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Deliverable D5.1
Inventory of pattern scenarios

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Abstract	The document includes a brief review of the latest wildfires affecting structures over the past few years, a synthesised summary of the lessons learnt focusing on factors, processes and consequences, and finally a schematic description of the theoretical standard basic 3D scenarios, which consequently reflect the lessons learned, to be considered for CFD simulations. These are complemented with the development of the corresponding 3D geometries which are delivered in FBX interchange format.

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1. About this deliverable

WUIVIEW stands for Wildland-Urban Interface Virtual Essays Workbench, and it is a project funded by the Directorate General for European Civil Protection and Humanitarian Aid Operations (DG ECHO) and coordinated by the Universitat Politècnica de Catalunya (Spain). The project objective is to develop a 'virtual laboratory' based on Performance Based Design (PBD) and Computational Fluid Dynamics (CFD) models for the analysis and assessment of the processes and factors driving structure affectation in forest fires. The results will serve as guidelines and recommendations of good practices for the protection and prevention of forest fires in European communities inserted in forested lands. The project is divided into 8 work packages, out of which work package 5 is devoted to the definition, study and modelling of forest fire scenarios affecting houses in Europe.

This document D5.1 is a compilation of the research activities within task A5.1 'Inventory of pattern scenarios' within WUIVIEW project, dealing with the identification of the potential microscale scenarios in forest fires affecting the **wildland-urban interface** (WUI) in Europe according to what has been observed in past forest fire events. The document includes a brief review of the latest wildfires affecting structures over the past few years, including some in the Northern countries, a synthesised summary of the lessons learnt, most of them as gathered in WUIWATCH project, focusing on factors, processes and consequences, and finally a schematic description of the theoretical standard basic 3D scenarios, which consequently reflect the lessons learned, to be considered for Performance-Based Simulations. These are complemented with the development of the corresponding 3D geometries which are delivered in FBX interchange format.

2. Introduction

2.1 The fire threat in the WUI

Forest fires affecting communities represent a rising problem in Europe. As the climate warms, hot and dry seasons in southern countries are lengthening and wildfires are behaving more often as real firestorms with huge intensities and large destructive potential. In addition, human pressure in Mediterrranean forests is continuously growing with an increase of ignitions and housing developments at the WUI. Therefore, WUI fires are posing tremendous management challenges in terms of civil protection and fire mitigation. These fires often exceed fire-fighters capacities, who have to respond simultaneously to wildfire suppression, community evacuation and structure protection, hence becoming self-protection a growing need. Furthermore, climate change is causing emergent WUI-fire prone zones in northern countries, whose policies and communities are not adapted nor designed to deal with large wildfires.

WUI fires have tremendous consequences in Europe. In 2007, forest fires raged across Peloponnese and southern Euboea (Greece) destroying several hundred structures, and claiming the lives of 84 people, including several fire fighters. In August 2016 a wildfire blazed Madeira Island (Portugal) spreading through the old quarter of the capital Funchal, forcing the evacuation of 1,000 residents, killing 3 people and entailing the destruction of 37 structures. In the same month of 2016 a fire started in Rognac, a town near Marseille (France), propelled by strong Mistral winds and quickly affecting several communities and cities, forcing the evacuation of 5000 people, destroying 25 houses and severely injuring 5 fire fighters. In September 2016 a forest fire in Javea (Spain) spread over 800 hectares near a large residential area, in a very popular tourist destination by the coast, entailing the evacuation of almost 2,000 people and severely affecting 20 houses. In june 2017 Central Portugal experienced the deadliest WUI fires in its history, accounting 66 deaths, 204 wounded, thousands displaced and around 1,500 houses severely affected or destroyed, in a series of almost simultaneous wildfires over Pedrógão Grande municipality. In July 2018 two simultaneous fires started in Attica Region, near Athens (Greece), one in Kinetta and other in Daou Penteli, near the densely populated residential areas of Neos Voutzas and Mati. As a consequence, the fire spread killed 102 people, wounded 187, destroyed nearly 600 houses and severely affected over 1,500. This is the deadliest forest fire in recent times after Black Saturday in 2009 in Australia. Over the past few years wildfires are systematically affecting northern European countries as well. In January 2014 the Laerdal fire (Norway) devastated the historic town of Lærdalsøyri (Unesco World Heritage), consuming at least 30 timber structures, displacing 300 people and injuring more severely to 50. In July of the same year, a fire spread over the county of Västmanland (Sweden), affecting 14,000 hectares of forested land and becoming the largest forest fire in Sweden's modern history. One thousand people were forced to evacuate, one person was confirmed dead, one was severely injured and several fire entrapments of volunteer firefighters occurred. All these episodes show that forest fires are a real threat on the rise, and a major concern for civil protection bodies in Member States across Europe.

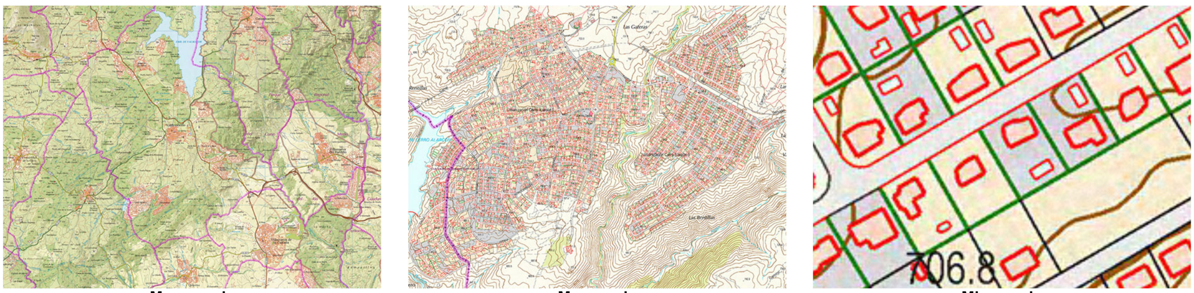
2.2 The WUIWATCH project

WUIWATCH is the European Observatory of Wildland-Urban Interface, a project also funded by DG ECHO in the period 2014-2016, which is a precursor of WUIVIEW. The project established a network of end-users (homeowners, practitioners, administrations, research entities, etc.) to share a growing database of lessons observed in forest fires affecting communities. Three international workshops took place along project lifecycle in which several subjects were treated, such as prevention, house vulnerability, human factor and fire fighting operations. A white book on fire protection in the WUI was edited and published. The main outcomes of the project and the materials produced can be found at www.wuiwatch.org

2.3 A trans-scalar approach

The complexity of a wildland-urban interface environment requires a systematic approach in order to understand the factors and processes that take place in case of a forest fire. To achieve this, a multi-scale approach was suggested in WUIWATCH project involving three levels of detail at three different scales of analysis (Fig.1), namely:

- The **macroscale**, is the spatial dimension and associated resolution for landscape risk assessment. Typically refers to scales ranging from 1:50,000 to 1:25,000 and spatial resolution of 10 to 50 m. This is the scale that is mostly used in the analysis of large portions of territory, such as provinces or municipalities. Settlements are considered as indivisible units and, frequently, assumed to be unburnable lands. Fuel models and fire spread models are of common use for fire management purposes, giving an overview of general fire behaviour, expected propagation speed and position of fire front over time. At this scale individual structures are not considered.
- The **mesoscale**, is the spatial dimension and associated resolution for community risk assessment. Typically refers to scales ranging from 1:25,000 to 1:10,000 and resolutions from 1 to 10 m. In this scale detailed maps of house occupation, street network and vegetation is regularly used. Houses are considered indivisible units and, frequently, assumed to be unburnable. Hedges, and ornamental plants are considered as blocks of vegetation. Fuel models are of no application and vegetation discontinuities are relevant in the simulation of fire spread, particularly the gaps due to the street and road network.
- The **microscale**, is the spatial dimension and associated resolution for the property risk assessment, such as lots and houses inside. Typically refers to very detailed scales ranging from 1:5,000 to 1:1,000 and submetric spatial resolutions. Detailed three-dimensional description of structures, garden elements, and other objects and materials is required for fire risk assessment. Complex simulation environments and tools are needed to estimate the potential sources of heat, the exposure of vulnerable elements and the expected affectation of structure components.



Macroscale (landscape) **Mesoscale** (community) **Microscale** (property)

Fig. 1. An example of the three working scales used for the fire risk assessment in Valdemorillo municipality, Spain.

This document, and the entire WUIVIEW project, is focusing on the factors, components and processes happening in the **microscale**, that is, the house and its immediate environment. This 'immediate' term refers typically to what is called the Home Ignition Zone (HIZ), corresponding to a buffer of 30 m surrounding the house. In this space the presence of vegetation, other structures, other materials and objects mostly —and primarily— affect the survivability of the house in case of a forest fire. The HIZ refers particularly to the surface occupied by the house as well, as the different surfaces conforming the structure shell may eventually receive firebrands, radiative heat or flame impingement from the closest fuel combustion. In practical terms, for the risk assessment of a property, the immediate space surrounding the house is that conformed by the lot limits, as it is within the property limits that the homeowner will take preventive and protection measures. The lot surface may or may not coincide with the HIZ, but generally speaking a property surface falls within the corresponding HIZ area of the house.

2.4 Fire phases in the WUI

Affectation of houses due to the presence of fire in the WUI is not an instantaneous process. Instead, there are several 'waves' occurring at different moments and at different rates which may overlap in time and with which render different consequences. Reading a WUI fire aftermath is sometimes confusing if at least four phases (see Fig.2) of forest fire interaction with houses are not considered. To better understand these phases, let us focus on a single house and observe the sequence of events around it over the time:

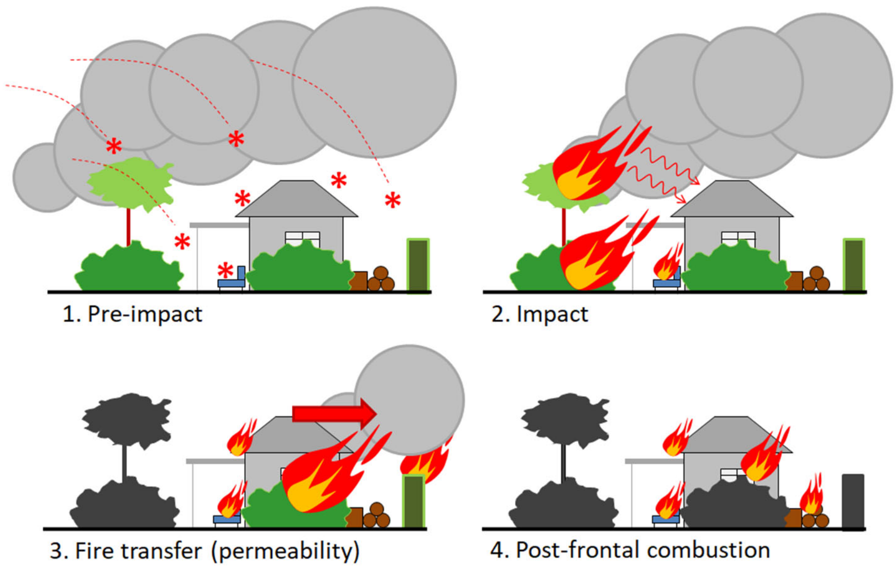


Fig. 2. The four phases of affectation of a forest fire in a WUI area, looking into the microscale.

