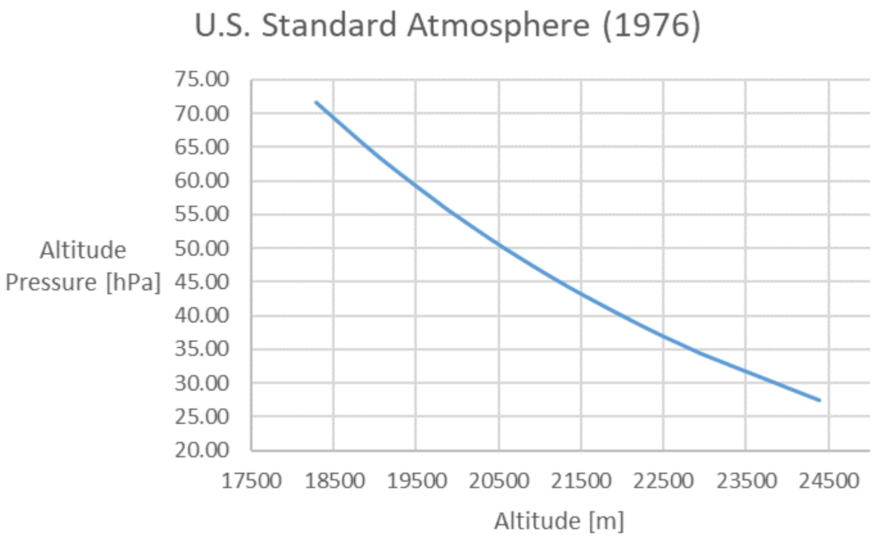


Figure 11 Atmospheric pressure according to U.S Standard Atmosphere (1976)

The Copernicus ERA5 database provides information on fixed pressure values. For this case, the closest option was 50 hPa, which according to the model of the Figure 11, corresponds to an altitude of approximately 20,500 m.

The area where the winds are needed is a bit bigger than the Area of Simulation where the fires and risks will be considered for the simulation. The trajectories that the HAPS will follow are geodesic lines, that are the shorter distance between two points on a sphere. This causes that, in some possible trajectories, the geodesic line will be out of the main AoS. Thus, the area of the winds will be bigger to provide wind data in these possible trajectories. Based on the dimensions and geography of the AoS, the most extreme trajectories have been checked to dimension the size of the wind area. In the Figure 12 these trajectories are shown, with a buffer of 2 degrees in all directions with respect to the main AoS (N:46º / S:33º / W: -12º / E: 31º), that was proven to be enough for these situations.

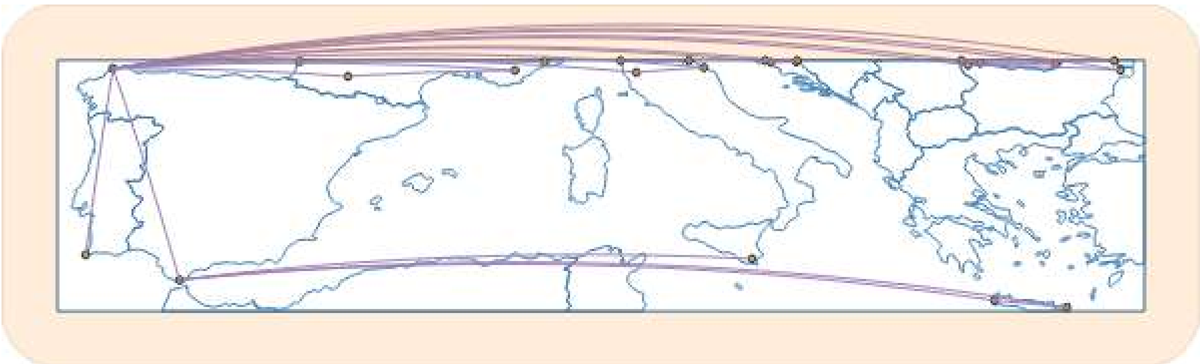


Figure 12 Extra area for winds due to geodesic lines in extreme trajectories

Wind Source

Source: Copernicus Climate Change Service (C3S) [RD-03].

Download Parameters:

- Product Type: Reanalysis.
- Variables:
  - U-Component of wind ($m \cdot s^{-1}$): This parameter is the eastward component of the wind. It is the horizontal speed of air moving towards the east. A negative sign indicates air moving towards the west. This parameter can be combined with the V component of wind to give the speed and direction of the horizontal wind.
  - V-Component of wind ($m \cdot s^{-1}$): This parameter is the northward component of the wind. It is the horizontal speed of air moving towards the north. A negative sign indicates air moving towards the south. This parameter can be combined with the U component of wind to give the speed and direction of the horizontal wind.
- Pressure Level: 50 hPa.
- Year: 2018, 2019, 2020, 2021, 2022.
- Month: May to September (both included).
- Day: all.
- Time: all.
- Geographical area: N:46º / S:33º / W: -12º / E: 31º.
- Format: GRIB.

5. METHODOLOGY

5.1. Input data integration

There are several sources of information from which the scenarios are prepared. Also, the data format, as well as the temporal and spatial resolution are different. For instance, the dataset of the winds provides the eastward and northward components of the wind for every hour, while the FWI changes on a daily basis. On the other hand, for the fires the available information is the beginning and end of the fires. From the spatial point of view, the data of winds and risks is provided on grid of 0.25 degrees, while for the fires, this is provided with polygons that represent the burnt area. Table 3 summarizes these different characteristics for each one of the data types to be used:

Table 3 Data types characteristics

Type	Format	Spatial Resolution	Temporal Resolution
Wind	GRIB	0.25 degrees	Hourly
Risks (FWI)	NetCDF	0.25 degrees	Daily
Fire	Shapefile	Not Applicable	Start and End of Fire

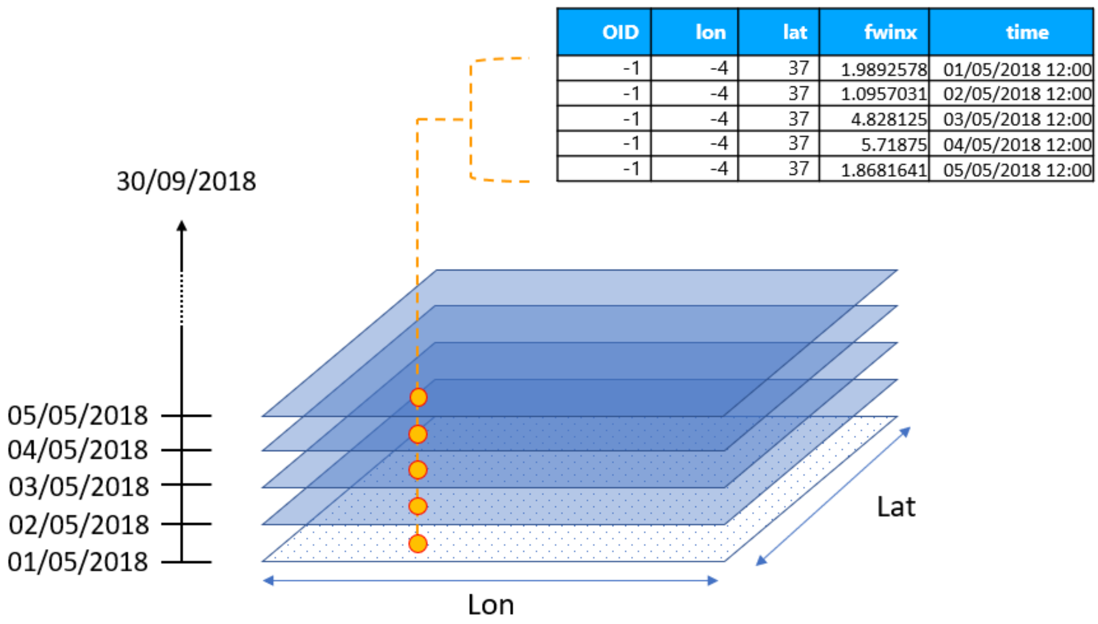
These differences in the format and resolution of the data make necessary a data processing. The main objectives of this preparation for the data are:

- Integrity: data is the same with respect to the original source.
- Completeness: all data needed for the simulation is available in the entire range of the Area of Simulation.
- Consistency: data format is uniform in the entire Area of Simulation.
- Granularity: data detail is deep enough to extract relevant results, but synthetized in order to optimize the processing time of the simulation.

5.1.1. Processing for FWI data

The FWI data used for the simulator comes from the Copernicus Climate Change Service (C3S). The data is available in two formats, GRIB2 and NetCDF, being the latest, the format selected due to faster processing of the request. See the Fire Weather Index Source section to see the parameters selected.

The result of the download is a single NetCDF (Network Common Data Form) file per year of data (2018-2022). This type of file format is commonly used by the scientific community for storing and sharing multi-dimensional scientific data (variables) such as temperature, humidity, pressure, wind speed, FWI, etc. The FWI data in the file is organized as a multi-dimensional file with FWI data covering daily data over 1 year period within the AoS.



OID	lon	lat	fwinx	time
-1	-4	37	1.9892578	01/05/2018 12:00
-1	-4	37	1.0957031	02/05/2018 12:00
-1	-4	37	4.828125	03/05/2018 12:00
-1	-4	37	5.71875	04/05/2018 12:00
-1	-4	37	1.8681641	05/05/2018 12:00

Figure 13 Layers of the multi-dimensional NetCDF file representing the FWI value for the same coordinate

Since the simulation is done over time, the input data provided must be structured into multiple files structured by the time of the FWI date. The processing of the data was achieved using a GIS software, in this case ArcMap from ArcGIS Suite. As a result, the data goes from a multi-dimensional file (NetCDF) with FWI data corresponding to 5 months of data, to multiple files (shapefile) separated by a time identifier stipulated by the day, month and year of the FWI. Shapefile is a type of format developed and regulated by ESRI, widely used in GIS software products, and is capable of representing points, lines or polygons.

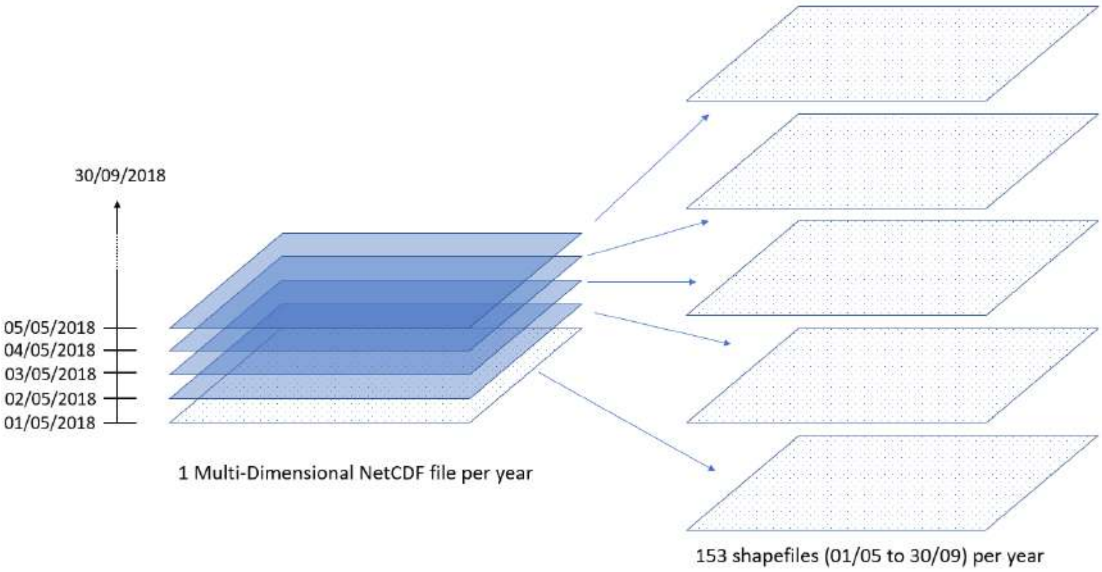


Figure 14 Re-structuration of FWI data from multi-dimensional file to single daily files

After the transformation process, the software generated a shapefile for each day of FWI data. The shapefile is composed of 5,808 points forming a grid that represents the FWI value for each 0.25 x 0.25 decimal degrees within the AoS.

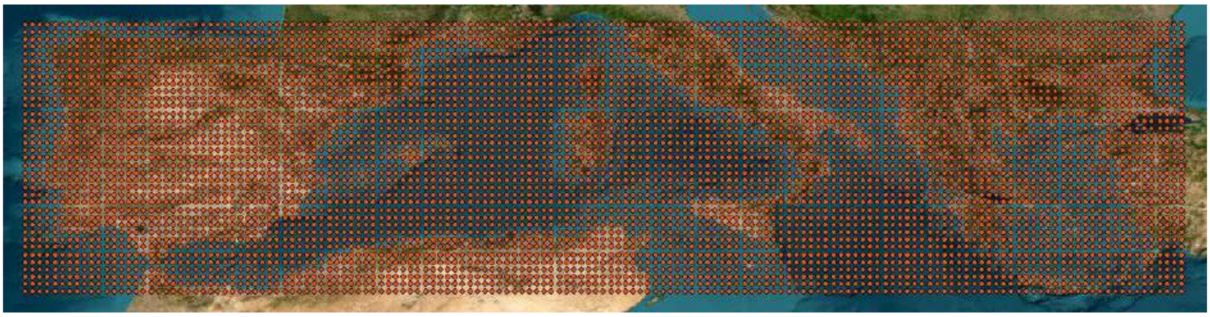


Figure 15 FWI within the AoS points shapefile

Following the transformation of the FWI values into points, additional optimization and processing were performed.

To begin with, the FWI points provide a fair amount of information not needed for the simulation. Aiming to optimize the simulation processing times, records registering FWI data in locations further than 25 km into the sea were erased. Additionally, FWI data from countries not selected for the scope of the simulation, such as North African countries, were also removed from the shapefiles. This process deleted about 47 % of data non-relevant for this simulation.

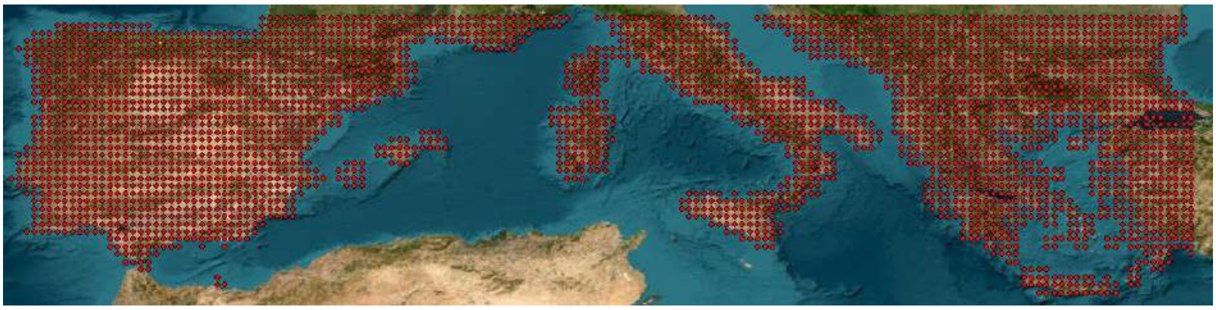


Figure 16 FWI data upon deletion of non-relevant data for the simulation

Following the deletion of data not relevant for this simulation, the FWI values for each day of data were transformed into raster files with a 0.25 x 0.25 decimal degrees pixel resolution.

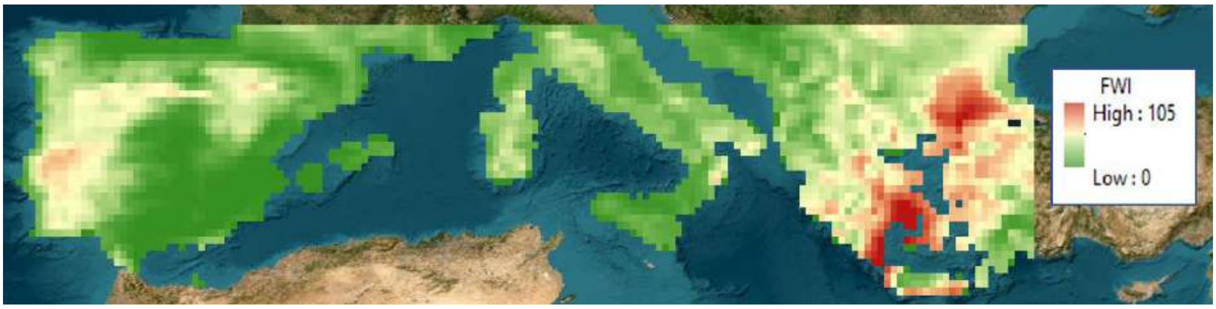


Figure 17 FWI raster image calculated with only relevant data for the simulation

The FWI values on each raster were grouped into 7 categories according to the EFFIS "Fire Danger Classes" (Table 2).

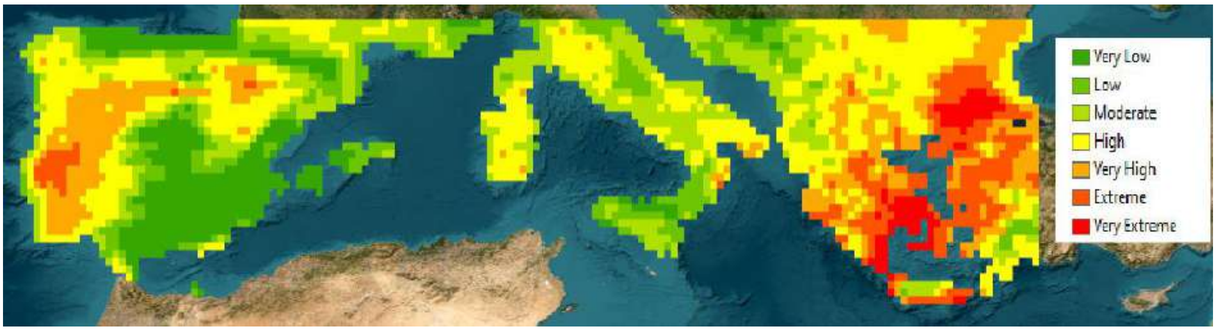
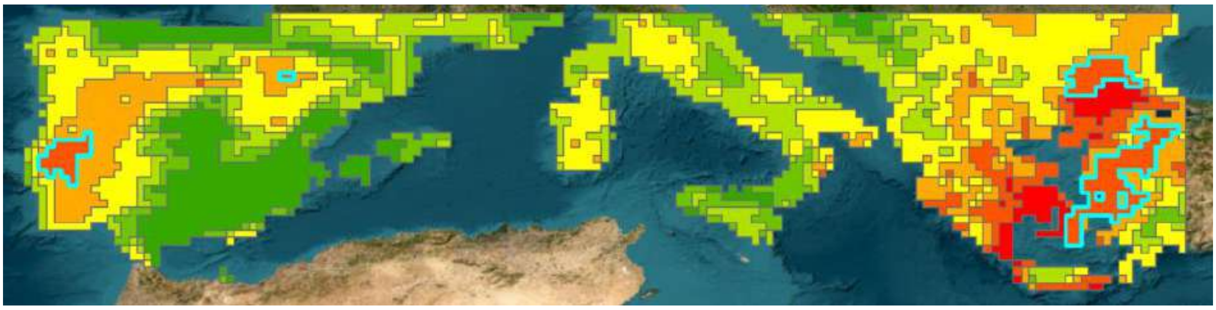


Figure 18 FWI data in raster format representing the FWI level classification

The raster was converted into a polygon-type shapefile by grouping all adjacent values of the same category in each polygon. Each polygon in this shapefile registered also the mean FWI of all points in the Copernicus database (see Figure 19) located within the area of that polygon. This benefits the simulation, providing more detailed granularization to discern the risk between different areas for detection.



FID	Shape	ID	RISK_LVL	RISK_AVG
77	Polygon	78	6	51
104	Polygon	105	6	60
222	Polygon	223	6	53
297	Polygon	298	6	56

Figure 19 FWI data in shapefile format (polygons) representing the risk level

To conclude the FWI transformation process, each polygon has received its time identifier (DD_MM_YYYY) based on the FWI date.

Table 4 Attribute table of the FWI data

FID	Shape	ID	RISK_LVL	RISK_AVG	DATE
35471	Polygon	145	5	44	10_08_2019
35472	Polygon	146	4	28	10_08_2019
35473	Polygon	147	3	17	10_08_2019
35474	Polygon	148	3	15	10_08_2019

FID	Shape	ID	RISK_LVL	RISK_AVG	DATE
35475	Polygon	149	2	9	10_08_2019
35476	Polygon	150	3	17	10_08_2019

Before the implementation of FWI data into the simulation, the information suffered several transformations. The following diagram provides an overview of the processes commented in this section.

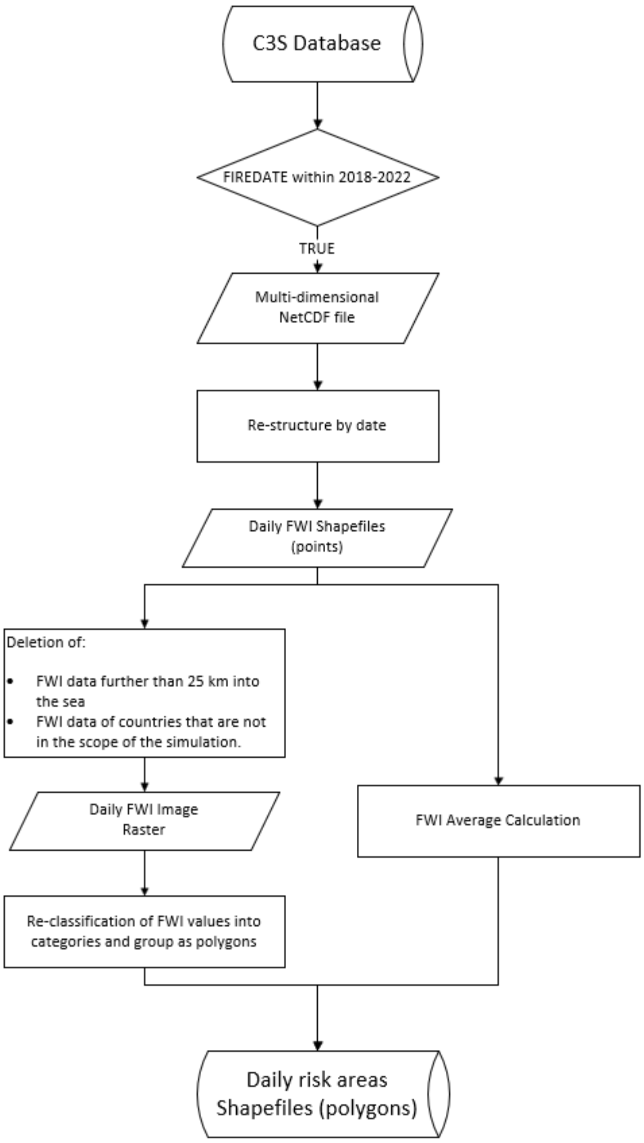


Figure 20 FWI data transformation diagram

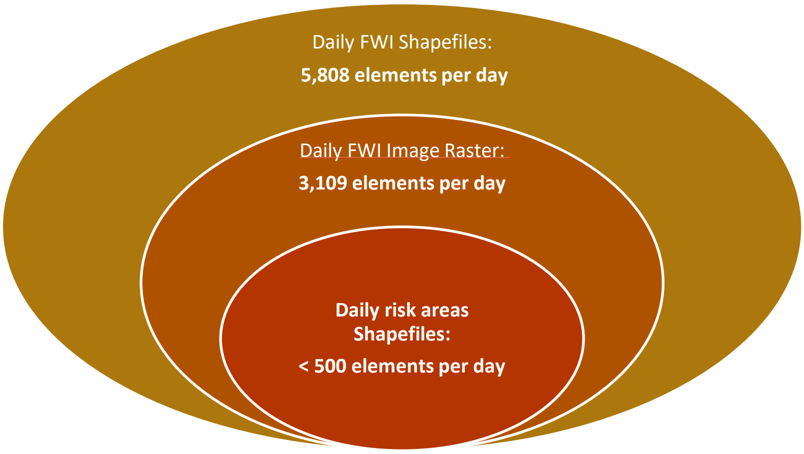


Figure 21 Euler diagram of the element's reduction with each transformation process

Table 5 defines the attributes of the risk areas identified through the processing of FWI data.

Table 5 Risk Area attributes

Attribute	Type
Risk ID	Integer that identifies the risk.
Polygon	Vertex points that form the polygon.
Centroid Point	Coordinates of the centroid of the polygon of the risk area.
FWI index	FWI Index of the polygon represented. It is updated every day of the simulation.

5.1.2. Processing for Fire data

The EFFIS database downloaded is a shapefile that contains the fires observed since the year 2000. The fires are represented as polygons, with the geometry of the polygon accounting the area burned, and several attributes with information about the event. The most relevant attributes for this simulation are:

- FIREDATE: Start date and time of the fire observed.
- LASTUPDATE: End date and time of the fire observed.
- COUNTRY: Code of the country where the fire has happened.
- AREA_HA: Total area burned of the fire.

Based on these attributes, several filters and processing have been implemented in the database to obtain the input database for the simulation.

The first filtering has been based on the dates of the fires. The scope of the simulations are the last 5 years, from 2018-2022. Based on this, only the fires whose "FIREDATE" was after or equal 2018-01-01and before or equal to 2022-12-31.

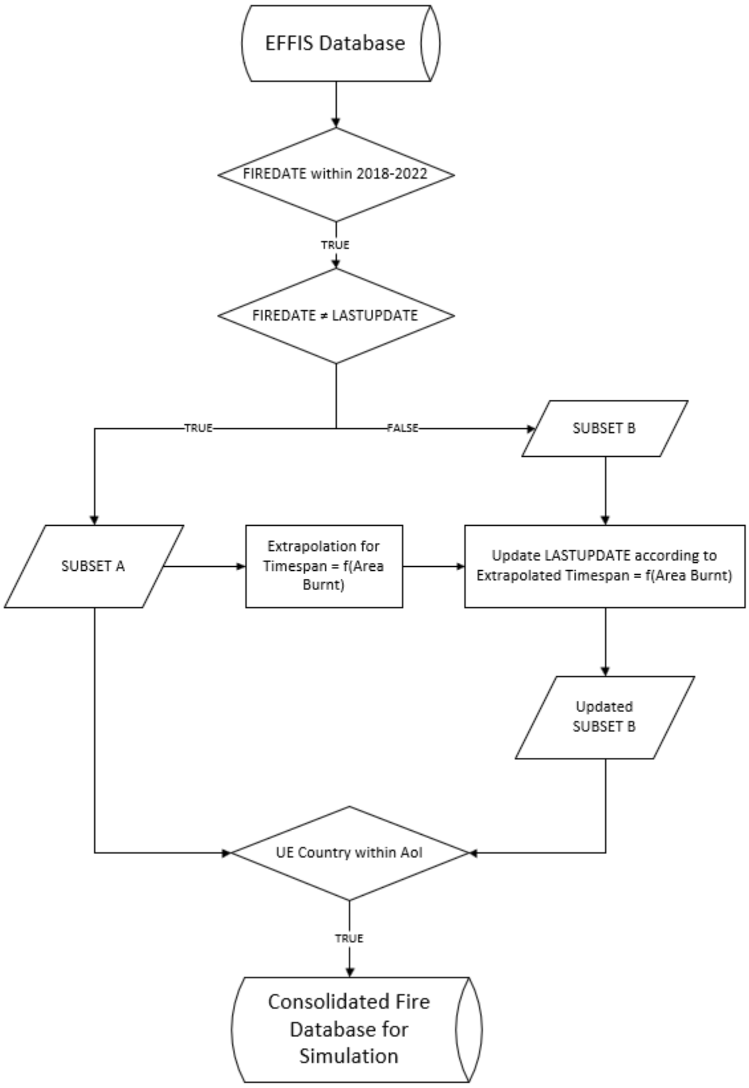


Figure 22 Diagram of the processing of fire input data

For the resulting set of fires between 2018-2022, the attributes "FIREDATE" and "LASTUPDATE" have been checked. The time passed between both attributes is the timespan of the fires. For the period 2018-2022, 52.43 % of the fires have a different date "FIREDATE" and "LASTUPDATE", meaning they have a valid timespan. For the sake of clarify and simplicity with the following explanation, this subset will be called subset A, in line with the Figure 22. On the other hand, a significant 47.57 % of the fires have the same dates and times for both attributes, while the area burnt was not zero neither unsignificant. With the assumptions of this simulation, that meant that these fires had no timespan, which did not make sense. This group of fires will be called subset B. Table 6 summarizes these values per each of the years of the period considered.

Table 6 Overview of fires with respect to timespan in 2018-2022

Year	Fires with timespan (subset A)	Fires without timespan (subset B)	Total Count of fires
2018	385 (31.77 %)	827 (68.23 %)	1,212
2019	105 (27.38 %)	2,806 (72.62 %)	3,864
2020	4,082 (60.27 %)	2,691 (39.73 %)	6,773
2021	4,679 (63.94 %)	2,639 (36.06 %)	7,318
2022	6,743 (51.25 %)	6,415 (48.75 %)	13,158
TOTAL	16,947 (52.43 %)	15,378 (47.57 %)	32,325

The fires without timespan (subset B) were not suitable for the simulation because of this lack of information. To solve this issue, 2 options were considered: remove these fires, or “fix” their data to include the timespan with an extrapolation. Due to the high number of fires of the subset B, the option of removing these fires from the database would make the results less representative. Hence, the option of removing these fires was discarded. The option of “fixing” the timespan was based on updating the “LASTUPDATE” of the subset B according to a correlation between the timespan and the area burned of the subset A. This second option was against the principle of the integrity of the dataset, because it implied to modify the original input data. However, this subset data was not correct for the simulation, and without a change to fix it was unusable. Thus, this change and deviation from the integrity principle has been understood as a fair price to pay to keep the whole database available for the simulation. In Figure 23 the average timespan is represented against the burned area for the subset A.

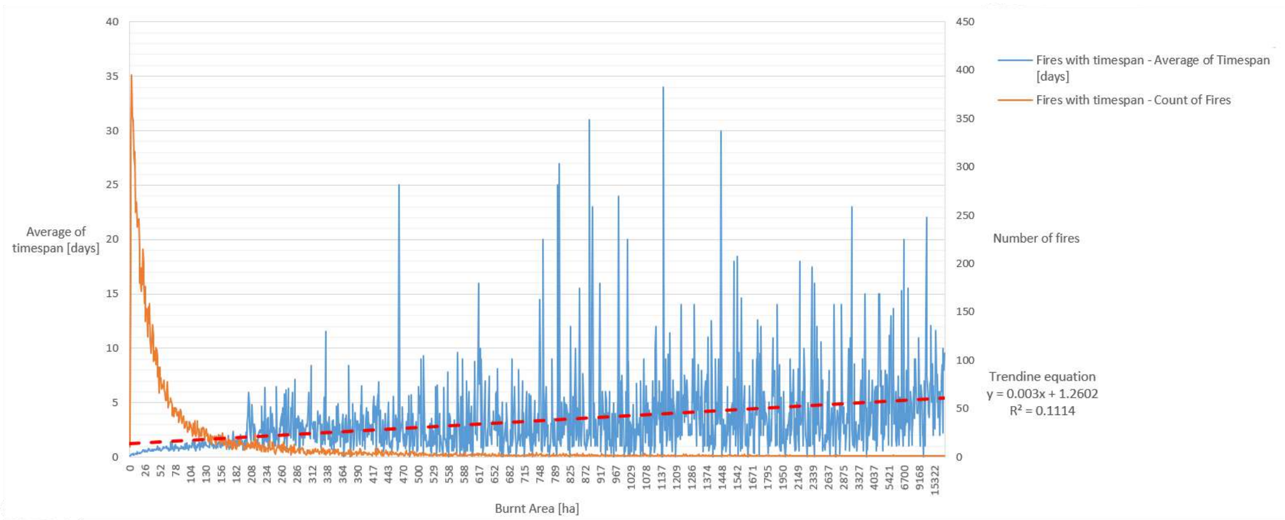


Figure 23 Average timespan with burned area (for fires with timespan not null)

With this chart, the linear trendline equation has been automatically calculated based on subset A, as:

$$Timespan\ [days] = 0{,}003 \cdot Burned\ Area\ [ha] + 1{,}2602$$

This equation has been applied to the subset B modifying the “LASTUPDATE”, and with it providing a not null timespan. The result of this extrapolation has been a database of the fires included in EFFIS from 2018-2022 with a different “FIREDATE” and “LASTUPDATE”, that are understood as the beginning and the end of the fires. The coefficient of determination obtained with this linear regression is quite low (0.1114). This is due to the variability of the dataset in the relation between the fire duration and the burnt area, where for the same area burnt the duration can vary significantly. This is a limitation of the linear regression, that cannot capture the complex variability of the fire events. Nonetheless, this is still the best approach found to extrapolate the missing data.

The last step of the processing of the database has been to filter and keep only the fires whose attribute “COUNTRY” was a member of the European Union. With this filter, the remaining fires are located in:

- Portugal
- Spain
- France
- Italy
- Malta
- Croatia
- Greece
- Bulgaria
- Romania

The resulting database prepared for the simulation is represented in Figure 24, with a total of 13,474 fires contained in the shapefile. Out of these set of fires, only the ones whose “FIREDATE” is between May and September will be considered in the simulation. Hence, the total of fires that will be simulated is 6,713. These 5 months represent 49.8 % of the fires of the dataset, and 79.5 % of the burnt area of the fires. Figure 25 shows the different subsets filtered in the processing of preparing the fires for the simulation.

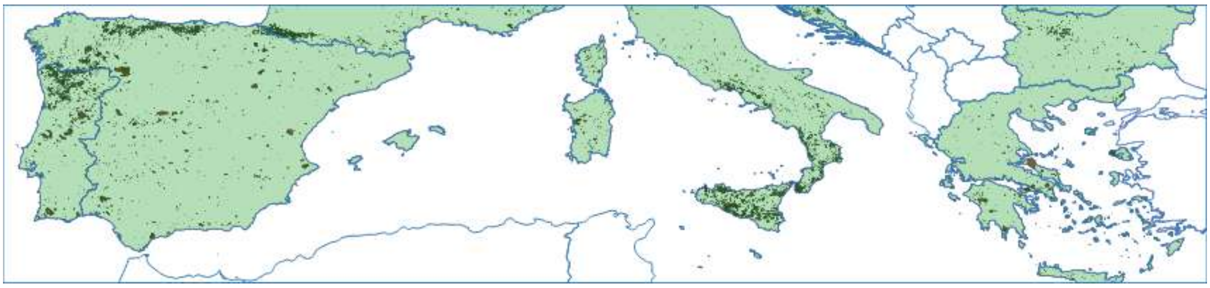


Figure 24 EFFIS fires shapefile representation in UE AoS (2018-2022)

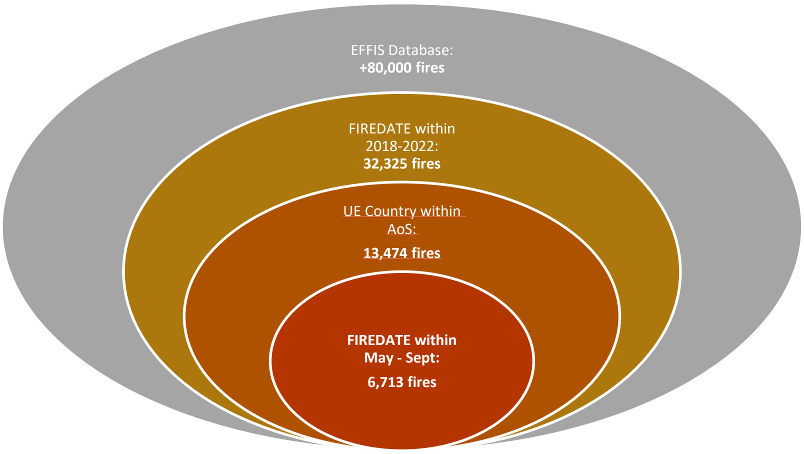


Figure 25 Euler diagram of the filters applied to the input fire database

The resulting database is distributed in a variable way along the years of the period 2018-2022. The quantity of fires registered increases each year, as shown in Figure 26.

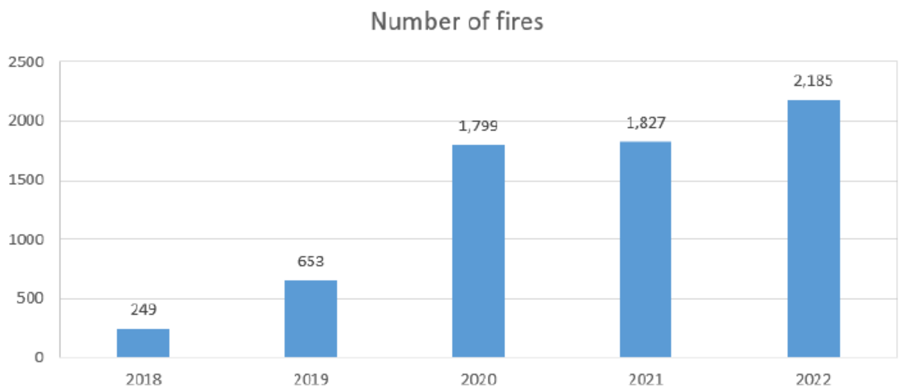


Figure 26 Fires per year in UE AoS (from May to Sept)

In the same way, for each of the years, the distribution of the fires is variable per months, having the summer months of July and August the maximum quantity of fires. Figure 27 represents this evolution from May until September for the selected years (2018-2022).

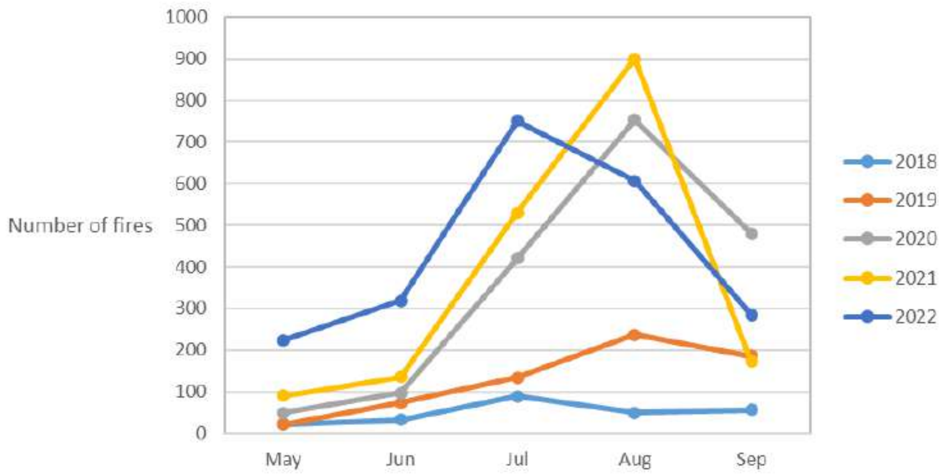


Figure 27 Number of fires per month in UE AoS (2018-2022)

Looking at the average burned area or the average timespan of the fires, they vary each year but without a clear tendency. In the last 5 years, within this Area of Simulation defined for the EU countries, the year 2020 represents a local minimum in terms of average burned area and timespan, although there were more fires registered than in the 2 previous years. Figure 28 shows the evolution of these 2 parameters.