Pre-impact is the phase in which a nearby fire front has not yet reached the house in the settlement. If such house is located within the forest fire zone of influence it is very likely that smoke and flying embers transported by wind are reaching the lot, the garden elements and the house. Firebrands are equivalent to airborne emissaries of the burning front and may arrive well before any flame is on sight. These firebrands are capable of setting fire in cured grasses, pine needles, hedges and ornamental plants and several other materials and objects present in the garden near the house or the house itself. In this pre-impact phase hot air may also reach the area, creating a desiccating effect on dead fuels and living plants, pre-conditioning such fuels before the passage of a fire front.

Impact is the phase in which a flame front is directly facing the house at such a distance in which flame impingement and radiant heat may affect —and eventually ignite— the components of the house, the vegetal elements of the garden and the several other objects and materials that are present in the lot (Figs.3, 4). This is particularly true for the lots and houses in the border of the settlement, directly facing a forested land (commonly addressed as 'friction').


Fig.3. A flame front impacts in one of the first houses in Mati fire, Greece.


Fig.4. Evidence of an intense fire impact in Llutxent, Spain..

Fire transfer is the phase in which a fire propagation occurs through the elements in the lot, commonly green hedges (Fig.5), trees and other vegetal elements, into the neighbouring parcels along the settlement. This 'permeability' to fire propagation may also happen through the new production and emission of firebrands from the burning elements in the lot into other remote parts of the settlement, particularly undeveloped unmanaged lots with cured grass and dense vegetation (Fig. 6).


Fig.5. A green hedge is spreading the fire across the settlement in La Nucía.


Fig.6. Fire transfer through undeveloped lots and green hedges in Benitatxell, 2016.

Post-frontal combustion is the phase in which all the objects, materials and house parts that ignited in any of the previous phases continue burning with or without flames for longer periods (Figs.7, 8) and which eventually can cause further affection or chained events (domino effect). In this phase a lot of energy and combustion gases can still be released.

Fig 7. A house keeps burning many hours after the fire pass in Mati, Greece.

Fig.8. Post-frontal combustion is observed in many objects and materials in Mati.

2.5 Why do our houses burn?

It is a recurrent question, why is it that some of the European houses, made of stone, clay or slate tiles, brick and mortar do burn in a forest fire? The answer is not an easy one, as there are many factors, processes and sometimes just little details that may be behind house affection or destruction. After the observation and study of several fires affecting the WUI, it became more and more clear that flying incandescent embers are a paramount agent behind house affection. Flying fire embers entering the house through open windows may start indoor ignition of curtains, furniture, papers or any other light material in the rooms. This may progress into full involvement of rooms and the eventual burning of the whole house structure. The presence of combustion of nearby objects and materials may entail the affection of window glazing (cracking, collapsing), hence giving way to the entrance of smoke, firebrands and flames produced. This is also true in the case of direct flame impingement onto window panes or other weak points within the house shell. Secondary or auxiliary buildings, such as garages, sheds or warehouses, generally are more vulnerable to fire embers, radiation and flame impingement and eventually may transfer the combustion to the main body of the house through internal doors, aisles, corridors or windows. Roofing is directly exposed to flying embers, radiation and even direct flame contact in a forest fire; the degree of maintenance and the accumulation of debris on the roof valleys and gutters are two of the suspected factors behind the entrance of fire in the attic, the involvement of the roofing structure and its eventual collapse. In many occasions, it is just little details what makes the difference between the survival or destruction of a house, such as leaving windows partially or completely open in the process of evacuation.

3. Past forest fires in the European WUI

One of the main sources of information about the factors and processes of houses affectation is the systematic survey, data gathering and detailed study of forest fires in the WUI. Information about meteorological conditions, fire behaviour, fire fighting and civil protection operations, victims and structure loss must be gathered in the aftermath of forest fires, preferably just within the first days after the event. A number of forest fires affecting WUI in Europe (Fig.9) are briefly presented in this document, with some details and lessons observed in the corresponding survey works that took place. They are:

- Funchal, Portugal (09/08/2016)
- Rognac, France (10/08/2016)
- Benitatxell, Spain (04/09/2016)
- Pedrógão Grande, Portugal (17/06/2017)
- Mati, Greece (23/07/2018)
- Llutxent, Spain (07/08/2018)
- Västmanland, Sweden (31/07/2014)

Fig.9. A synthetic map showing the ignition points of the recent relevant fires affecting WUI in Europe. Also marked, but not reported, is the urban conflagration in Lærdalsøyri, Norway, historic village famed for its well-preserved 18th- and 19th-century wooden houses. Dozens of residents were hospitalized. In Monchique, Portugal, a fire erupted on the 3rd of August 2018 and raged over 30,000, but only six structures were affected and no victims were reported.

3.1 Funchal, Portugal (09/08/2016)

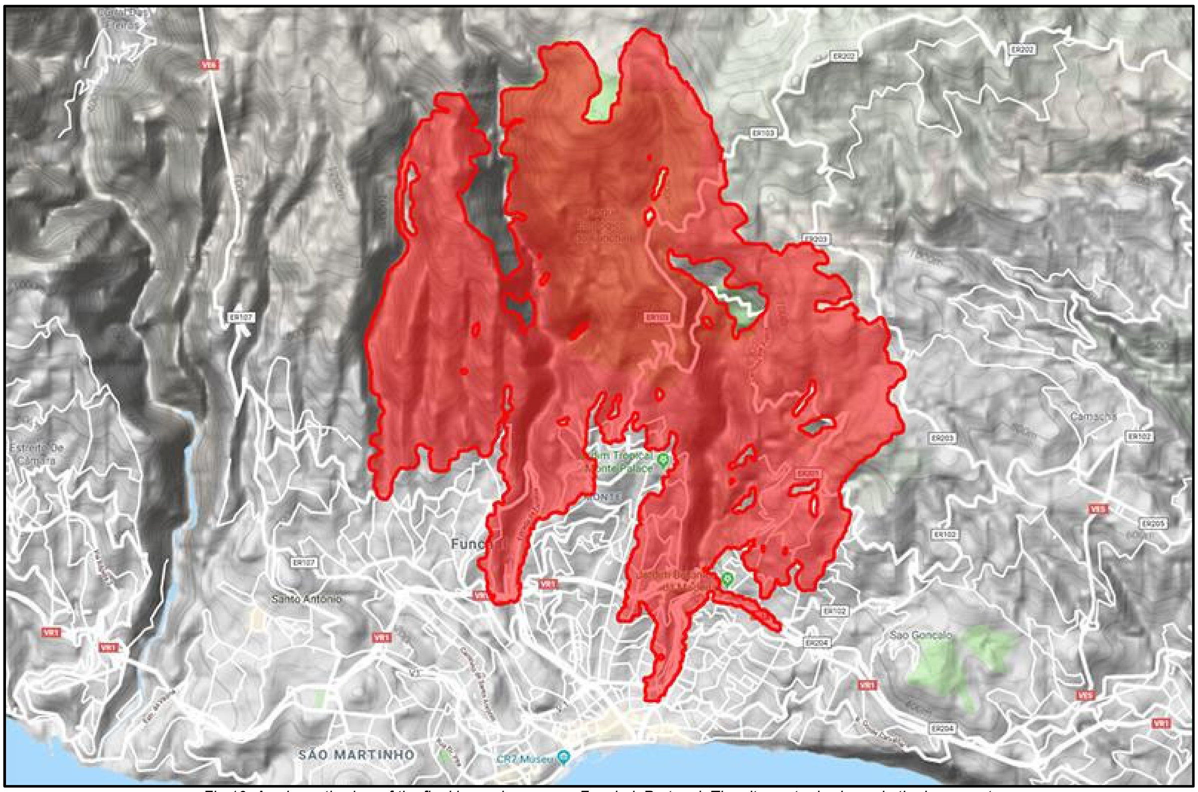


Fig.10. A schematic view of the final burned area near Funchal, Portugal. The city centre is shown in the lower part.

On the 8th of August 2016 a fire set by an arsonist in San Roque parish, not far away from Funchal city in the Island of Madeira (Portugal). Madeira was suffering a heat wave as never seen before, with sustained minimum temperatures of 28ºC during the night. People in Madeira was not accustomed to witness fires, as this is an island with a small record of historic forest fires. But these days, two large fires erupted almost simultaneously. The fire in Funchal area spread quickly sidewards, under winds abnormally blowing from North at 20-30 km/h and gusts of 50-80 km/h. In the first moments a number of houses are threatened by the fire, while smoke was spreading toward the city of Funchal. Early in the afternoon the fire front impacts on a water treatment plant, devoid of any prevention measure or protection installation, which is the focus of attention of firefighters as this station is providing water pressure to all the distribution network, including fire fighting hydrants. Given that in Madeira no aerial means are available, all the suppression operations and civil protection actions are performed by ground means. As the night is approaching, the fire front creeps down the slope and the smoke spreads over Funchal city and surrounding neighbourhoods, forcing the evacuation of 234 people of one of the affected Hospitals. The second day (9th of August) the fire front increases activity in two of the many ravines running in parallel to the wind direction, packed with fuel and with almost vertical walls which eventually catch fire laterally and affect the many houses on top. By that moment 36 structures are severely affected, another hospital is evacuated and a five-star residential lodge is also forced evacuation. At the end of the day, three people are trapped in a house surrounded by residential fuel (Fig.12) and some vegetation, two of them are impeded prostrated in bed, the third one attempts a rescue, and all three are killed on the spot. A large station of gas canisters just below is also affected by fire. This house has no direct access for firefighters, which can do little for the trapped people. At the same time a massive firebrand shower falls onto Funchal city and several houses are burned, which causes the movement of a number of firefighters. Well into the night, Choupana Hills five-star lodge (Fig.11) is hit by fire, and 22 of the 60 bungalows are destroyed. Nearby houses are also severely affected. In total, nearly 1,000 people were forced evacuation and a total of 154 houses were severely affected or completely destroyed.

Fig.11. One of the destroyed bungalows in Choupana Hills five star residential complex.

Fig.12. The remains of the house in which three people were killed, near Funchal.