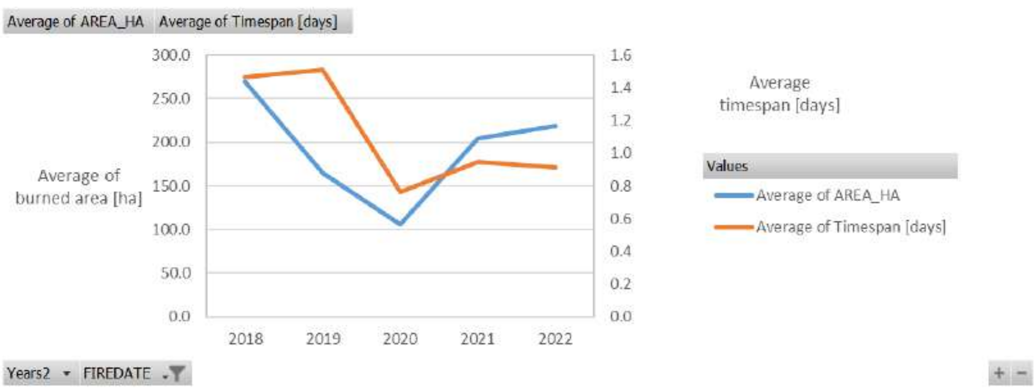


Figure 28 Average area burned and timespan per year in UE AoS fires (from May to Sept)

As a summary, Table 7 contains the numbers of the fires and their characteristics in the - period 2018-2022.

Table 7 Characteristics per year of fire database prepared for simulation in UE AoS (from May to Sept)

Year	Number of fires	Average of Timespan [days]	Max of Timespan [days]	Average of Burned Area (ha)	Max of Burned Area (ha)
2018	**249**	**1.5**	**10.0**	**269.4**	**27,635**
2019	**653**	**1.5**	**6.2**	**164.5**	**9,924**

Year	Number of fires	Average of Timespan [days]	Max of Timespan [days]	Average of Burned Area (ha)	Max of Burned Area (ha)
2020	**1,799**	**0.8**	**10.1**	**106.1**	**16,758**
2021	**1,827**	**0.9**	**15.5**	**204.4**	**51,881**
2022	**2,185**	**0.9**	**9.5**	**219.3**	**32,528**
Grand Total	**6,713**	**1.0**	**15.5**	**181.4**	**51,881**

5.1.3. Processing for Wind data

Source wind data is obtained from ERA5 Copernicus Climate Change Service (C3S) [RD-03] in compressed GRIB format. To ensure an optimal performance during the simulation, the GRIB file is translated into an SQLite database comprised by a single table containing the winds, which delivers the best file read performance. Must be considered that data is not transformed or manipulated in any way during the transition from GRIB to SQLite. To attain this format transition, an application called “WindGrid2Sqlite” was developed.

The table layout in the SQLite database is as follows:

Table 8 Wind attributes

Attributes	Type
Id	Int
Latitude	Double
Longitude	Double
U	Double
V	Double
Time	String

5.2. Fire model

To represent the evolution of the fire with the time, a basic model has been created. This model has been applied to all fires in the database for simplification. It is clear that every fire behaves differently, with different burning ratios and spread lines. For this simulation, due to the lack of that information for such a big dataset, this model will allow to represent the evolution of all fires of the database with time during their timespan.

The data available in the EFFIS database for the fires is:

- Start date (FIREDATE).
- End date (LASTUPDATE).
- AREA_HA (Burned area as a total fixed value).
- Shape of the polygon.

The main objective of the fire model is to represent the burned area as a function of time. The analysis to generate the model has been based on several assumptions:

- The burned area at "FIREDATE" is 0.
- The burned area at "LASTUPDATE" is "AREA_HA".
- The burning ratio reaches a maximum in the middle life of the fire timespan.
- The burning ratio is increasing over time until it reaches a maximum in the middle life of the fire timespan, and then it starts to decrease until reaching 0 at "LASTUPDATE" time.

Based on these assumptions, the function selected to represent the evolution of the area burned over time has been a cosine:

Equation 1 Fire model functions (burned area and burning ratio)

- $t \leq t_s: \; A(t) = 0 \,, \; \frac{dA}{dt}(t) = 0$
- $t \geq t_e: \; A(t) = A_m \,, \; \frac{dA}{dt}(t) = 0$
- $t > t_s \; and \; t < t_e:$

$$A(t) = \frac{A_m}{2} \cdot \left(1 - cos\left(\frac{\pi}{(t_e - t_s)}(t - t_s)\right)\right)$$

$$\frac{dA}{dt}(t) = \frac{A_m \cdot \pi}{2\,(t_e - t_s)} \cdot sin\left(\frac{\pi}{(t_e - t_s)}(t - t_s)\right)$$

Where:

- A (t) = burned area evolution with time [ha].
- dA/dt = burning ratio evolution with time [ha/h].
- t_s = start time of fire [h] (FIREDATE).
- t_e = end time of fire [h] (LASTUPDATE).
- A_m = max burned area [ha] (AREA_HA).
- dA/dt = burning ratio [ha/h].

With these functions, the area burned for each fire can be calculated during the simulation, not as a unique fixed value, but as a parameter that evolves over time and represent the variation of the fires. With this approach, the burning ratio can be also calculated, and it provides valuable information about the evolution of the fires to know if they are accelerating or slowing down.

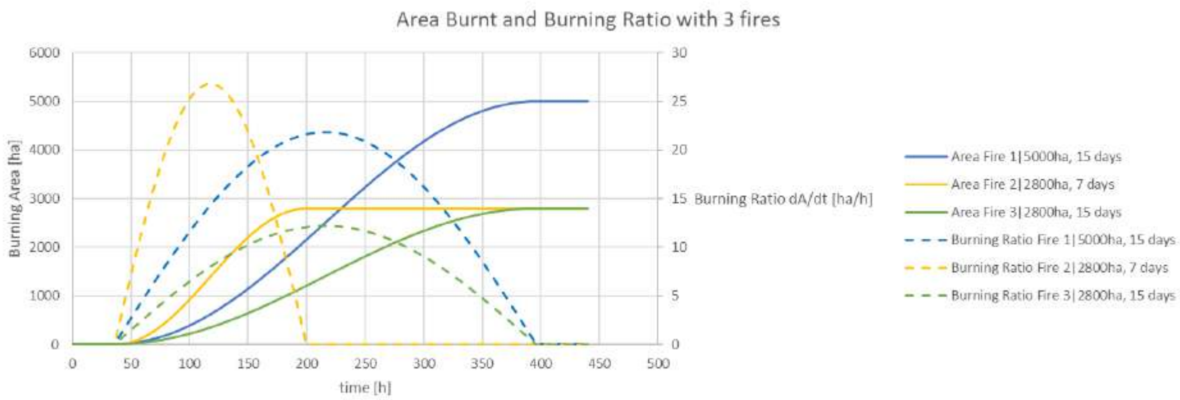


Figure 29 Area burned and burning ratio of 3 fires with the fire model

From the spatial perspective, the fire model will represent the fires as a single point located in the centroid of the polygon. This will facilitate the assignation of the HAPS, stablishing a target location in the form of a single point in the map.

With this approach the fires of the database, that are steady polygons with the attributes of the fire, become single points with attributes that vary with time and represent the evolution of the fire.

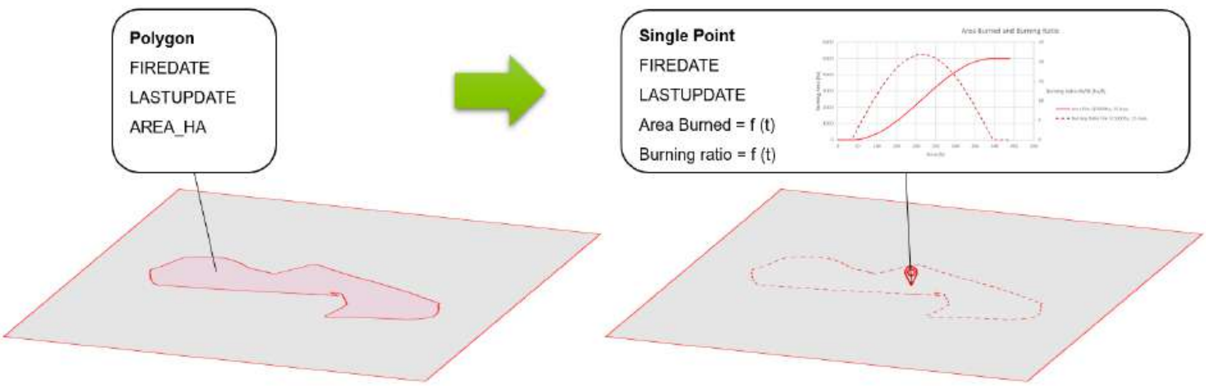


Figure 30 Fire model transformation

Table 9 Fire model attributes

Attribute	Type
Fire ID	Integer that identifies the polygon.
Centroid Point	Coordinates of the centroid of the fire.

Attribute	Type
Start Fire	Date and time of the fire start (FIREDATE).
End Fire	Date and time of the fire end (LASTUPDATE).
Total area burned [ha]	Total area burned (AREA_HA).
Current area burned [ha]	Current area burned, updated on each step of the simulation.
Burning ratio [ha/m]	Burning ratio of the fire, updated on each step of the simulation.

With regards to the monitorization of the fires by the HAPS, a *state machine* has been defined to track the different phases in which a fire can be. First, only some fires will be eligible to be monitored by the HAPS. For small fires, the firefighters usually have other resources to monitor the fires. As the quantity of HAPS will be limited, they will be targeted to monitor and to provide information of the fires that are lasting more or with an area burned of relevant dimensions. The fires of this type are the ones where the HAPS can provide more added value, since they can monitor large areas to provide imagery that improves the situational awareness for the firefighters.

Based on this approach, the fires that have a timespan higher than 12 hours, or with a total burned area of more than 500 ha will be eligible to get a HAPS assigned for monitorization. Among all fires happening at a single moment, the ones fulfilling one of the two previous conditions will be in the state “Alert”. The HAPS will be assigned to fires in state “Alert”, giving preference to the fires with highest priority. The fires that get a HAPS assigned will be in state “To be monitored” while the HAPS is on its way to the target location of the fire (centroid). Once the HAPS arrives and starts the actual monitoring, the fire state will change to “Monitored”. As time passes, the priority of this fire in state “Monitored” will be reduced, and eventually the HAPS will be assigned to another fire, leaving the current one. After that event, the fire will change to the state “Already monitored”. This last state helps to differentiate between fires that currently do not have a HAPS, but have had one in the past (“Already monitored”), from fires that currently do not have a HAPS and have not had any before (“Alert”). Figure 31 summarizes all the states of the fires and the transitions between them. The times that each fire spends in each state will be recorded during the simulation for further analysis. The sum of all these times is the timespan of the fire.

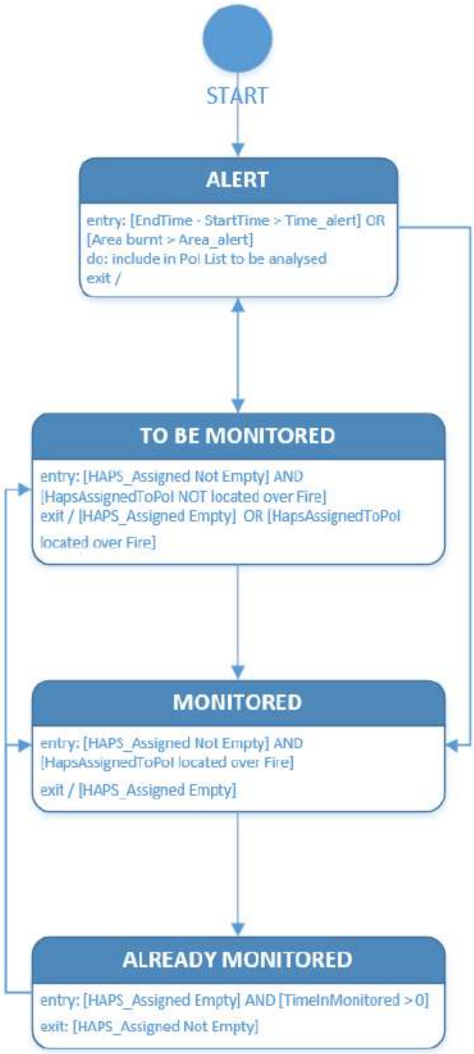


Figure 31 Fire state machine diagram

5.3. HAPS model

The HAPS platforms that form the fleet will be modelled as single points that follow geodesic trajectories towards their target destination. The speed at which they fly is the result of the sum of their True Air Speed (TAS) with the wind vector at the stratosphere (50 hPa) in the location where the HAPS is. Based on the intensity and direction of the wind in every step of the simulation, the HAPS platform will adapt their TAS angle (α) to assure that the resulting trajectory follow the geodesic line towards the destination. If the wind conditions make that trajectory impossible for a HAPS due to their intensity, that specific platform will not be eligible for that target. Figure 32 shows the triangle of velocities. Depending on the wind and its direction, the HAPS will fly faster than their TAS when there is tailwind, that is favourable wind. On the other hand, with headwind (wind against) the HAPS platform will fly slower than its TAS. As a consequence, the time needed to arrive to a certain target will vary based on the stratospheric conditions during the trajectory.

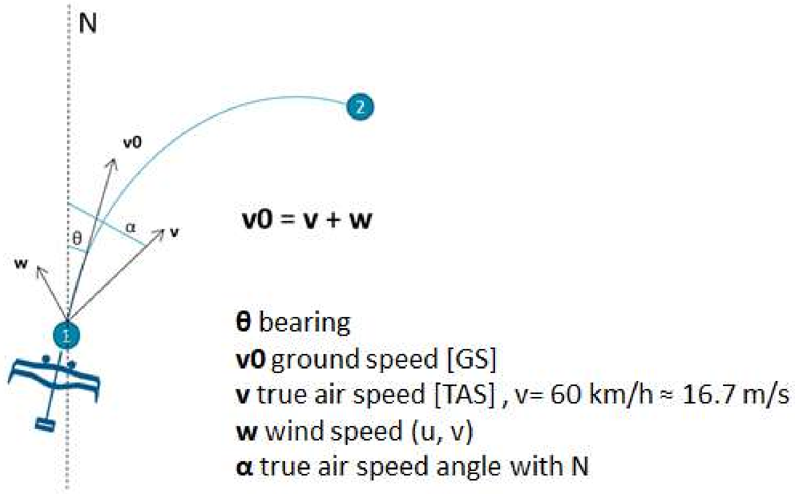


Figure 32 HAPS model wind triangle

During the simulation, the HAPS platforms of the fleet will be assigned to monitor ongoing fires or to be in detection mode in areas of high fire risk. The assignation of HAPS to these points of interest will be based on their priority. Once a HAPS is assigned to a target location with a specific task (detect/monitor), it starts to fly towards that point. After arrival to the target destination for a monitoring, the HAPS will perform a specific trajectory to capture the fire based on its current area. In the case of fire detection on a high-risk area, the HAPS will perform a trajectory to cover the area following a pattern adapted to its figure. While a HAPS is detecting or monitoring a fire, it can be assigned to a different point of interest in case the new one has more priority than the current one. In that event, the HAPS will leave the current assignation and head for the new target location assigned.

The HAPS will be represented as a single point, characterised by an active task, and a target destination. Each HAPS will have one or more operational areas where they can monitor and detect, and they will only be assigned to points of interest inside their allocated operational areas. Each HAPS will have a “start service date” and an “out service date”, and they will be operational in the time between both.

The activity of the HAPS is tracked for the later analysis to understand their usage on each task and the times spent moving to destination and at destination. For that, a HAPS *state machine* has been defined, as shown in Figure 33.

The HAPS will be “In-Service” after their entry into operations, after “OperationStart” date. Once “OperationEnd” date is reached, they will be decommissioned (at simulation level). During their service, they will have 3 main tasks:

- Monitor: assignment to monitor a fire.

- Detect: assignment to cover a high-risk area without fires.
- Standby: no assignments for monitor or detect available.

For the states “Monitoring” and “Detection”, there is a middle state to account for the time spent by the platform on their way to the target location. These middle states are called “Move-to-Monitoring” and “Move-to-Detection”.

In addition, when a HAPS is in state “Monitoring” and there is another fire nearby, it can monitor both, as long as it can maintain an hourly provision of images for the two. This means that the second fire has to be located in an approximate radius of 25 minutes from the first fire. If these conditions are met, the HAPS will monitor both fires, and it will move to the state “Multi-monitoring”. This functionality allows to augment the number of fires monitored with the same HAPS fleet.

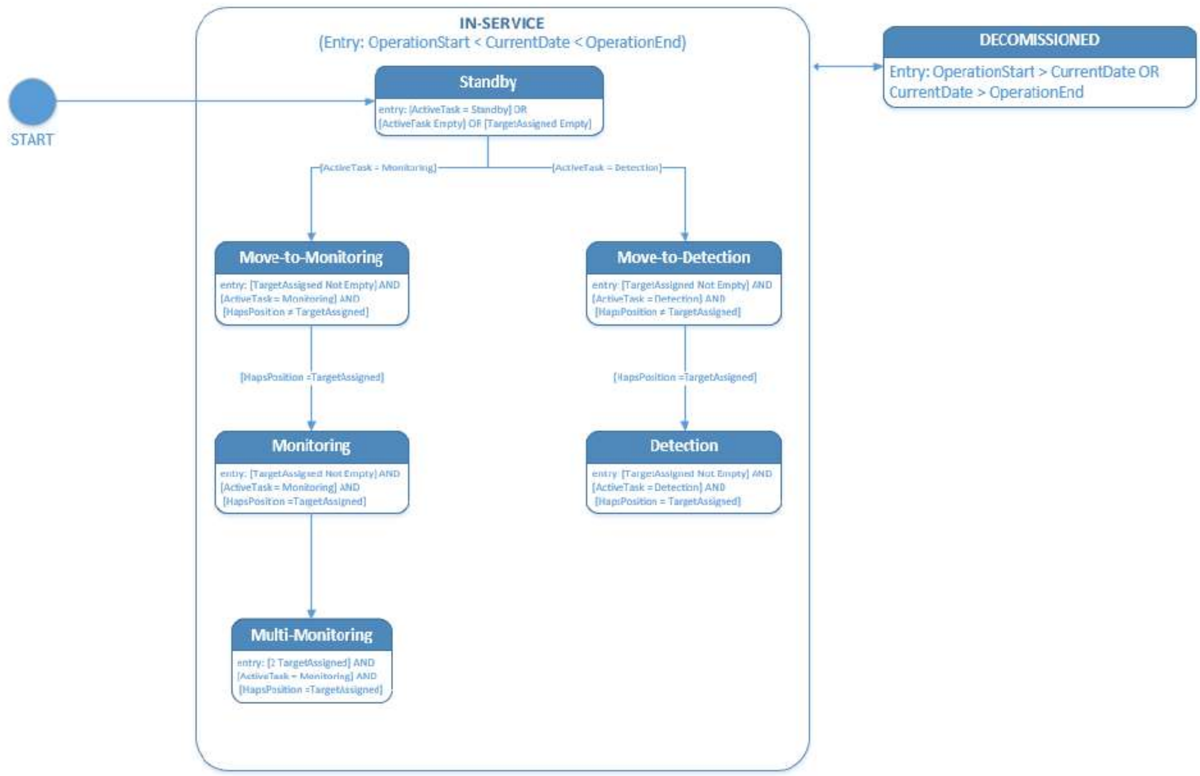


Figure 33 HAPS state machine diagram

5.4. Definition of Point of Interest

The HAPS fleet will be assigned either to monitor fires or to detect them in high-risk . The possibilities for the assignation of the HAPS are then a fire or a risk area without fire. These two elements represent a different reality, and they have different characteristics. The solution to manage both with the same assignation criteria has been merging them into Points of Interest (PoI). These points can represent either a fire or an area of risk, and they will get a priority that represent their importance with respect to the rest of the PoIs happening at the same time.

With regards to the fires, only the fires that are in "ALERT" state (please see Figure 31) will be included as PoIs. This is because only the ones in this state are eligible for the assignation of a HAPS for their monitoring. On the other hand, all the risk areas identified for each day will be included as PoIs. Figure 34 shows the criteria to build the table of the Points of Interest.

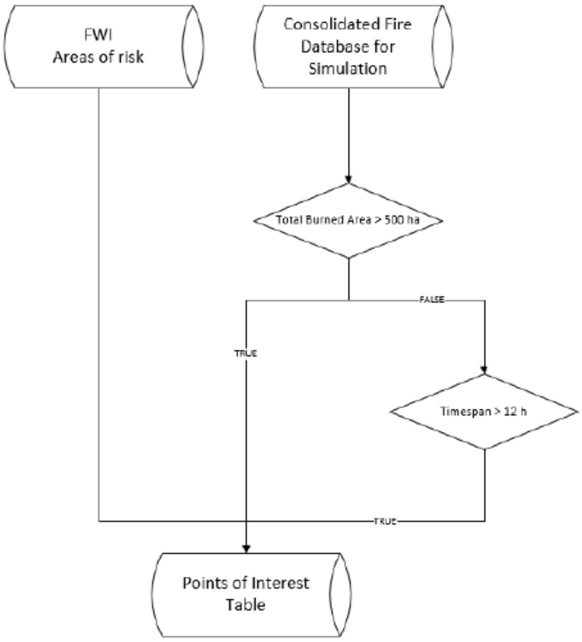


Figure 34 Point of Interest composition

The PoIs are modelled as single points with the following attributes:

Table 10 Point of Interest attributes

Attribute	Type
PoI ID	Integer that identifies the PoI.
Centroid Point	Coordinates of the centroid of the polygon of the fire or the risk area.
AoI	Integer that identifies the Area(s) of Interest where the centroid point is located.
Burning ratio [ha/m]	Burning ratio of the fire, or 0 in case of an area of risk.
FWI index	FWI value of the risk area to which the centroid belongs.
Priority	Priority value calculated based on burning ratio and FWI attributes.

With this solution, the HAPS fleet assignation will be based on a list of PoIs, that will represent the reality of the territory in a given moment, with a prioritization between them. This list of PoIs will include all fires and also all the areas of risks identified for each day. Figure 35 is the graphical representation of this merge of two different layers into one that collects all the relevant information.

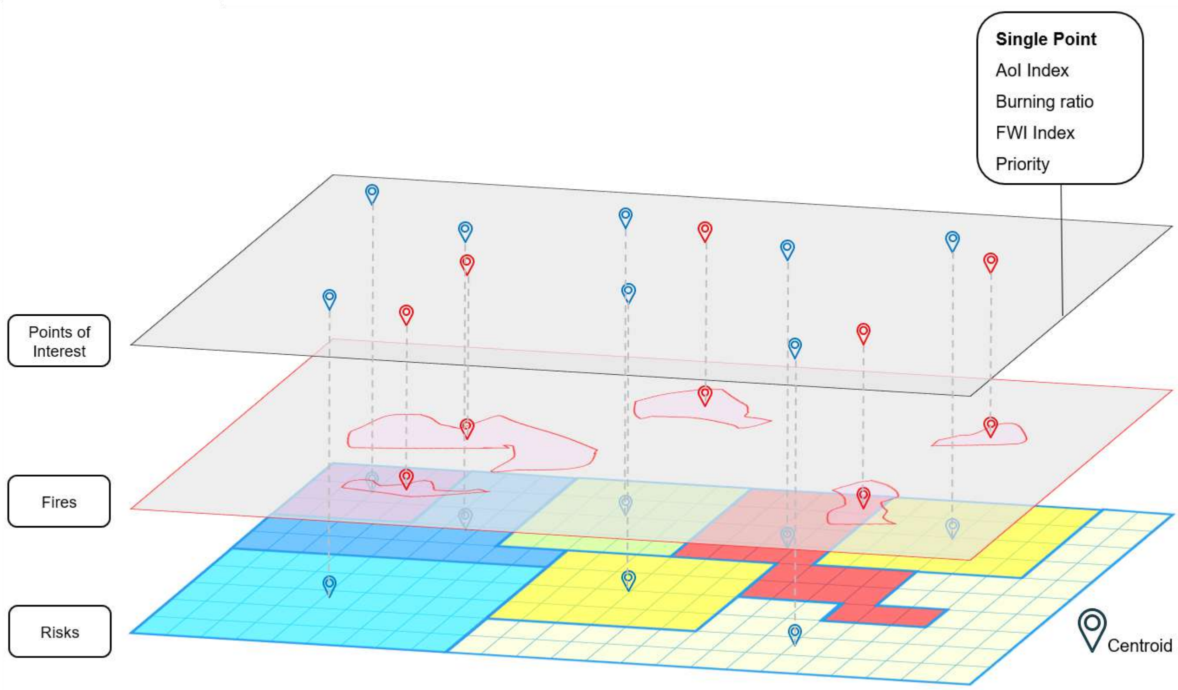


Figure 35 Points of Interest layer composition

5.5. Prioritization of Points of Interest

The assignation of the HAPS to the different PoIs will be based on their priority. This attribute has been defined to represent with a single value which points should have priority to get a HAPS to monitor or detect. It is a non-dimensional value that can go from 0 to 100, being 100 the maximum priority. The prioritization of the points has been based on two factors with different weights: the burning ratio and the Fire Weather Index (FWI). The burning ratio is the speed at which the fire is burning in terms of area. This has been selected as the primary factor to prioritize because it represents the potentiality of damage. The current area burned of the fires was considered as an option to be used as primary factor, but it was discarded against the burning ratio. The rationale of this decision is to focus on the potential damage that can happen in the next hours, rather than on what has already happened and it cannot be reversed. In this sense, the current area burned does not provide, by itself, enough information about the potential damage. A fire with a big area burned that it has been extinguished (burning ratio zero) would not have the same priority than a smaller fire with a higher burning ratio that is starting. FWI has been selected as the secondary factor to assess the priority of the Points of Interest. This term has several functions in the calculation of the priority:

- To tip the scales between fires with similar burning ratio. In this case, the FWI will give higher priority to the fire where the risk of spreading is greater.
- At times when there are no fires happening, FWI will provide a value that helps to select which areas have a bigger risk of fire to assign the HAPS for detection mode.

The priority is not an absolute characteristic, but rather something relative based on the needs and the resources available. The same fire can be important if it is the only one at a given moment, or it can be less relevant if there are other five bigger fires happening at the same time. This idea of the priority has been transferred to the formula by dividing both the burning ratio and the FWI by their maximum values between the PoIs included in an Area of Interest.

Lastly, the two terms selected for the prioritization of the PoIs do not have the same weight in the overall result value. The main objective of the HAPS is to monitor fires and provide imagery to the firefighters. In the absence of fires, then the HAPS will be located in areas of high risk of fires to detect. Thus, the burning ratio term, that is directly related to the fires (and not the risk areas) has a weight of the 80 % of the priority. On the other hand, the weight of the FWI term is 20 %. With this, the formula selected to measure the priority of the PoIs is like follows:

Equation 2 Priority formula

$$\text{Priority} = \text{weight}_{Area} \cdot \frac{\frac{\text{dA}}{\text{dt}}_{Current}}{\frac{\text{dA}}{\text{dt}}_{Max}} + \text{weight}_{FWI} \cdot \frac{FWI}{FWI_{Max}}$$

Where:

- Weight area = 0.8 [-].
- Weight FWI = 0.2 [-].
- dA/dt current = burning ratio of the PoI (0 if the PoI is a risk area) [ha/h].
- dA/dt max = max burning ratio in the AoI(s) of the PoI [ha/h].
- FWI = Fire Weather Index of the PoI [-].
- FWI max = max Fire Weather Index in the AoI(s) of the PoI [-].

Figures 36 and 37 show the representation of the priority function variating the two terms of the burning ratio and FWI. Instead of providing absolute values, this representation based on the quotients can be applied to all cases and provide a better idea of the prioritization in relative terms. Figure 37 shows the variation of the priority for constant quotients of the FWI. As expected, the priority is higher if the burning ratio quotient approaches 1, meaning that the burning ratio of the fire is the highest of the area of interest.

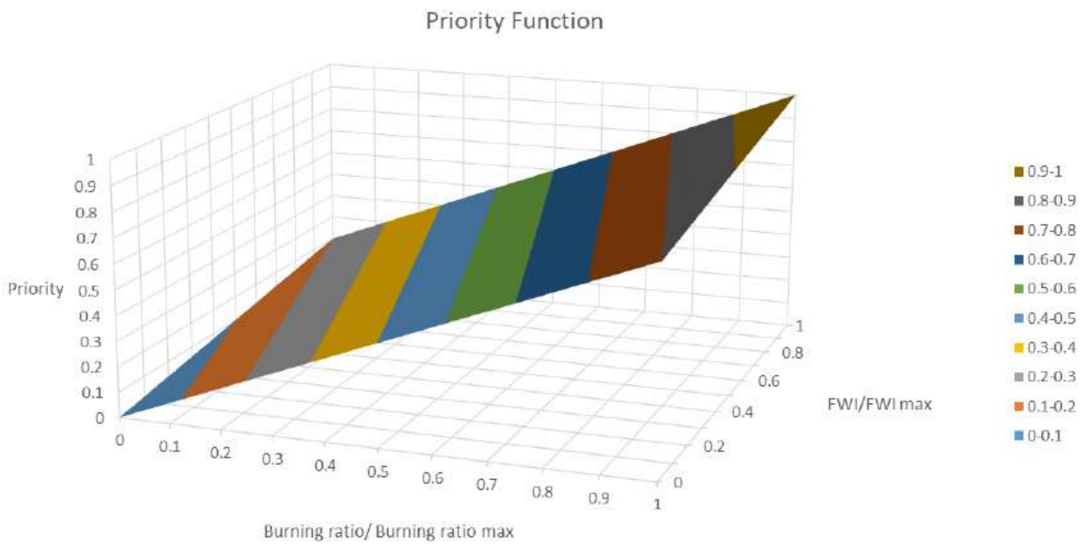


Figure 36 Priority surface in 3D

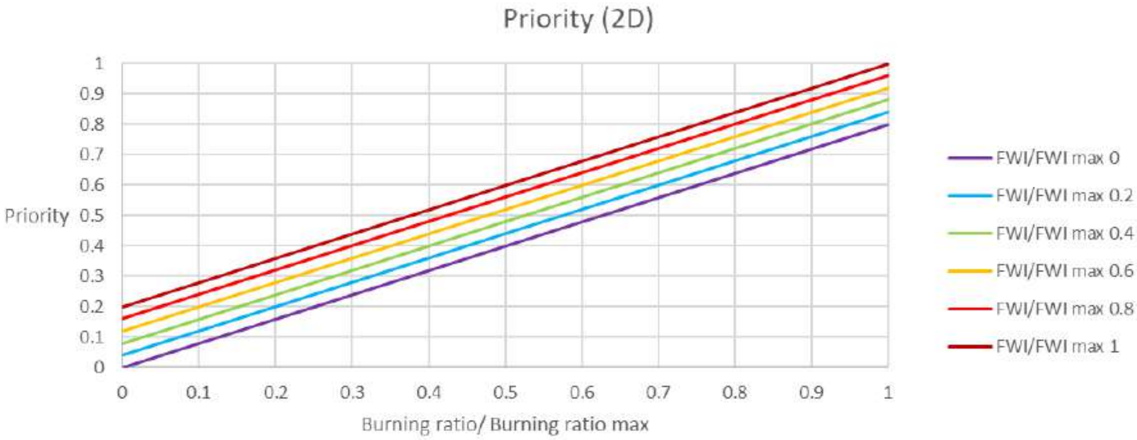


Figure 37 Priority lines in 2D

5.6. HAPS Assignment to Points of Interest

Once the Points of Interest are processed with their priority on each step of the simulation, the HAPS will be assigned to the PoIs with higher priority. The assignation of the HAPS to the Point(s) of Interest will be done from the PoI with highest to the lowest priority until there are no more HAPS non-assigned.

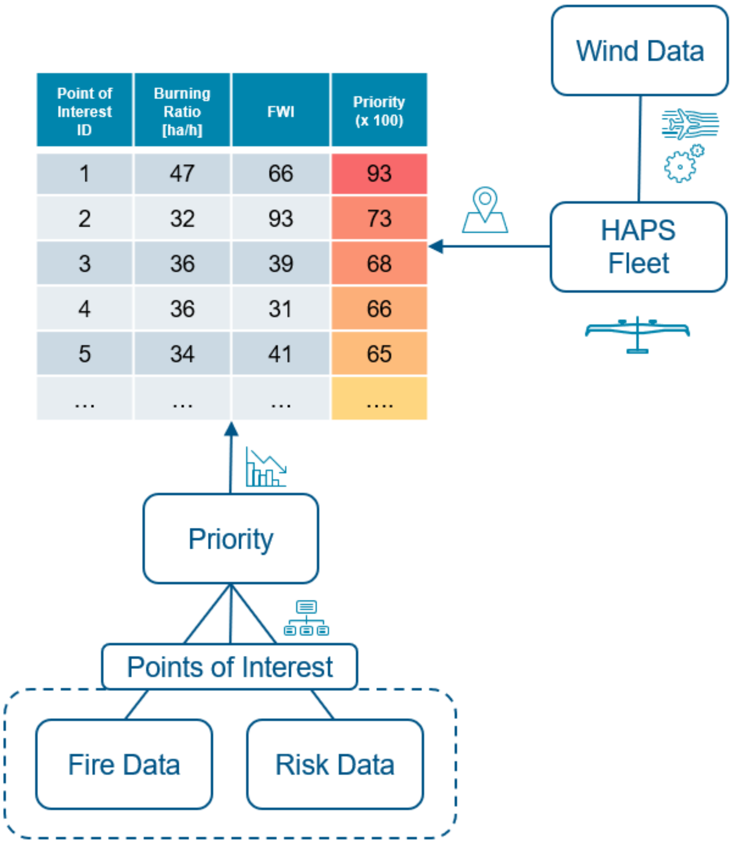


Figure 38 General architecture of the simulator

The assignation will start from the PoI with the highest priority. For this point, the Estimate Time of Arrival (ETA) of the HAPS allocated to its Area of Interest will be calculated, taking into account the stratospheric winds of the geodesic trajectory. The HAPS which is closer in time to the PoI will be assigned to this point, becoming "blocked" for the rest of the assignations of this step. Due to this, the ETA of this HAPS will not be calculated for the rest of the PoIs.

Then, the next PoI in order of priority will be assessed, and the same process will be done for the HAPS allocated to its AoI. This process will be repeated until all HAPS are assigned.

As an example of how the assignation of the HAPS fleet has been designed for this simulation, the following scenario is explained:

- The Area of the Simulation (AoS) contains 3 different Areas of Interest (AoIs).
- The HAPS fleet is composed of 5 platforms, that are allocated to the 3 AoIs, as shown in the Figure 39.

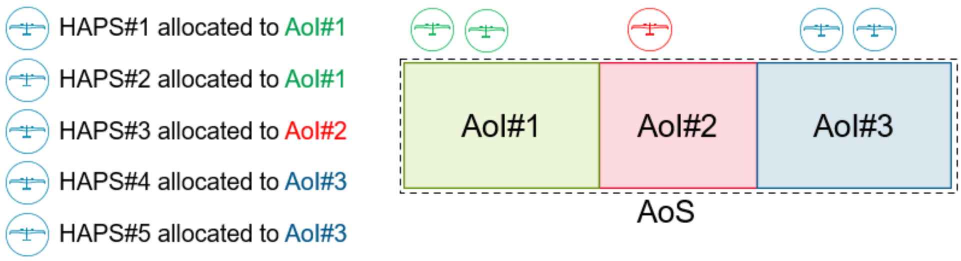


Figure 39 AoIs and HAPS allocation example

In the step t_0 of the simulation, the situation in the AoIs is the following:

- In AoI#1, there are 3 PoIs:
  - 2 fires ongoing (PoI IDs 1 and 3).
  - 1 area of risk (PoI ID 2).
- In AoI#2, there are 2 PoIs:
  - 2 fires ongoing (PoI IDs 9 and 10).
- In AoI#3, there are 5 PoIs:
  - 4 fires ongoing (PoI IDs 4, 6, 7 and 8).
  - 1 area of risk (PoI ID 5).

The PoI's attributes ordered by priority is shown in Table 11. The burning ratio, the FWI and the priority have been formatted from red to green, being red the highest values. The priorities have been calculated with respect to the maximums of each of the AoIs. In this example, it is relevant to point out that PoI ID 10 has higher priority than PoI ID 6, that is just below, while the burning ratio and FWI of the latter is higher. This might be seen as incorrect or even unfair, but it is important to understand that the priority is relative to the AoI of the PoI, and the assignation of the HAPS will be based on the HAPS allocated to each AoI. In this case, although PoI ID 10 is above, it is only eligible for the HAPS of AoI#2, while PoI ID 6 is eligible for the HAPS fleet of AoI#3 (Table 12).

Table 11 PoI Table example

ID	Type	AoI	dA/dt [ha/h]	FWI [-]	Priority
7	Fire	3	486	70	100.00
1	Fire	1	479	66	94.19
10	Fire	2	395	24	88.57
6	Fire	3	481	30	87.75
3	Fire	1	381	39	72.02
8	Fire	3	336	51	69.88
9	Fire	2	179	56	56.25
4	Fire	3	268	31	52.97
2	Risk	1	0	93	20.00
5	Risk	3	0	41	11.71

Table 12 Maximums per AoI for previous PoI Table

	Burning ratio [ha/h]	FWI
Max AoI#1	479	93
Max AoI#2	395	56
Max AoI#3	486	70

The simulation will process the PoI in a single table for the efficiency of the performance. But from a logical point of view, the assignation of the HAPS will produce the same result as if there were 3 separated tables, one per each AoI.

Figure 40 PoI table split by AoI

Once the PoI table is calculated, the assignation of the HAPS fleet starts. In this example, there are 5 HAPS to be assigned to 10 PoIs. The assignation has to take into account also the allocation of the HAPS to the AoIs. Table 13 shows the process for the assignation of the HAPS to the PoIs that will take place on each step of the simulation. The first PoI of the table is ID 7, located in AoI#3. The calculation of the ETA times is only done for the HAPS not assigned that are eligible for AoI#3. In this case, there are 2 HAPS. HAPS#4 has the minimum ETA of the ones available, so it is assigned to monitor PoI ID 7. Next, the following PoI of the list is ID 1, from AoI#1. The HAPS eligible for this assignation are HAPS#1 and HAPS#2, so only for those the ETA has been calculated. HAPS#1 is the closest-in-time platform to the PoI, so it is assigned to monitor it. The next PoI in priority, ID 10, gets assigned HAPS#3, that is the only one allocated to AoI#2. In forth position it is PoI ID 6, for which there is only one HAPS of AoI#3 available, HAPS#5, as the other has been assigned to PoI ID 7. Because of that, only ETA for HAPS#5 is calculated. Lastly, PoI ID 3 gets HAPS#2 assigned. For the rest of the PoIs no ETAs are calculated, and they do stay without a HAPS assigned.

Table 13 HAPS assignation to PoIs example

							ETA Table				
							AoI#1		AoI#2	AoI#3	
ID	AoI	dA/dt [ha/h]	FWI [-]	Priority	PoI Status		HAPS#1	HAPS#2	HAPS#3	HAPS#4	HAPS#5
7	3	486	70	100.00	HAPS Assigned	→				101	381
1	1	479	66	94.19	HAPS Assigned	→	16	552			
10	2	395	24	88.57	HAPS Assigned	→			209		
6	3	481	30	87.75	HAPS Assigned	→					106
3	1	381	39	72.02	HAPS Assigned	→		792			
8	3	336	51	69.88			ETA not calculated; all HAPS already assigned				
9	2	179	56	56.25							
4	3	268	31	52.97							
2	1	0	93	20.00							
5	3	0	41	11.71							

Based on this example, the final assignation of HAPS will be as in Table 14.

Table 14 PoI - HAPS final assignation

PoI ID	AoI	Assignation
7	3	HAPS#4
1	1	HAPS#1
10	2	HAPS#3
6	3	HAPS#5
3	1	HAPS#2
8	3	No HAPS Assigned
9	2	No HAPS Assigned
4	3	No HAPS Assigned
2	1	No HAPS Assigned
5	3	No HAPS Assigned

This process is reassessed on each step of the simulation, resetting the assignations at the beginning. If the list of PoI maintains their priorities, the assignation will be kept. In the event that the list of PoIs changes the amount or order of the PoIs, there will be changes in the assignations. It may seem that this method would induce much variability to the assignations of the HAPS. But the simulations have shown that the HAPS keep their assignations until they arrive to provide imagery in most cases, proving that the assignations are stable.

In case the PoI assigned to a HAPS is a fire, the task mode of the HAPS will be "Monitoring". In case it is a risk area, the HAPS will be in "Detection". For the HAPS in "Monitoring", after the assignment to a PoI, a check is done for multi-monitoring:

- Look out for fires in a 25 min-radius around the fire.
- If there is any, select the fire with the highest priority inside the buffer.

In Figure 41 an example of the multi-monitoring is represented. Following with the previous scenario, now several fires of the AoI#3 were located in the same region: PoI ID 4, 6 and 7. With the assignation of HAPS#4 to monitor PoI ID 7, the multi-monitoring check is performed. Drawing a 25 min radius around this fire, there are two other fires in the circle, PoI ID 4 and 6. As PoI ID 6 has a higher priority, it is also assigned for monitoring to the HAPS#4, which will be in multi-monitoring mode, providing images of the two fires on an hourly basis. As a direct consequence of this, PoI ID 8, next in the priority list, has an available HAPS that is assigned. Thanks to the multi-monitoring functionality, the usage of HAPS is maximised and the number of fires that can be monitored augments.

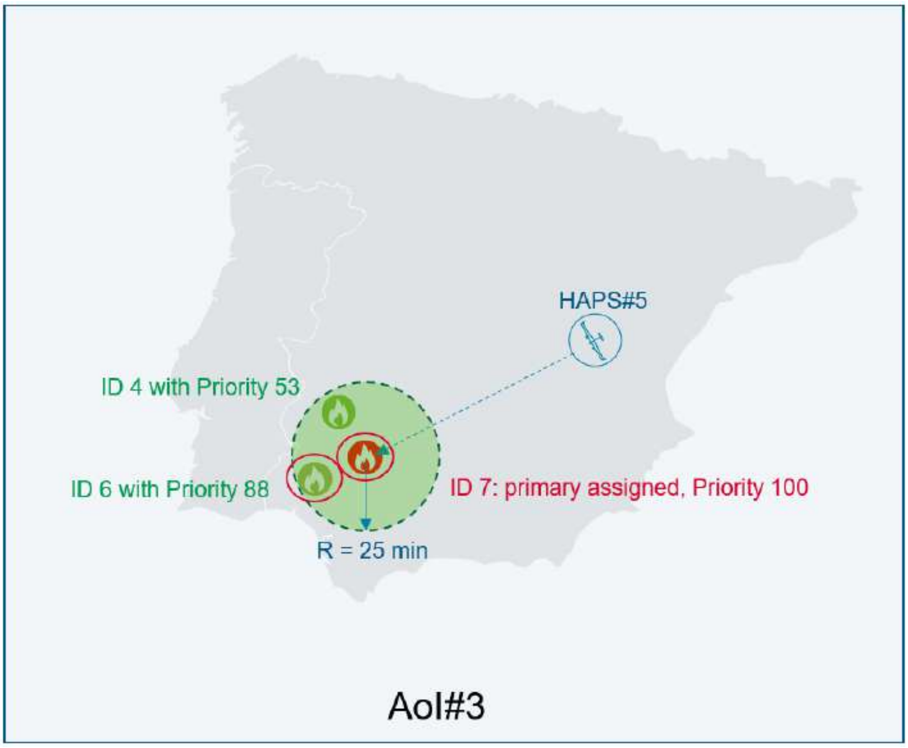


Figure 41 Multi-monitoring example

Table 15 shows the resulting PoI table after the assignation of the HAPS in the scenario of multi-monitoring. With the same number of HAPS, an additional fire can be monitored.

Table 15 HAPS assignation to PoIs example – Multi-monitoring

							ETA Table				
							AoI#1		AoI#2	AoI#3	
ID	**AoI**	**dA/dt [ha/h]**	**FWI [-]**	**Priority**	**PoI Status**		**HAPS#1**	**HAPS#2**	**HAPS#3**	**HAPS#4**	**HAPS#5**
7	3	486	70	100.00	HAPS Assigned	→				101	381
1	1	479	66	94.19	HAPS Assigned	→	16	552			
10	2	395	24	88.57	HAPS Assigned	→			209		
6	3	481	30	87.75	HAPS Assigned	→					
3	1	381	39	72.02	HAPS Assigned	→		792			
8	3	336	51	69.88	HAPS Assigned	→					326
9	2	179	56	56.25			ETA not calculated; all HAPS already assigned				
4	3	268	31	52.97							
2	1	0	93	20.00							
5	3	0	41	11.71							

The assignment problem of the fires-HAPS has been solved with this "linear" approach. But during the development of the project, other methods were considered for this assignment problem. Among those, the Hungarian method was the one with better results for its implementation.

Both the Hungarian and "linear" approach were compared with the same test simulation to analyse their results to decide the final method to be implemented in the simulation. The Hungarian method is a mathematical algorithm that solves optimal assignment problems by efficiently assigning a set of resources (HAPS) to tasks (Fire Monitoring). It finds the optimal solution by computing the cost matrix through a cost function, aiming to minimize (or maximize) the total cost of HAPS assignments to a fire. The conclusions of these analyses showed that the Hungarian method offered a more optimized assignment, but that the HAPS did not arrive as much to the fire destination due to the constantly changing environment. On the other hand, the linear method had a less optimized assignment of fires-HAPS, but the HAPS arrived more effectively to the destinations, improving the executed monitoring time. Lastly, the implementation of the multi-monitoring functionality was more complex with the Hungarian method, while it was already working with the linear one. Due to all these facts, the linear method was selected for the usage in the simulation.

6. TESTING STRATEGY

The design of the simulator allows a great variety of combinations for the parameters introduced on each simulation. The definition of the areas of interest, the number of HAPS deployed each month or their allocation to the areas of interest are some examples of this flexibility. With the aim to standardize the testing of the simulations, a strategy has been defined with the objective to find the optimal fleet size and monthly deployment.

Two different testing campaigns will be performed: one at European level, and another one at regional level, located in the Living Labs that are covered by the Area of the Simulation. In both cases, the testing strategy and target KPIs will be the same.

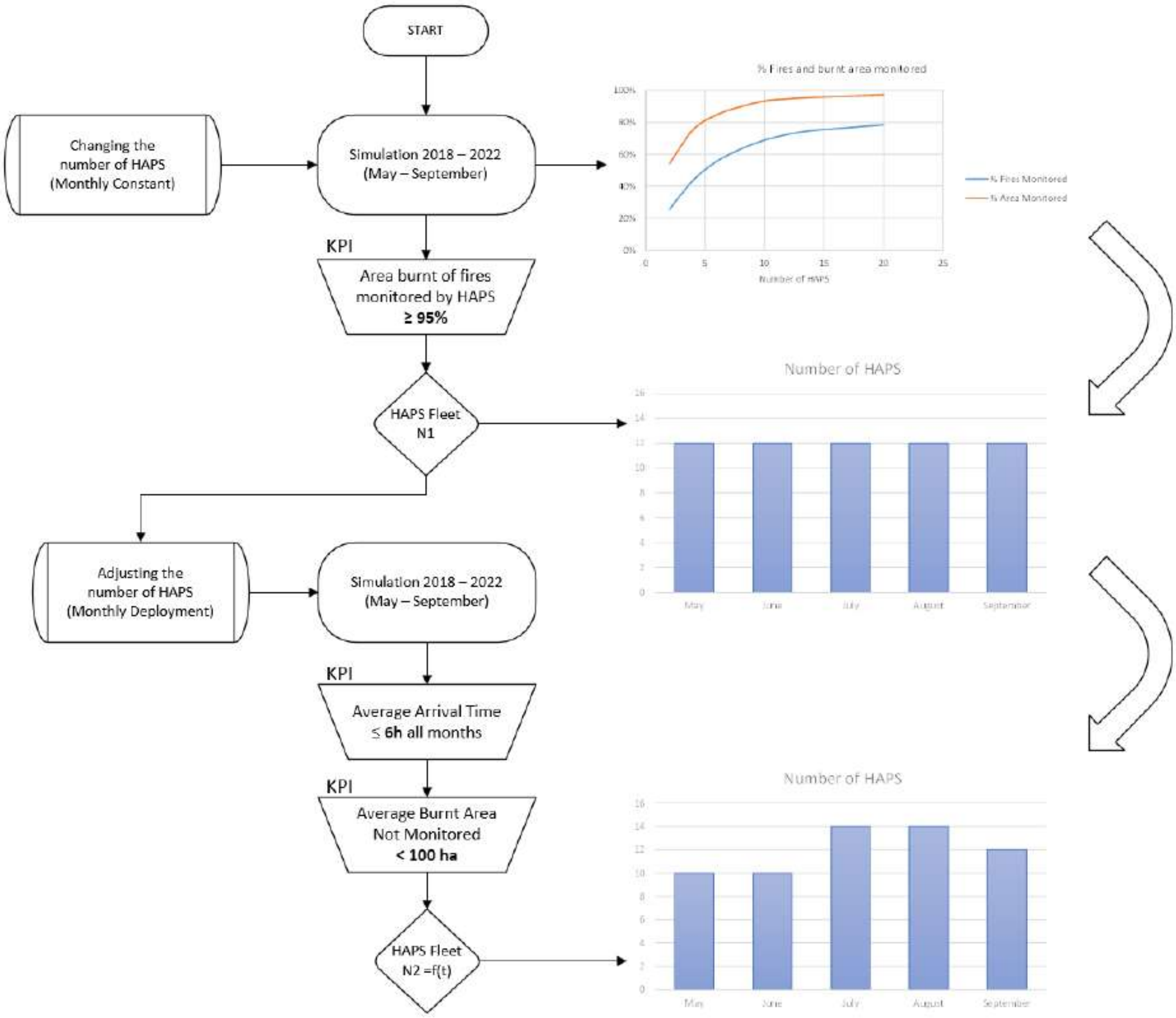


Figure 42 Testing strategy

Figure 42 shows the different steps planned to find the optimized fleet size. In the first phase, the 5 years of the simulation are run changing the size of the fleet. The results will allow to see the influence of the number of HAPS with respect to the different KPIs. With the objective to have a good view of this influence, the simulations will be done for 2, 4, 6, 8, 10, 12, 14 and 20 HAPS initially. In the case this is not enough to identify a tendency, more simulations will be done with another fleet sizes. In this first phase, all HAPS will be deployed from May to September, maintaining the total amount of HAPS deployed constant over time.

The main indicators to be checked with the results of this first phase are:

- Percentage of fires monitored by HAPS with respect to the total amount of fires eligible for HAPS (+12 hours or +500 ha).
- Percentage of burnt area of the fires monitored by HAPS with respect to the total burnt area of fires eligible for HAPS.
- Average characteristics of the fires not monitored.
- Average characteristics of the fires monitored.

- Average times of the service:
    - Arrival time to the fires monitored.
    - Monitoring time of the fires monitored.
    - Monitoring ratio per fire.
- Average area burnt at the arrival for the fires monitored.

The two main indicators will be the percentage of fires monitored by the HAPS, and the percentage of burnt area that those fires represent. The input fire database contains many small fires that last long, but with a minor area burnt. On the other hand, there are some few fires with an important area burnt. This distribution of the fires makes that the percentage of area monitored can be highly increased with a smaller percentage of the number of fires monitored. The main output of the first phase will be the fleet size that guarantees a minimum area burnt of the fires monitored of at least 95 % of the total area burnt. This value is needed to assure that most of the fires are monitored, and that the rest of the parameters analysed are representative.

With this first estimation on the fleet size, the next phase will focus on provide an average arrival time to provide imagery of equal or less than 6 hours. For that, based on the previous results, the HAPS fleet will be adjusted per months, increasing the number of HAPS deployed in the months where the arrival time is above this target, and reducing the quantity in the months where the arrival time is below. In general terms, it is expected that the number of HAPS needed will be higher in the months of July and August, where more fires take place, according to Figure 27.

The criteria of the 6 hours has been based on the goal of arriving to monitor the first night of the fire. For example, according to [RD-06], the hour of the day with more fires in Spain is around 4 pm. Based on this, with the 6 hours criteria the HAPS could guarantee to arrive before the end of the day.

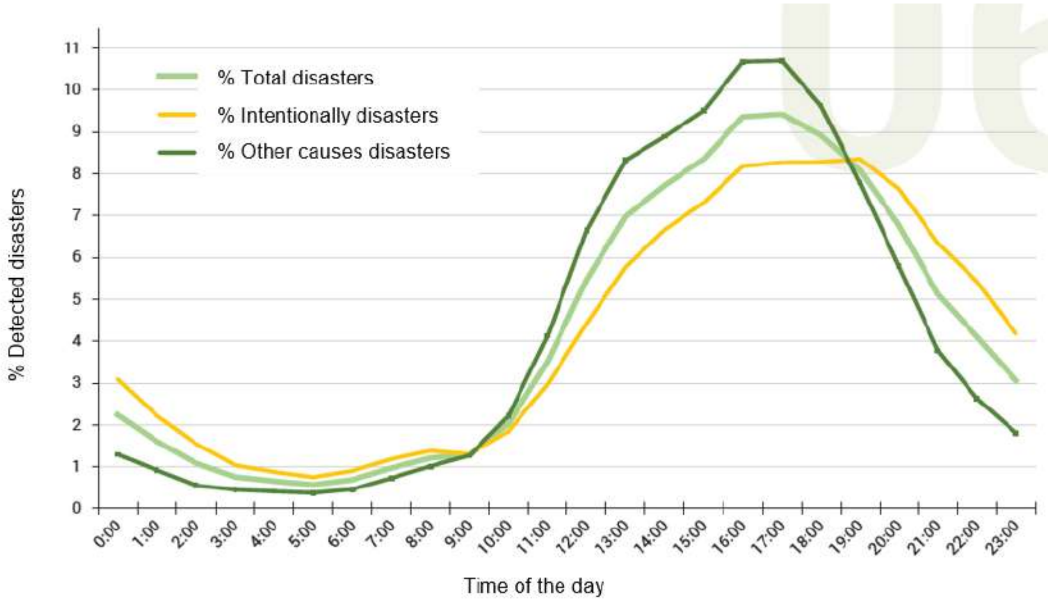


Figure 43: Percentage of fires per hour of detection in Spain (2006-2015)

Lastly, a check will be done to the fires not monitored. The goal of this last check is to assure that the fires unattended are effectively smaller, and hence less important. If the previous indicators are good, but the average burnt area of the fires not monitored is high, the monitoring service should be reinforced. For this last check, the average burnt area of the fires not monitored should be less than 100 ha. With the Living Labs, the same approach will be followed but focused on each location.

7. RESULTS EUROPEAN LEVEL

7.1. Phase 1: Size fleet

In this section the results of the phase 1 of the simulations are shown and explained, with their main findings. This first analysis will serve also as the basis for the second phase, where the same indicators will be checked per months.

Initially, the main figures to check are the number of fires monitored and the amount of area burnt that the fires monitored represent. Figure 44 and Figure 45 show the evolution of both metrics with the number of HAPS deployed. Both values augment with the higher number of HAPS deployed, and they tend to a horizontal asymptote that is the total number of fires or area burnt. This means that with a fleet of dozens of HAPS it is not possible to monitor all fires, but it is possible to monitor most of them. The two curves (number of fires and total area) are different between them in their proximity to the asymptote line. The amount of the area burnt monitored rises at a higher pace than the number of fires. This is due to the fact that the area burnt of the fires is not equal between all and the HAPS are assigned to the bigger fires, increasing rapidly the amount of area with respect to the total.

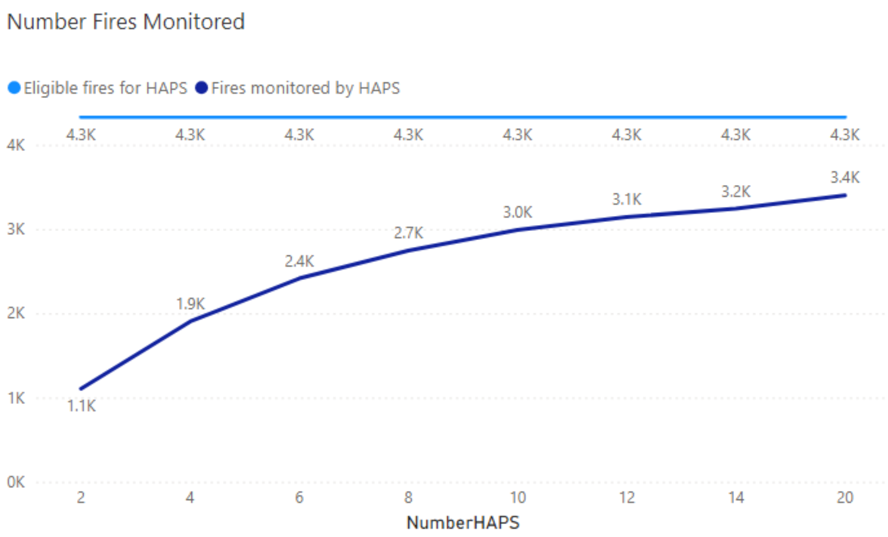


Figure 44 Number of fires monitored by HAPS

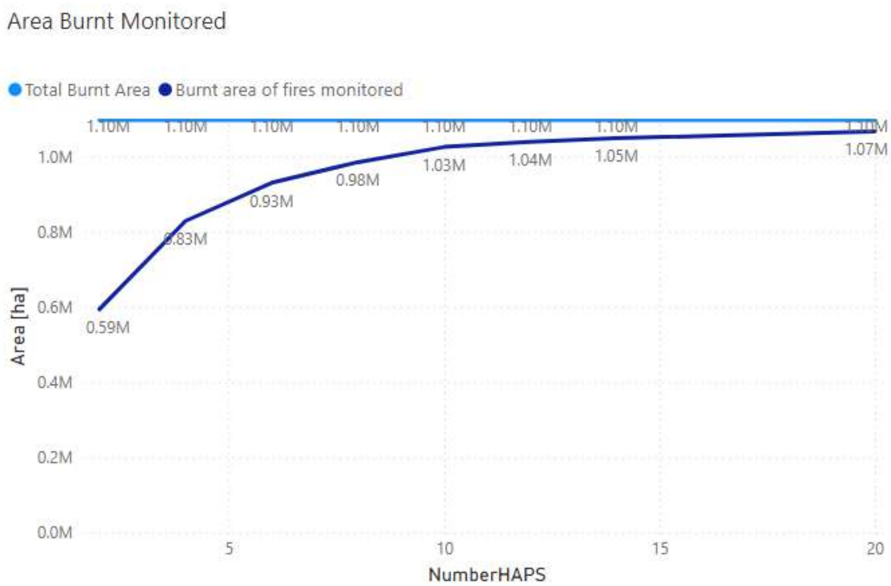


Figure 45 Area burnt monitored by HAPS

Another take away of this initial study is shown in Figure 46, with the percentage of number of fires and area monitored. A fleet of 12 HAPS can monitor 73 % of the eligible fires, but they represent already 95 % of the area burnt of the fires eligible for HAPS-monitoring.

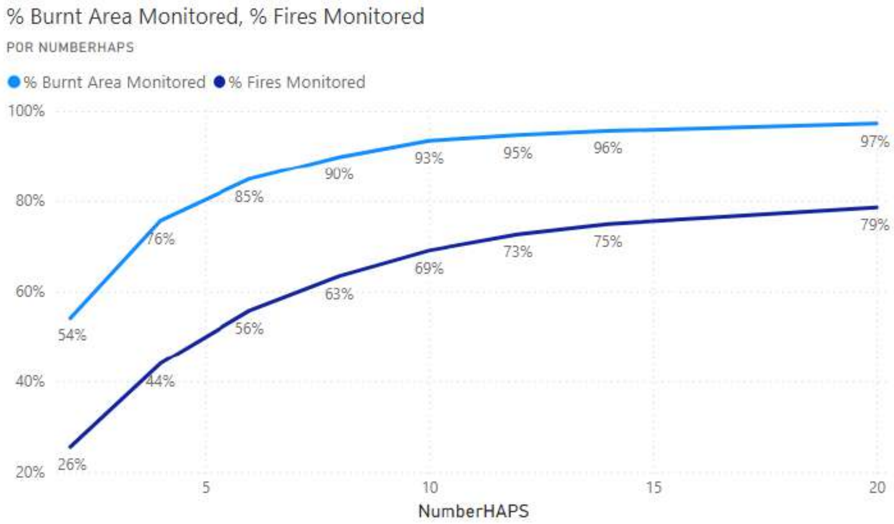


Figure 46 Percentage of fires and area burnt monitored by HAPS

The results of this figures are included in Table 15.

Table 16 Summary of general results of phase 1 (European level)

Numbe rHAPS	Eligible fires for HAPS	Fires monitored by HAPS	Total Burnt Area [ha]	Burnt area of fires monitored [ha]	% Fires Monitored	% Burnt Area Monitored
2	4,326	1,106	1,096,927	593,739	25.57 %	54.13 %
4	4,326	1,901	1,096,927	828,639	43.94 %	75.54 %
6	4,326	2,413	1,096,927	930,168	55.78 %	84.80 %
8	4,326	2,742	1,096,927	984,961	63.38 %	89.79 %
10	4,326	2,987	1,096,927	1,025,208	69.05 %	93.46 %
12	4,326	3,142	1,096,927	1,039,025	72.63 %	94.72 %
14	4,326	3,240	1,096,927	1,048,640	74.90 %	95.60 %
20	4,326	3,398	1,096,927	1,066,860	78.55 %	97.26 %

The next step will be to look into the characteristics of the fires monitored and not monitored, to see their variation with the number of HAPS deployed. Figure 47 displays the average area burnt per fire monitored as well as the average duration of the fires monitored. With more HAPS deployed, these averages are being reduced because more fires are monitored, but they tend to be smaller either on duration or area burnt (due to the prioritization of the fires monitored). The average duration of the fires monitored tends to be steady, around the 36 hours, with 8 or more HAPS deployed. On the other hand, the average area burnt of the fires monitored is above the 300 ha even with 20 HAPS deployed.

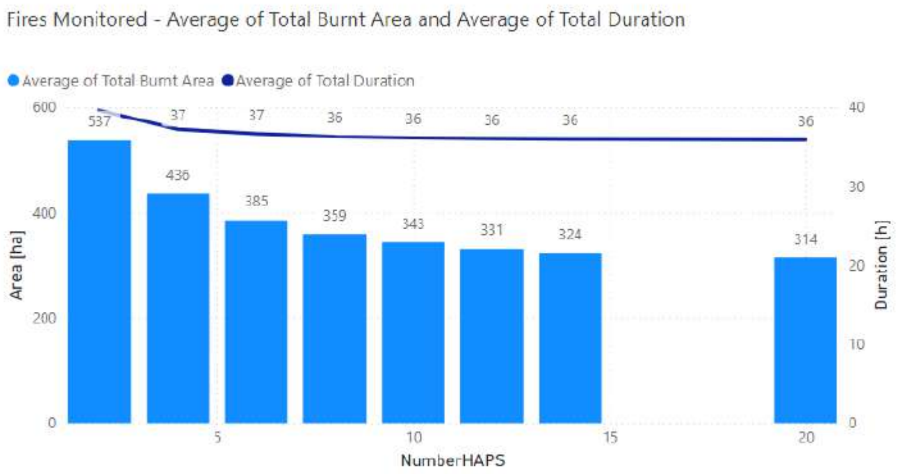


Figure 47 Average total burnt area and duration per fire monitored

The characteristics of the fires monitored is really representative of the service that a fleet of HAPS could offer, as it helps to understand the support it can bring to the firefighters. But it is also very illustrative to see the characteristics of the fires that could not be monitored by the HAPS fleet, to assess the importance of the fires unattended, and think of other resources for their monitoring. In this line, Figure 48 shows the average area burnt and average duration of the fires not monitored by HAPS. With a fleet of at least 10 HAPS, the average area burnt is around 50 ha, with an average duration of 32 hours. In comparison with the fires monitored, these are smaller in area burnt, but with almost the same duration, which indicates that they are fires with a lower burning ratio.

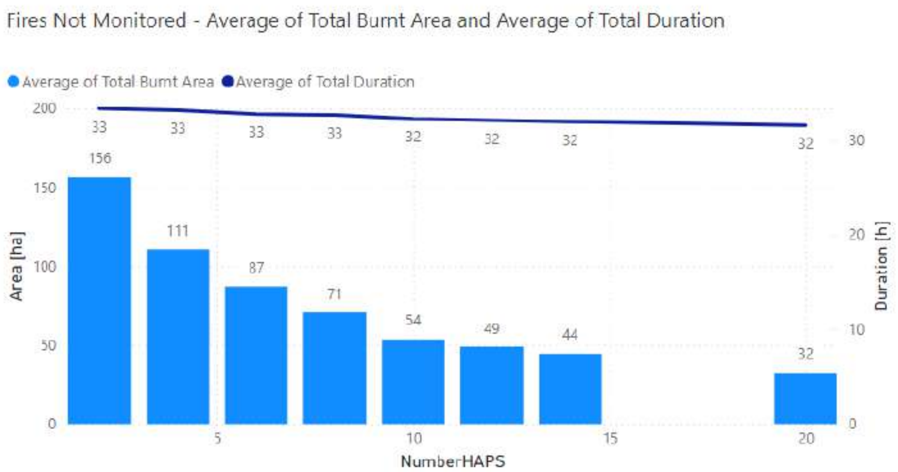


Figure 48 Average total burnt area and duration per fire not monitored

Focusing on the fires monitored by HAPS, Figure 49 contains the average times of the different fire status of the lifecycle model implemented in this document (Fire model). The time in “To be Monitored” represents the time of arrival of the HAPS since its tasking to the fire until the HAPS arrives to monitor it. After that, the monitoring time represents the duration of the service while the HAPS is providing imagery of the fire. There is a tendency that shows that the arrival time (To be Monitored) is reduced with the augment of HAPS deployed. As average, with more than 10 HAPS the arrival time is less than 7 hours, and with 14 HAPS less than 6 hours (5.7h). This provides a first hint to the size of the HAPS fleet with the goal to provide a 6 hours arrival time service during the months of the summer period. The monitoring ratio, that is the percentage of the timespan of the fire that is being monitored, is also represented in this figure. With more than 10 HAPS, the monitoring ratio is above 60 % of the duration of the fires monitored.

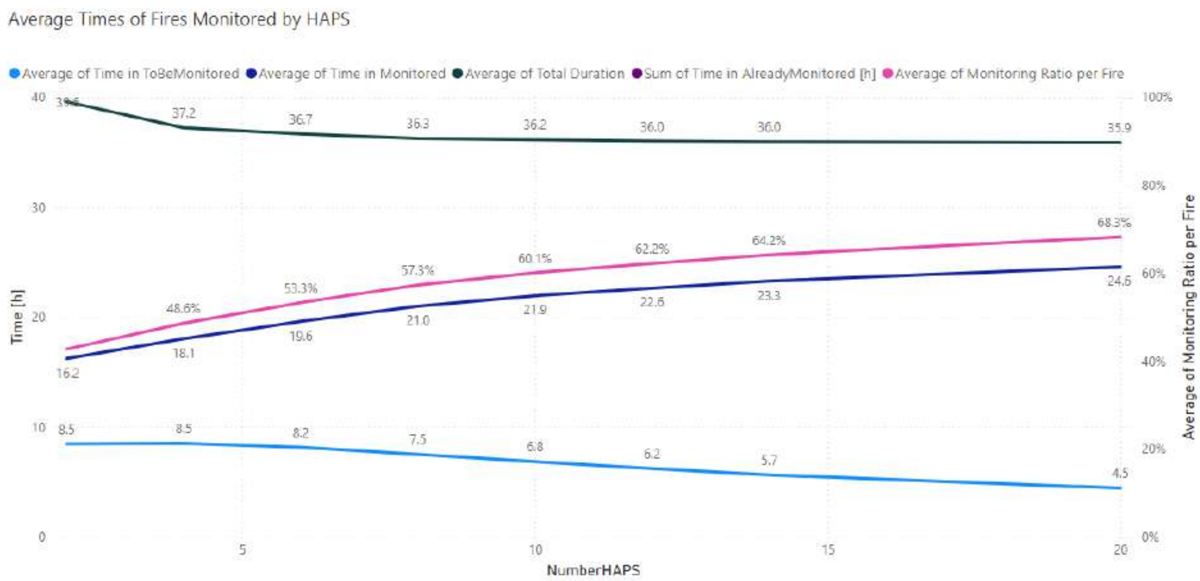


Figure 49 Average times of fires monitored by HAPS

These arrival times can be translated in burnt area at the arrival of the HAPS according to the fire model defined. For sure, the real areas burnt in the first hours of the fires will be different from fire to fire, and this is just an estimation according to the model. Figure 50 shows the average area burnt at arrival and its evolution with the variation of the number of HAPS. Also, in the same graph, the average total area burnt of each fire monitored is included as a reference to assess the area burnt at arrival. With 10 HAPS or more, the area burnt at arrival is less than 50 ha, for fires with an average total burnt area of more than 300 ha, which represents the major part of the area burnt.

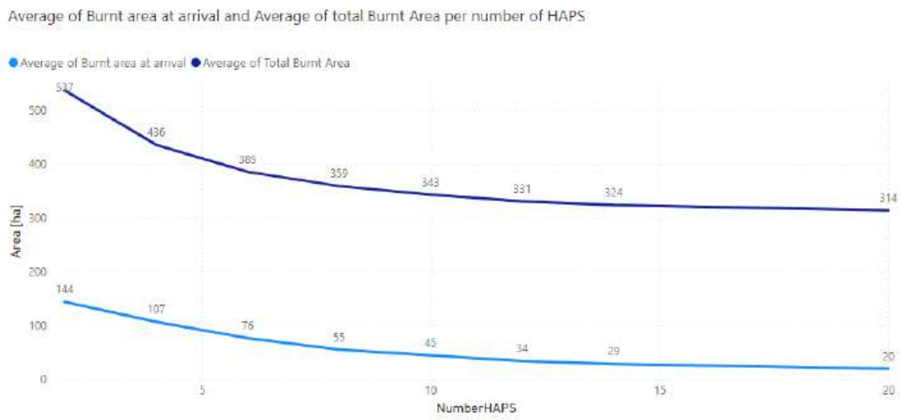


Figure 50 Average of burnt area at arrival of fires monitored

Based on these results, a fleet of 12 HAPS could cover the 95 % of the area burnt of the fires monitored. With this preliminary figure, in the next phase the goal will be to tune the number of HAPS deployed each month to provide an arrival time of equal or less than 6 hours. In parallel to this research for the optimal HAPS fleet size, the rest of the results contained in this section will be re-assessed per each month, providing more granularity about the monitoring service of the HAPS fleet.

7.2. Phase 2: Monthly deployment

Based on the previous results, Figure 49 shows that the arrival time for 12 HAPS is of 6.2 hours as average. This performance is above the target of 6 hours, so the fleet of HAPS needs further customization. In this second phase, instead of varying the number of HAPS as a whole, their quantity will be based on the arrival time per each month of the summer period. This is because the quantity of fires is different in May than in August, and so it does the number of HAPS needed. Looking at the months specifically, the number of HAPS may be reduced to less than 12 HAPS in some months and increase in others where the load is higher.

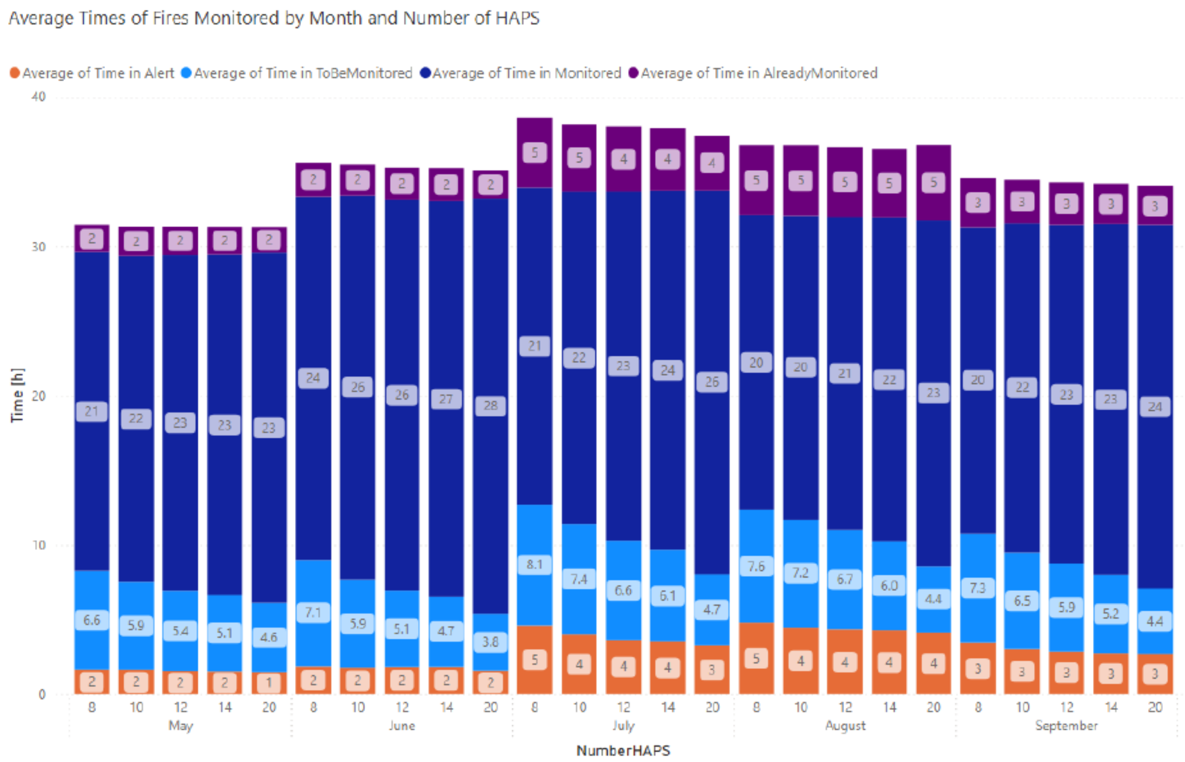


Figure 51 Average times of the fires monitored per month and number of HAPS

In Figure 51 the different state times of the fire are represented per each month of the season and for different fleet sizes. This state times of the fire are in accordance with the fire model defined in Fire model section. The “time in alert” represents the time since the start of the fires until it gets a HAPS assigned for its monitorization. Once the HAPS is assigned, the time of arrival is accounted in the “to be monitored” time. The time of the HAPS providing imagery of the fire is represented in the “time in monitored”. Lastly, the “time in already monitored” represents the time of the fire since the HAPS leaves to another location until its extinction. This time takes place in the final hours of the fire, when the fire is already under control, close to extinction, and there are other fires with higher priority that need to be monitored.

In general terms, this allows to see how the arrival time to the fires is diminishing with the augment of HAPS. And this time reduction is transformed in an increase of the monitoring time, thus improving the service. Figure 51 shows also the monthly variation in the load of fires. For the same fleet size, the arrival times are increased in July and August. The reason of this is because the number of fires during July and August augments, and the HAPS cannot maintain the same arrival times than in May or June. Also, this shows that the HAPS used to leave the fires between 2 and 4 hours before the extinction of other fires with more priority.

Based on the goal of providing an arrival time of less than 6 hours, Figure 51 indicates that a fleet of 10 HAPS could fulfil the requirement for the months of May and June. In September, 12 HAPS would be needed, 2 more than at the beginning of the period. In July, a fleet of 14 HAPS provide an average arrival time of 6.1 hours, a bit above of the target time. The same fleet of 14 HAPS provide in August an average time of 6.0 hours, in the limit of the target time. For August, 14 HAPS will therefore fulfil the target time, but this would not be enough for July. In this month, it is expected that a fleet of 15 HAPS would achieve the target time. Nonetheless, from the operational point of view the deployment of one HAPS platform for a single month is not very realistic due to the short duration of the flight. Based on this, and with an arrival time of almost 6 hours in July, the recommended HAPS fleet size for July and August is 14 HAPS.

With these results, a HAPS fleet that could provide a monitoring service with an average arrival time of equal or less than 6 hours would have the following monthly deployment shown in Table 17 and Figure 52.

Table 17 Monthly HAPS deployment ≤ 6 hours

Month	May	June	July	August	September
Number of HAPS	10	10	14	14	12

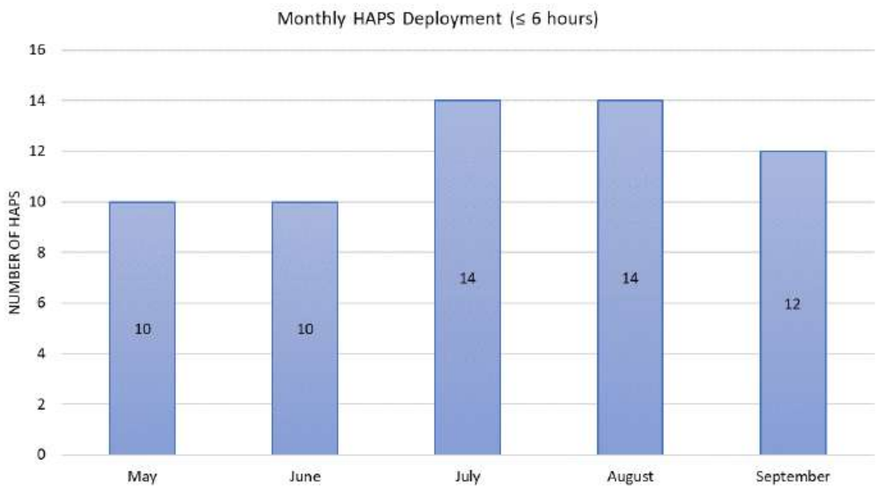


Figure 52 Monthly HAPS deployment for 6 hours arrival time

With the definition of this HAPS fleet, the 5 years of simulation were run together to check if the results were as expected with the study.

Figure 53 and Figure 54 show the number of fires monitored and the amount of area burnt that those fires represent. The gap between the number of fires monitored with respect to the total amount of fires is increased during the months of July and August. But, if the area is checked instead, this gap is significantly smaller. This means that the fires monitored represented the majority of the area burnt.