Victims

Three deaths are attributed to the wildfire and over 200 people injured, 80 people had medical assistance in several hospitals suffering from burns and smoke inhalation, including two in a serious condition.

Structure affectation

A total of 154 houses were severely affected or completely destroyed. Most of them presented evidence of combustion from inside, with collapsed roofs. Many were surrounded by residential fuels, little orchards, unmanaged vegetation or eucalyptus forests. In general houses were made with average to poor materials and construction methods, particularly window glazing and roofs were the generalised weak points in structures. There was a remarkable exposure of houses to the very steep walls of ravines, particularly those placed around the edge. In some cases, house to house ignition was also observed. All the fatalities occurred inside structures. Affection of houses inside the urban fabric of Funchal were due to likely open windows of a population not used to forest fires (particularly a distant one).

Fig.13. A general view from the cable cabin of the house complex in which three people were killed (lower-right corner). Observe the narrow corridor in the lower part, the only escape to the streets which was compromised as well by the fire.

Fig.14. One of the houses hanging in the steep slopes of the ravines near Funchal. The fire displayed very aggressive behaviour in these parts.

Fig.15. A house completely destroyed with the collapsed roofing in Funchal fire, as a consequence of the fire that propagated from an attached auxiliary building.

Fig.16. One of the affected houses in the middle neighbourhoods of Funchal, which was affected by a dense shower of firebrands.

Fig. 17. A general view of several of the houses visited by fire in the lower part of the urban development in Funchal, 2016.

Fig.18. A view of the ravines with some fire runs in between, as a consequence of the action of firebrands. Erosion and runoff is a follow-up concern for firefighters.

3.2 Rognac, France (10/08/2016)

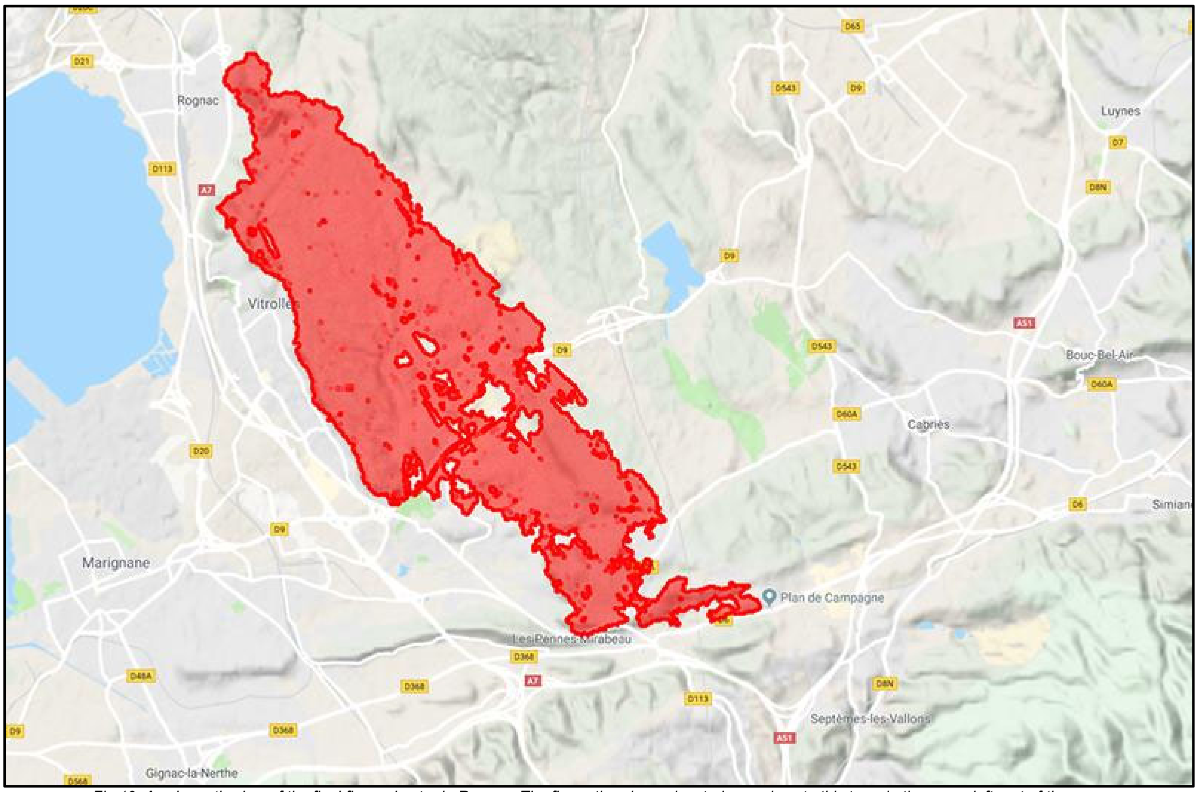


Fig.19. A schematic view of the final fire perimeter in Rognac. The fire outbreak was located very close to this town in the upper left part of the map.

On 10th August 2016 a fire erupts at 15:09 in the municipality of Rognac (Fig.19), not far away from the Marignane airport in Marseille, France. The cause of the outbreak is a cigarette negligently casted onto a pile of dry vegetal debris in an area under works. Mistral wind is blowing from Northwest with gusts of 50-80 km/h and quickly impels the incipient fire towards a densely populated area with many services such as the international airport of Marignane, several highways, the TGV train station, the Plan de Champagne large shopping area and a 400 kV power line crossing the zone. Vegetation shows evidence of a long drought period, with no rains since April, not recorded as such since 1954. That day 4 of the Canadair water bombers are inoperable as they are under reparation of the landing gear. However, another six planes and 1 helicopter join the intervening air fleet. Flame front spreads at phenomenal speeds, with registered peaks up to 7 km/h, projecting flying embers ahead, and soon reaching Campanile Hotel in less than two hours from fire start. At 19:00 an evacuation is ordered in the Pennes-Mirabeau, area which is placed right in the main axis of fire propagation. Fire manages to jump into the median strip of the highway and run along, threatening the Estaque area. At 20:00 the airport operations are suspended and the main highways (A7 and A51) are closed to the traffic. By that time firefighters apply tactical fire in two critical points in order to protect the large shopping area and the North city bounds of Marseille. Firebrands and spot fires are reported at distances up to 1 km ahead. By 22:00 the fire runs entirely out of control. It is early in the morning of the following day when new forces join the suppression efforts and by noon the fire is controlled.

Fig.20. View of one of the destroyed structures, a green house refurbished as house.

Fig.21. One of the severely affected houses, with evidence of affection due to firebrands and the combustion of local vegetation near the structure.

Victims

No fatalities are reported in this fire. However, 33 people suffered smoke intoxication (20 firefighters, 10 policemen and 3 civilians). Around 1,000 people were forced evacuation, and 7,000 were directly or indirectly affected by the episode.

Structure affectation

This fire affected 156 structures, out of which 24 were completely lost, 15 partially destroyed and 117 suffered slight to moderate damage. Main destruction was observed along the fire propagation axis primarily, and one structure was severely affected outside fire perimeter, most likely because the action of flying embers entering the house through an open window. Other main structures of services and business were also affected, such as a school and a car dealer.

Fig.22. A newly refurbished house destroyed in the main path of the fire spread.

Fig.23. Given the distance to the main fire front, this structure is likely to be affected by long-distance projected firebrands. Several other houses in the area were unaffected.

3.3 Benitatxell, Spain (04/09/2016)

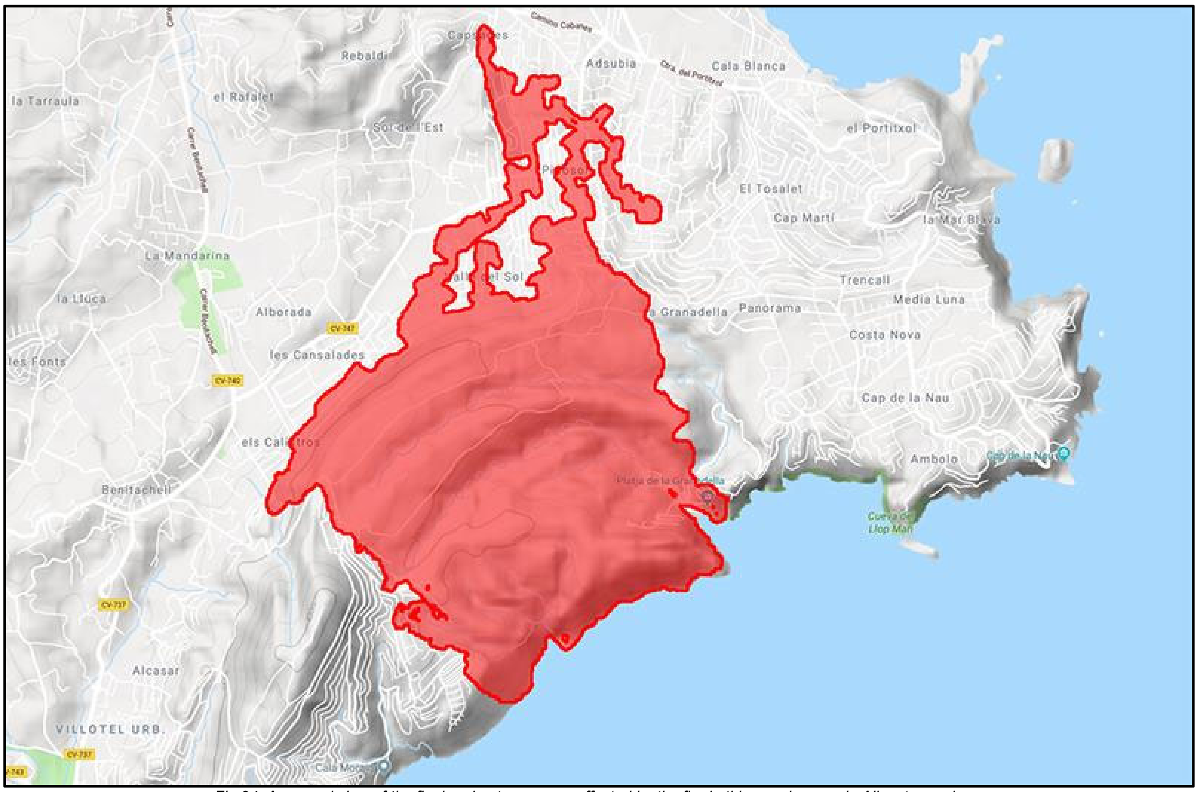


Fig.24. A general view of the final perimeter an area affected by the fire in this popular area in Alicante province.