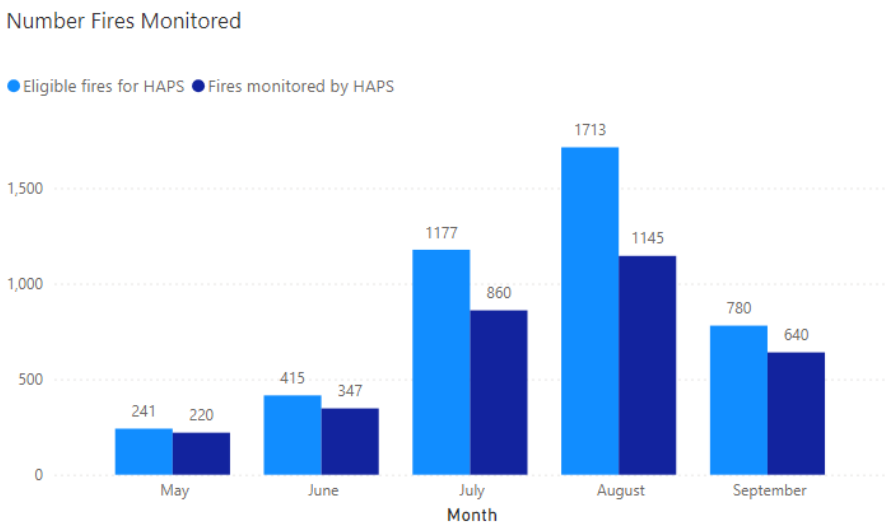


Figure 53 Number of fires monitored by HAPS (deployment of 6 hours)

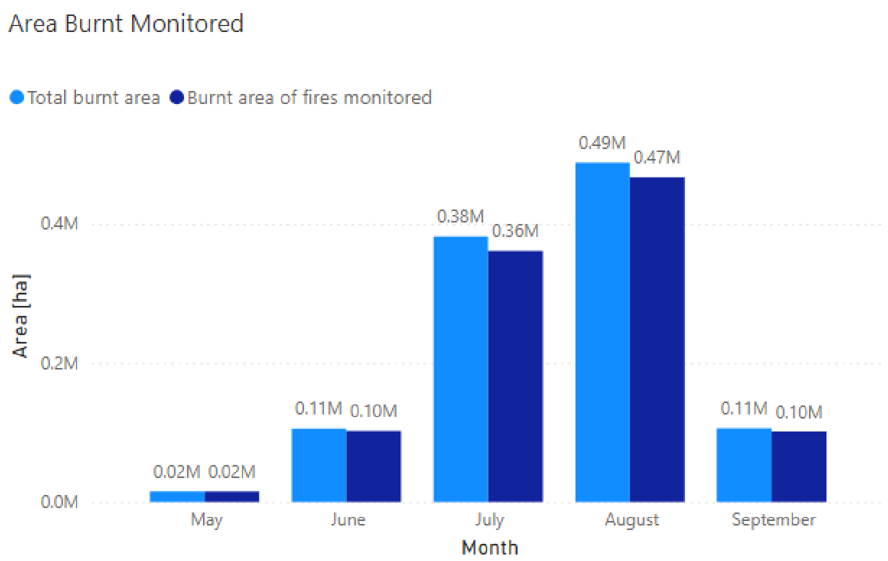


Figure 54 Area burnt monitored by HAPS (deployment of 6 hours)

This can be seen in Figure 55, where the percentages of monitored fires and area are represented against the totals. Here, it can be seen that, although the percentages of fires monitored vary from 91% to 67 %, the area monitored can be found between 99 % and 95 %.

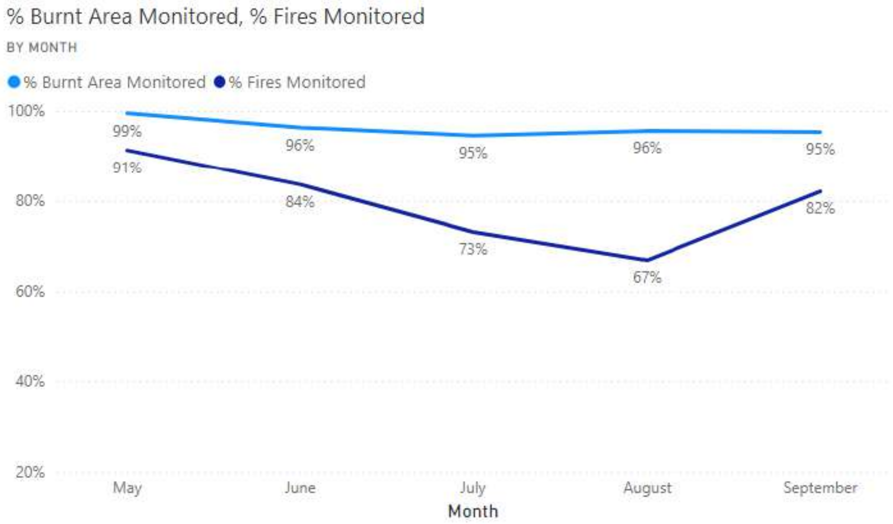


Figure 55 Percentage of fires and area burnt monitored by HAPS (deployment of 6 hours)

Looking into the average characteristics of the fires monitored and not monitored, Figure 56 and Figure 57 show their duration and area burnt per each month of the period. The timespan of the fires varies from 31 hours in May to 38 hours in July. The longest fires are found in the months of July and August, but the variation in duration is not so big with respect to the rest of the months. On the other hand, the average area burnt of the fires monitored experiences a great change in the months of July and August, with the average above the 400 ha.

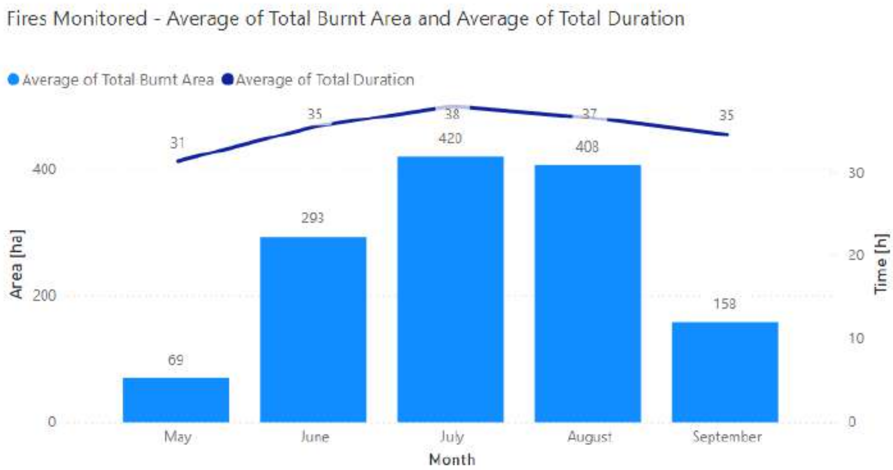


Figure 56 Average total burnt area and duration per fire monitored– (deployment of 6 hours)

Checking at the fires not monitored, their duration is a bit shorter, between 28-33 hours, and with an average area burnt between 4 and 65 ha. In comparison with the average of the fires monitored, these are significantly smaller in extension, but in the same order of magnitude with respect the timespan. This results also guarantee that the third check, the average area burnt not monitored less than 100 ha, is achieved.

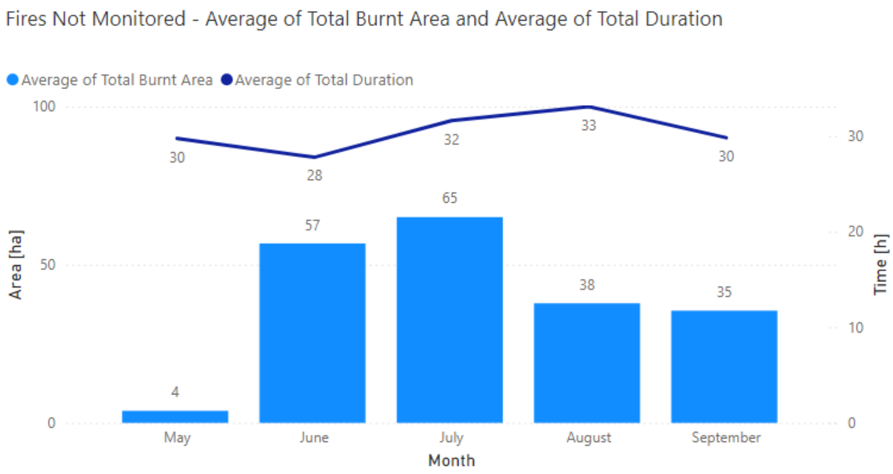


Figure 57 Average total burnt area and duration per fire not monitored (deployment of 6 hours)

Overall, the HAPS fleet of 10-10-14-14-12 proves to be monitoring the majority of the area. On top of this, the characterization of the fires shows that the big fires are monitored, and the ones that are not monitored are quite smaller in size.

Next, with the focus on the fires monitored, the average times spent on the different fire states defined are checked. Figure 58 shows these times per each of the months of the period. The arrival time can be confirmed to be less than 6 hours for the months of May, June and September. In July, this value is a bit above, 6.1 hours, and in August the fleet provides 6.0 hours of arrival time. With these times, the first night of the fires could be monitored by the HAPS, and from there, the monitoring time is between 21.7 and 25.7 hours, depending of the month. This means that the HAPS would be providing imagery continuously to the firefighters, improving the situational awareness on the initial hours of the fire, contributing to control the fire in the first 24 hours. The "time in alert" represent the time of the fire in which it is identified as eligible for a HAPS due to its potential, but it does not have yet any assigned. This time depends on the prioritization of the fires and the number of HAPS available for assignation. In a way, this time simulates the period between the start of the fires until the firefighting units request the support of a HAPS to monitor the fire. In the cases where a fire is identified as very important since the detection, this alert time could be reduced to almost zero.

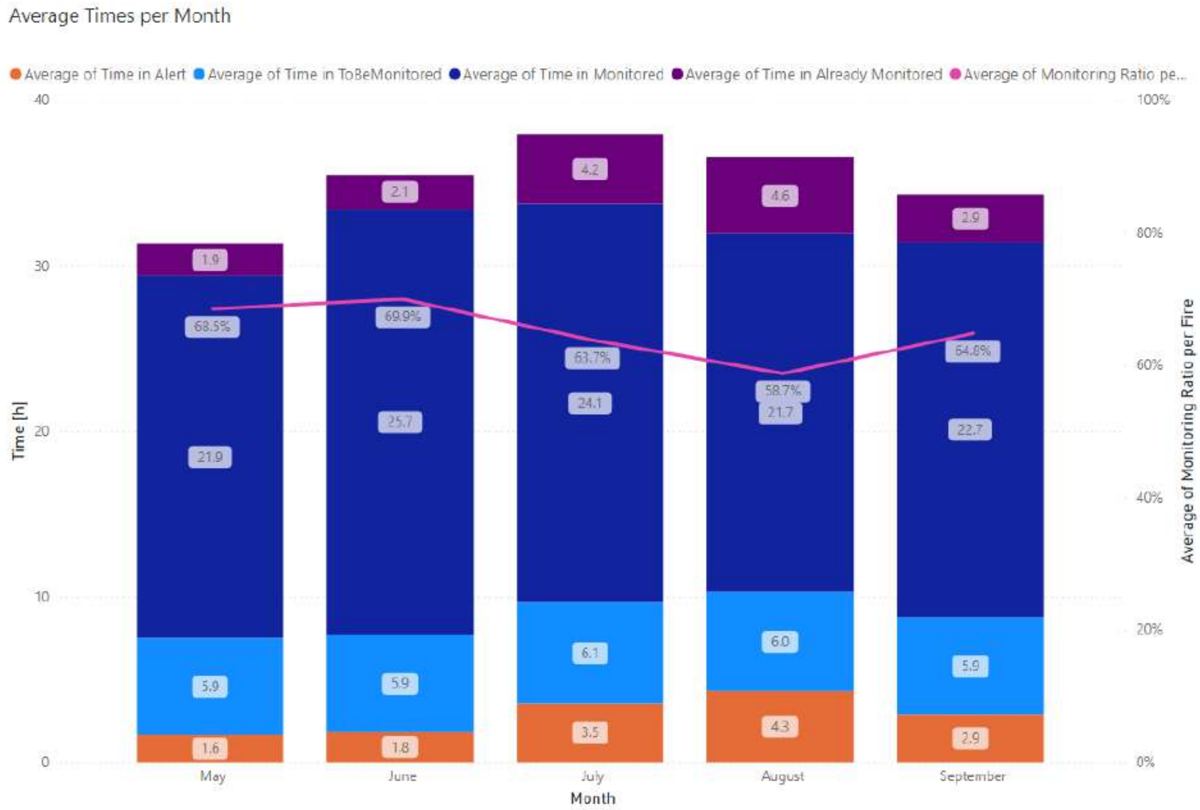


Figure 58 Average times of the fires monitored per month (deployment of 6 hours)

With these arrival times and based on the fire model defined in this document, it can be calculated what would be the area burnt at the moment of arrival of the HAPS to the fire. Figure 59 shows the average area burnt at arrival, and the total area burnt as average of the fires monitored, to provide a reference. The HAPS fleet recommended would arrive to the fires with less than 50 ha burnt for the worst case in July, with most of the area of the fire still to be burnt.

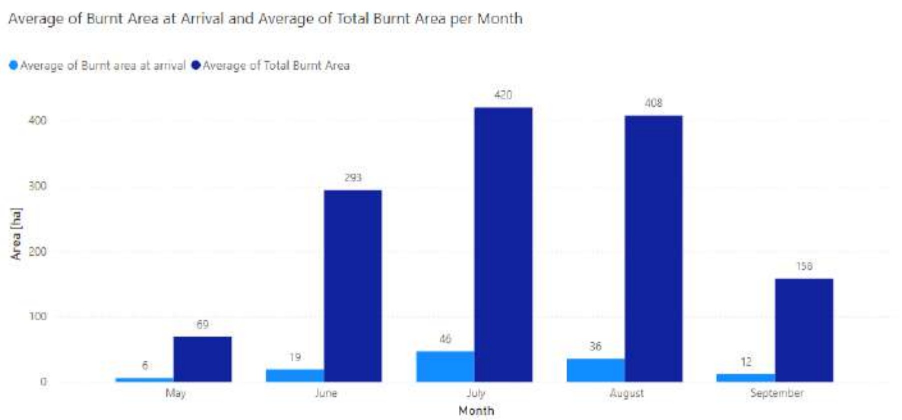


Figure 59 Average of burnt area at arrival of fires monitored (deployment of 6 hours)

From the perspective of the HAPS fleet, the results of the simulation allow to analyse the percentage of time dedicated to each task. Figure 60 shows the percentage of time of the HAPS fleet that provides the 6 hours of arrival time (10-10-14-14-12). The usage of the HAPS platforms monitoring fires ascends to almost 29 % of the time they are flying, that is close to one third of their time. In the absence of fires, the HAPS are commanded to the high-risk areas to work in detection mode, and this represents a 37.5 % of their time, that is the biggest part. A quarter of their time (i.e. 25.7 %) the HAPS are moving towards the high-risk areas of the day. The detection functionality helps also to pre-position the HAPS in the highest risk areas, and this can be one of the main factors of the lower time dedicated by the fleet into the displacement towards the fires, that represent 8.1 % of the time. On the other hand, the detection time, together with the time the HAPS are moving towards detection, represents a time that the HAPS could be assigned to other needs of the authorities providing observation services.

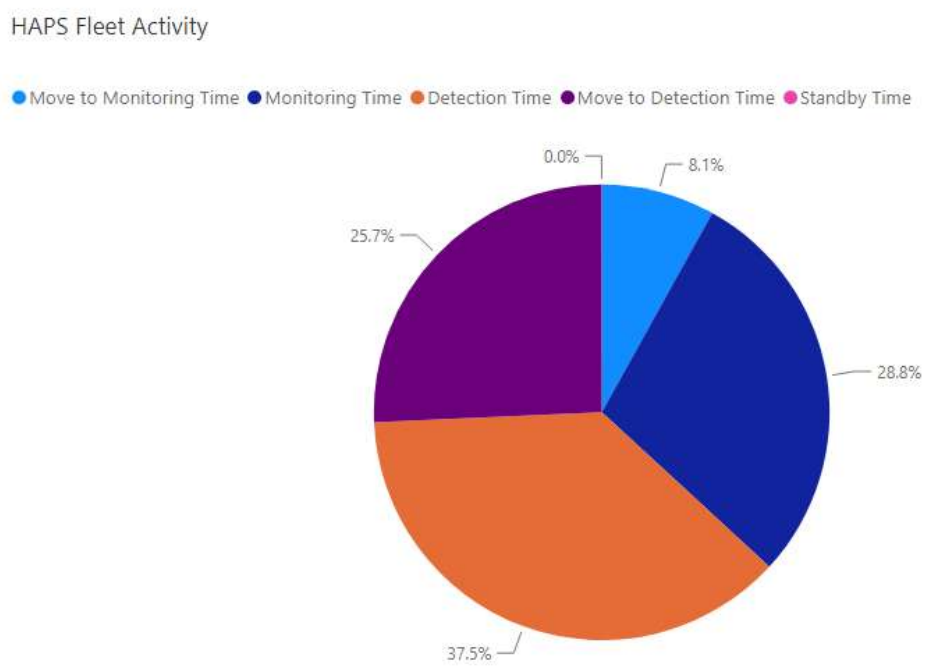


Figure 60 HAPS fleet activity

8.RESULTS LIVING LABS

In this section, the results of the simulations involving seven Living Labs from southern European countries are evaluated. The participating Living Labs are in Aquitania, Bulgaria, Catalonia, Galicia, Greece, Portugal and Sardinia. Each one of them is initially assigned a specific number of HAPS based on the surface area they are responsible for covering. Then, with the first results obtained, these initial fleet will be confirmed or updated based on the performance to meet the requirements established.

Table 18 illustrates the initial distribution of HAPS, which remains constant across the months and years of the simulation. This stable configuration serves as a baseline for assessing the effectiveness of HAPS deployment among the Living Labs.

Table 18 HAPS Fleet Configuration 1 for Living Labs simulation

Living Lab	Code	May	June	July	August	September
Aquitania	AQ	1	1	1	1	1
Bulgaria	BUL	1	1	1	1	1
Catalonia	CAT	1	1	1	1	1
Galicia	GAL	1	1	1	1	1
Greece	EL	3	3	3	3	3
Portugal	POR	3	3	3	3	3
Sardinia	IT	1	1	1	1	1

With the aim of facilitating the reading of the results, the main conclusions are explained here, and the detailed results per Living Lab are contained below in section Results Configuration 1.

The analysis of the results will follow the same structure than at European Level. In this case, due to the smaller extension of most Living Labs, the variation of the fleet size may not be needed. The three main criteria to check are:

- Burnt area of the fires monitored is ≥ 95 %.
- Arrival time is ≤ 6 hours.
- Average burnt area of fires not monitored is ≤ 100 ha.

The results of the configuration 1 shows that except for Galicia and Sardinia, each Living Lab achieves the objective of covering 95 % or more of the burnt area. Moreover, Aquitania and Catalonia meet this target across all the months with a unique HAPS platform. Nevertheless, Bulgaria, Greece and Portugal do not reach the 95 % threshold for burnt area monitored in September.

Focusing on the arrival time, the initial fleet performance does not exceed the 6 hours of arrival time average. Furthermore, the maximum recorded arrival time is 4 hours in September in Greece with a 3 HAPS fleet, as shown in Figure 77. Conversely, Figure 69 illustrates the minimum arrival time with a value of 34 minutes in September in Catalonia.

Regarding the average burnt area of the fires not monitored, Aquitania, Bulgaria and Portugal satisfy the requirement across all months. In Catalonia and Sardinia is observed that the burnt area exceeds the 100 ha threshold in only one month. In Galicia and Greece, the burnt area average surpasses 100 ha in multiple months.

Each Living Lab analysis is based on three main criteria. Firstly, the percentage of the burnt area covered must be equal to or greater than 95 % of the burnt area. Secondly, the arrival time must be 6 hours or less. Finally, the average burnt area of the fires that could not be monitored should not exceed 100 ha. Table 19 summarizes the results extracted from Figure 61 to Figure 87 according to these criteria.

Table 19 HAPS fleet configuration 1 analysis of performance in Living Labs

Living Lab	Code	95 % Area Monitored	6 hours arrival time	≤ 100 ha Average Not Monitored
Aquitania	AQ	**YES**	**YES**	**YES**
Bulgaria	BUL	**YES**	**YES**	**YES**
Catalonia	CAT	**YES**	**YES**	**NO (June)**
Galicia	GAL	**NO**	**YES**	**NO (July, Sep)**
Greece	EL	**YES**	**YES**	**NO (Jul, Aug, Sep)**
Portugal	POR	**YES**	**YES**	**YES**
Sardinia	IT	**NO**	**YES**	**NO (August)**

As it can be observed, from May to July Aquitania does not have any HAPS assigned. The reason is that Aquitania only experienced fires in August and September from 2018 to 2022, as observed in Figure 63. Table 19 indicates the achievement of the goals of a single HAPS fleet in Aquitania. Consequently, a unique HAPS covers effectively all the fires in Aquitania.

Figure 64, Figure 65 and Figure 67 show compliance with the established criteria in Bulgaria. This fleet achieves an average arrival time of 2 hours and 24 minutes, a monitored area percentage of 98.4 % and an average burnt area of 43 ha for the non-monitored fires. Therefore, one HAPS in Bulgaria could cover most fires and meet all the requirements effectively.

In Catalonia, the burnt area covered and arrival time are within the established limits, as indicated in Table 19. Moreover, Catalonia does not experience fires during May. On the other hand, looking at the unattended fires, the average burnt area exceeds 100 ha in June. Based on this, the HAPS deployment in Catalonia is delayed to June, with 2 HAPS units to cover the peak, and then it is reduced to just 1 HAPS from July onwards.

Focusing on Galicia, the average arrival time is 1 hour and 47 minutes. However, the initial fleet based on a single HAPS offers a monitored area percentage of 93.4 %, as shown in Figure 72. It is noted that in July and September the monitored area average decreases and the average burnt area of the unmonitored fires increases, as observed in Figure 75. In July and September, a single HAPS cannot cover most of the fires when Galicia experiences large fires in terms of area. To improve this performance, Galicia will have 2 HAPS more in July and September, as indicated in Table 20.

In Greece, Figure 76 and Figure 77 show a performance that achieves the area coverage and the target arrival time. The initial HAPS deployment in Greece provides as average 3 hours and 36 minutes of arrival time and 96.5 % of the area is covered. However, the average burnt area of the unmonitored fires exceeds the 100 ha threshold from July to September. Consequently, the HAPS deployment in Greece needs a reinforcement in those months. On the other hand, the achievement of the 3rd criteria in the months of May and June suggests that the fleet could be reduced at the beginning of the period. With this, the proposed deployment in Greece would be of 2 HAPS in May and June, with an increase of 2 more HAPS units from July to September, and an extra unit in August to cover the peaks of that month.

The initial HAPS deployment in Portugal consists of 3 HAPS per month. Its performance complies with all the established criteria since it provides 3 hours of average arrival time, 97 % of burnt area covered and 34 ha of average burnt area of the unmonitored fires. Consequently, it is considered that two HAPS during May, June and September could offer similar results. July and August remain with the initial HAPS deployment since the fires monitored are large in terms of area.

Except for August, in Sardinia the fleet of each month achieves the objective of covering 95 % or more of the burnt area, having an arrival time lower than 6 hours and not exceeding 100 ha of average burnt area of the unmonitored fires. However, in August only one of the three requirements is fulfilled. Consequently, the fleet of Sardinia needs a reinforcement of 1 HAPS in August.

The performance of the configuration 1 fleet on each Living Lab has served as a guide to enhance the HAPS fleet deployment into configuration 2. Table 20 contains this new configuration, and it indicates the variation of the HAPS deployment across all months with respect to configuration 1.

Table 20 HAPS fleet configuration 2 for Living Labs simulation

Living Lab	Code	May	June	July	August	September
Aquitania	AQ	↓0	↓0	↓0	1	1
Bulgaria	BUL	1	1	1	1	1
Catalonia	CAT	↓0	↑2	1	1	1
Galicia	GAL	1	1	↑3	1	↑3
Greece	EL	↓2	↓2	↑4	↑5	↑4
Portugal	POR	↓2	↓2	3	3	↓2
Sardinia	IT	1	1	1	↑2	1

With this analysis, the new configuration 2 has been used for a simulation of the period 2018-2022 in the same conditions than before. The detailed results of each of the Living Labs are contained in section Results Configuration 2. For the sake of simplicity, their analysis is done next.

In Aquitania, the deployment of 1 HAPS in the months of August and September guarantees the achievement of the performance for the monitoring service (Figure 88, Figure 89 and Figure 90).

For Bulgaria, the HAPS deployment remains the same as in configuration 1 due to the good performance provided. In any case, this second simulation serves to confirm the monitoring service indicators for the Living Lab, with a 98 % of the area monitored, an arrival time of less than 4 hours and an average burnt area of 43 ha for the unattended fires.

During the month of May there were no fires in Catalonia, and configuration 1 was not sufficient to cover the fires in June. With this second simulation, the reinforcement of 1 extra HAPS during the month of June assures the achievement of the criteria, leaving no fires without monitoring, and providing an arrival time of 2 hours or less.

In the case of Galicia, the reinforcement in the months of July and September with 2 HAPS more has elevated the percentage of area covered to more than 95 %. But on the other hand, it has proven to not be enough to reduce the average burnt area of the fires not monitored. With these results, Galicia would need an additional HAPS in these two months, reaching a fleet of 4 HAPS in July and September, and just 1 in the rest of the months, when there have been less fires in the period.

In Greece, the first two requirements were already met with configuration 1, but the area burnt unattended was significantly above the bar. With this simulation of the configuration 2, results show that the reinforcement stayed short in the months of July and September, where there are still fires of more than 100 ha of burnt area not monitored. With these results, an additional HAPS would be needed there, leaving the HAPS fleet deployment recommended in Greece from July to September in 5 HAPS units.

For Portugal, the HAPS fleet in configuration 1 provided a good performance, fulfilling the three criteria defined. In this case, the new configuration 2 intended to prove that the same KPIS could be achieved with 1 HAPS less in the months of May, June and September. After analysing the results of the new simulation, this refinement of the HAPS fleet deployment is confirmed with the same achievement of the requirements.

Lastly, the new configuration 2 of Sardinia, which has an extra HAPS unit deployed in the month of August, has confirmed the achievement of all three criteria. With this configuration, more than 97 % of the area burnt is monitored, with a minimal arrival time and an average burnt area unattended of less than 100 ha.

The summary of this analysis is collected in Table 21. The results of configuration 2 fulfil almost all requirements in all Living Labs. The exception is in Galicia and Greece, where the criteria of not having unattended fires of more than 100 ha burnt as average is not achieved in the months of July and September. Due to this, configuration 3 will be simulated, where the only difference with configuration 2 is a reinforcement in the number of HAPS deployed in July and September in Galicia and Greece. The monthly deployment of the fleet is shown in Table 22 below.

Table 21 HAPS Fleet Configuration 2 Analysis of Performance in Living Labs

Living Lab	Code	95 % Area Monitored	6 hours arrival time	≤ 100 ha Average Not Monitored
Aquitania	AQ	**YES**	**YES**	**YES**
Bulgaria	BUL	**YES**	**YES**	**YES**
Catalonia	CAT	**YES**	**YES**	**YES**
Galicia	GAL	**YES**	**YES**	**NO (July, Sep)**
Greece	EL	**YES**	**YES**	**NO (Jul, Sep)**
Portugal	POR	**YES**	**YES**	**YES**
Sardinia	IT	**YES**	**YES**	**YES**

Table 22 HAPS fleet configuration 3 for Living Labs simulation

Living Lab	Code	May	June	July	August	September
Aquitania	AQ	0	0	0	1	1
Bulgaria	BUL	1	1	1	1	1
Catalonia	CAT	0	2	1	1	1
Galicia	GAL	1	1	↑4	1	↑4
Greece	EL	2	2	↑5	5	↑5
Portugal	POR	2	2	3	3	2
Sardinia	IT	1	1	1	2	1

The results of the configuration 3 are analysed with the focus only on Galicia and Greece, where there have been some changes with respect to configuration 2. The diagrams of the results are contained in section 8.3.

The main goal of the extra HAPS added in July and September is to decrease the burnt area of the fires not monitored. Nevertheless, this reinforcement enhances the whole fleet performance in Galicia. The deployment of configuration 2 in this Living Lab already accomplishes two out of three of the identified requirements: covering more than 95% of the burnt area and not overpassing 6 hours of waiting time. During July and September, the previous fleet configuration results exceed the 100 ha requirement concerning the unattended fires. However, the new fleet configuration outcome illustrates that this requirement is fulfilled (Figure 117).

In Greece, the goal of the additional HAPS was the same as in Galicia. However, in this case, the extra HAPS did not provide the expected result, and the average area of the fires not monitored remained above 100 ha in the months of July and September (Figure 121). This result was not expected. With the increment of 1 HAPS, the forecast was to reduce the average unmonitored area. In consequence , these results were analysed in depth to understand this specific outcome. The output data showed that in July, in Greece, there are 4 unmonitored fires, out of which one has 1,167 ha burnt with a duration of 1 hour 40 min, another of 197 ha in 24 hours, and the other two quite small in area (23 and 3 ha). This indicates that, although the average unmonitored area is high, it is mostly caused by one big fire. Unfortunately, the monitoring of this fire is very complicated because it lasts around 1 hour and a half, and the HAPS do not have enough time to arrive after the alert. In September, something similar happened in Greece. There were 5 fires not monitored, out of which only one exceeds the 100 ha (508 ha), and makes that the average area also surpasses this limit. These three fires of more than 100 ha burnt in July and September had a HAPS assigned, but they did not arrive on time.

Table 23 shows the summary of performance of the configuration 3.

Table 23 HAPS Fleet Configuration 3 Analysis of Performance in Living Labs

Living Lab	Code	95 % Area Monitored	6 hours arrival time	≤ 100 ha Average Not Monitored
Aquitania	AQ	**YES**	**YES**	**YES**
Bulgaria	BUL	**YES**	**YES**	**YES**

Living Lab	Code	95 % Area Monitored	6 hours arrival time	≤ 100 ha Average Not Monitored
Catalonia	CAT	**YES**	**YES**	**YES**
Galicia	GAL	**YES**	**YES**	**YES**
Greece	EL	**YES**	**YES**	**NO (Jul, Sep)**
Portugal	POR	**YES**	**YES**	**YES**
Sardinia	IT	**YES**	**YES**	**YES**

Configuration 2 and 3 provide a good performance and fulfil almost all requirements defined. However, the deployment that follows is not realistic with the current concept of operations of the HAPS fleet, in the cases where the fleet is reduced for a month and increased in the next one. The fleet of HAPS for each regional location should be sized on the average demands, and not on the peaks, to avoid the oversizing of the fleet and the underuse out of these peaks. Instead, to cover the peaks, a hybrid solution with regional and Pan-European fleets could be a better approach. This means that the regional fleets are sized for the average demands, and a Pan-European fleet is dedicated to cover the peaks of the different regions in times of higher demands of monitoring. As the peaks do not happen all at once, the reinforcement fleet can be used in different regions when they are needed, maximizing their utilization. This mixed approach provides a more efficient usage of the resources, and can provide a similar service with less. With the aim of testing this solution, the configuration 4 (Table 24) tries to represent this hybrid approach, where there are HAPS assigned exclusively to the Living Labs, and there is a fleet at EU level, that can go to all Living Labs as a reinforcement. This configuration 4 also removes the steep changes in the fleet size for periods of just 1 month, making it more realistic. The sizing of the Living Labs fleet has been done based on previous results, and there are significant differences between Living Labs. In this sense, Greece and Portugal have bigger fleets due to their territory surface and the number of fires happening. The EU HAPS fleet has been defined to cover the peaks of the different Living Labs while providing a smooth deployment of HAPS in the regional and Pan-European level.

Table 24 HAPS Fleet Configuration 4 for Living Labs simulation – mixed approach

Living Lab	Code	May	June	July	August	September
Aquitania	AQ	0	0	0	1	1
Bulgaria	BUL	1	1	1	1	1
Catalonia	CAT	0	1	1	1	1
Galicia	GAL	1	1	1	1	1
Greece	EL	2	2	4	4	4
Portugal	POR	2	2	3	3	2
Sardinia	IT	1	1	1	1	1
EU	EU	0	1	2	2	2

The assignation for monitoring of the EU HAPS will be done, as for the rest, based on the higher priorities, guaranteeing that they will be assigned to the most prioritized peaks of the Living Labs. In this sense, it is relevant to clarify that this EU fleet will only be monitoring the fires that take place in the areas of the Living Labs, leaving the rest of the

EU inside the AoS without monitoring. One concern about this approach would be that this EU HAPS fleet should be covering fires in all the territory, not only on the Living Labs. While this is true, the sizing of the EU HAPS fleet has been done based on the demands of the Living Labs only, and the aim of this study is to check their impact on the Living Labs regional level. If the fleet was to be covering the UE territory, the sizing of the fleet would be bigger (due to the higher demand), and the results of that study would be different. In summary, the HAPS fleet has been sized only for the Living Labs peaks, and in consequence will be only targeted to those areas.

The results of the simulation with configuration 4 are contained in section 8.4. In general terms, this hybrid approach offers similar performance than configuration 3, with a smaller number of HAPS deployed during the season, thanks to an improved allocation of resources. In contrast, some requirements are not fulfilled in specific cases.

As with previous simulations, the average area of the fires not monitored is above 100 ha in Greece during the months of July and September. The rationale behind this has been explained above. Another trade-off happens in Galicia, where this average area in July is of 111 ha, a bit above the filter.

In Sardinia, the average area monitored is reduced to 94 %, and the average area of the fires unattended rocketed to 774 ha. In this Living Lab, both indicators failed due to the same cause. In August, there are two fires not monitored: one with 101 ha that lasted 13.68 hours, and another of 1447 ha that lasted 1 hour. This second fire burnt a great amount of surface in just 1 hour. The HAPS allocated to Sardinia was assigned to monitor it, but it did not arrive on time.

With respect to the average time of arrival of the HAPS, in Bulgaria the time is increased with respect to configuration 3 and surpasses the 6 hours in July. At first, this seems counterintuitive because in Bulgaria the number of HAPS was maintained as in previous configurations, and this did not happen before. With Configuration 4, there were additional HAPS to cover the peaks. The rationale of this outcome is that the increase in time of arrival is caused because the EU fleet HAPS take longer than the regional HAPS to arrive, augmenting the average times. On the other hand, the number of fires monitored is increased.

Although the results of Configuration 2 or 3 were slightly better than with Configuration 4, the latter ones are more realistic. The sizing of configuration 2 and 3 was driven on the demand of the monitoring, without considering a realistic deployment of the fleet. Instead, configuration 4 proposes a realistic approach in line with the current concept of operations of the HAPS fleet, and provides a good performance of the monitoring service. Because of this, the recommended fleet for the Living Labs scenario is this mixed approach of fleet at regional and European level.

The results performance against the requirements defined are summarized in Table 25.

Table 25 HAPS Fleet Configuration 4 Analysis of Performance in Living Labs

Living Lab	Code	95 % Area Monitored	6 hours arrival time	≤ 100 ha Average Not Monitored
Aquitania	AQ	**YES**	**YES**	**YES**
Bulgaria	BUL	**YES**	**NO (Jul)**	**YES**
Catalonia	CAT	**YES**	**YES**	**YES**
Galicia	GAL	**YES**	**YES**	**NO (Jul)**
Greece	EL	**YES**	**YES**	**NO (Jul, Sep)**
Portugal	POR	**YES**	**YES**	**YES**
Sardinia	IT	**NO (94 %)**	**YES**	**NO (Aug)**

8.1. Results Configuration 1

8.1.1. Aquitania – Configuration 1

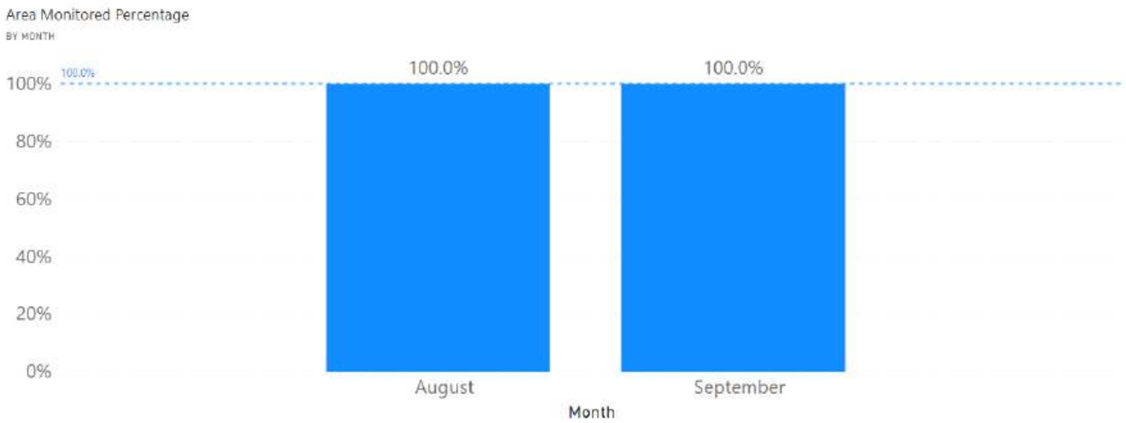


Figure 61 Percentage of area burnt monitored– Aquitania, conf 1

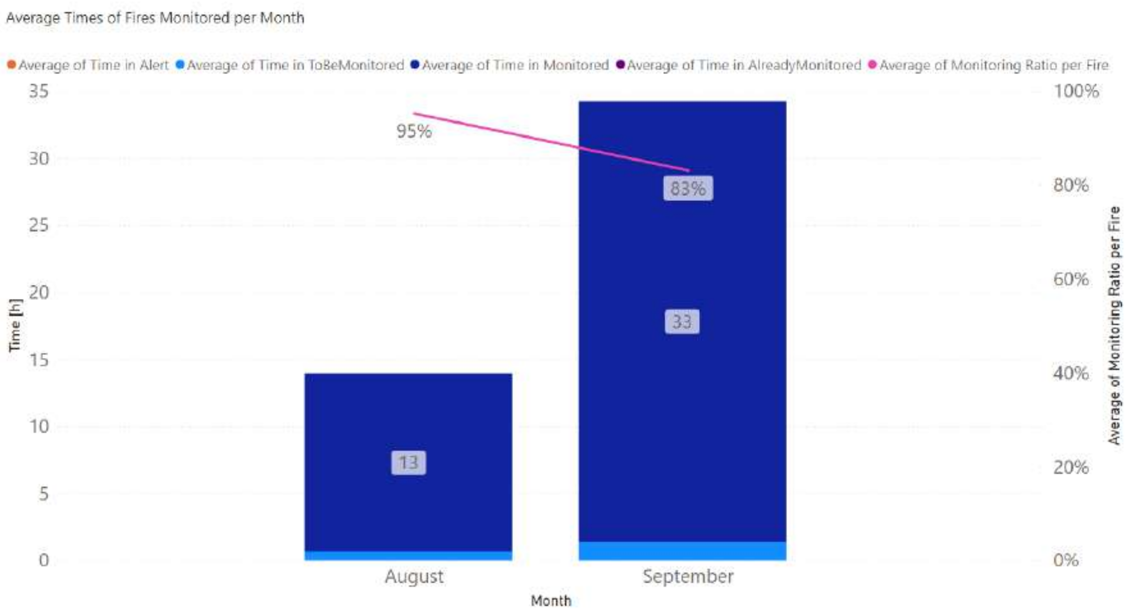


Figure 62 Average times of the fires monitored per month – Aquitania, conf 1

Figure 63 Average total burnt area and duration per fire monitored - Aquitania, conf 1

8.1.2. Bulgaria – Configuration 1

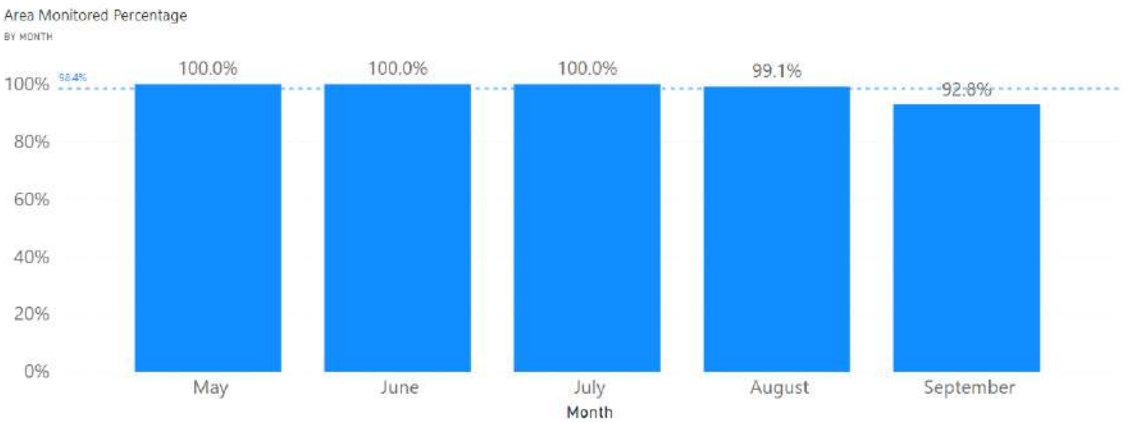


Figure 64 Percentage of area burnt monitored– Bulgaria, conf 1

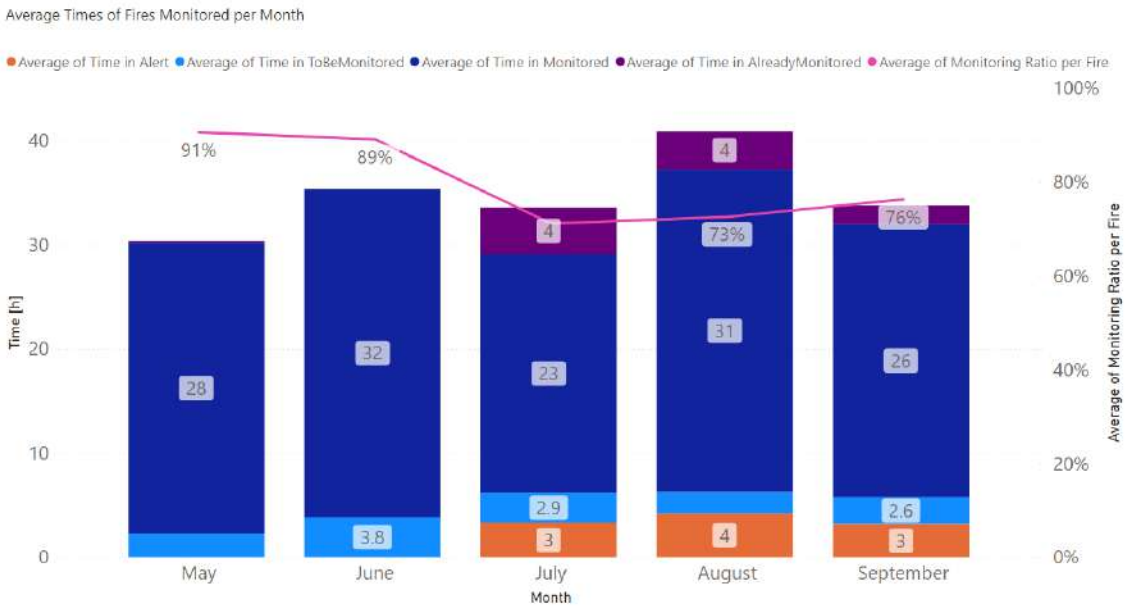


Figure 65 Average times of the fires monitored per month – Bulgaria, conf 1

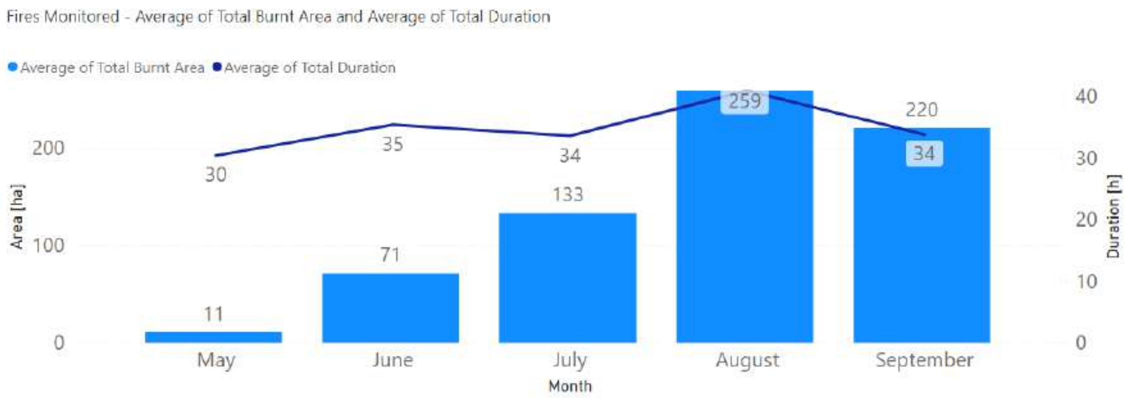


Figure 66 Average total burnt area and duration per fire monitored - Bulgaria, conf 1

Figure 67 Average total burnt area and duration per fire not monitored – Bulgaria, conf 1

8.1.3. Catalonia – Configuration 1

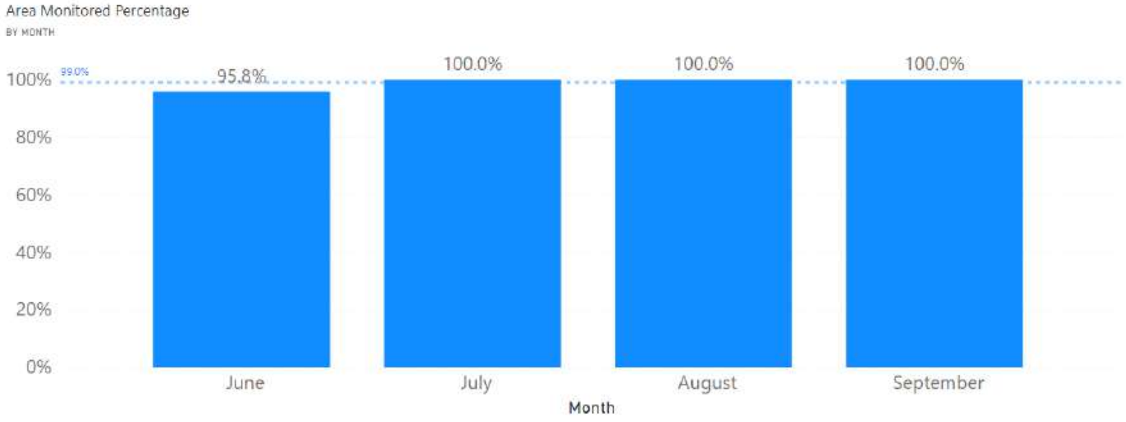


Figure 68 Percentage of area burnt monitored– Catalonia, conf 1

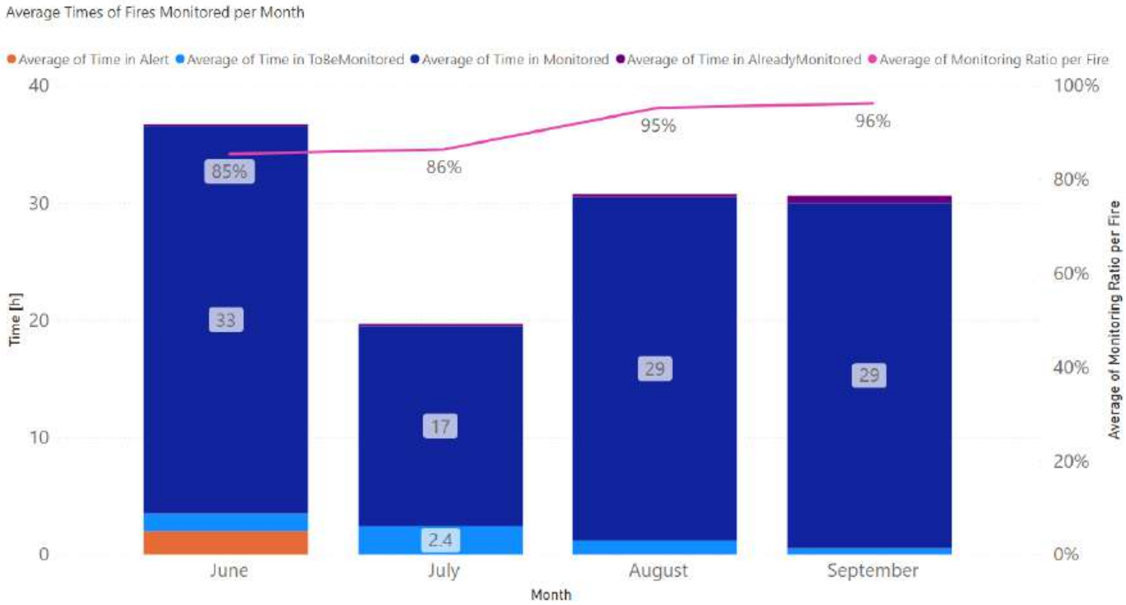


Figure 69 Average times of the fires monitored per month – Catalonia, conf 1

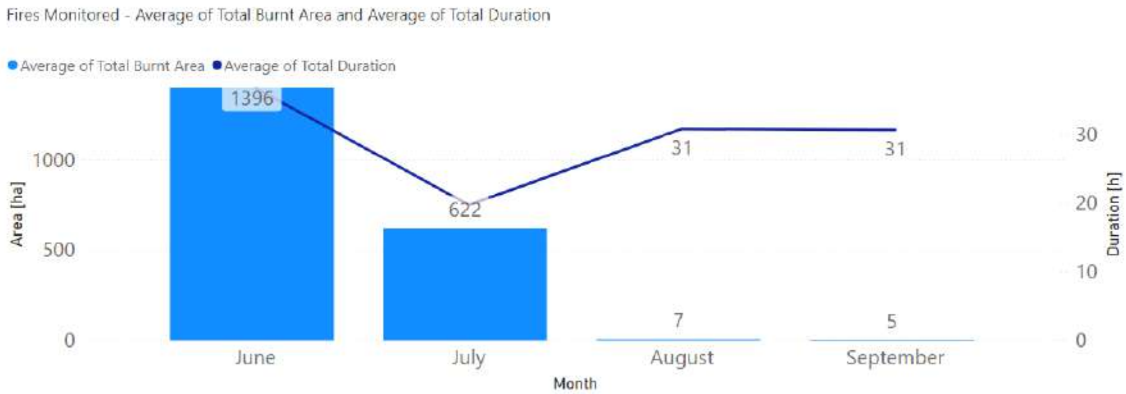


Figure 70 Average total burnt area and duration per fire monitored - Catalonia, conf 1

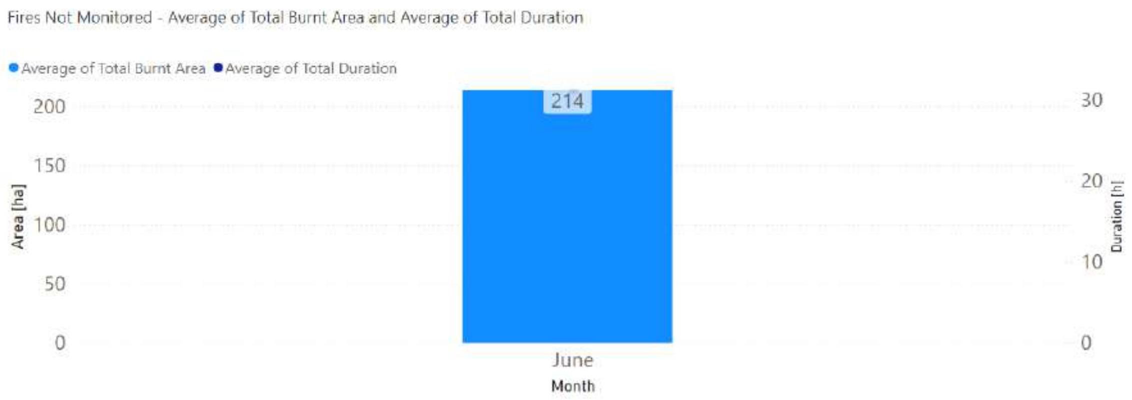


Figure 71 Average total burnt area and duration per fire not monitored – Catalonia, conf 1

8.1.4. Galicia – Configuration 1

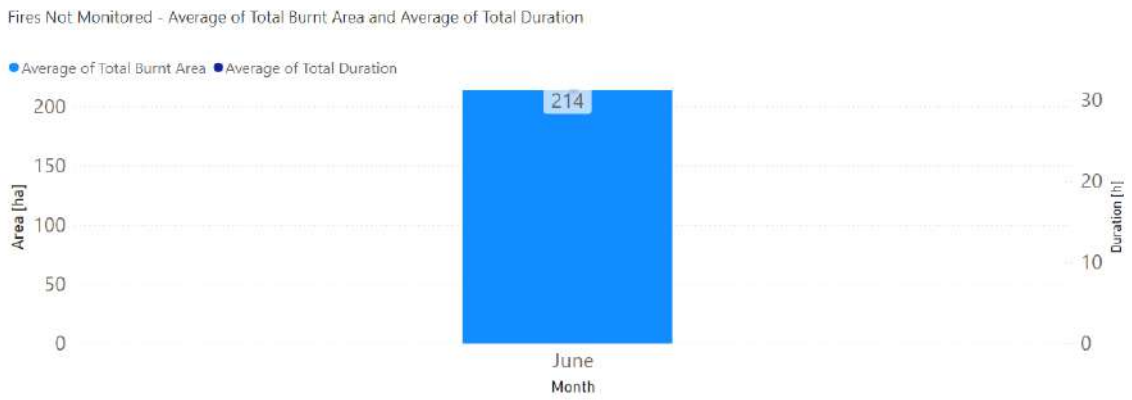


Figure 72 Percentage of area burnt monitored– Galicia, conf 1

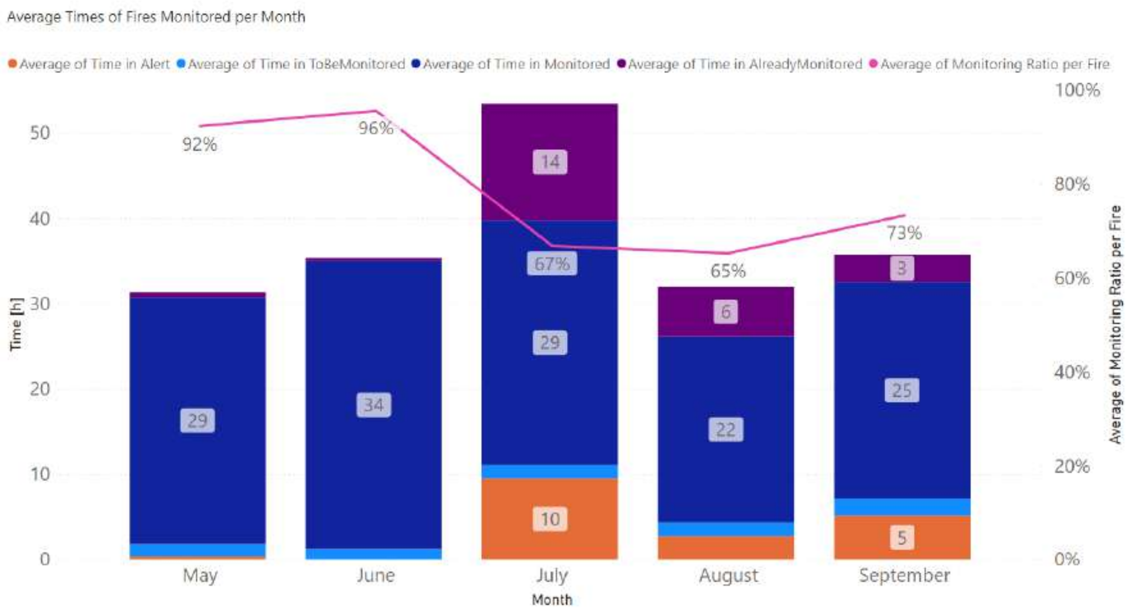


Figure 73 Average times of the fires monitored per month – Galicia, conf 1

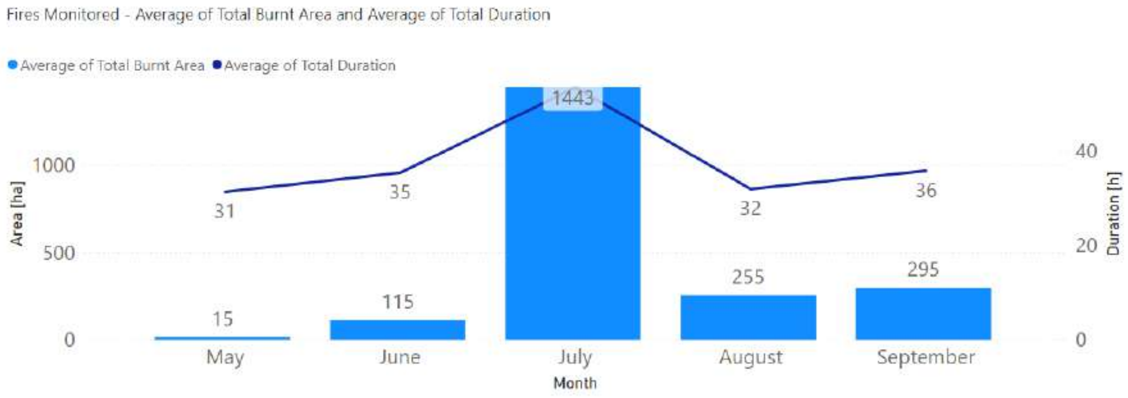


Figure 74 Average total burnt area and duration per fire monitored - Galicia, conf 1

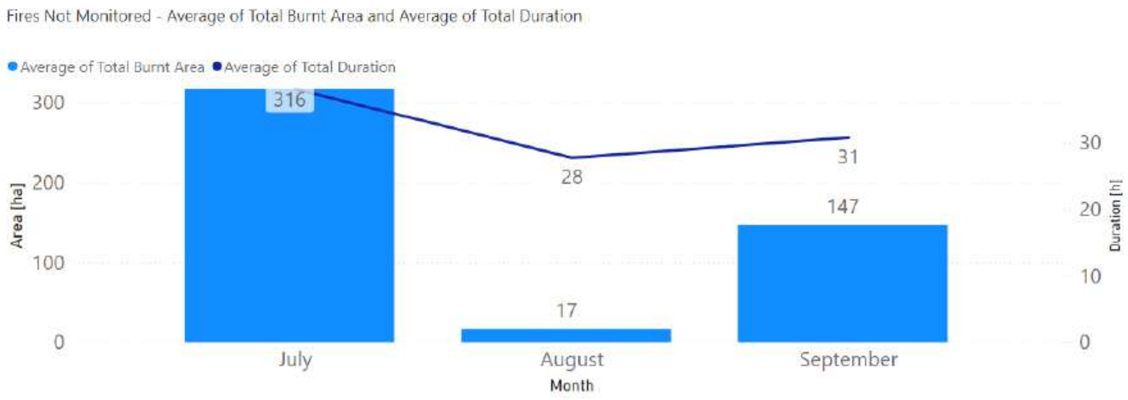


Figure 75 Average total burnt area and duration per fire not monitored – Galicia, conf 1

8.1.5. Greece – Configuration 1

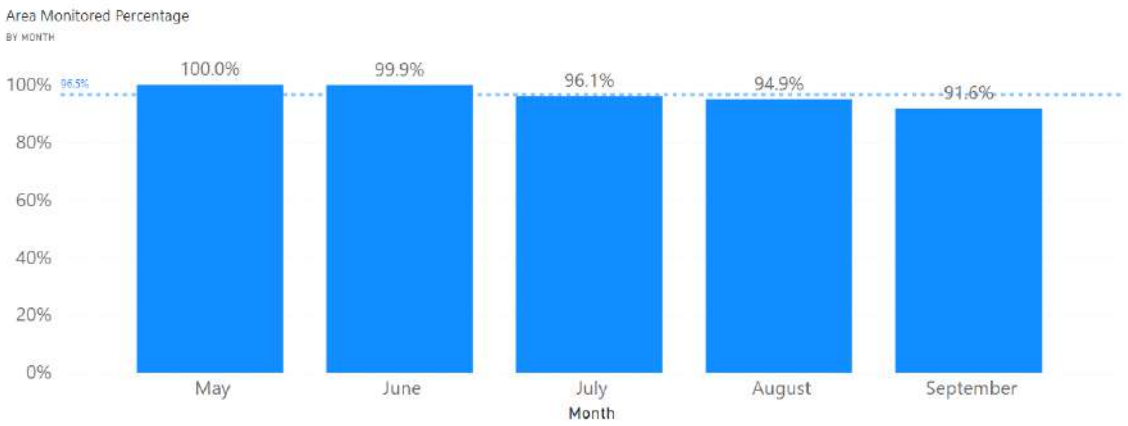


Figure 76 Percentage of area burnt monitored– Greece, conf 1

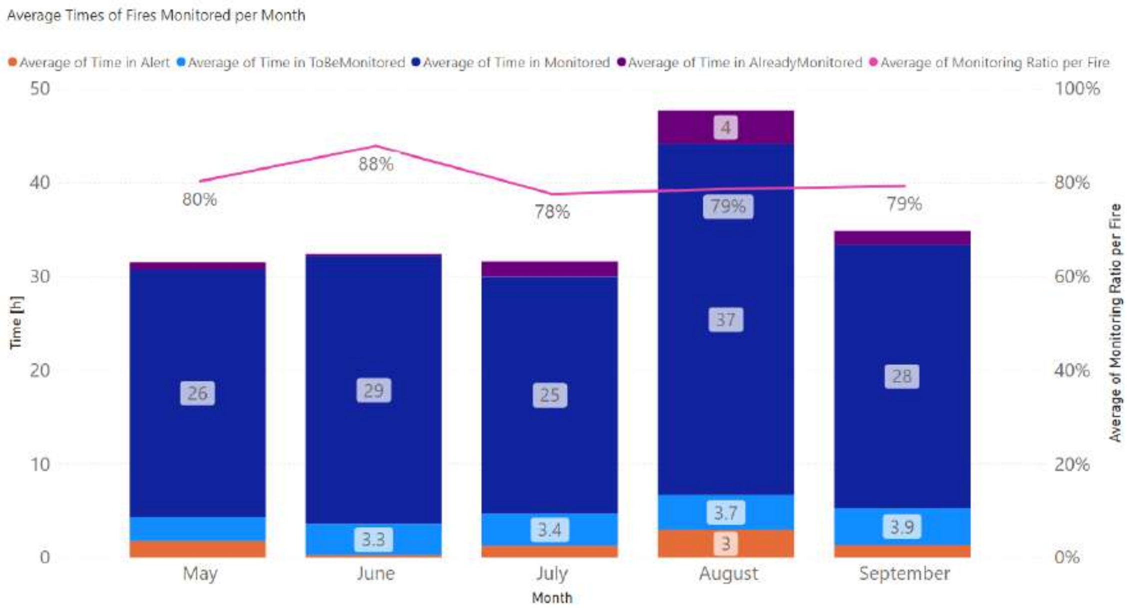


Figure 77 Average times of the fires monitored per month – Greece, conf 1

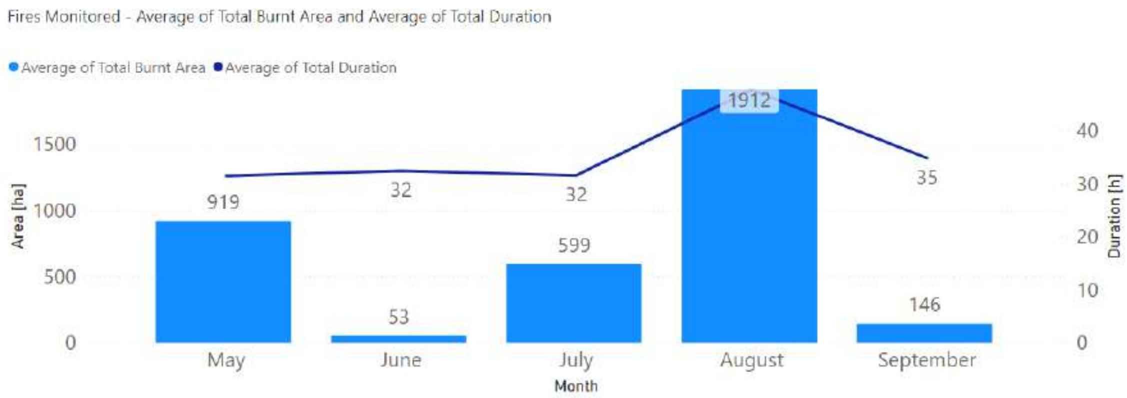


Figure 78 Average total burnt area and duration per fire monitored - Greece, conf 1

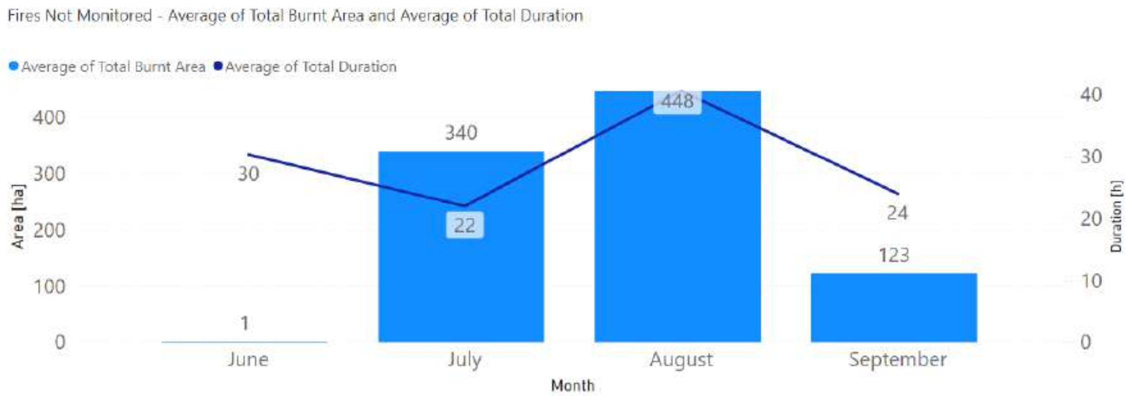


Figure 79 Average total burnt area and duration per fire not monitored – Greece, conf 1

8.1.6. Portugal – Configuration 1

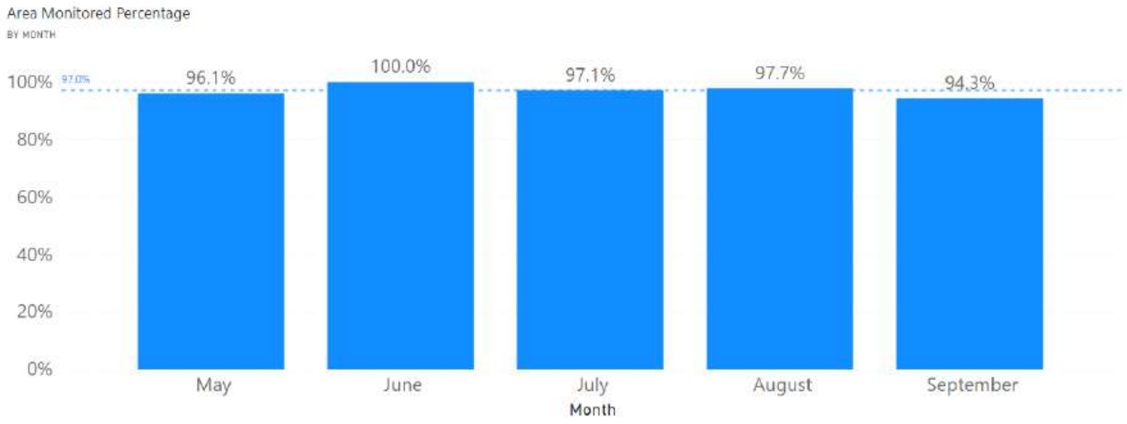


Figure 80 Percentage of area burnt monitored– Portugal, conf 1

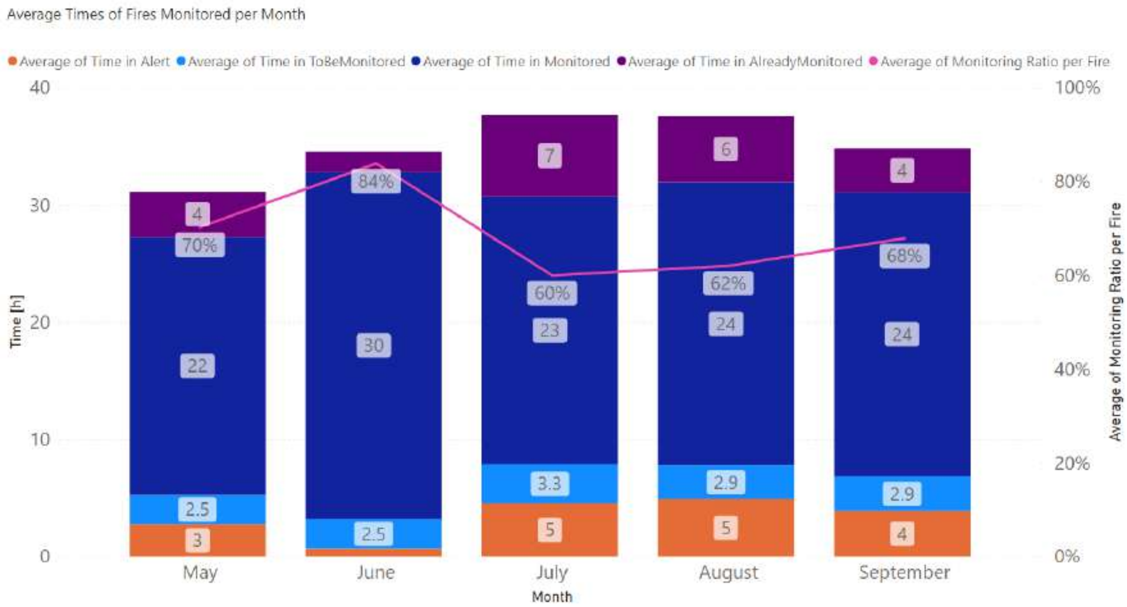


Figure 81 Average times of the fires monitored per month – Portugal, conf 1

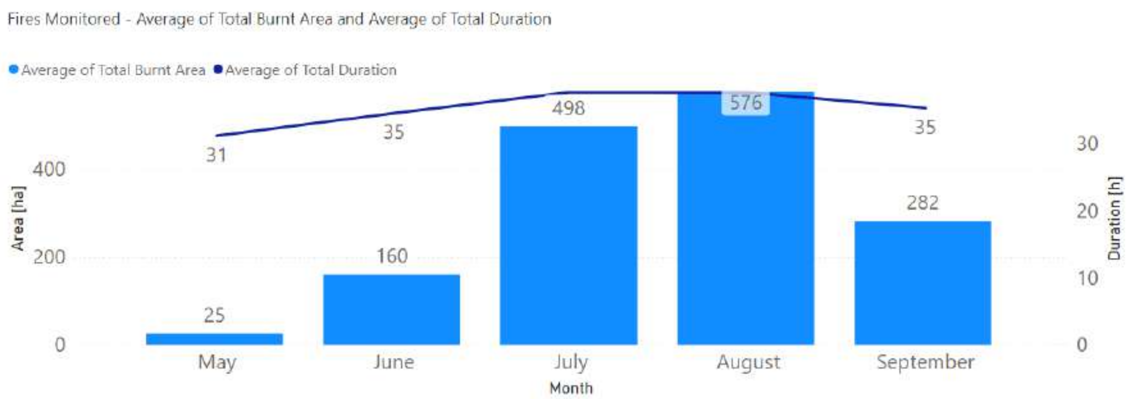


Figure 82 Average total burnt area and duration per fire monitored - Portugal, conf 1

Figure 83 Average total burnt area and duration per fire not monitored – Portugal, conf 1

8.1.7. Sardinia – Configuration 1

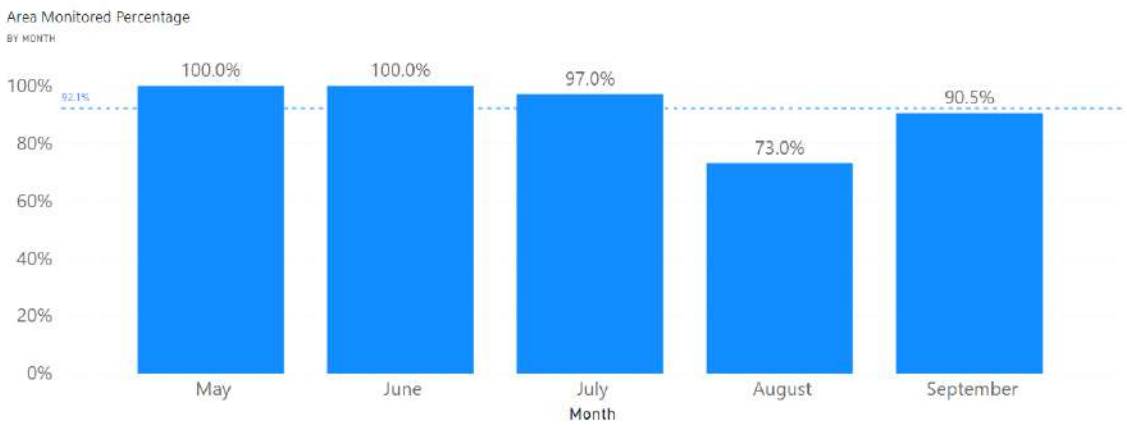


Figure 84 Percentage of area burnt monitored– Sardinia, conf 1

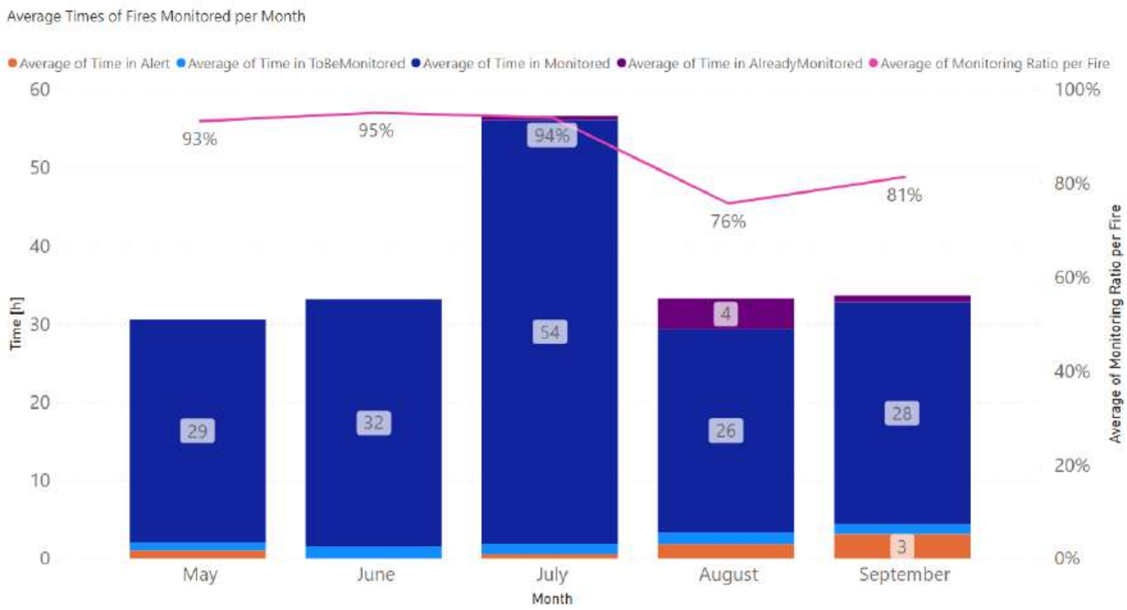


Figure 85 Average times of the fires monitored per month – Sardinia, conf 1

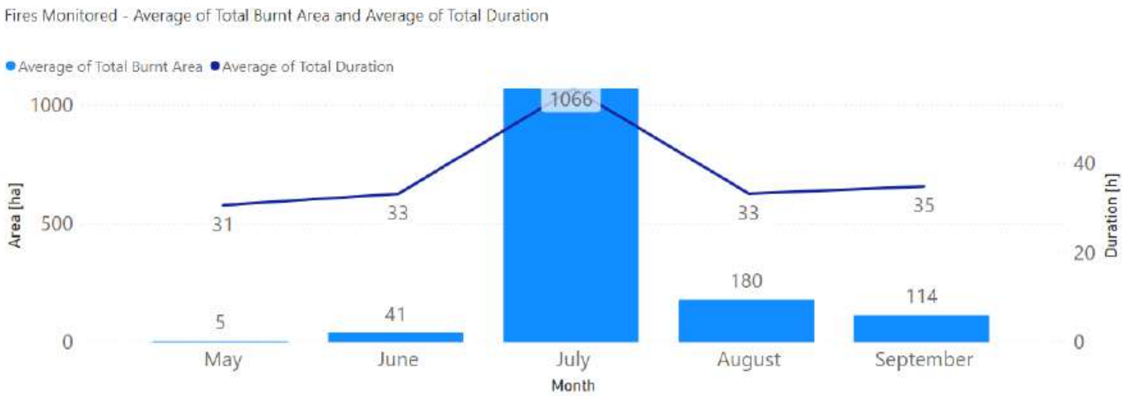


Figure 86 Average total burnt area and duration per fire monitored - Sardinia, conf 1

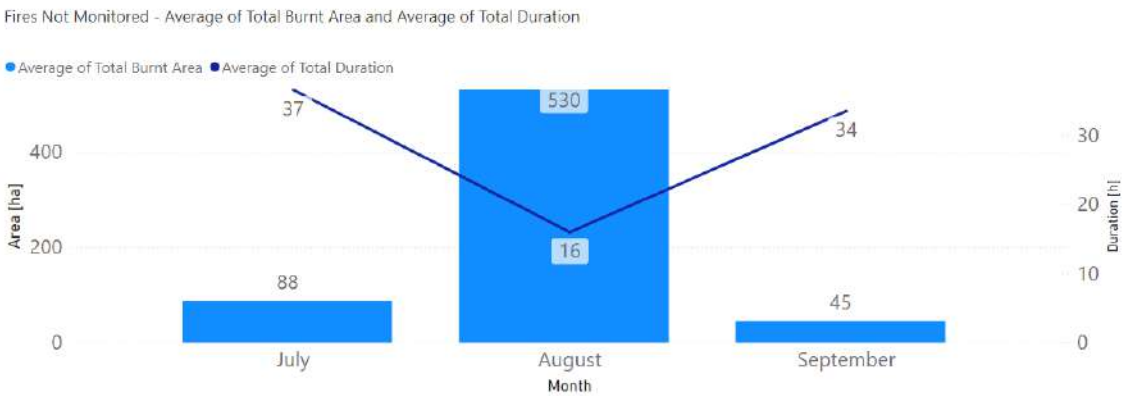


Figure 87 Average total burnt area and duration per fire not monitored – Sardinia, conf 1