On the 4th of September 2016 a forest fire starts at 15:31 in the municipality of Poblenou de Benitatxell, Alicante (Spain) as a consequence of arsonism in the place known as Puig de la Llorença, in a day with record temperatures of 35ºC and low relative humidity below 25%. At that time the wind is blowing at a speed of 24 km/h from Southwest, wind gusts of 52 km/h, pushing the fire along the ridge towards the Northeast and threatening several settlements in the area. In the same day, two other important fires are happening in Bolulla and Moixent, which are requesting a good number of firefighting forces. Although the incipient fire in Benitatxell is quickly attended, some of the deployed firefighting units are relocated to the other fires, just before a reactivation of the firefront by a spot fire around 17:20, giving an intense run and projecting a massive shower of fire embers into the nearby settlements. In this moment the wind and the prevailing slopes are aligned, creating an elongated fire perimeter which is percolating in the Valle del Sol and Pinosol settlements up to 2.5 km thanks to the spot fires which are catching fire in undeveloped lots, forested corridors and gardens (Fig.25). This creates multiple emergencies to be attended to, by the time that wind is rolling Westerly causing the opening of the right flank. Evacuations of the affected settlements are ordered, and continue until 03:00 am. Some of the neighbours refuse to leave their houses for which the intervention of the police is required. The Rodat Hotel is ordered evacuation by that time, where guests are asked to gather and leave together.

Fig.25. A general view of the Benitatxell fire aftermath and its penetration in one of the most populated housing areas in Pinosol.

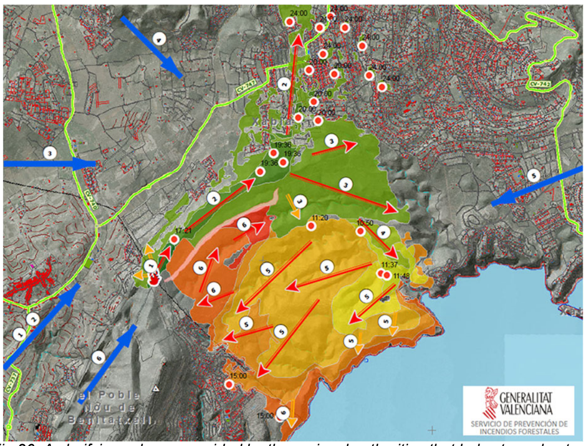


Fig.26. A clarifying scheme provided by the regional authorities that helps to understand the many changes in wind direction and fire propagation.

The wind keeps in a sustained 25 km/h over all night and this is a challenge for the ground fire crews that try to attend all the generated fire outbreaks and corresponding emergencies. Some of the LPG tanks in the private lots start jet fires. Some of the people are disoriented because the thick smoke and need for assistance in the evacuation process. At 04:00 am the deployed agents report that everyone is finally safely relocated. Electric power supply is shut down for safety reasons as requested by firefighters. Early the next morning the fire shows a dormant behaviour favoured by a thermal inversion, but at 09:00 wind picks up again from Northwest, blowing with intensities up to 30 km/h and driving the right flank of the fire and generating new spot fires, running down a ravine towards Cala Granadella in the coastline. Around 11:30 the wind turns direction from Northeast-East reactivating the fire front, generating new spot fires in the opposite slope and giving an intense and fast run towards the Southwest threatening another set of housing areas in Cumbres del Sol, which is hit around 14:00. Given that this settlement has sparse vegetation the propagation inside causes less affectation of structures (Fig.29). Finally, a new turn of wind direction, blowing from the Southwest, pushes the fire against the already burned land at the Northeast, completing the final spiral shape of the front evolution.

Victims

No fatalities were reported in this event. Around 1,400 people were finally forced evacuation. Three evacuees reception centres were set up in schools and sports centres, operated by Red Cross Spain and the Military Emergency Unit. Many of the affected population were elderly retired residents from other countries. According to Red Cross Spain, 470 people received medical care and 3 were finally transferred to hospitals.

Structure affectation

Around 200 structures were finally visited by fire, most of them due to the spotting that happened late on the first day. Only three were reported severely damaged (Figs. 27, 28), and none had structural affection. The houses in all of the 16 settlements in the area are high standard constructions and the street network have durable pavement and is well maintained. However, some of the severely affected houses had accumulation of residential fuels close to the structure and, in other cases, windows were left open despite the fact that evacuation took place with relatively enough time. Several of the secondary structures in the parcels were affected by the combustion of nearby ornamental vegetation, more in particular green hedges of flammable species. The active protection of the houses was challenging for firefighters, primarily due to the number of disparate emergencies that happened across the area during the night of the first day. Some of the structures displayed clear affectation of window glazing, mainly due to the closest fuels (vegetation, debris, objects, materials) under combustion. In general, most of the structures well endured the passage of fire and the massive shower of firebrands. None of the structures showed roofing affectation or collapse.

Fig.27.This house received the impact of the left flank of the approaching fire. The existing residential objects and materials entailed the ultimate affectation of the house.

Fig.28. Another house severely affected in the interior. Evidences point to an entrance of firebrands through one of the windows that, presumably, was left open.

Fig.29.The aftermath of a fire run in Cumbres del Sol. The vegetation in this settlement was more sparse, so the observed house affectation was lower.

Fig.30.One of the several LPG tanks exposed to the combustion of surrounding vegetation.

3.4 Pedrógão Grande, Portugal (17/06/2017)

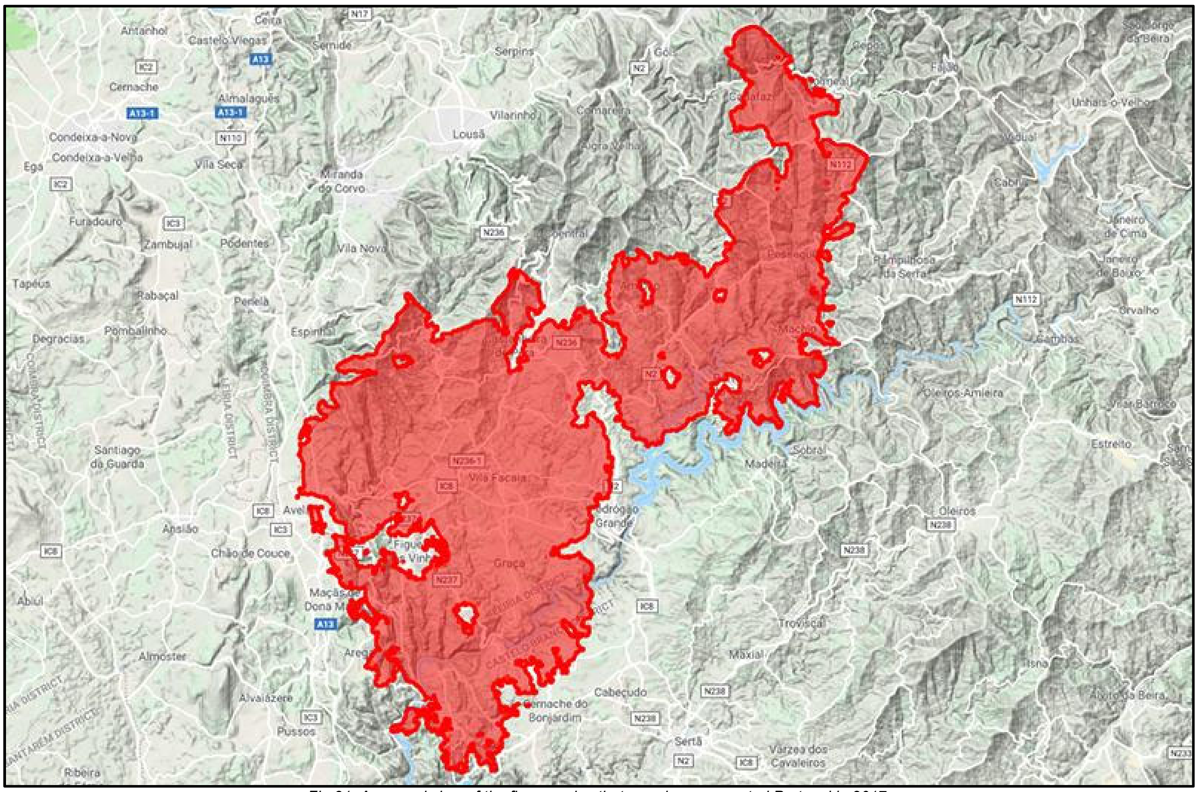


Fig.31. A general view of the fire complex that raged across central Portugal in 2017.

On the 17th of June 2017 a battery of dry thunderstorms passed across Central Portugal leaving a trace of lightning strikes some of them entailing fire outbreaks. That day, five fires erupted (Cabecas, Moninhos, Pardieiros, Góis and Pedrógão Grande) creating a forest fire complex, out of which the one in Góis and the one in Pedrógão entailed together one of the deadliest episodes in Portugal History, with 65 fatalities and over 46,000 hectares burnt. The country was suffering a long and deep drought period, entailing the hydric stress of pine and eucalyptus stands and the very low moisture content of the fine dead fuel on the ground. The 17th was a record in temperatures, reaching 46ºC and relative humidity below 25%, coupled with high atmosphere instability and the presence of dry thunderstorms who eventually entailed dramatic changes in wind direction and speed. The Pedrógão fire started around 14:30 in Escalos Fundeiros, the first in a series that happened in different municipalities and that developed a devastating run in the afternoon of the same day. The origin of the fire is electrical failure of a medium-voltage power line without protective strip. In the initial phase of the fire front was spreading to a moderate to high speed, giving eventual crowning and posing difficulties to firefighters that tried containment in the flanks. By 14:52 a second alarm was received of a fire caused by a lightning strike in Fonte Limpia, municipality of Góis. The wind was generally blowing from North to Northwest at moderate speed but increasing intensity. By 16:00 the existing atmospheric instability starts to influence the air flow, increasing intensity and entailing strong wind gusts which boost fire activity and firebrands projection at long distance creating new fire outbreaks. By 16:50 wind starts rolling towards North to Northeast component. The fire plume is showing indications of influence of the convective instability, which eventually could entail a downburst. By 18:00 the wind direction changes rapidly to East to Northeast, increasing speed, pushing the firefront towards Troviscais and the industrial estate of Pedrógão Grande and developing a *pyrocumulus*. By 19:00 the wind turns more erratic and stronger as a result of the formed plume feedback. At 20:00 it is reported a *downburst* due to the collapse of the plume, which eventually caused a dramatic change in the fire behaviour, spreading the fire in all directions at phenomenal speeds. This event triggered the run away of many of the villagers in the area. Simultaneously, this rapid spread outrun a group of people in their vehicles in the E236 road connecting Castanheira da Pera and Figueiró dos Vinhos, who were trying to escape the fire blast, causing a major entrapment and the killing of 34. The next day, the fire scorched the surroundings of Castanheira da Pera and reached Figueiró dos Vinhos, continuing general spread towards South. In the afternoon, a new increase of activity rendered a burning rate of more than 1,000 hectares per hour, at spread rates near 4 km/h. The 21st of June, four days after the outset, the fire had burned way over 30,000 hectares. It was finally declared extinguished at 16:43.