8.2. Results Configuration 2

8.2.1. Aquitania – Configuration 2

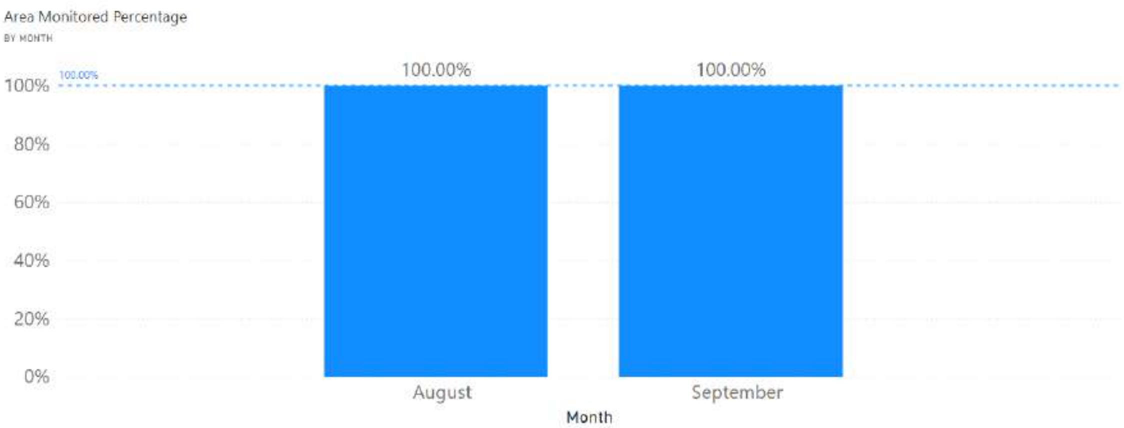


Figure 88 Percentage of area burnt monitored– Aquitania, conf 2

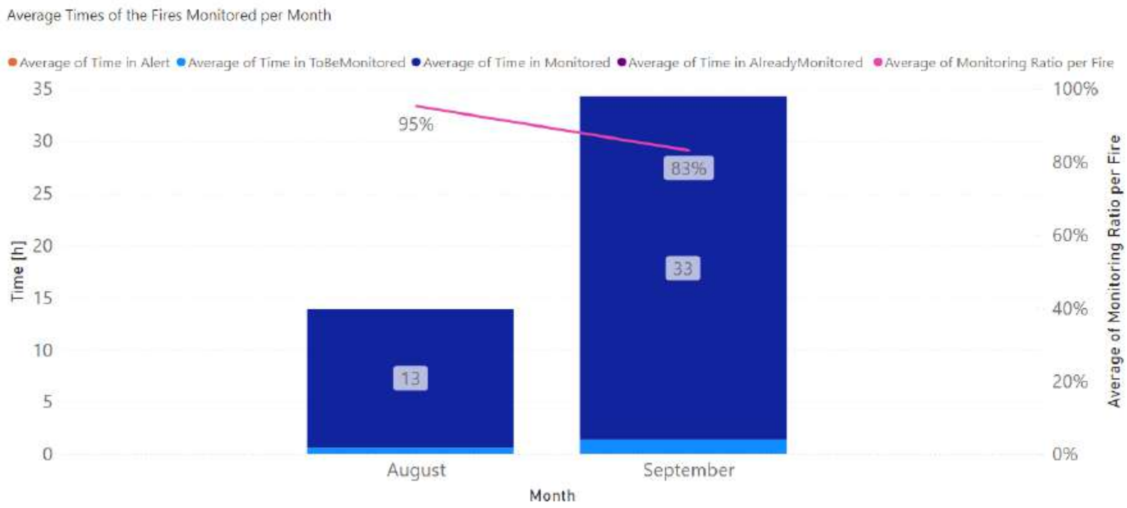


Figure 89 Average times of the fires monitored per month – Aquitania, conf 2

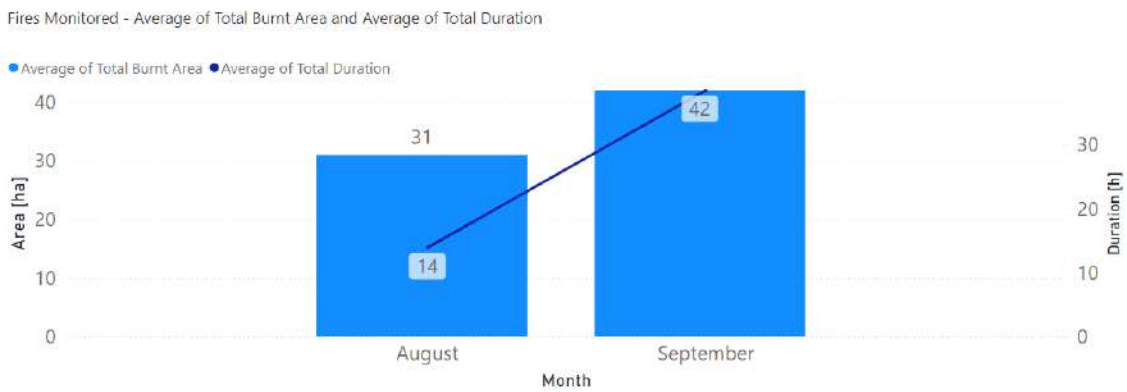


Figure 90 Average total burnt area and duration per fire monitored - Aquitania, conf 2

8.2.2. Bulgaria – Configuration 2

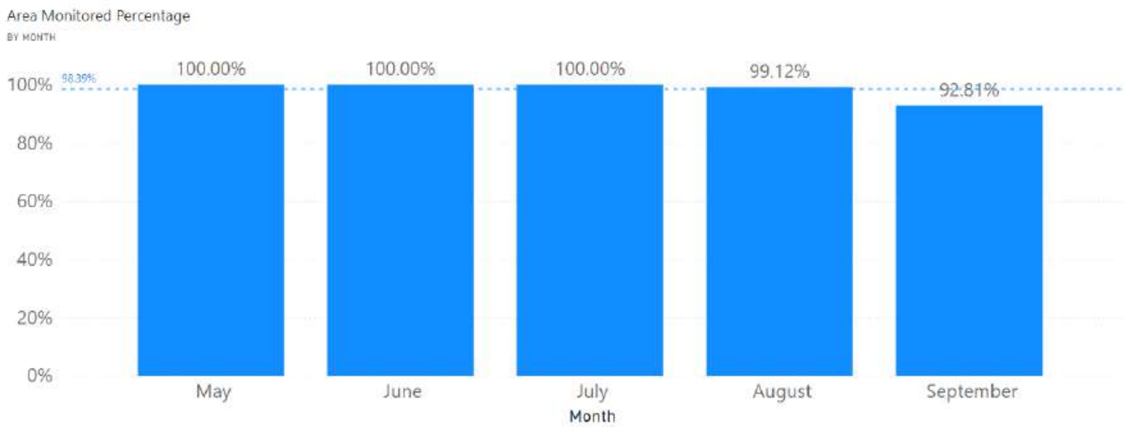


Figure 91 Percentage of area burnt monitored– Bulgaria, conf 2

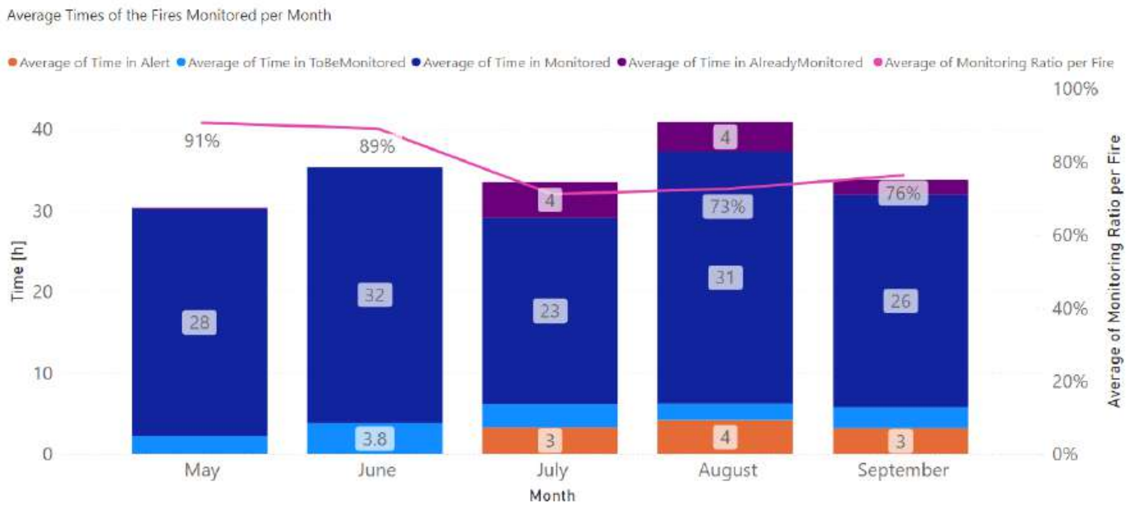


Figure 92 Average times of the fires monitored per month – Bulgaria, conf 2

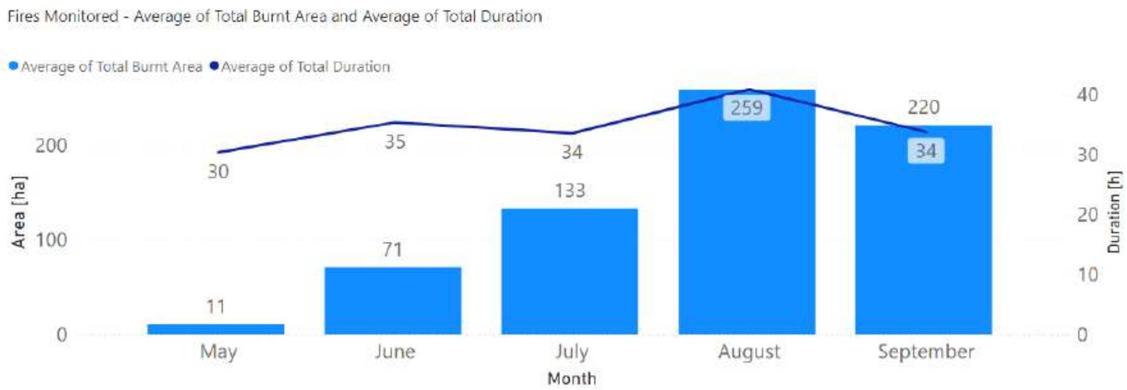


Figure 93 Average total burnt area and duration per fire monitored - Bulgaria, conf 2

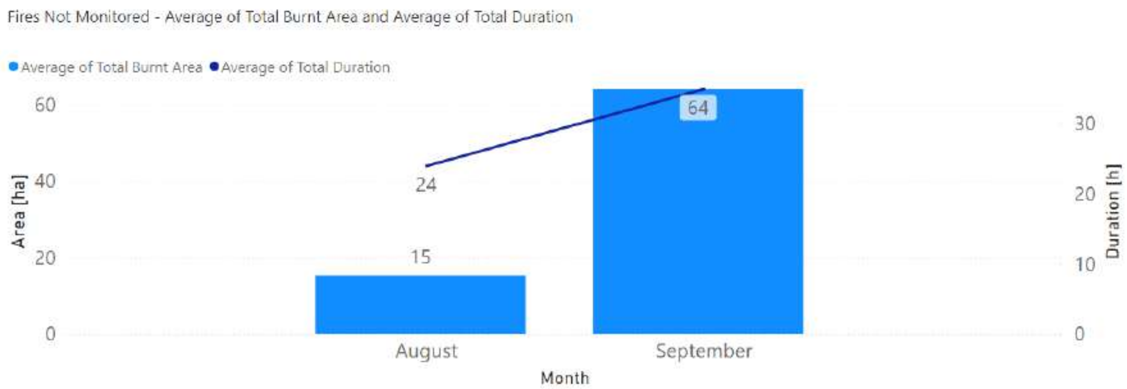


Figure 94 Average total burnt area and duration per fire not monitored – Bulgaria, conf 2

8.2.3. Catalonia – Configuration 2

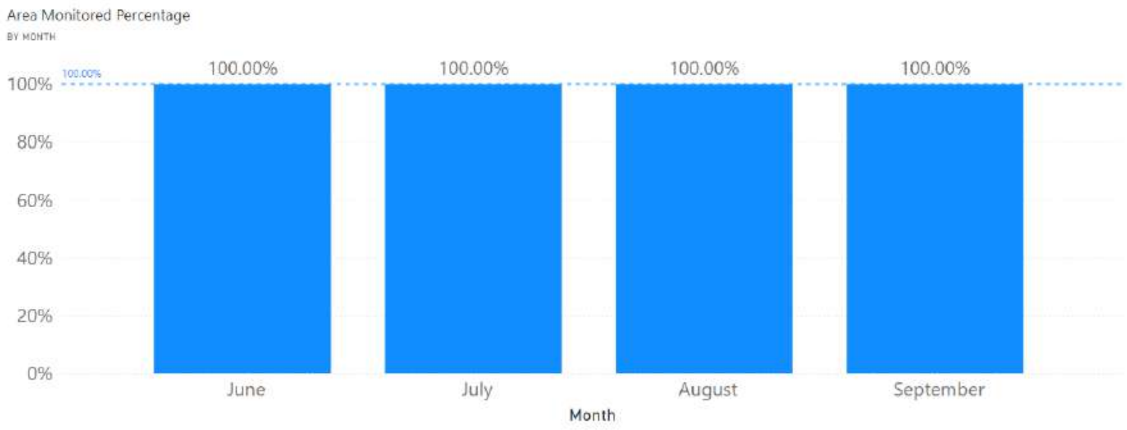


Figure 95 Percentage of area burnt monitored– Catalonia, conf 2

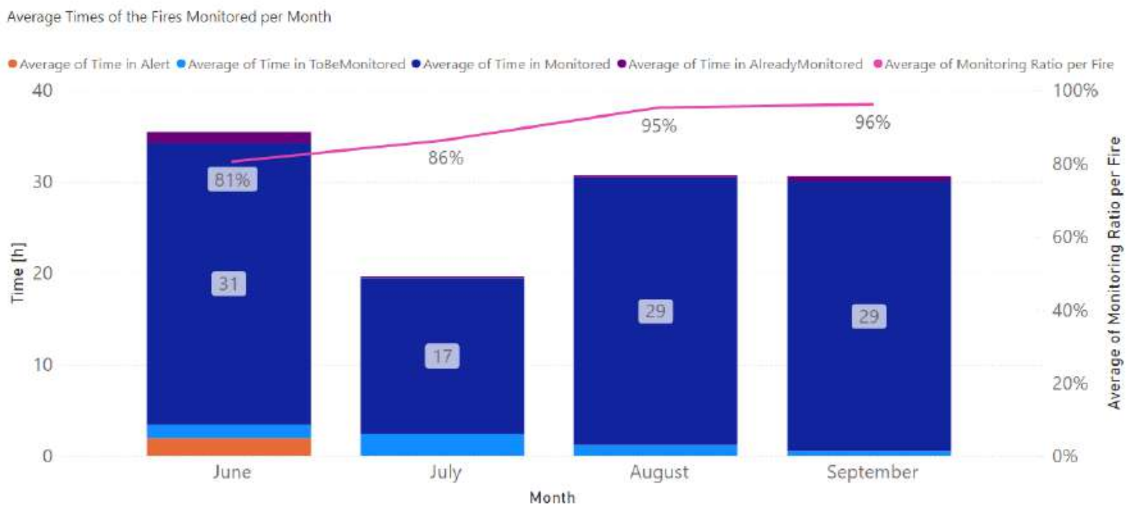


Figure 96 Average times of the fires monitored per month – Catalonia, conf 2

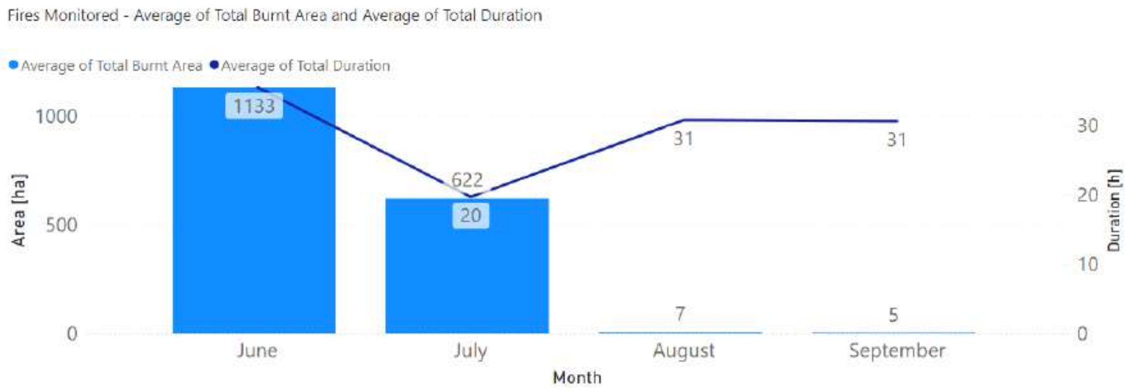


Figure 97 Average total burnt area and duration per fire monitored - Catalonia, conf 2

8.2.4. Galicia – Configuration 2

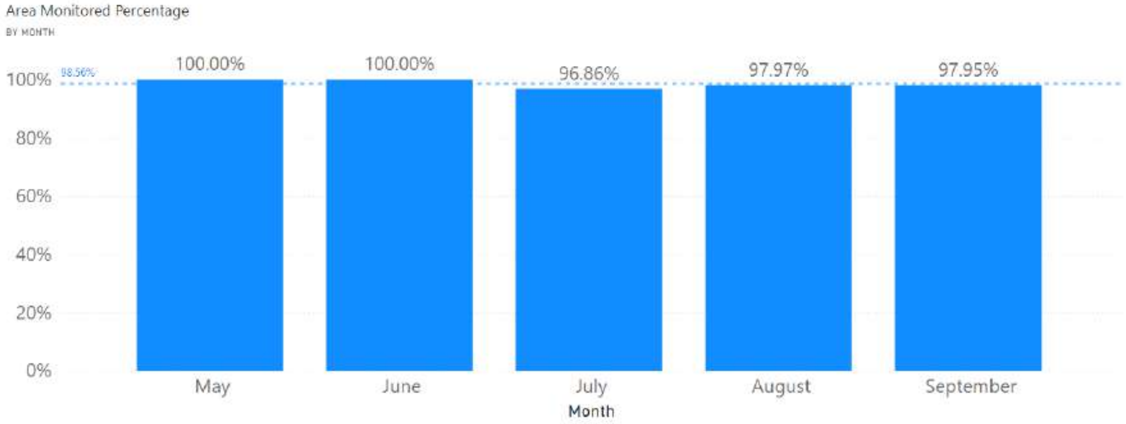


Figure 98 Percentage of area burnt monitored– Galicia, conf 2

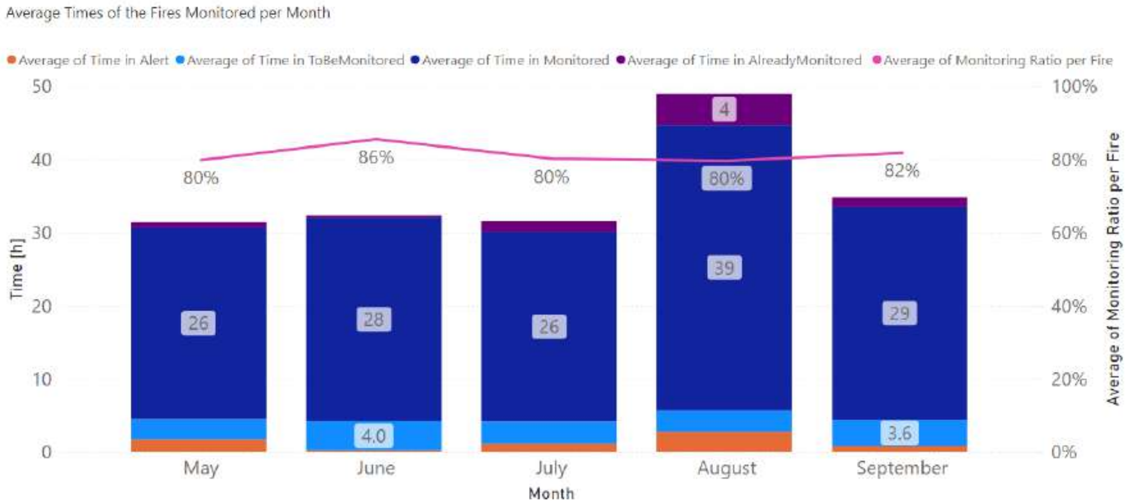


Figure 99 Average times of the fires monitored per month – Galicia, conf 2

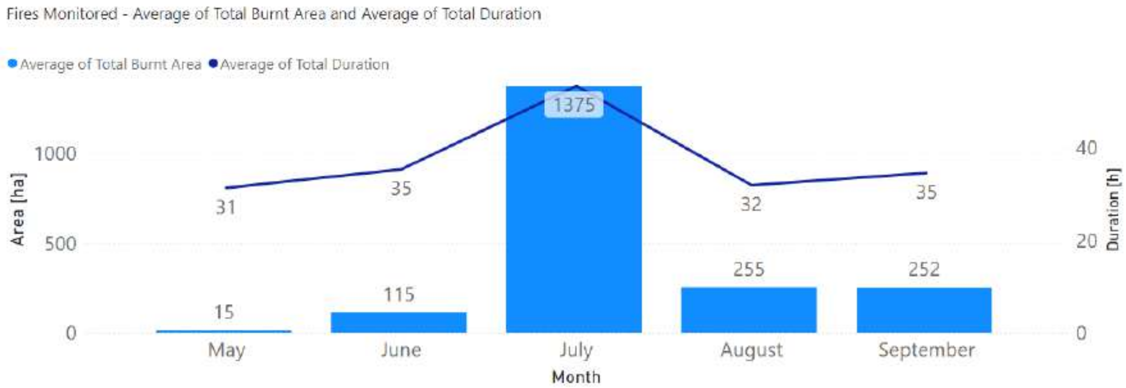


Figure 100 Average total burnt area and duration per fire monitored - Galicia, conf 2

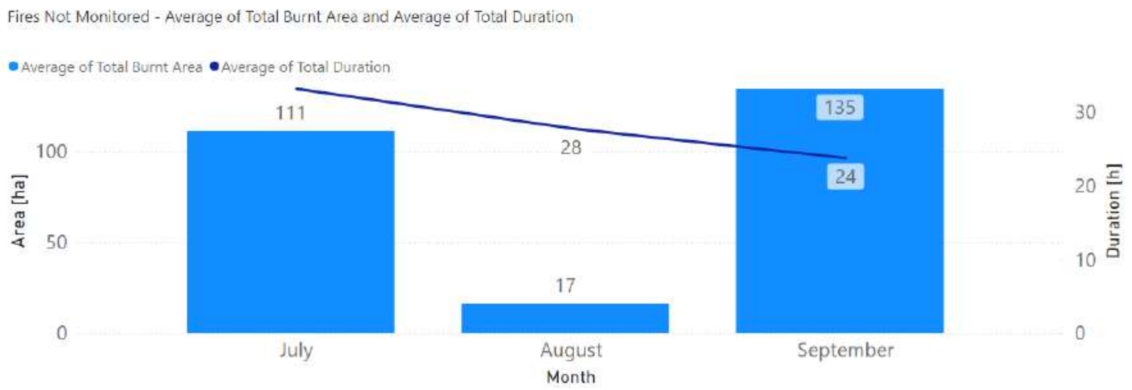


Figure 101 Average total burnt area and duration per fire not monitored – Galicia, conf 2

8.2.5. Greece – Configuration 2

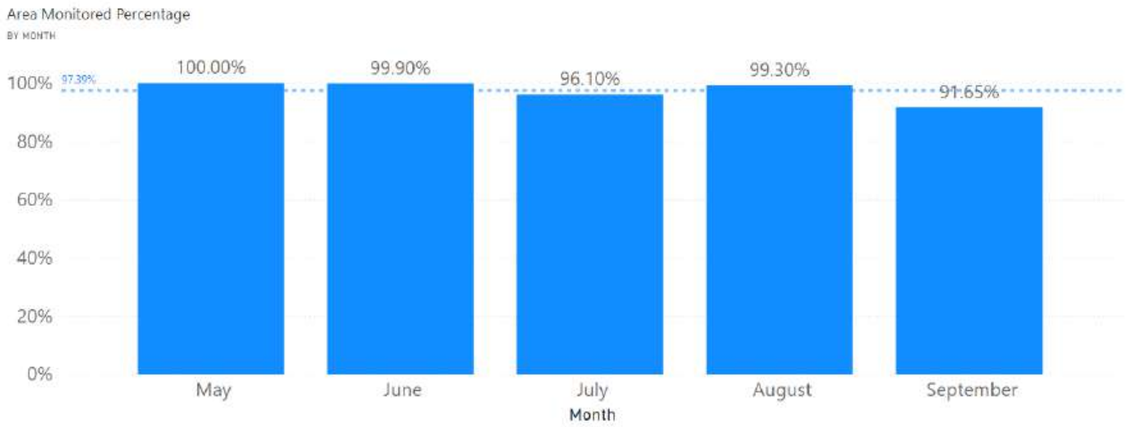


Figure 102 Percentage of area burnt monitored– Greece, conf 2

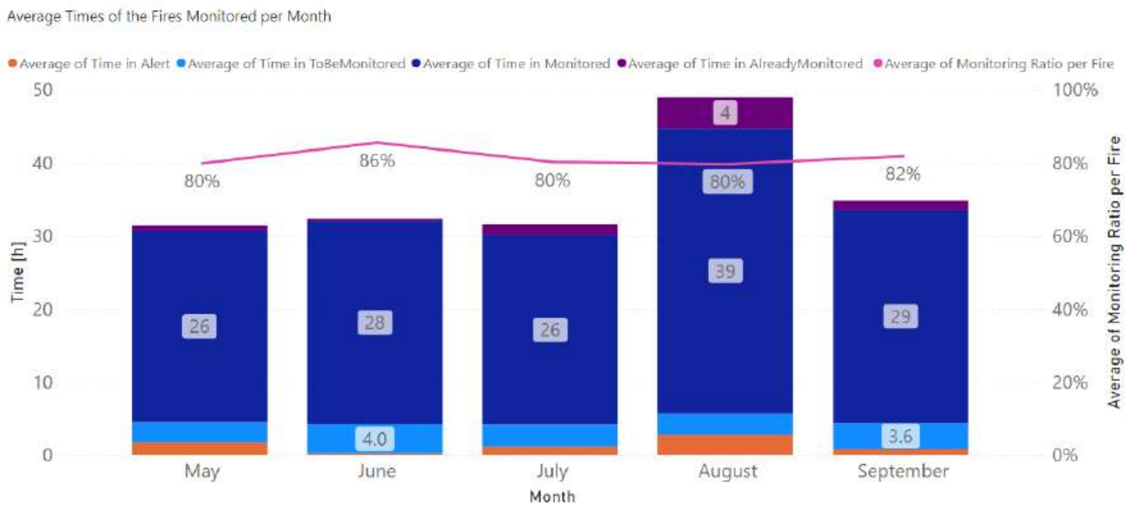


Figure 103 Average times of the fires monitored per month – Greece, conf 2

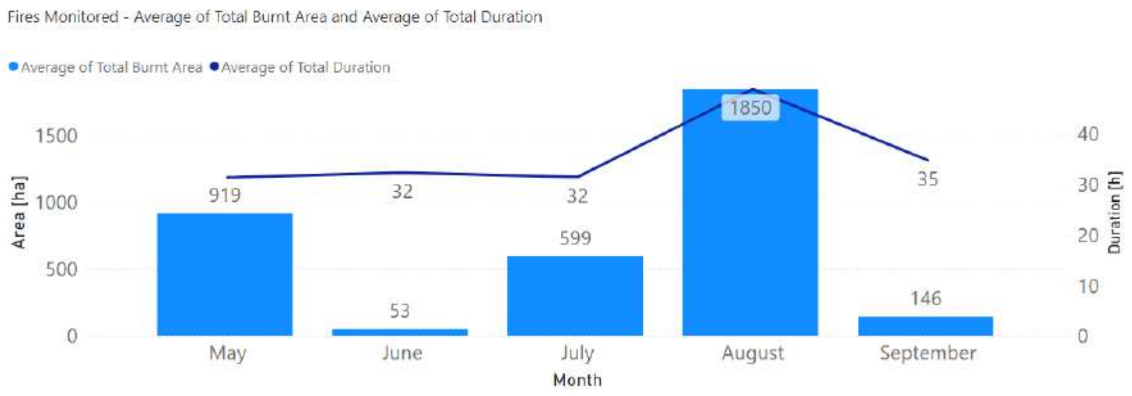


Figure 104 Average total burnt area and duration per fire monitored - Greece, conf 2

Figure 105 Average total burnt area and duration per fire not monitored – Greece, conf 2

8.2.6. Portugal – Configuration 2

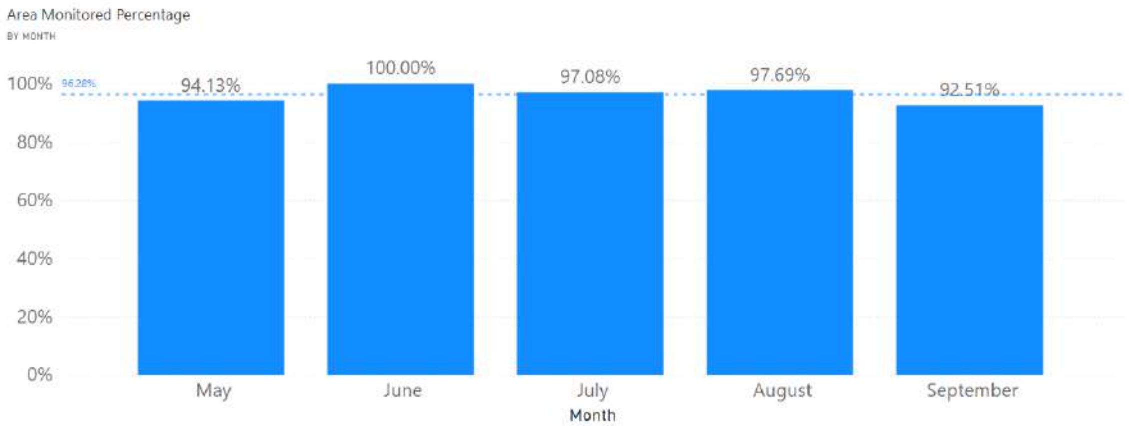


Figure 106 Percentage of area burnt monitored– Portugal, conf 2

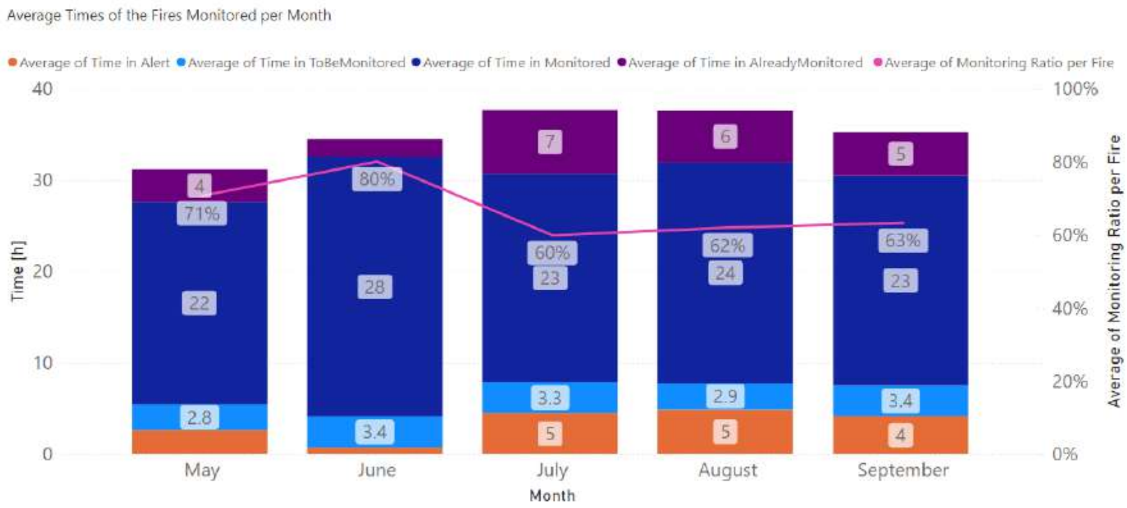


Figure 107 Average times of the fires monitored per month – Portugal, conf 2

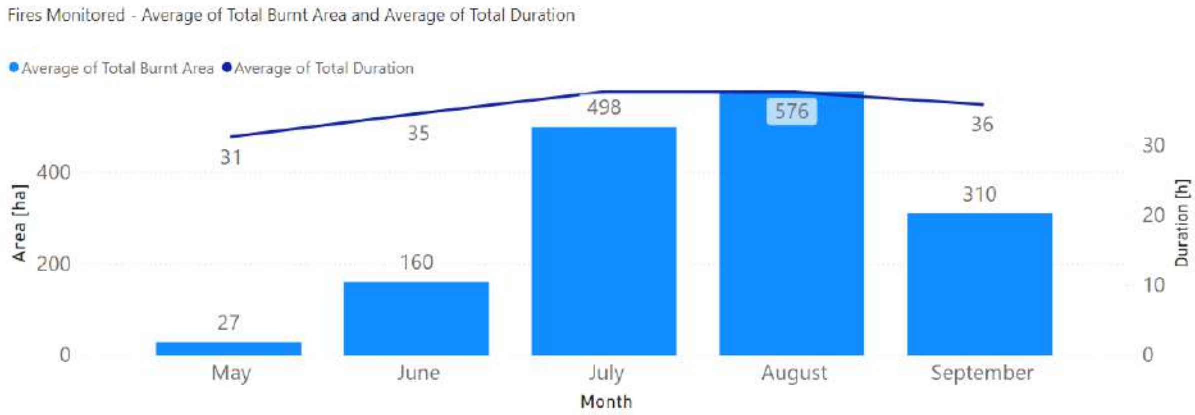


Figure 108 Average total burnt area and duration per fire monitored - Portugal, conf 2

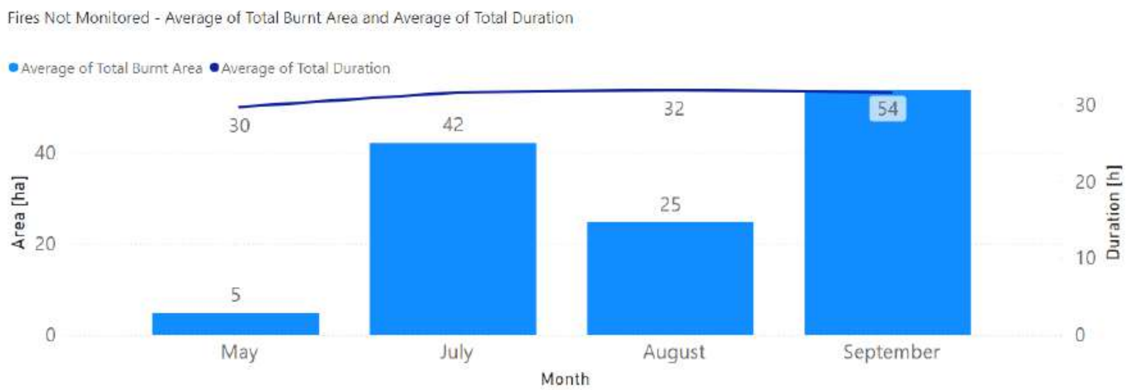


Figure 109 Average total burnt area and duration per fire not monitored – Portugal, conf 2

8.2.7. Sardinia – Configuration 2

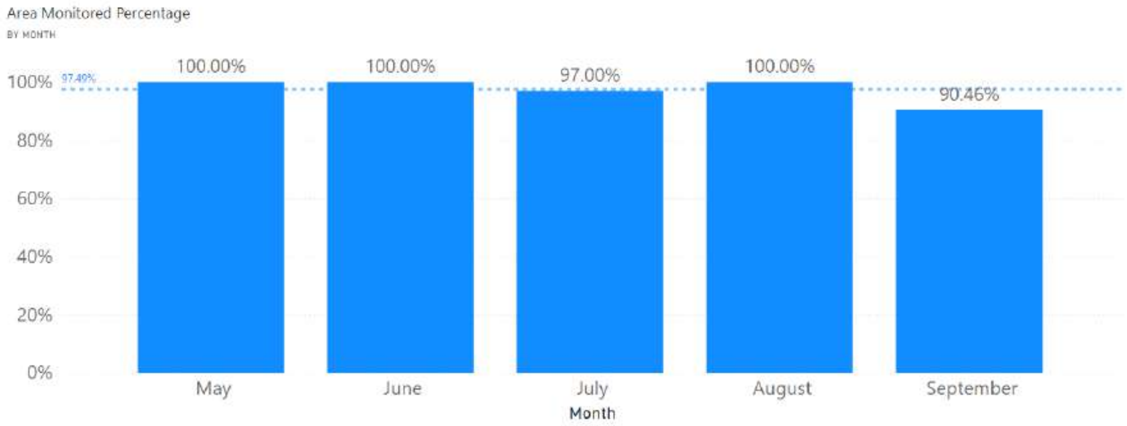


Figure 110 Percentage of area burnt monitored– Sardinia, conf 2

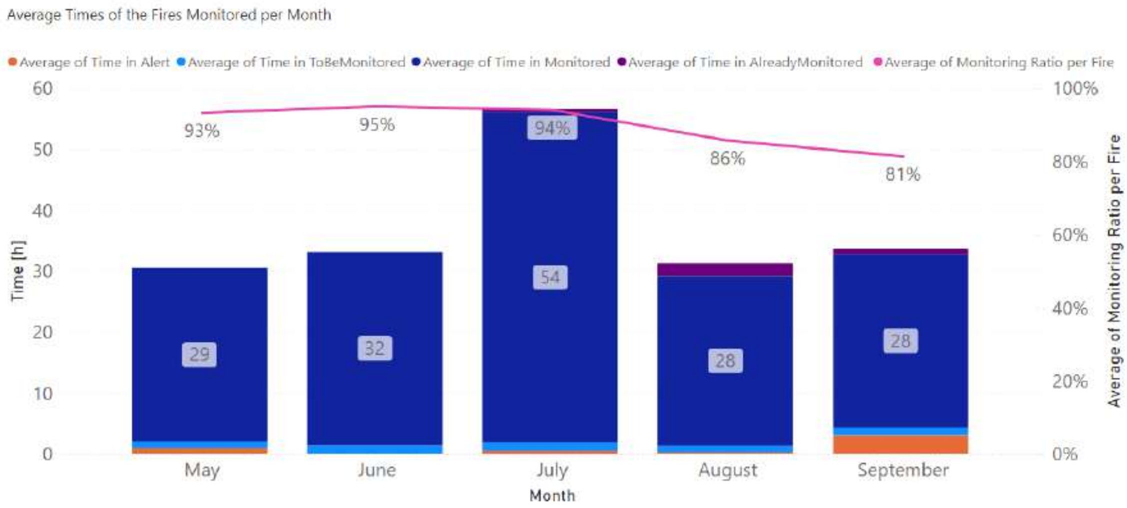


Figure 111 Average times of the fires monitored per month – Sardinia, conf 2

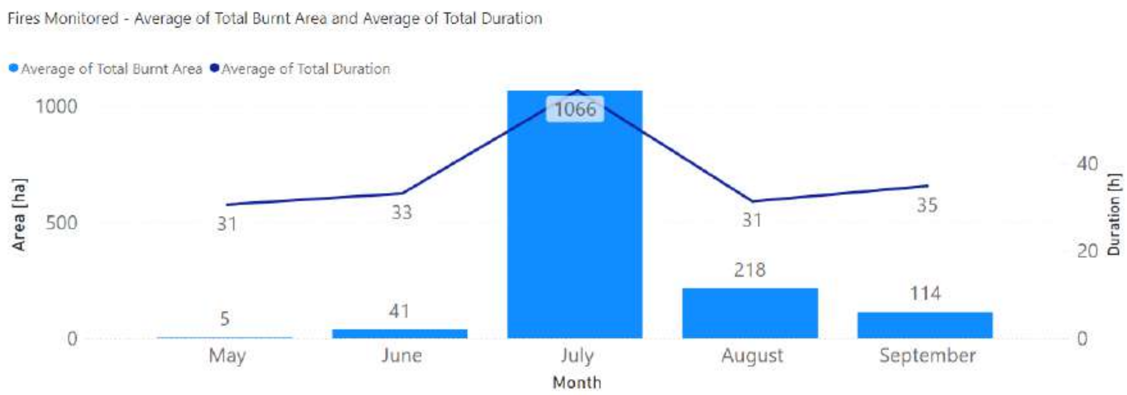


Figure 112 Average total burnt area and duration per fire monitored - Sardinia, conf 2

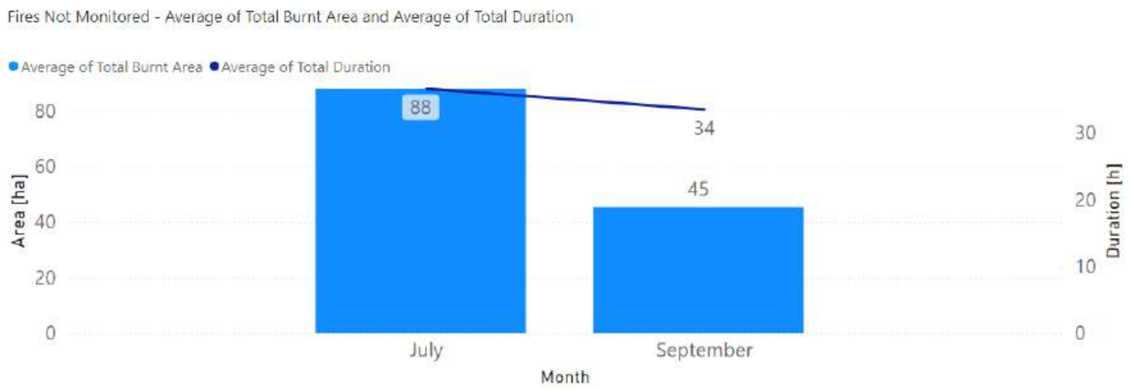


Figure 113 Average total burnt area and duration per fire not monitored – Sardinia, conf 2

8.3. Results Configuration 3

8.3.1. Galicia – Configuration 3

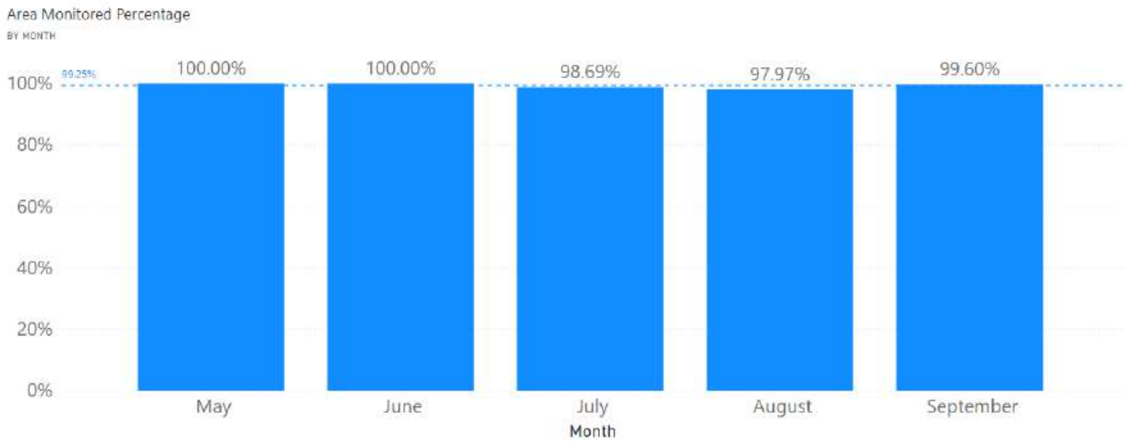


Figure 114 Percentage of area burnt monitored– Galicia, conf 3

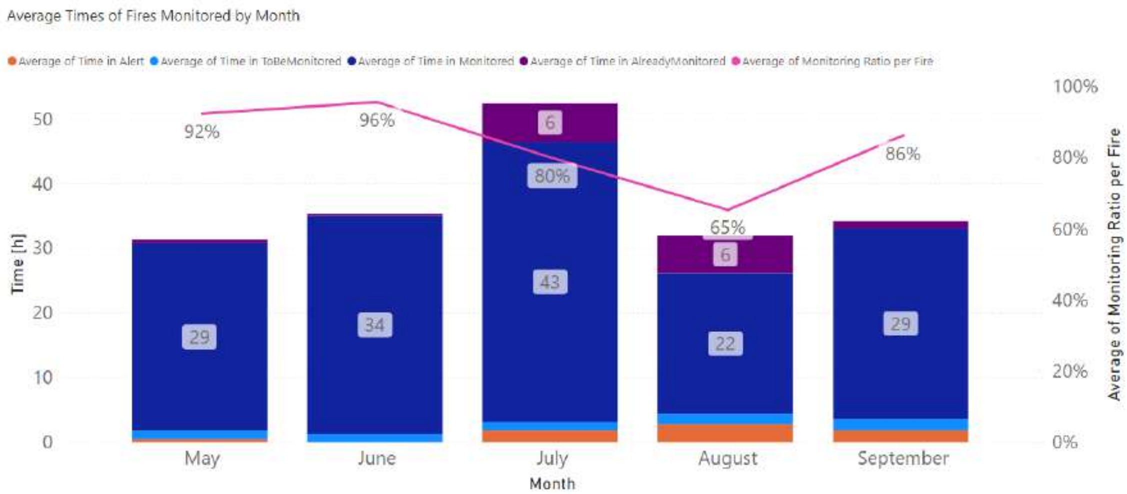


Figure 115 Average times of the fires monitored per month – Galicia, conf 3

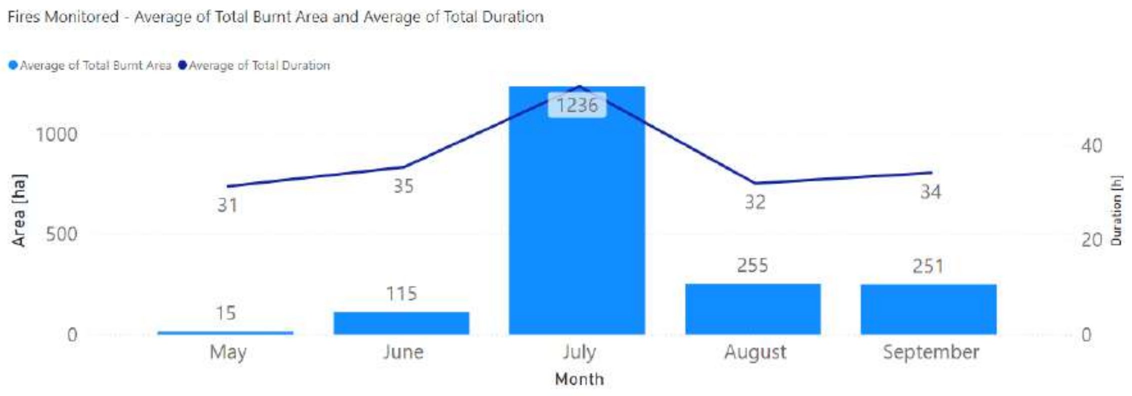


Figure 116 Average total burnt area and duration per fire monitored - Galicia, conf 3

Figure 117 Average total burnt area and duration per fire not monitored – Galicia, conf 3

8.3.2. Greece – Configuration 3

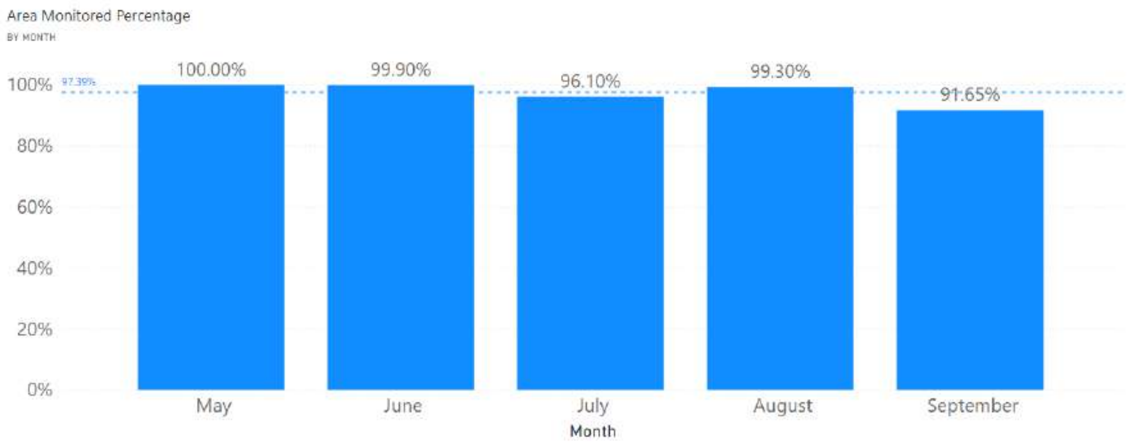


Figure 118 Percentage of area burnt monitored– Greece, conf 3

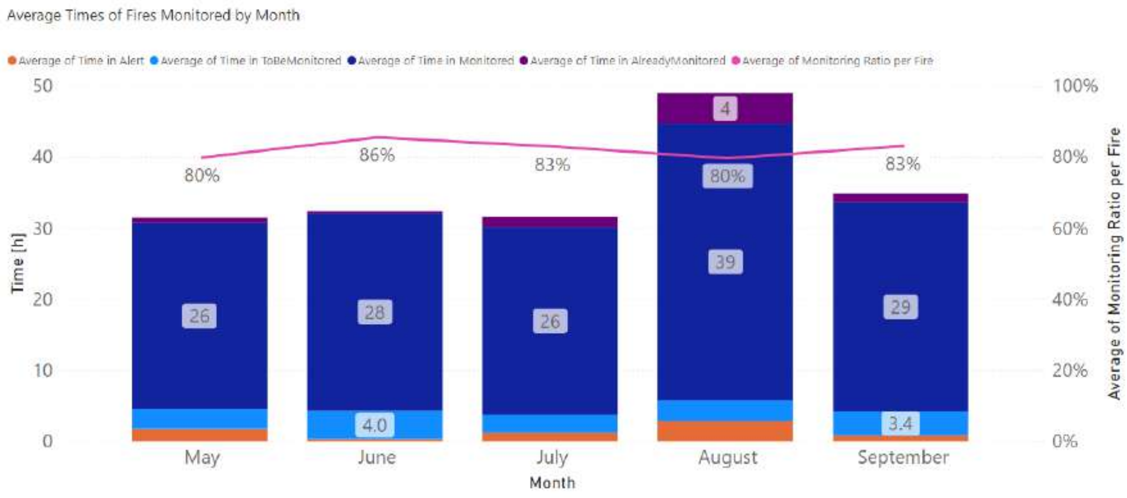


Figure 119 Average times of the fires monitored per month – Greece, conf 3

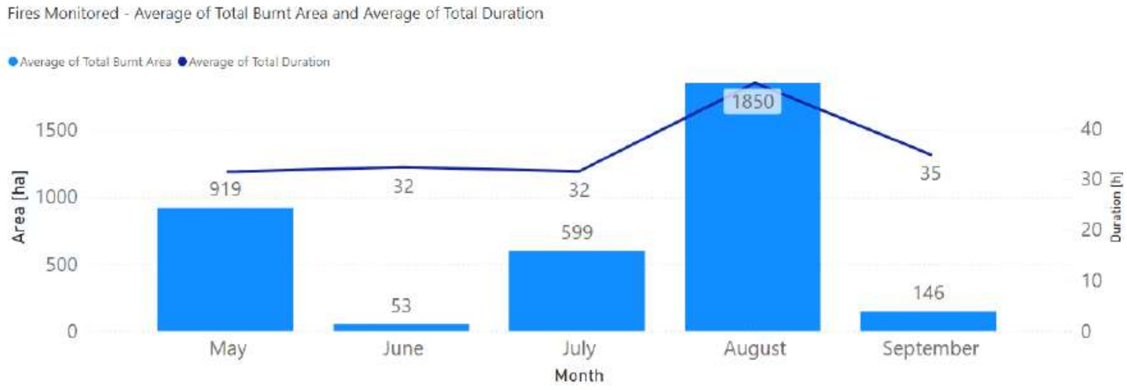


Figure 120 Average total burnt area and duration per fire monitored - Greece, conf 3

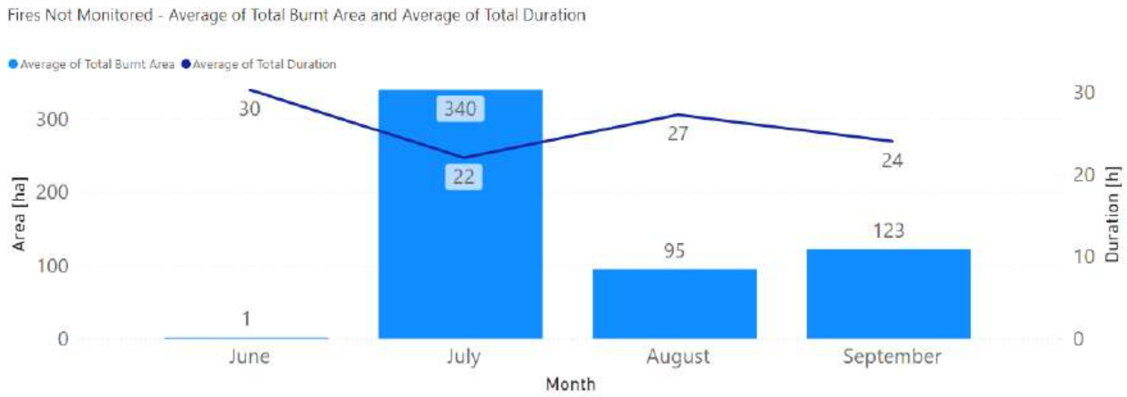


Figure 121 Average total burnt area and duration per fire not monitored – Greece, conf 3

8.4. Results Configuration 4

8.4.1. Aquitania – Configuration 4

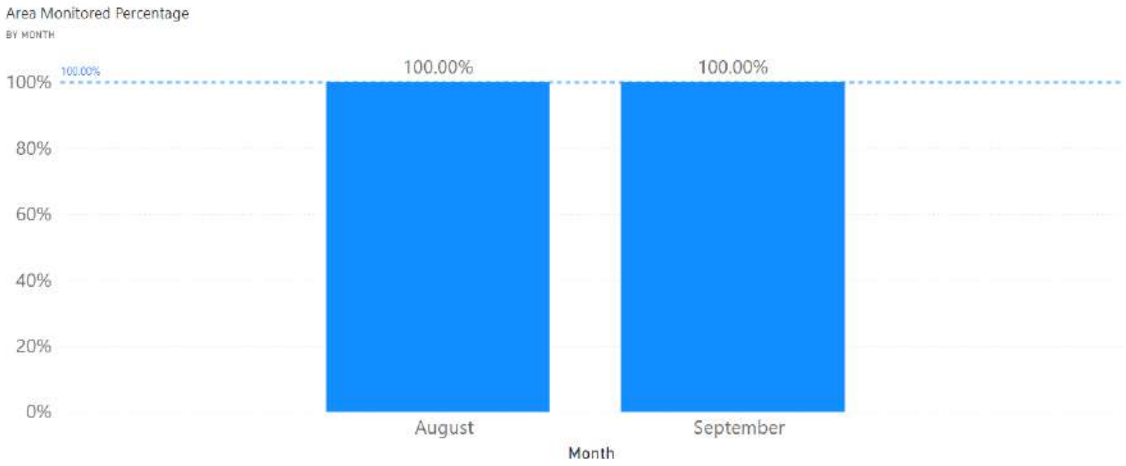


Figure 122 Percentage of area burnt monitored– Aquitania, conf 4

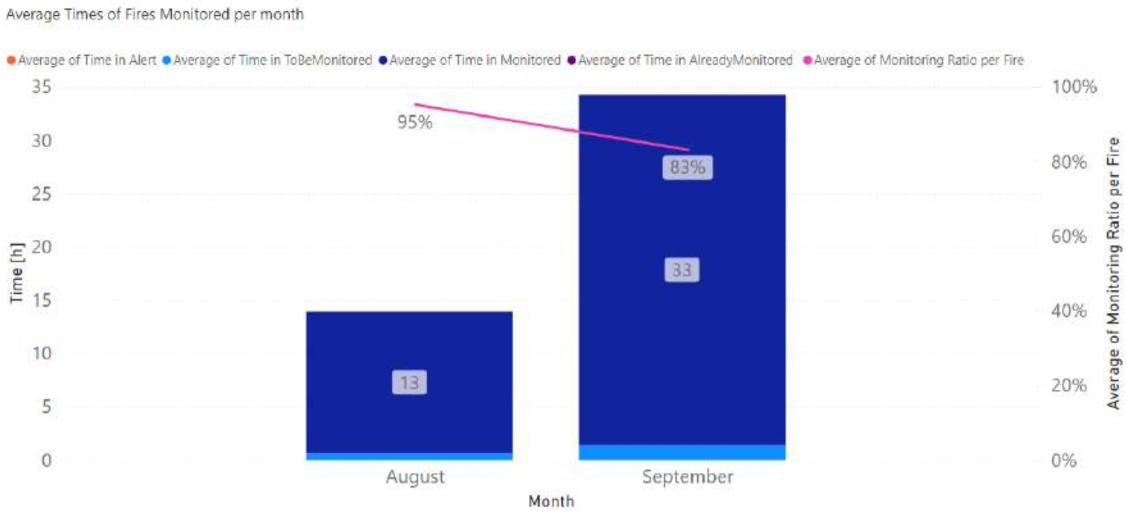


Figure 123 Average times of the fires monitored per month – Aquitania, conf 4

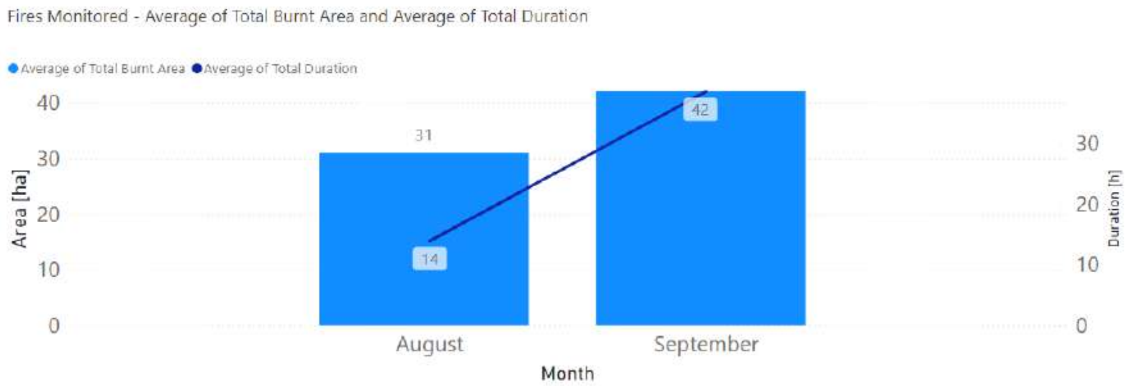


Figure 124 Average total burnt area and duration per fire monitored - Aquitania, conf 4

8.4.2. Bulgaria – Configuration 4

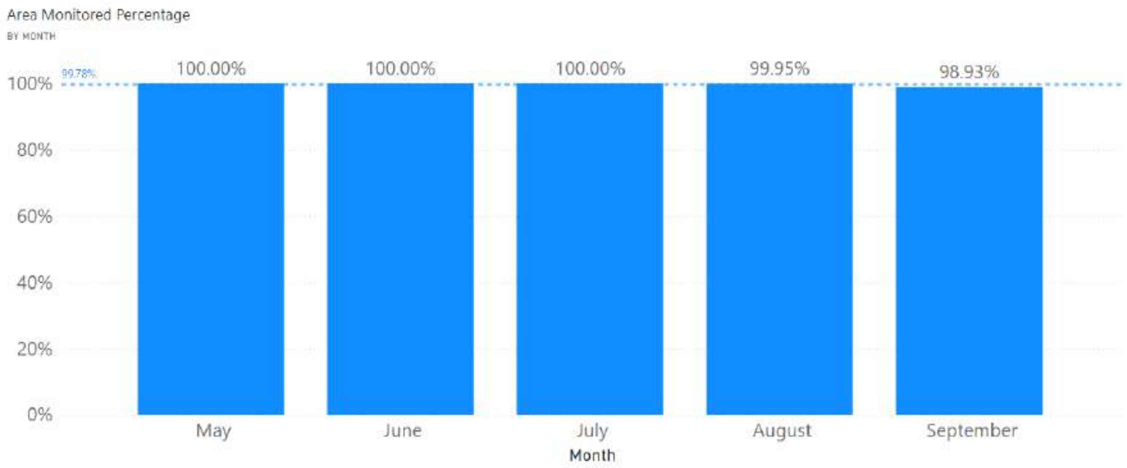


Figure 125 Percentage of area burnt monitored– Bulgaria, conf 4

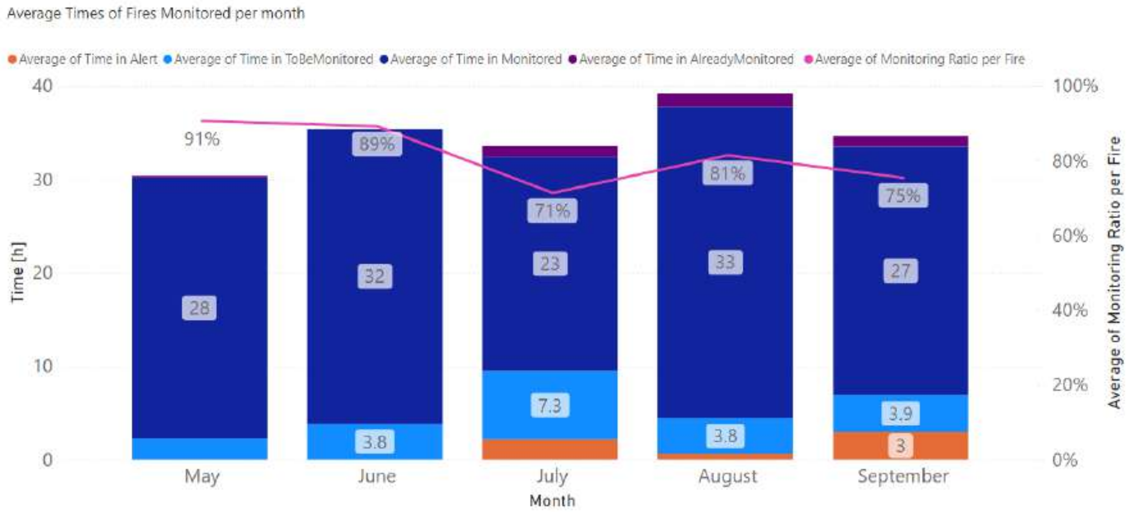


Figure 126 Average times of the fires monitored per month – Bulgaria, conf 4

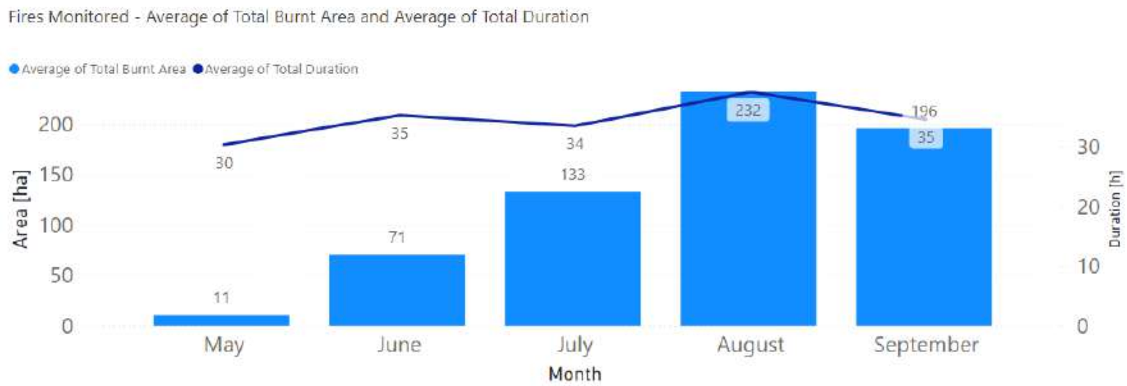


Figure 127 Average total burnt area and duration per fire monitored - Bulgaria, conf 4

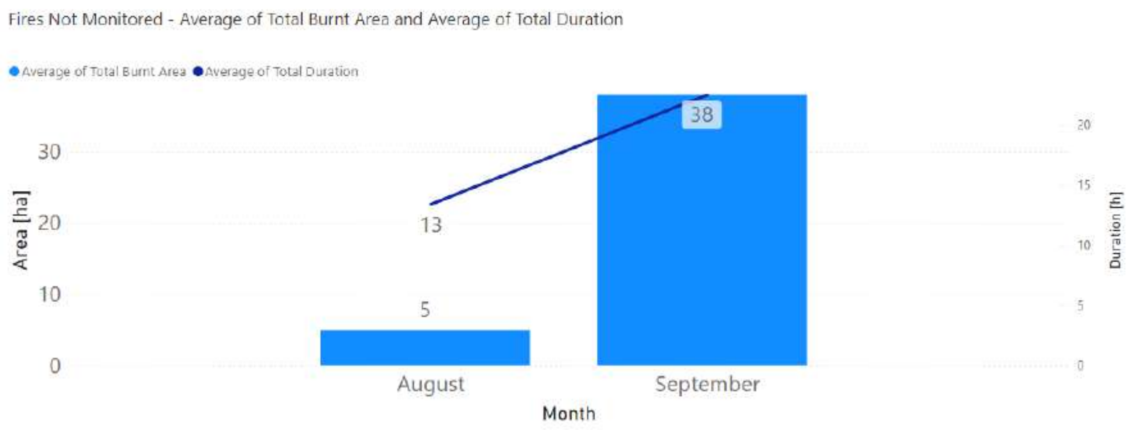


Figure 128 Average total burnt area and duration per fire not monitored – Bulgaria, conf 4

8.4.3. Catalonia – Configuration 4

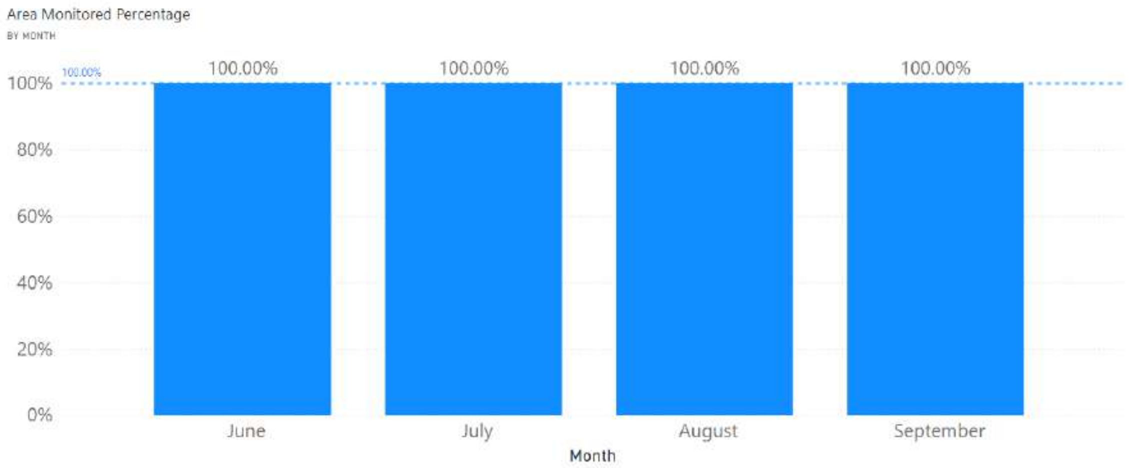


Figure 129 Percentage of area burnt monitored– Catalonia, conf 4

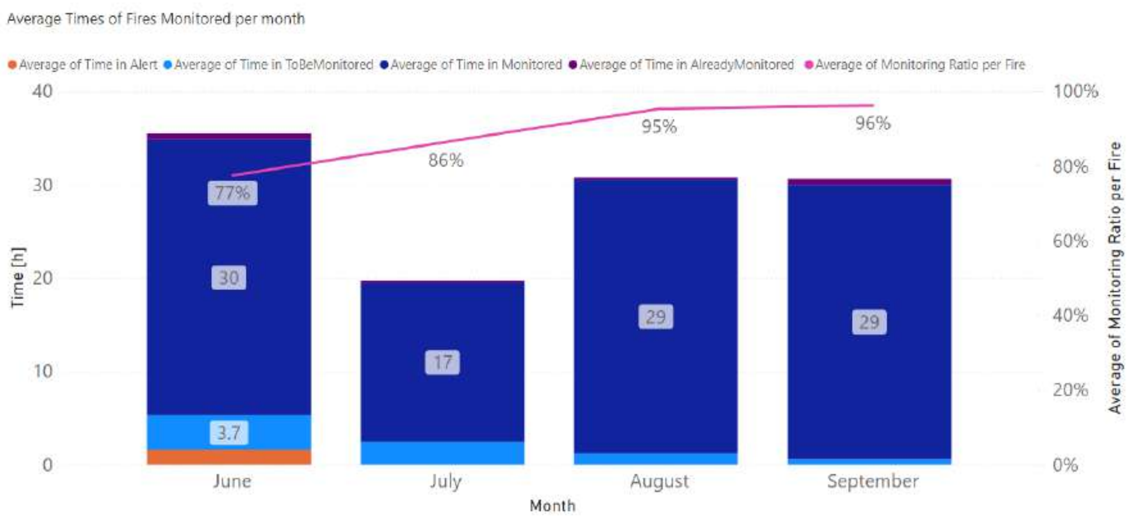


Figure 130 Average times of the fires monitored per month – Catalonia, conf 4

Figure 131 Average total burnt area and duration per fire monitored - Catalonia, conf 4

8.4.4. Galicia – Configuration 4

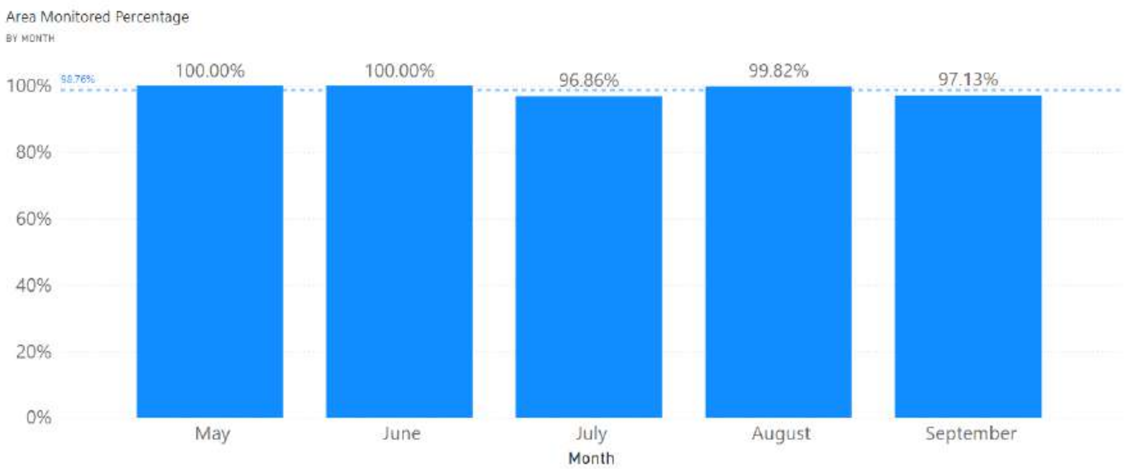


Figure 132 Percentage of area burnt monitored– Galicia, conf 4

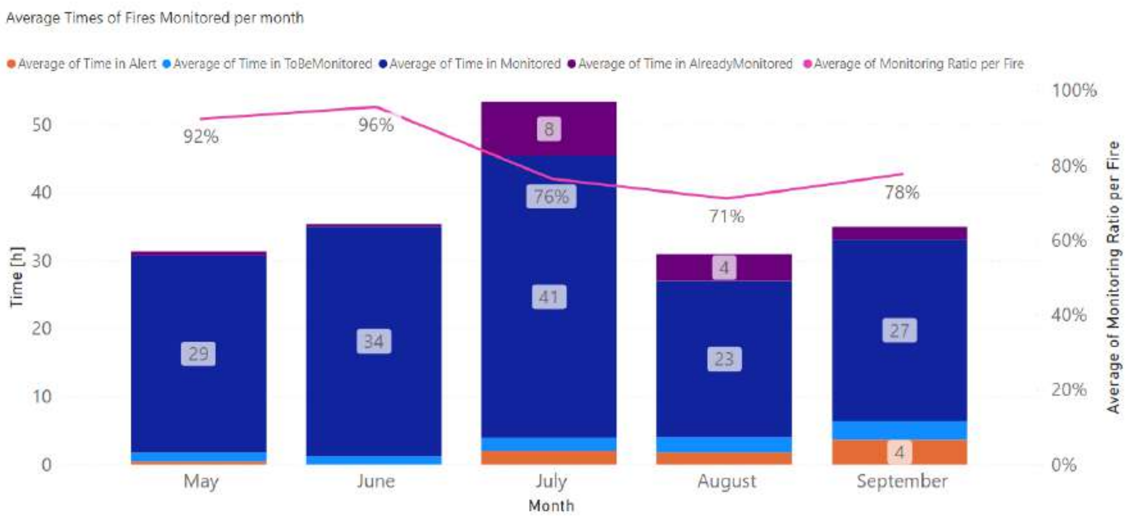


Figure 133 Average times of the fires monitored per month – Galicia, conf 4

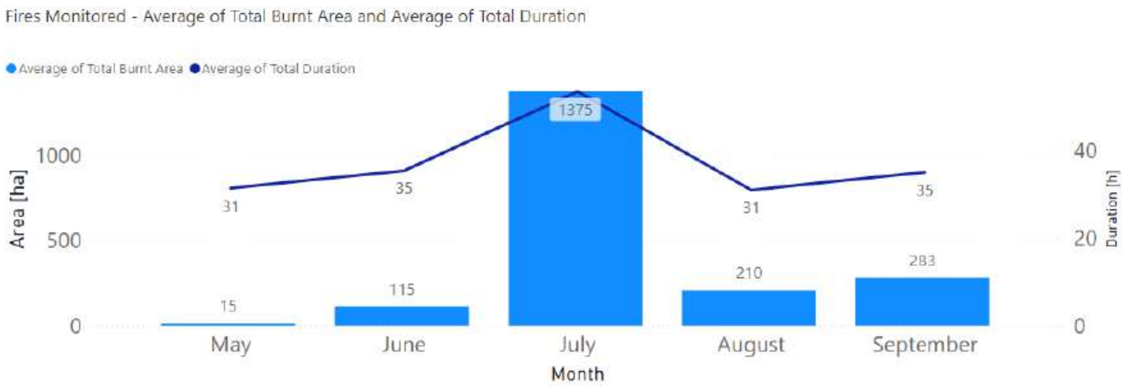


Figure 134 Average total burnt area and duration per fire monitored - Galicia, conf 4

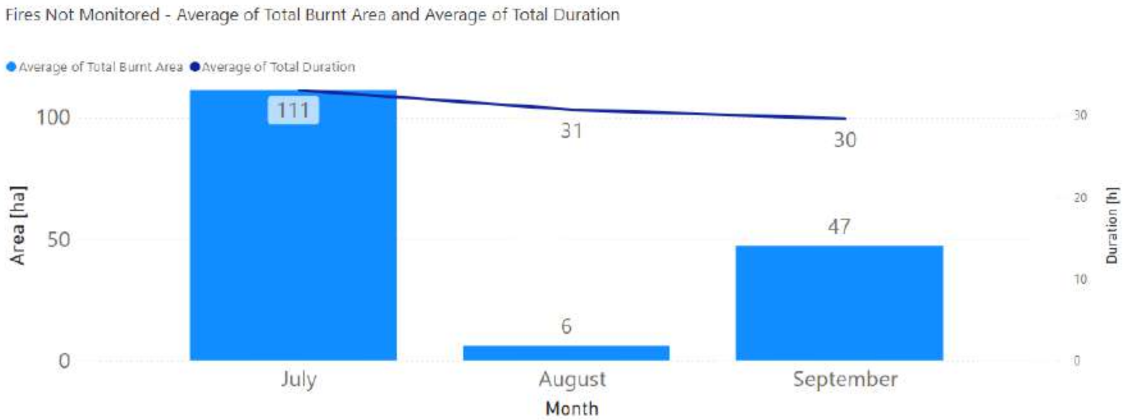


Figure 135 Average total burnt area and duration per fire not monitored – *Galicia*, conf 4

8.4.5. Greece – Configuration 4

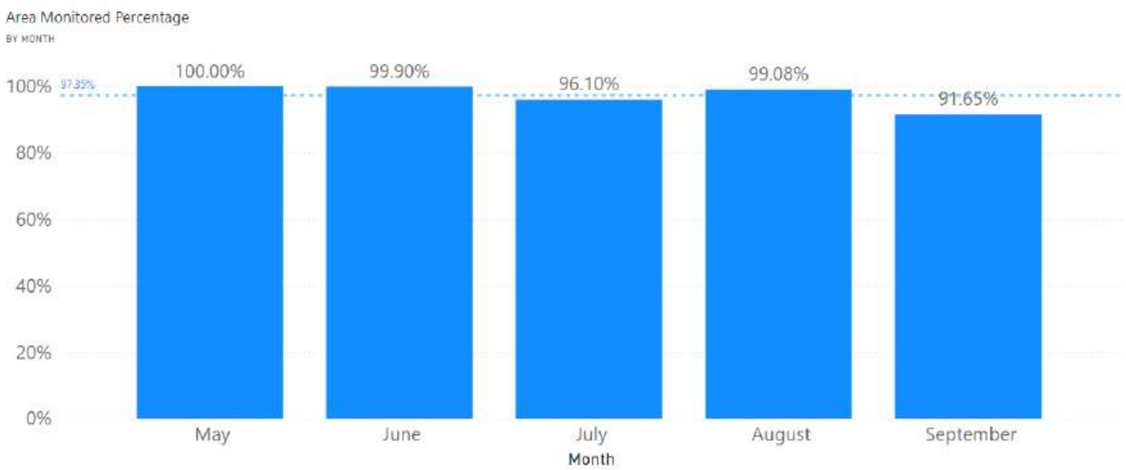


Figure 136 Percentage of area burnt monitored– Greece, conf 4

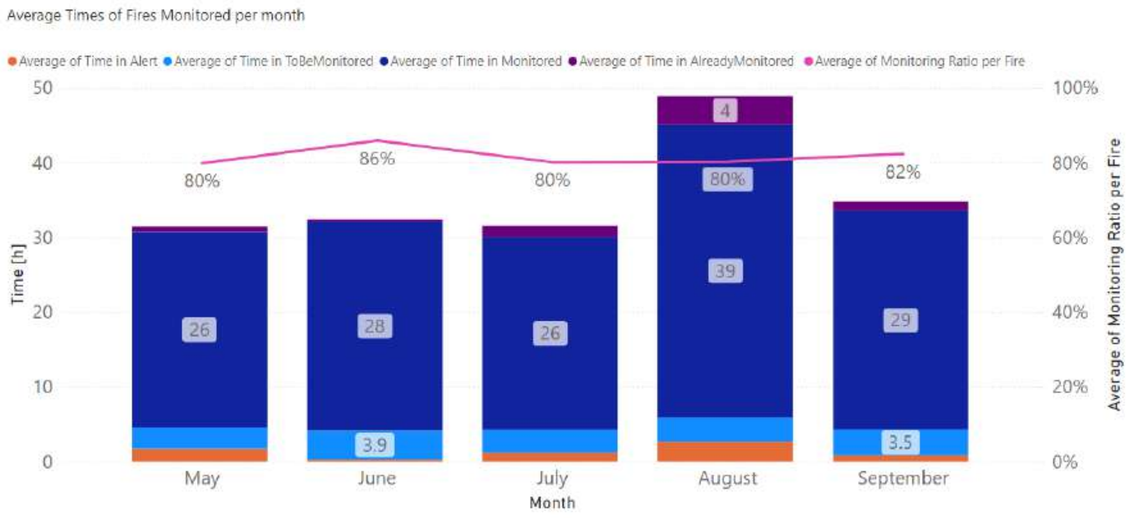


Figure 137 Average times of the fires monitored per month – Greece, conf 4

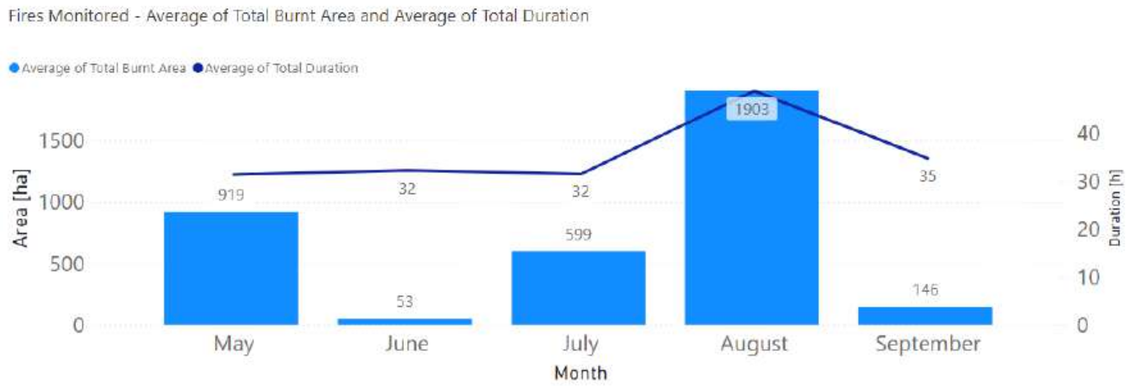


Figure 138 Average total burnt area and duration per fire monitored - Greece, conf 4