Victims

This complex wildfire claimed the lives of 65 people. Out of these, 34 perished in the car entrapment that happened in the E236 road. More than 200 people were injured. Nine people left the safety of the house in the last minute as a reaction to run away from fire, and did not survive. In some cases, people who stayed in settlements and towns survived the passing of the fire. According to reports, 24 of the victims were 60 years old or older, and 9 of the fatalities were younger than 15 years old. In several places, survivors found refuge for their lives while staying inside pools or open water tanks. Many other cases are reported of survivors staying inside their homes, taking care of the ignitions that happened around the structure

Structure affectation

According to a detailed study carried out by ADAI-CEIF, more than 1,000 structures were affected in this large fire, most of them were support structures, such as sheds, warehouses or barracks but a 25% were houses for permanent or temporary residents and 91 were completely destroyed. According to this research, more than 60% were ignited by landing fire brands, whether onto the roofs or through the windows. The age of the structures and the degree of maintenance played a critical role for their survivability, as well as the presence of survivors enduring the passage of the fire and attending the little ignitions around the house. The municipalities most affected by the fire were Pedrógão Grande, Figueiró dos Vinhos and Castanheira da Pera, coinciding were the fire acquired most intensity during the first days.

3.5 Mati, Greece (23/07/2018)

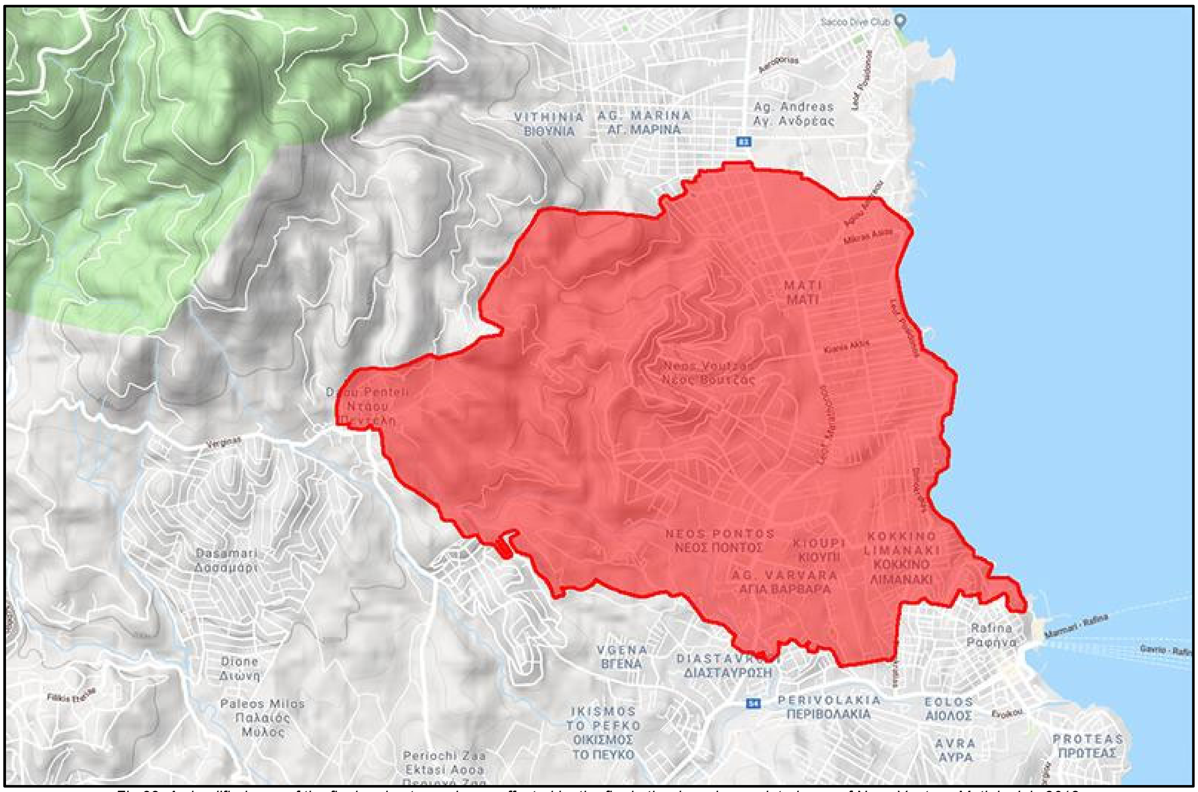


Fig.32. A simplified map of the final perimeter and area affected by the fire in the densely populated area of Neos Voutzas-Mati, in July 2018.

On July 23rd 2018 a fire starts at 16:38 in Daou Penteli, a small residential area within the Northeast part of Attica region (Greece), not far from Athens, as a consequence of reported negligence by a man burning some vegetal debris. In the same day, around noon, a first wildfire happened in the West Attica near the city of Kinetta potentially threatening its population and an oil refinery. This event entailed the deployment of a good number of fire fighting forces and aerial means to that area, which is separated 70 km straight line towards the West from Mati. In the area of Mati, the days before the incident, several episodes of rain were observed. The forest fuel, both live and dead, presented an unusually high moisture content for the moment in the fire season in Greece (end of July usually presents much lower fuel moisture content readings), with readings of around 100% in most of live fuels (Xanthopoulos et al., 2019). Besides, the wind pattern was unusual as well: at this period of the year the local Meltemi wind is blowing from Northeast or North, but not from the West or West-Northwest, as observed on that day. Strong winds, between 80 and 100 km/h, cancelled most of the benefits of a relatively high moisture in the fuel bed.

The fire front rages through well cured high grass and quickly affects some structures, escaping through a mild rugged terrain covered with pine forest regeneration and sparse shrubs. In less than one hour the intense fire front impacts on the first houses in the West part of a residential area, Neos Voutzas. The fire front continues a downslope fast run through ravines, engulfing dense pine stands and finally jumping perpendicularly over Marathon Avenue (Fig.33), a four lane highway which separates Neos Voutzas from the densely populated area of Mati. Showing indicators of extreme behaviour, the fire continues burning through a mixed pattern of houses and vegetation, mostly and particularly thanks to the projection of massive shower of firebrands.

Fig.33.The moment in which the forefront passes through the 4-lane Maraton Avenue highway from Neos Voutzas (to thee right) to Mati (to the left)

Fig.34. An aerial view of the Mati aftermath, showing all types of structures affected.

Nearly 4,000 people are directly or indirectly affected in the event, out of which a majority manages to escape on their own through the narrow streets and roads, as no evacuation order is set out. Others run for their lives towards the sea as a last resource, both by car and by foot, but only 700 could make it as there were just a few access points to the safety of water in a coastline mainly dominated by a cliff. One of the access points is collapsed by cars in their attempt to quickly reach the sea, creating a deadly traffic jam across the neighbouring streets. Simultaneously, a group of 26 persons are trapped between fire and the cliff in their attempt to find a safe exit, finally perishing on the spot embracing each other. Some hours later, a small fleet of volunteering vessels rescue most of the people who waited helplessly in the water, some of them badly injured, for some sort of aid. As a consequence, 78 people are reported dead that same day and many others are injured and being transferred to hospitals.

Victims

This forest fire caused 102 fatal victims —amongst them 11 children— and 187 people were injured. In the same day of the events, 78 are reported dead, 3 inside structures and all the others in the outdoors. Out of them, 33, die in Posidonos area (13 reported drowned in the sea). A fire entrapment happened in Kokkino Limanaki, killing a group of 26, who appeared embraced each other. A girl in flames falls 15 m to her death from a cliff. Another 4 are killed in Panos St. in Mati, near their home, two of them children. Besides, 7 fatal victims are found in Neos Voutzas and a 6 month old baby dies while transferred to the hospital. Many others (23) died days or weeks after in hospitals as a consequence of their burnings. This is the recorded deadliest forest fire in recent times, second to Black Saturday episode in Australia in 2009.

Structure affectation

This fire accounted for nearly 2,000 houses affected (Fig.34), out of which nearly 600 were entirely destroyed. Most of the structures present in the area of Neos Voutzas-Mati are residential, with a few other buildings used as warehouses, sheds, garages and secondary cottages within the same parcel. In the area all types of buildings are found, mostly single homes erected by owners in the 60's and 70's but also new villas, hotels, blocks of flats, camp cottages or military barracks. Despite of the used building materials, shape and methods, there is no clear relationship between these factors and the degree of destruction. Indeed, almost all types of structures present were affected at a certain degree.

Fig.35.The first house severely affected by the fire, in Daou Penteli.

Fig.36.One of the hundreds of structures severely affected or completely destroyed in Mati. Many of the houses showed indication of combustion inside the building.

In this area, the type of roofing varies greatly. The most frequent are flat and gable roofs, with a variety of shapes found in villas (hipped, cross gabled, simple hip etc.). Roof coverage also varies from clay tile shingles, slate tiles, flat concrete or metal roofing amongst others. Roof structure is frequently made of wood, particularly in single houses. Glazing is generally generous in size, mounted on plastic, metal or wood frames. It is frequent to see single pane glazing as a reminiscent from the 60's and 70's, while new villas and blocks of flats frequently have double pane for thermal and noise insulation.

In Daou Penteli, where the fire started, just four buildings were affected, one of them severely. In Neos Voutzas just a few houses were totally destroyed, particularly in the lower part of the settlement near Marathon Av., but many others were affected. It was in Mati where the destruction took place in a more generalised pattern. Particularly where the fire made the three entrances in Mati as a consequence of the downslope runs along ravines in Neos Voutzas a higher degree of destruction is observed. In the central part (sector 8), as mentioned, along Pefkalis and Akropoleos streets, where a long plot of pine and shrubs burned violently; in the South part (sector 10) all the area between Fisiolatron and Panos street, mostly due to the fire run along the ravine ending in Psiloriu street, which affected the EOF Fisiolatron residential area, with several cottages inside. This area had another jump into sector 11, near the coast, with several houses destroyed and where the group of people was trapped; in the North part along Egeou and Mikras

Asias streets, which received the fire run from Manou Katraki ravine; and all around the area where buildings are destroyed or affected separately. According to the fire patterns observed, most of the destruction happened by local burnings of fuels due to ignitions caused by firebrands. Local fuels had a direct and clear role, particularly those touching or near the structures. But several other buildings were affected without any vegetation in the surroundings, or particular flats in a block; this points at open windows left in the run away, the presence of other flammable materials or a combination of the two. Also, there are indications that firebrands played a key role in the ignition of houses through the roofing.