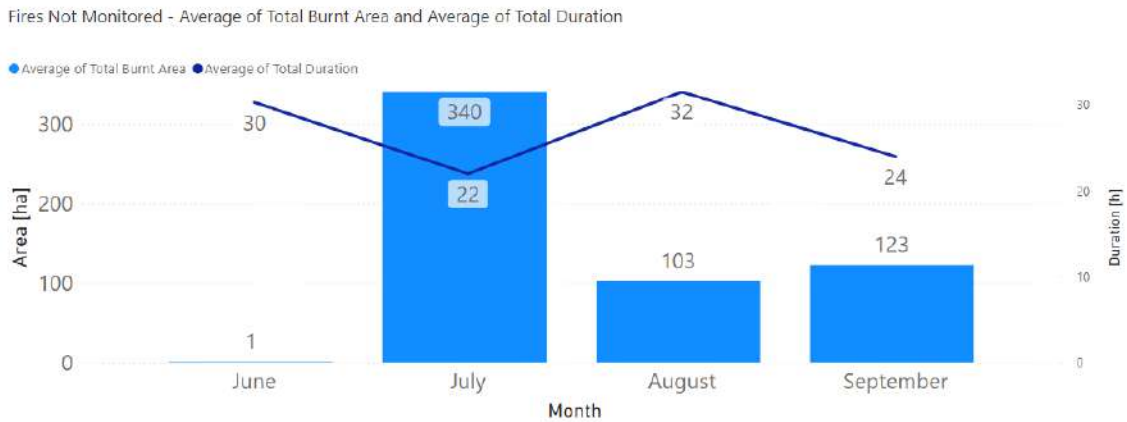


Figure 139 Average total burnt area and duration per fire not monitored – *Greece*, conf 4

8.4.6. Portugal – Configuration 4

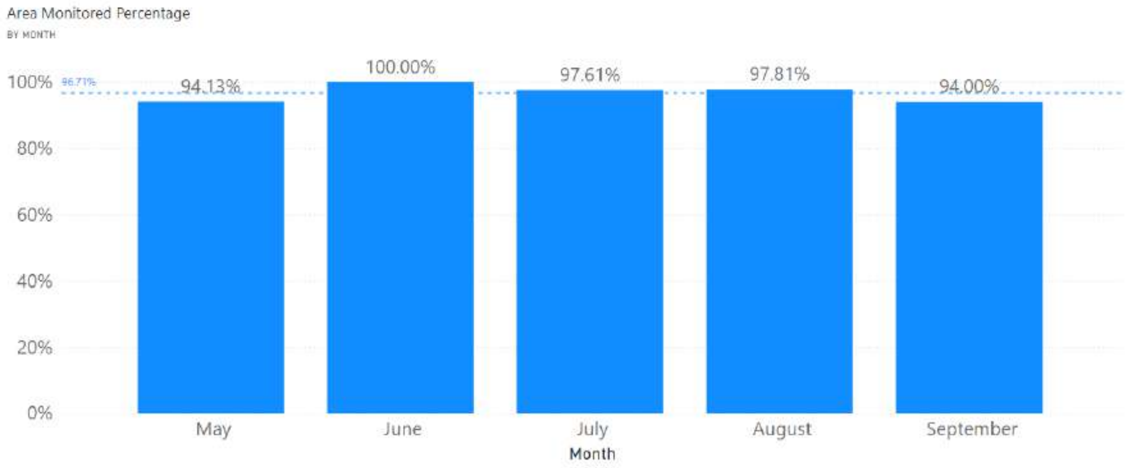


Figure 140 Percentage of area burnt monitored– Portugal, conf 4

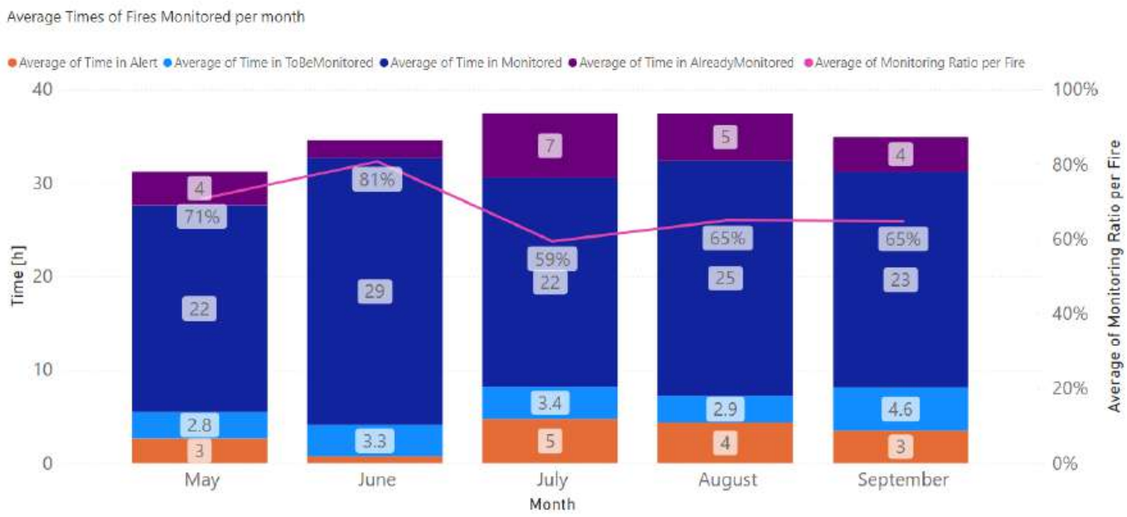


Figure 141 Average times of the fires monitored per month – Portugal, conf 4

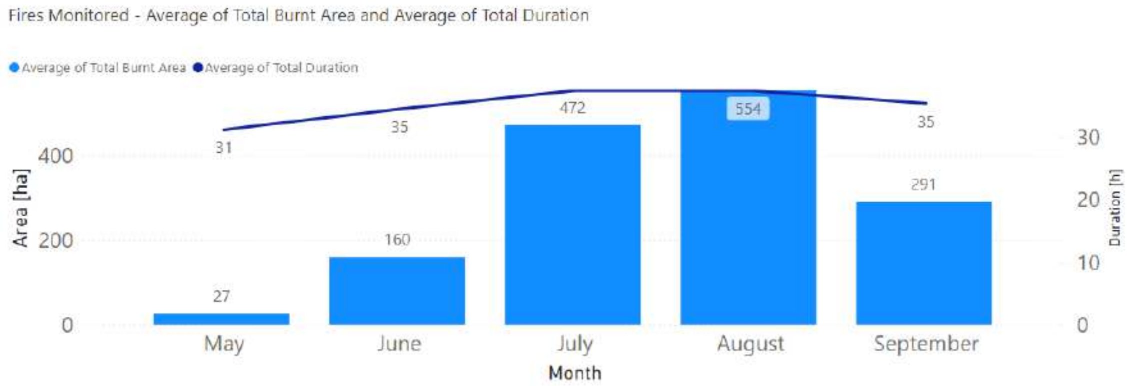


Figure 142 Average total burnt area and duration per fire monitored - Portugal, conf 4

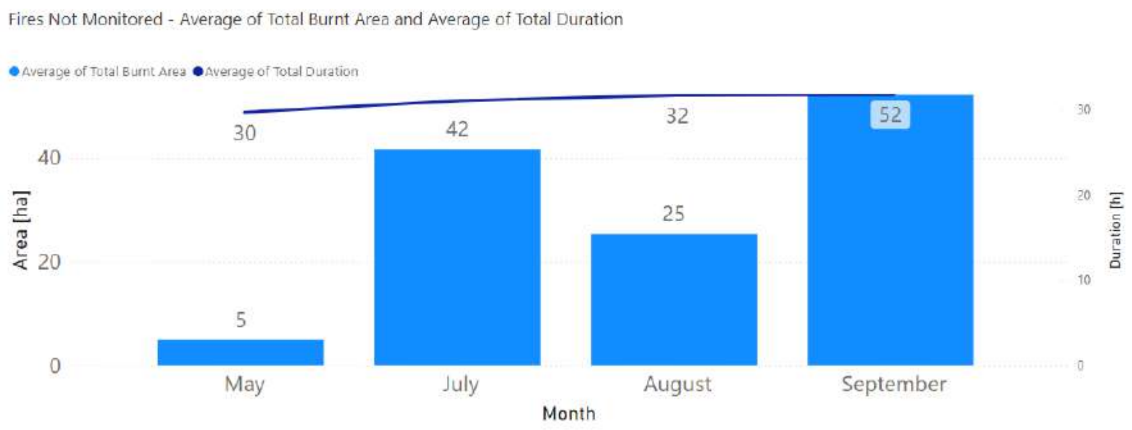


Figure 143 Average total burnt area and duration per fire not monitored – *Portugal*, conf 4

8.4.7. Sardinia – Configuration 4

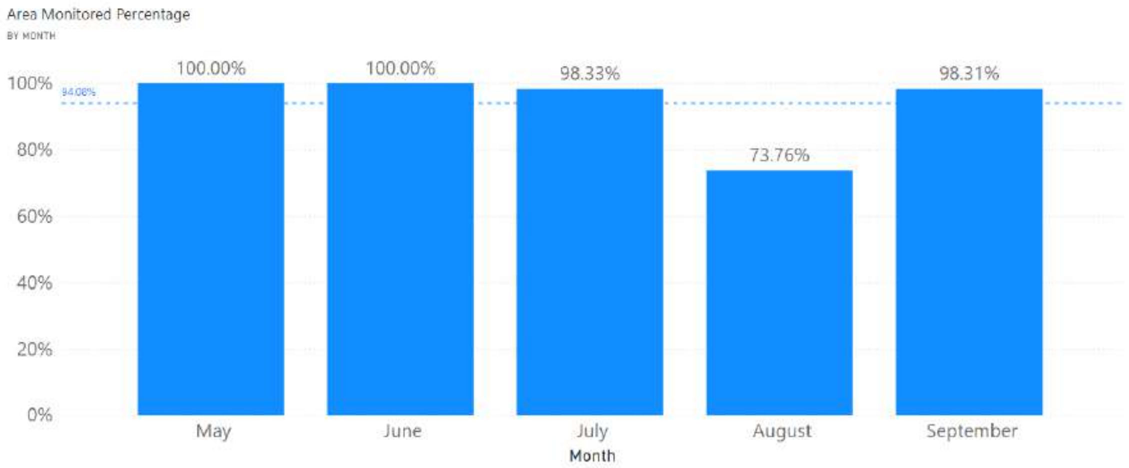


Figure 144 Percentage of area burnt monitored– Sardinia, conf 4

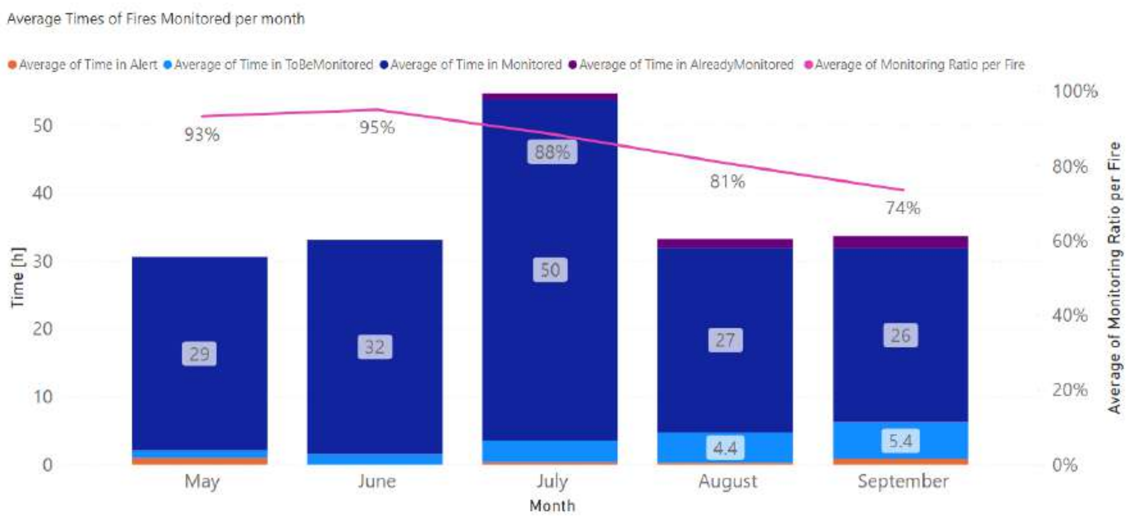


Figure 145 Average times of the fires monitored per month – Sardinia, conf 4

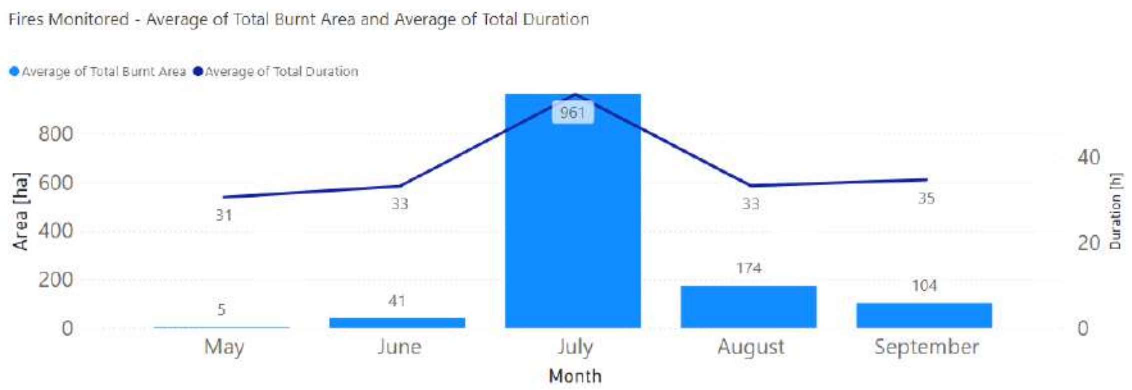


Figure 146 Average total burnt area and duration per fire monitored - Sardinia, conf 4

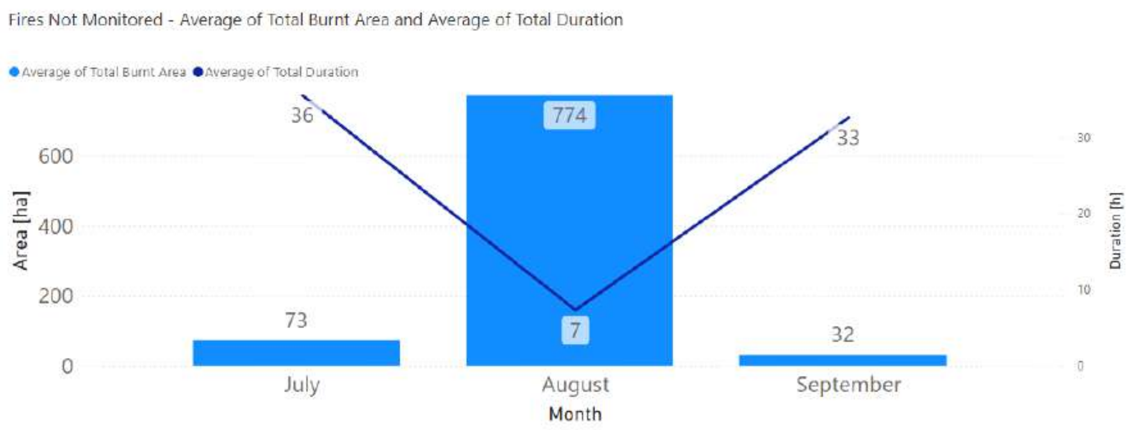


Figure 147 Average total burnt area and duration per fire not monitored – *Sardinia*, conf 4

9. CONCLUSIONS AND RECOMMENDATIONS

9.1. Technology Readiness Level

In terms of TRL, a clear distinction shall be made between the simulator itself and the technologies it simulates. For the simulator, the authors started from a list of high-level principles constituting TRL 1 and brought it to a validation in lab, which corresponds to TRL 4 according to [RD-18]. A higher TRL was not achieved because the simulator was run with historical data, which gives the advantage of knowing from the start how important an incipient fire will be. The simulator was not validated in a relevant environment with live, real-time data and in consequence, it didn't reach TRL 5.

However, the technologies simulated are already at higher TRL:

- Zephyr 8B aircraft (Airbus fixed-wing HAPS cumulating 127 days of test flights in the stratosphere): TRL 7 or 8
- OPAZ v2 (current version of Airbus Earth Observation optical payload for HAPS with 109 days of test flights in the stratosphere): TRL 7 or 8
- OPAZ v3 (next version of Airbus Earth Observation optical payload for HAPS, not yet flown to the stratosphere at the moment of releasing this document): TRL 6
- Infrared Earth Observation camera on HAPS (prototype not integrated in OPAZ, flown for 21 days in the stratosphere): TRL 7
- Combined optical and infrared Earth Observation payload for fixed-wing HAPS: TRL 3

9.2. Summary of assumptions

The HAPS fleet simulator has been designed to be as representative of the reality as possible, but because the reality of forest fires is complex, some simplifications or trade-offs were needed to achieve a feasible solution. This section summarises the assumptions taken. For a detailed justification of each assumption, please read the full text above.

- <u>The simulator's time resolution is 1 hour</u>
  Risk maps, fire events and HAPS tasking are reviewed on an hourly basis. The state of the winds and the fires changes every hour, but the Fire Weather Index changes on a daily basis.
  Estimated impact on results: null.

- <u>Simulation limited to fixed-wing heavier-than-air HAPS</u>
  Manoeuvrable balloons and airships are not simulated due to the lack of available navigation algorithms. Lighter-than-air HAPS manoeuvrability is still at low TRL in Europe.
  Estimated impact on results: high (balloons and airships would provide significantly different KPI results).

- <u>Zephyr aircraft used as model</u>
  Flight performance parameters are taken from Zephyr, the Airbus-owned HAPS, which is fully representative of its class.
  Estimated impact on results: null.

- Simulation playground is limited to south of parallel 44° N
  This is considered a reasonable average limit for current fixed-wing HAPS, which show degraded performance at high latitudes due to daylight duration and sun incidence angle when moving away from the summer solstice. The selected simulation playground is considered representative because it concentrates most of the burnt area in the European continent.
  Estimated impact on results: medium (required fleet size will increase when covering further north).

- EFFIS Fire Weather Index selected as fire risk indicator
  Complete and homogeneous dataset all over the continent, timely updated and adopted by EFFIS network.
  Estimated impact on results: null.

- EFFIS Fires Database selected as fire events source
  EFFIS offers more homogeneous and complete database all over the European continent in comparison with national/regional registers.
  Estimated impact on results: null.

- Only fires larger than 500 hectares or longer than 12 hours were selected
  This is a filter to remove small fires from the simulation, assuming that the value added of HAPS is higher on larger fires.
  Estimated impact on results: medium (lowering this threshold would increase the required fleet size).

- Simulation limited to five months: from May to September
  The simulated season from May to September was selected to match the months in which fixed-wing HAPS like Zephyr can reach European latitudes currently. Although it is expected that future versions of these platforms can fly beyond September, the authors preferred keeping the exercise within the current limits. This assumption may be excluding from the simulation several episodes like October 2017, with more than 380,000ha burned in the European Union, especially because of wildfires in Spain (~57,000ha) and Portugal (~322,000ha). However, beyond these specific episodes, the majority of fires are included.
  Estimated impact on results: medium.

- Simulation based on historical data from 2018 to 2022 (five years)
  Five years was considered a representative period to soften/average the intrinsic variability of wildfires among consecutive seasons and to make the simulation smoother (the simulation is very process-intensive and requires long processing times). However, the simulation has still shown peaks and valleys in some regional results, like Galicia, that are directly linked to specific bad or good seasons. In this regard, please, see the recommendations at the end of this document.
  Estimated impact on results: medium.

- No regulatory or air traffic constraints
  HAPS are assumed to fly freely inside the playground area, moving in straight lines (geodetic curves) with no areas prohibited to air traffic. This is the expectation of the authors for the mid-term, when specific High-Altitude Operations regulation is in place.
  Estimated impact on results: low.

- HAPS flying at fixed altitude, approximately 20,500 metres
  Although fixed-wing HAPS increase its flying altitude along the day and decrease it during the night, wind data from ECMWF ERA5 is only available at specific pressure levels. The closest pressure level is 50 hPa, corresponding to 20,500 metres altitude. Winds at different altitudes might be different.
  Estimated impact on results: low.

- Simplified burning ratio used for priority computation
  With the aim to emulate firefighters' decision-making, burning ratio is assumed to be a key parameter to trigger the call for a HAPS to monitor an ongoing fire. In fact, the burning ratio curve is different per each fire. As this information is not available for EFFIS historic fires, a simple cosines curve has been applied in the simulation.
  Estimated impact on results: low.

9.3. Conclusions

Hundreds of simulations have been launched with different input parameters and increasing number of HAPS in the fleet, divided in two main approaches:

1. A single fleet covering the full AoS (Area of Simulation): HAPS can move freely all over the south of Europe.
2. HAPS are constrained to countries or regions: one or multiple HAPS per each region. FIRE-RES Living Labs have been used.

The first approach simulates a service funded by the European Union institutions (i.e. Copernicus Emergencies Program) available to the whole union territory, while the second represents a service model based on each specific regional or national authority contracting a number of HAPS to operate in their territory. Results and conclusions are provided below, referencing the two approaches.

A first group of KPI is dedicated to assessing the completeness of fires monitored among the fires selected for the simulation. This is expressed by counting the fires that are monitored and by counting the total burnt surface monitored.

Conclusion 1: A high percentage of burnt area is monitored with a relatively small fleet: 8 HAPS reach 90 % of burnt area, 14 HAPS reach 96 % for both, the full southern Europe simulation and the Living Labs simulation.

The figures look a bit less performant when counting the number of fires monitored: 8 HAPS reach 63 % of fires and 14 HAPS reach 75 %. This is explained because the fire events prioritisation algorithm works well and only the smallest fires are left unattended (44 ha in average).

A second group of KPI is meant to measure the different phases of the fire's lifetime. Four phases are identified:

- Time *in alert*: from the moment the fire alarm is received to the moment a HAPS is tasked to monitor it.
- Time *to be monitored*: from the moment a HAPS is tasked to monitor the fire to the moment in which the HAPS arrives to the fire location and starts monitoring.
- Time *monitored*: from the HAPS arrival to its departure, either because the fire is extinguished or because the HAPS is called to a higher priority.
- Time *already monitored*: from the HAPS departure to the fire end.

The first, third and fourth are linked to the authors' subjective emulation of the human behaviour through the prioritisation algorithm. Other prioritisation rules would provide different results. Therefore, the key parameter is the second, which is exclusively linked to the size of the AoS and the number of HAPS available.

Conclusion 2: the average time of HAPS arrival to a fire (time *to be monitored*) is significantly better for the regionalised deployment approach (Living Labs) than for the pan-European approach. Example: 14 HAPS result in <3 hours (regionalised) and <6 hours (pan-European).

Conclusion 3: Even with the less performant pan-European deployment approach, HAPS will be normally covering the first night of the fire, when aerial means are usually less or not available.

Conclusion 4: the average time of HAPS arrival to a fire could be reduced by increasing the fleet size. However, the contribution of every new HAPS added is lower until being marginal.

The third group of KPI looks at the HAPS themselves, accounting the time they spend in one activity or another.

Conclusion 5: HAPS on a pan-European fleet dedicate 29 % of its flight time to monitor fires, in average. The time spent travelling to fires or risky areas is 34 %. Therefore, almost two thirds of the fleet's flight time is dedicated to its highest value use case: fire monitoring.

Conclusion 6: The remaining 37 % of flight time is allocated to fire detection. Knowing that fire detection is not a strong requirement in Europe, where most fires are reported by the general public, this time may be reallocated to other emergency, security, surveying or environmental services. This creates a solid argument for the adoption of HAPS on a multi-service basis.

Conclusion 7: increasing the number of HAPS reduces the fraction of time dedicated to high value activity, releasing more time for fire detection or other activities.

When looking at KPI by month, it is quickly understood that the demand is not constant along the fire season. The number of HAPS can be optimized monthly. The authors have launched simulations with a varying number of HAPS along the season.

Conclusion 8: for a pan-European fleet, the optimal fleet size is estimated: 10 HAPS in May and June, 14 HAPS in July and August, 12 HAPS in September.

Conclusion 9: for a regionalised fleet, applied to FIRE-RES Living Labs, the optimal fleet size would be:

Table 26 HAPS Fleet Configuration 4 for Living Labs simulation – mixed approach

Living Lab	Code	May	June	July	August	September
Bulgaria	BUL	1	1	1	1	1
Catalonia	CAT	0	1	1	1	1
Galicia	GAL	1	1	1	1	1
Greece	EL	2	2	4	4	4
Portugal	POR	2	2	3	3	2
Sardinia	IT	1	1	1	1	1
EU	EU	0	1	2	2	2

**Aquitania is excluded because it was not fully within the AoS*

9.4. Recommendations

The results gathered from this study suggest that both, a pan-European fleet and a regional approach centred around singular areas, either selected due to their specific vulnerability or because they can afford integrating this new technology in their operative capabilities, bring relevant added value points to the table.

Hence, a first recommendation is to consider both types of solutions and work towards a mixed approach, with dedicated aircrafts for specific areas (national or regional) while still advocating for a base layer of HAPS assets shared across Europe to enable continental solidarity and to cover extreme peaks of fire or fire risk whenever and wherever necessary.

By implementing a regional component, time reaction will improve considerably in those regions willing to adopt the capabilities, reaching a very reactive solution towards most fire events in their area of interest. A shared European service acting as a baseline for the southern part of the continent would provide a capability not subject to local funding, that could contribute during peak events on those areas affected the most by wildfires. This shared service, although not as reactive as a dedicated regional asset, would be able to prioritize critical events across a wider region to contribute to the overall European resilience.

In addition, the mixed approach makes sense because it matches the firefighting and emergencies budgetary distribution in the European Union, which is significantly atomized, mostly at regional level with some exceptions at national level. The Copernicus Program might play the role at EU level with its emergencies program line, and more specifically the EFFIS service.

The simulation process was focused in optimizing the fleet size on both scenarios, regional and pan-European. The optimization resulted in a different number of HAPS every month, otherwise the size of a constant fleet would be adjusted either to satisfy the average demand, being short on peaks, or to satisfy the peak demand, being redundant on lower demands. Although this is a good theoretical optimization, it might not be aligned with the operational constraints. In consequence, a second recommendation is, for future iterations of the fleet sizing exercise, to incorporate operational and logistical constraints on the service delivery.

Finally, the regionalised approach simulated using the FIRE-RES Living Labs shows that the five-year simulation period might not be sufficient to soften the extreme variability of wildfires. For future iterations of this simulation, a third recommendation is to extend the simulation period to 10 years.

10. ANNEX 1. REQUIREMENTS OF SIMULATOR

This annex contains the main requirements that were used to design the simulator. This was part of an iterative process, where the definition of the requirements helped to conceptualize the simulator and how it should work, and the implementation of the design in the code improved the definition of the requirements.

10.1. General simulation requirements

HAPS-REQ-01. The duration of the simulation shall be configurable.

HAPS-REQ-02. The simulation shall be executed in the fixed Area of Simulation N:44° / S:35° / W:29° / E:-10°.

HAPS-REQ-03. For each step of the simulation, the simulator shall:

- Calculate the status of the scenario (fires, risks and priorities).
- Calculate the position of the HAPS.
- Assign the HAPS to the Points of Interest.
- Store the HAPS-PoI assignations and main parameters for a final export.

Figure 148 Simulator step sequence

HAPS-REQ-04. The step of the simulator shall be configurable and set to 3,600 seconds by default.

HAPS-REQ-05. The export frequency of the data for each step of the simulation shall be configurable.

10.2. Input data requirements

HAPS-REQ-06. The simulator shall read and process historic fire events extracted from the [RD-01] and considering the period from 2018 to 2022 (5 years).

HAPS-REQ-07. The simulator shall read and process historic risk data of the simulation extracted from the [RD-02] and considering the period from 2018 to 2022 (5 years).

HAPS-REQ-08. The simulator shall read and process wind data in the stratosphere (50 kPa) extracted from the [RD-03] and considering the period from 2018 to 2022 (5 years).

HAPS-REQ-09. The simulator shall read and process the HAPSConfigurationFile.txt with the configuration of the HAPS fleet for the simulation.

HAPS-REQ-10. The simulator shall read and process the configuration of Areas of Interest for the simulation define in a Shapefile.

10.3. Data model requirements

HAPS-REQ-11. The simulator shall model the fires according to the following equations:

$t \leq t_s: \; A(t) = 0 \, , \; \frac{dA}{dt}(t) = 0$

$t \geq t_e: \; A(t) = A_{max} \, , \; \frac{dA}{dt}(t) = 0$

$t > t_s \; and \; t < t_e :$

$$A(t) = \frac{A_m}{2} \cdot \left(1 - cos\left(\frac{\pi}{(t_e - t_s)}(t - t_s)\right)\right)$$

$$\frac{dA}{dt}(t) = \frac{A_m \cdot \pi}{2\,(t_e - t_s)} \cdot sin\left(\frac{\pi}{(t_e - t_s)}(t - t_s)\right)$$

Where:

- A (t) = Area burned evolution with time [ha].
- dA/dt = burning ratio evolution with time [ha/h].
- t_s = start time of fire [h].
- t_e = end time of fire [h].
- A_m = max Area burned [ha].
- dA/dt = burning ratio [ha/h].

HAPS-REQ-12. The simulator shall assign a priority to each Point of Interest in accordance with the following equation:

$$\text{Priority} = \text{weight}_{Area} \cdot \frac{\frac{\text{dA}}{\text{dt}}_{Current}}{\frac{\text{dA}}{\text{dt}}_{Max}} + \text{weight}_{FWI} \cdot \frac{FWI}{FWI_{Max}}$$

Where:

- Weight $_{area}$ = 0.8 [-].
- Weight $_{FWI}$ = 0.2 [-].

- $dA/dt_{current}$ = burning ratio [ha/h].
- dA/dt_{max} = burning ratio [ha/h].
- FWI = [-].
- FWI_{max} = [-].

HAPS-REQ-13. The simulator shall model the fires according to the following states machine:

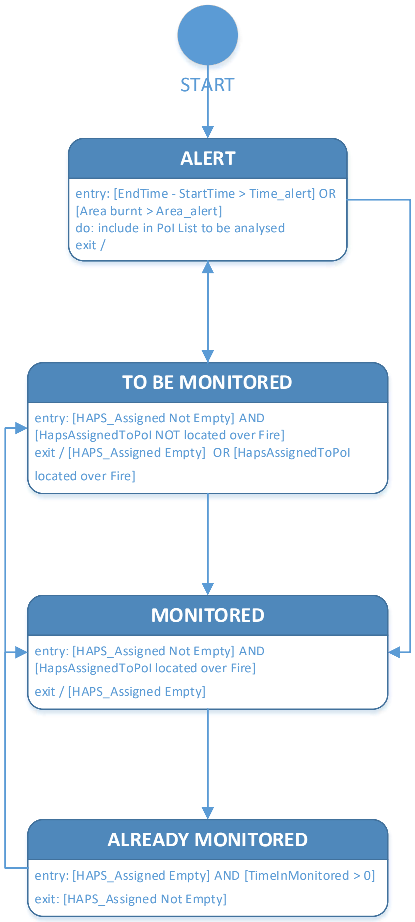


Figure 149 Fire states machine

HAPS-REQ-14. The simulator shall model the HAPS according to the following states machine:

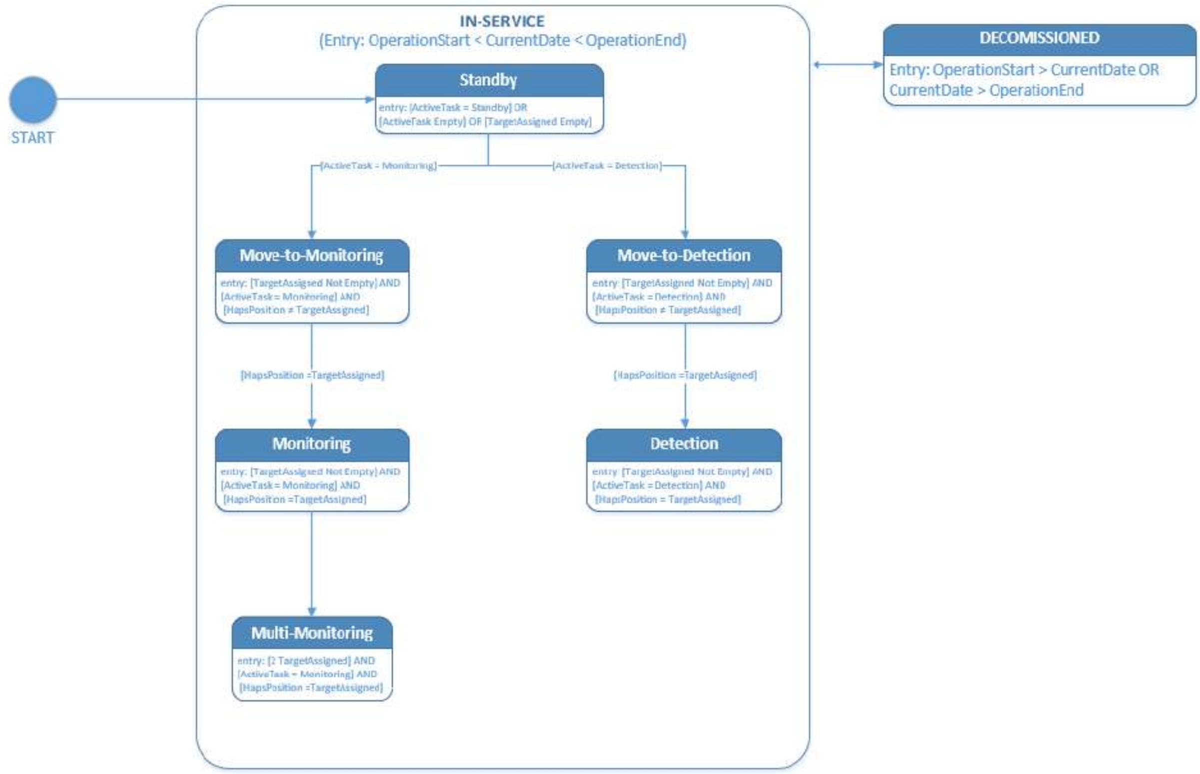


Figure 150 HAPS states machine

10.4. HAPS fleet requirements

HAPS-REQ-15. The assignation of the HAPS to the Point(s) of Interest (PoI) shall be done from the PoI with highest to the lowest priority until there are no more HAPS unassigned.

HAPS-REQ-16. The PoI with the highest priority without a HAPS assigned shall get assigned the HAPS with the lower ETA among the HAPS allocated to the Area of Interest to which the PoI belongs.

HAPS-REQ-17. In the case there are no HAPS allocated to the Area of Interest of a PoI unassigned, the simulator shall leave the PoI without HAPS and process the next PoI in priority order.

HAPS-REQ-18. The HAPS shall have the following configurable parameters:

- HapsId: integer.
- Area(s) of Interest assigned: Integer. 1 or more AoI assigned to the HAPS. If empty, all AoI are assigned.
- StartServiceDate: date in which the HAPS appears in the StartPoint and is eligible for assignments of PoI (only during its WorkingHours). The default hour is 00:00 of the day defined.

- OutServiceDate: date in which the HAPS is decommissioned. The default hour is 23:59 of the day defined. From that moment, the HAPS cannot get assignments.
- StartPoint: coordinates LAT/LON. Point where the HAPS will appear at StartServiceDate 00:00h.
- WorkingHours: (StartHour, OutHour) [0-23,0-23], StartHour > OutHour.

HAPS-REQ-19. The HAPS shall have a unique identifier during each simulation.

HAPS-REQ-20. The HAPS shall have one (1) or more Areas of Interests allocated for their operation.

HAPS-REQ-21. The HAPS shall monitor only Points of Interest that are inside their allocated Area(s) of Interest.

HAPS-REQ-22. The HAPS shall move with a constant TAS of 60 km/h.

HAPS-REQ-23. The HAPS shall take into account the direction and magnitude of the wind in the stratosphere to determine their trajectory and Ground Speed.

HAPS-REQ-24. If a HAPS is assigned to monitor a fire or is monitoring a fire, and there are other fires in radius of 0.21 degrees from the initial fire, the HAPS shall multi-monitor the original fire assigned and the next fire inside the radius of 0.21 degrees with higher priority.

HAPS-REQ-25. The HAPS shall follow the geodesic trajectory from their position towards their assigned target location.

10.5. Output requirements

HAPS-REQ-26. The simulator shall count the time each HAPS is on each of the possible states during the duration of the simulation.

HAPS-REQ-27. The simulator shall count the time each fire is on each of the possible states during the duration of the simulation.

HAPS-REQ-28. The simulator shall record each Point of Interest that is assigned to each HAPS during the duration of the simulation.

HAPS-REQ-29. The simulator shall provide as an output an Excel file with:

- Info: Start and End date, simulation step, HAPS TAS, Criteria for Fire Alert (duration, area), multi-monitoring radius.
- HAPS KPIs: list of all HAPS platforms with their summary of times in each status during the duration of the simulation.
- PoIs: list of all PoIs with their main parameters on each step of the simulation.
- HAPS: list of all HAPS with their main parameters on each step of the simulation.
- Fire Statuses: list of all fires with their summary of times in each status during the duration of the simulation.

FIRE-RES