Fig.37. The firefront raged towards the coastline engulfing houses and people. The sea was not a guarantee of survival. Many affected houses have their roofing collapsed. The structure, in many cases, is made of timber.

Fig.38. One of the several blocks of apartments in Mati affected by the fire, in this case by fire embers entering through open windows, as no immediate vegetation is seen.

Fig.39. Many of the houses, flat roof, were built in the sixties and seventies, with much less quality on materials and construction standards, which ended in major affections.

Fig.40. The pos-frontal combustion inside the houses entailed in many occasions the severe affectation of the building structure, which was assessed by inspectors in the few days after the event.

3.6 Llutxent, Spain (06/08/2018)

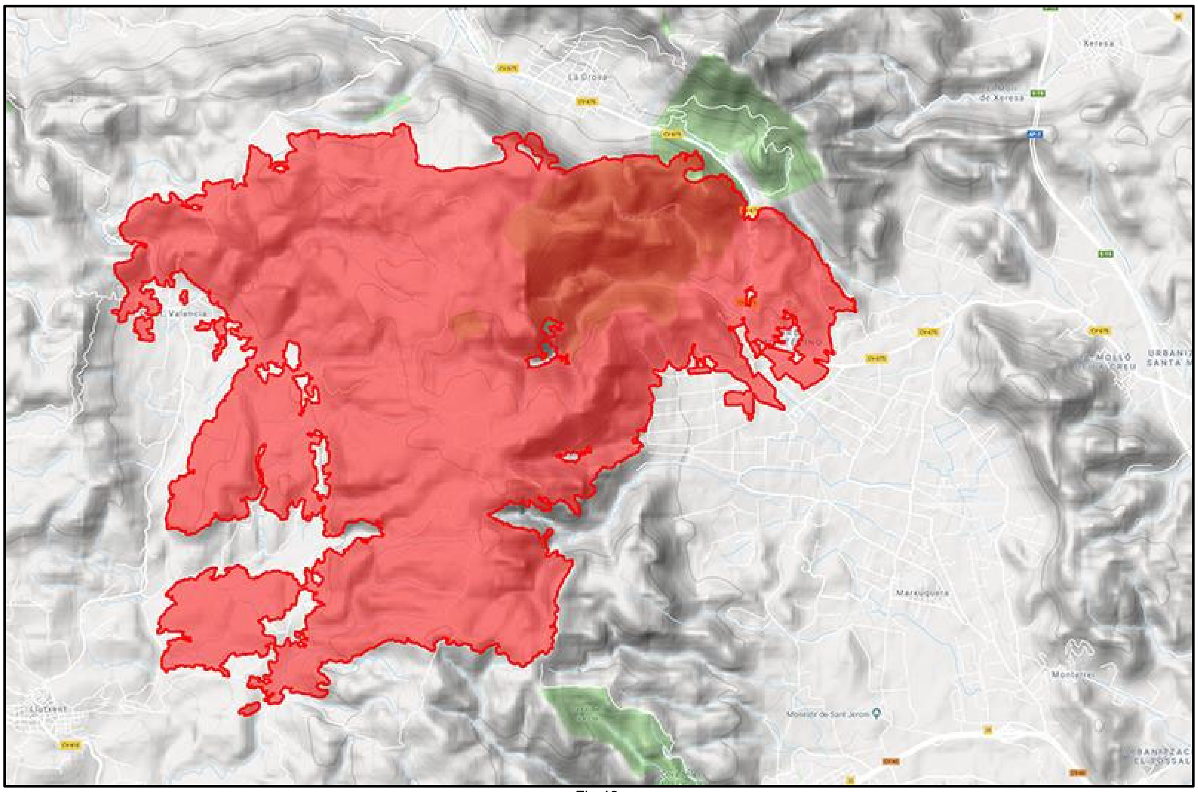


Fig.42.

On the morning of the 6th of August 2018 a latent lightning strike of a thunderstorm the night before, activates a forest fire around 15:00 in a rather inaccessible slope in the municipality of Llutxent, Spain. The location and East winds favours a rapid and intense evolution of the incipient fire heading towards West, so airborne firefighting resources are sent immediately. Despite the great efforts done by helitacks, the weather conditions boost fire activity in the head, and more resources are needed.

Fig.43. A convective behaviour of the Llutxent fire as an indicator of the atmospheric instability.

Fig.44. The view of the fire from the advanced command post in Pinet, showing a very active and destructive behaviour. The main settlements and towns were evacuated.

At that time, on the same day, another five fires erupted, many of them as cause of lighting strikes. During the day, the wind increases speed and turns direction, blowing from South to Southeast bringing the already developed right flank towards North to Northwest. The municipality of Pinet is mostly affected. The existing atmospheric instability helps to quickly create a massive convection column (Fig.43) that can be seen kilometers around. The towns of Barx and La Drova are evacuated preventively, summing 2,500 people displaced. The fire continues propagating in the same direction and the build-up of the fire plume is threatening with a potential downburst. The decision is taken early in the night to evacuate the nearby settlements of Rochera, Las Cumbres, Montepino and Montesol towards the sports centre of Llutxent. Red Cross Spain set up a reception centre in Raval Gandía Pavillon. The next day the winds start rolling in the Northeast direction making the left flank to progress towards Pinet town, where the advanced command post is located. The 163 people in Pinet and the ACP are evacuated. By late afternoon, the fire is conducted towards the settlements already evacuated the day before, engulfing houses and giving little chances to firefighters for their protection. In the South, the fire front spreads again towards Llutxent. A total of 3,270 hectares are burned, and the fire is reported completely extinguished by 13th of August.

Structure affectation

Around 50 structures were affected in 3 of the settlements engulfed by flames in the plume collapse event on Tuesday the 7th late afternoon. Out of them, 10 houses were completely destroyed (Figs.49, 50). In the aftermath in field survey and structure loss assessment, many of the houses in the border with forested area (dense pine stands with understory) that suffered direct impact of flame front did not resulted in noticeably affectation, while others ended in severe affectation due to the combustion of the immediate materials and objects (Fig.48). The fact that the evacuation was ordered the day before resulted in better house configurations, particularly in regards to windows that generally were left closed and in many cases with the blinds shut. That definitely added a degree of protection (Figs.45, 47).

Fig.45.One of the affected houses in the upper part of the settlement of Montepino. The pine stand at the left created a high intensity exposure and projection of firebrands.

Fig.46.One of the houses receiving direct impact (radiation) over the roofing and affecting the insulation layer in the eave and transferring combustion into the attic.

Fig.47. This fire run across the pine stand consumed most of the fuel in the pine crowns and developed an intense firefront. Despite of this, many of the houses were unaltered.

Fig.48. A house severely affected in Montepino settlement. Post-frontal combustion of the many objects and materials in the terrace involved, eventually, the upper part of the building.

Fig.49. One of the few timber structures that was burned down to ashes.

Fig.50. A second wooden structure completely destroyed.

3.7 Västmantland, Sweden (31/07/2014)

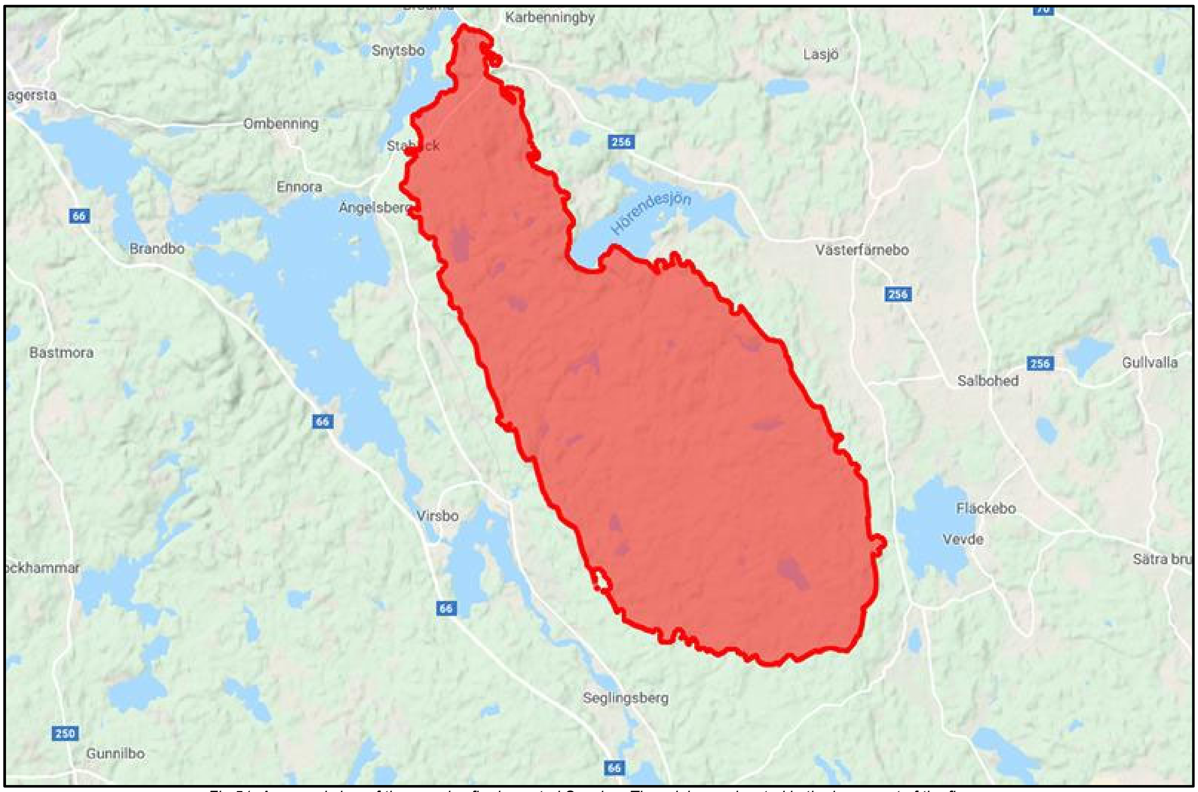


Fig.51. A general view of the massive fire in central Sweden. The origin was located in the lower part of the figure.

On the 31st of July 2014, around, 13:29 a call is received in the emergency service in regard to an incipient fire that broke out from a soil reparation machine near Seglingsberg, between Surahammar and Sala in the county of Västmanland, central Sweden. The first crew of firefighters is sent to the wrong place, so initial attack over the fire was delayed some precious minutes. Västmanland is a county bordering to the counties of Södermanland, Örebro, Gävleborg, Dalarna and Uppsala. The region was suffering from a long and deep drought period, affecting live and dead forest fuels, including moss in the ground. The first day the wind was blowing from the Southwest at 19 km/h which pushed the fire towards Öjesjön lake, burning 150 hectares. The second day the fire continued its run towards the Northeast and surrounding the lake, expanding to 700 hectares. In the morning of the third day the wind rolled to Southeast component, almost 90º, and the left flank turned into a wide front and aggressively spreading the fire towards the North. Two tactical burnings were applied ahead of the main propagation in order to contain the fire front, one in that very night and the second in the following day in the afternoon. On the third day, the fire had already burned 2,000 hectares, and in the fourth day it increased to 3,000 hectares. By monday 4th of August 2014, around noon, a phenomenal run towards North-Northwest took place, with the generation of a dense plume by 16:00 hours which created an out of control scenario. The average rate of fire spread was 48 m/min with (almost 3 km/h) peaks of 100 m/min (6km/h), and projection of fire embers was observed at distances over 2 km ahead of the fire front, jumping over the Snyten lake. According to the observed fuel, most of the fine and medium particles in the forest, the understory and the ground fuels (moss) took place in the propagation. The fire ran over several housing areas, creating complete destruction of several dozens, particularly in the town of Stabäck which was in the main path of the fire run. A person was killed and another one was severely injured. By August 11th the fire was under control, but it took several months, until April 2015, to completely extinguish the smoldering lands.

Victims

One person was reported dead and another one was seriously injured.

Structure affectation

There were 71 structures destroyed. The town of Stabäck was one of the most affected housing areas, which received the fire front impact on 4th of August. Despite the violent impact of the fire, no permanent dwellings were destroyed.

Fig.52. A view of one of the historic buildings reduced to ashes.

Fig.53. The majority of the houses are made of timber. Some survived the pass of the fire.

Fig.54.This photo shows some of the materials and objects that can be found around the houses in the area of the fire.

Fig.55. A very explicit image that shows the phenomenal fire progression on the 4th of August 2014.

4. Lessons learnt on the WUI microscale

Following, a distilled set of practical lessons observed in the fires reported in the previous section, and sometimes supported by laboratory experiments, are briefly presented. These are the baseline for an in-depth understanding of WUI microscale scenarios, factors and processes.

Part I. About the house

A house is a building serving as home to humans. Other secondary buildings, such as sheds, garages or warehouses, may be present either attached or detached from the main house, providing different services and uses. Following a set of factors and components which are most involved in forest fires and the affectation of structures are presented.

4.1 Location

- Location of the lot where the house is installed in the landscape plays a key role in the type, extension and intensity of exposure to flame fronts, fire embers and smoke. Indeed, houses placed in the midslope, ridges or hilltops are potentially more exposed than those located in the lower parts, wide valleys or flat terrain.
- Houses placed in saddles or box canyons are more exposed to wind channeling and acceleration, hence it is more likely to receive denser smoke, showers of firebrands and more intense fire runs.

Fig.56.Three locations of housing with three different exposures to potential fire runs in Ibiza Island (Spain). The one placed on the hilltop is exposed to an eventual approach of a fire front from several directions.

Fig.57.A number of houses in Neos Voutzas settlement (Greece) were placed on top of the slope and exposed to intense fire runs through ravines in the 2005 fire.

- In case that the house is part of a community, lots corresponding to the settlement fringe are potentially more exposed to flame fronts, of approaching fires than those placed inside the settlement. In case of an intermix of houses and vegetation, inner lots are exposed to the combustion of surrounding vegetation, commonly ornamental plants, hedges and vegetation covering undeveloped lots. In case of houses placed inside a dense urban fabric (cities, towns, housing developments), there is not such an exposure. In all cases, however, there exists likely exposure to firebrands and smoke from a nearby developing wildfire. This is referred to as the ‘zone of influence’ of a wildfire.

Fig.58. The building at the left in this settlement of Ibiza is in direct friction with forested area; the second one, at the right, shows some friction with internal vegetation.

Fig.59. An urban fabric usually provides more protection of buildings located in the interior (centre) than those placed in the border with forested area (left).

4.2 Type of house

There are many types and configuration of houses, but a rationalised classification is needed for a systematic approach. In this document the classification and naming followed in the TABULA[1] project is adopted. According to this initiative, a first level of classification into five general types is described:

SFH Single Family House
TH Terraced House
MFH Multi-Family House
AB Apartment Block

The classification provides additional levels according to the country, region and construction year class (i.e. before 1960, from 1960 to 1980, from 1980 to 2000 and after 2000), so rendering further levels of detail. Each resulting class and subclass has an associated record about the used construction materials, methods and elements, giving photographic examples. In this document, for the sake of simplicity and clarity, just the general types of houses (as listed above) and the four mentioned age classes which are commonly exposed to forest fires are considered.

To this classification it is required to add light constructions and informal settlements made with poor quality or inadequate construction materials and methods and which are extremely vulnerable in case of a forest fire. These dwellings are commonly associated to specific social strata, appearing in some parts of our territories or intermingling within other classes of housing settlements.

Recently, in WUI areas, movable dwellings are also representative. Although not considered as true standing structures, they are commonly part of the urban fabric and hold people, although in

[1] *Typology Approach for Building Stock Energy Assessment http://episcope.eu/building-typology*

some cases just temporary and should be considered in the risk assessment as they are also very vulnerable to forest fires.

4.3 Roofing

- Roofing is one of the components mostly related to house survivability in case of a forest fire. As observed in other non-EU countries, the roof is one of the parts of the house most exposed to an incoming flame front, the associated radiation and eventually the landing firebrands.
- There are different types of roofing and associated geometry, but all of them offer one or more planes (slopes), at a certain inclination and in most of cases intersecting between them. This geometry and intersections create ridges, hips and valleys, affecting the local circulation of air, the exposure to radiative heat and the eventual accumulation of debris. The most common types observed in forest fires in Europe are gable roof, hip roof, intersecting roof and shed roof. In some countries (i.e. Greece) flat roofs are also commonplace. Modern houses may offer complex geometries and combinations of the above.

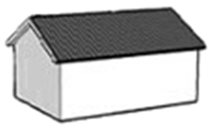
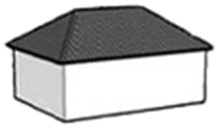
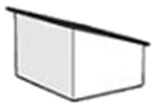
				
Gable roof	Intersecting roof	Hip roof	Shed roof	Flat roof

Fig.60. Some frequent tipologies of roofing found in Europe.

- Roof maintenance is as important as roofing type and material when it comes to evaluating its resistance to heat sources.
- Roof under overhanging tree branches, particularly pine trees, tend to accumulate fine fuel, such as pine needles, particularly in the valleys and other convex shapes or flat roofing. These points, eventually in the case of forest fire, also accumulate flying firebrands and provide local combustion which may entail the involvement of the roof structure.
- Clay tiles are very frequent in several of the European countries, particularly in Southern Europe. Although fire-resistant, clay tiles may break or displace creating little to medium size gaps through which flying embers (firebrands) can easily enter and cause the ignition of the roof structure (Figs.61, 62).

Fig.61. A clay tile roofing affected by spot fires in the Funchal wildfire in 2016.

Fig.62. Missing, displaced or broken tiles often expose roofing layering to embers.

- Eaves are protruding parts of the roof particularly exposed to radiation and flame contact and generally entail the entrance and affectation of roof structure. More specifically, eaves' soffit vents are eventual entrances of firebrands or flames, driving them to the attic structure. Also exposed timber rafter ties which, in case of combustion, can drive the fire inside the attic. This is particularly relevant when ornamental vegetation or nearby tree branches are near or even touching timber rafter ties.
- Gutters accumulate vegetal debris which, in case of a forest fire, may burn and slowly but steadily involve external parts of the eave and eventually the structure of the roof. Half round and other PVC gutters generally melt, deform and eventually fall in case of a nearby source of heat, or due to the combustion of the debris they hold. This may separate flame contact from eaves and other elements thus preventing their involvement. Metal gutters (zinc, tin) do better resist the effect of radiation or flame contact, thus keeping the burning debris close to the eave's fringe and easing the involvement of external elements.

Fig.63. A single point of contact between the cypress and the eave of this house in the Rognac fire entailed the ignition and whole destruction of the building.

Fig.64. A detailed view of this very particular friction.

4.4 Terraces, decks and other horizontal elements

- In Europe, particularly in Mediterranean countries, horizontal external parts are very common and popular. Buildings may present roof terraces, balconies, galleries, terraces, loggias and decks. Porches are also common, whether they are overhanging parts of the structure or external parts attached.
- The upper part of these horizontal elements, when uncovered, commonly accumulate vegetal debris from overhanging trees, particularly pine needles. Also, they are commonly populated with garden furniture, barbecues, basins, and other service elements and props.
- These are places in which owners tend to pile objects and materials as external, secondary storage areas. Frequently, in case of fire, they create a source of heat, in post-frontal combustion, which accumulates affecting the house.
- The lower part of these horizontal elements commonly generate accumulation of heat in case of a fire, particularly in the corners. These slabs or decks also modify air flow and, depending on the material they are build, they may serve as protection of the moving hot gases generated in a combustion.


Fig.65.


Fig.66.

4.5 Windows and glazing

- Windows are frequently one of the most exposed elements in a house to a source of heat in a forest fire, together with roofing. According to facts observed, windows are places through which flames and flying embers enter the house, entailing its combustion and eventual destruction.
- Windows vary greatly in size, framing, casement, glazing and opening systems. Framing generally is aluminum or iron. Also very frequent is timber or PVC, particularly in rural areas. Opening system is generally in-opening side hung casement window, also horizontal sliding and less frequently horizontal pivot. In some service of the house jalousie windows are also observed. In modern houses is common to see large size glazing, either fixed or horizontal sliding.
- In Mediterranean climate areas, given the importance of providing shading in summer and light in winter, windows casing is generally set within generous rebates (reveal and sill). Old houses generally mount small single pane glazing and recently double glazing is also

commonplace. Soft waterproof seals are made of synthetic rubber and mounting sealing is commonly silicon.

- Cracking of window panes is frequently observed in forest fires, particularly as a consequence of flame impingement or, alternatively, because of differential exposure to radiation between the glass hiding behind the frame and the pane itself. Any other partial screening caused by any element on the glass may also entail cracking.

Fig.67. A window pane weakened and finally broken by the effect of the near combustion of a mix of residential and vegetal fuels. Benitatxell 2016.

Fig.68. Glazing collapse in Neos Voutzas, as the local effect of the combustion of the touching pine tree.

- Collapsing of window panes is also frequent, particularly when glasses are exposed to a quick heat release or flame impingement and suffered major damage. Also when glass sealing or bedding is degraded by the effect of heat. Glass melting is also observed in situations of continuous exposure to combustion of nearby objects and materials.
- In general, it is observed that double glazing, reinforced glass, tempered glass and reflective glass is more resistant to radiation than laminated single pane glasses.
- In some cases double glazing with dehydrated air or an inert gas inside (i.e. argon, kripton), when exposed to a heat source, entails the expansion of gases and the application of inner pressure to the panes, sometimes contributing to their cracking or collapse.
- In other cases, the failure of the supporting frame entails the displacement of the whole double glass system —without any appreciable cracking or collapse—due mainly to the action of the system weight, thus leaving some small entrances in the wall to smoke, embers and flames.
- It is very frequent in rural areas that old (abandoned) houses present windows with cracked glasses or even missing glazing. These structures are particularly vulnerable to the entrance of firebrands, smoke and flames.
- But above all, it is window configuration (open, semi-open, closed) in the event of forest fire that mostly entail the entrance of firebrands, smoke and flames, eventually causing the combustion of the interior of the house. This is particularly true in the case of last-minute evacuations or self-evacuations, observed especially in hotels or block of flats regularly rented to foreign people. Leaving windows open make any structure vulnerable

to firebrands, smoke and flames, even when there is no immediate fuel surrounding the building.

Fig.69. This building in Mati, shows a flat completely burned, as a result of the entrance of flying embers through a window left open.

Fig.70. Many of the old houses in Monchique fire (Portugal) had no glazing protecting the windows, hence facilitating the entrance of embers and flames.

4.6 Blinds, shutters

- In Mediterranean countries it is common to find means of protecting windows from sunlight and, as a complement, to simultaneously allowing air circulation. Rolling shutters are mounted external to the window and made of aluminum, PVC or, less frequently, of wood slats. Running track is normally made of aluminum. The enclosure and barrel is normally internal to the house and in some cases (particularly old houses) is frequent to see tilting rolling shutter, allowing the air to enter the house.
- The resulting panel of unfolded rolling shutters offer an extra protection to the incoming radiation or flame impingement, but PVC slats easily melt and fall, hence offering partial sheltering to the window pane. Foam filled aluminum roller shutters offer a higher degree of protection, as they endure radiation and flame impingement for longer times.

Fig.71. A PVC rolling shutter melted in Monchique fire.

Fig.72.Experimental burnings in Portugal exposing several types of shutter materials, such as PVC (right) and aluminum (left).

- In many European countries swinging blinds are commonplace, made of timber or metal. In Balearic Islands a particular louvered blind type (Mallorquina) is very frequent in houses, screening most of the sunlight but allowing the air to circulate. The slats are made of timber which, generally, do not sustain combustion.
- Timber French blinds are in general a good protection. Sustained combustion is observed in South expositions of the house, when wood moisture is lower than 12%; in North expositions it is more likely to have self-extinction of combustion.
- Swinging or folding metal blinds normally do endure radiant heat and flame contact, generally offering a great degree of protection.

Fig.73. This timber shutter did not sustained combustion in the Rognac fire.

Fig.74. A metal shutter endured the flame impingement due to the combustion of nearby materials and objects in Cadalso de los Vidrios, Spain (2019)

4.7 Other openings

- Vents are openings designated to facilitate air circulation. Most common vents are located in the roof (zinc vents, vent tiles, ridge closer vents, or vented closing pieces in eaves' fascia). Other vents are found as part of the wall siding, frequently protected with screens and grilles. Baseboard vents are mandatory for rooms with gas installations, such as kitchens, and they must be covered with a grille.
- Vents are commonly places through which firebrands, smoke and eventually fire can enter, particularly if there is no screening. In some fires happening in rural areas, little openings and splays connecting with basement provided entrance to burning elements and entailing the affectation of the house.

Fig.75. This house shows many entrances to the fire in the basement. Forest fire in Rafina, 2005.

Fig.76. A house with openings in the basement without any protection. Cadalso de los Vidrios, Spain, 2019.

Part II. About the fuels

In the WUI microscale all objects and materials within the area surrounding a house which are potentially entailing ignition and combustion —hence sources of heat— are considered fuels.

4.8 Surrounding forest fuels and undeveloped lots

- Parcels in the fringe of a community (Fig.77) within a forested area commonly show friction with wildland fuels (shrubs, tree canopies or a mix of both) and continuity with hedges and other ornamental elements in the garden. Frequently, owners of these properties allow a seamlessly presence of forest species in their gardens, giving them a sense of wilderness and providing them with shadow (Fig.78).

Fig.77. A house in a lot immediate to the forested area in the fire of Benitatxell.

Fig.78.Some owners allow the wildland vegetation to enter their lots, as shown here in a settlement in Ibiza, Spain.

- It is very common to have unmanaged parts in the immediate exterior to the community, thus presenting high forest fuel loads and fuel continuity. This is aggravated by the presence and piling-up of vegetal remains as a result of continuous dump of gardening slash over the years. In case of fire, these locations develop high intensity fires.

- Undeveloped lots within the settlement commonly show high loads and continuity of forest fuel, mixed with vegetal remains and frequently several other abandoned objects and materials (Fig.79). The presence of cured grass and other fine dead fuels make these plots particularly vulnerable to firebrand landing, which eventually develop intense local fires affecting nearby houses (Fig.80).

Fig.79. Vegetal debris piling up in a settlement in Menorca, Spain.

Fig.80. High intensity local combustion of undeveloped lots in Benitatxell fire, 2016.

4.9 Pine needles and fine debris

- Pine needles and other tree leaves accumulate in remarkable quantities in settlements located under tree stories. The moisture of these dead fine particles depend strongly upon the surrounding air humidity and temperature. In dry and hot days, fine fuels as these are prone to ignite, whether they are new fire outbreaks or spot fires due to firebrand landings.
- As pine needles and other light vegetal debris tend to accumulate in the same locations where flying embers land, these are vulnerable spots in the microscale. Incipient fires may afterwards catch other materials and objects and build up stronger combustion.
- Pine needles are normally found accumulated on the ground, over flat roofs, in the valleys of cross roofs (Fig.81, 82), on the upper part of decks and terraces, particularly in corners, inside gutters, in ornamental clay pots, over the top of green hedges, in the exterior of cars, boats and other objects with hollow spaces, decks and horizontal surfaces.

Fig.81. Overhanging tree branches touching the roof of this house in Puentelasierra, Spain. The accumulation of pine needles is remarkable.

Fig.82. Accumulation of pine needles on a roof in San Martín de Valdeiglesias, Spain. Several homeowners use the house just a few days in a year.

- In some of the recent fires (i.e. Mati 2018), the abundant presence of pine needles almost everywhere —as a consequence of unmanaged WUI— contributed to a more efficient propagation of the fire inside the settlement as well as the ignition of objects, materials and houses. As these are detached parts of the plant, they can fly freely under strong winds, creating more chances of spot fires ahead of the fire front.

4.10 Cured grass

- The presence of dead (cured) grass zones generally does not entail an increase in heat release but instead is a driving factor for the initiation and quick spread of fire fronts in the WUI. Fine dead fuels with vertical arrangement like cured grasslands are common in the perimeter of settlements and in undeveloped lots inside them. The moisture content of such fine dead fuels depend much upon the existing conditions (humidity, temperature) of the immediate atmosphere which, in hot and dry days, may entail a high probability of ignition. Initial spread is also affected by surface wind speed. Grass-dominated lots are dangerous under such circumstances, as any small fire outbreak can quickly develop into devastating wildfires (i.e Mati fire in 2018).
- Grass-dominated grounds are particularly vulnerable to firebrand landings, thus eventually creating multiple ignitions (spot fires) which may interact and create stronger fast fire fronts and, likely, further involvement of heavier fuels, materials and objects. This is particularly dangerous when such objects and materials are seamlessly and continuously mixed with cured grass.

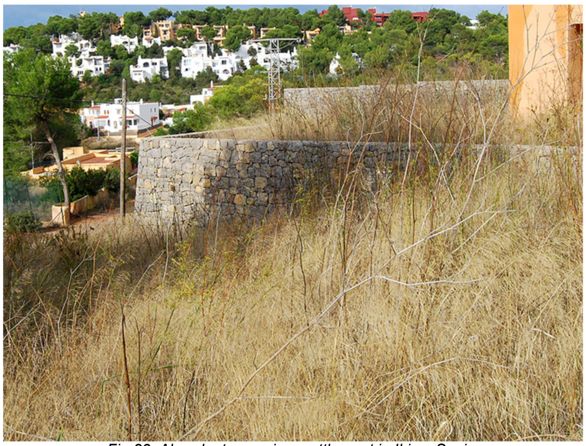


Fig.83. Abundant grass in a settlement in Ibiza, Spain.

Fig.84. Fire spreads rapidly over cured grass, as in this fire in Madrid, Spain.

- Multiple ignitions in a WUI area create a very challenging scenario for firefighters, particularly under strong wind conditions which may lead to high speed rates of spread. These considerations point to the need of treating cured grass-dominated lands with much care inside and outside a WUI area.
- As observed, the presence of masonry or stone walls may reduce or even stop this fast fire propagation over grass-dominated lots. In many cases such walls have prevented the involvement of hedges, ornamental plants, objects, materials or the house itself into further and more intense combustion.
- Given that these fine dead fuels are very reactive to air humidity changes, pre-conditioning watering of cured grasses, for example with regular garden sprinklers, may help to reduce the likelihood of new fire outbreaks due to flying embers. Some dedicated water cannons have proven their efficiency in real fire events, such as in Carcaixent fire, Spain (2016).

4.11 Hedges and ornamental plants

- Green hedges play a key role in the propagation of fire inside a settlement. When placed in settlement fringe lots they receive —and frequently upscale— the fire activity, transferring the propagation along lined up hedges, particularly when and where the hedge axis coincide with the main wind direction.
- Not all species react in the same way to fire. Some species, such as in the family of cypress and other conifers, ignite, burn and propagate flames with easiness, generating great difficulties for firefighters. Furthermore, these linear propagations frequently involve other ornamental plants, objects, materials or even secondary structures or the main house.


Fig.85. A fire spreading over grass is meeting a tall hedge of cypress in this fire in Colmenar Viejo, Spain, increasing the intensity.


Fig.86. Cypress is both flammable and combustible. These hedges transfer fire very efficiently through the settlement, as in this case in Benitatxell 2016.

- Other species, such as *Buxus*, *Ligustrum*, *Prunus*, *Nerium*, *Hedera*, burn when exposed to radiation and flame contact but do not propagate fire with such an ease (Figs.87, 88). Allegedly, this is a consequence of the amount of dead fine fuel inside hedge structure, caused by a combination of species selection (flammability) and the gardening treatment applied (such as pruning and clipping). Watering routines also add to the amount of moisture content in green leaves so they affect flammability.


Fig.87. Hedera helix charred in the Benitatxell fire.


Fig.88.Buxus sempervirens burning but not transferring propagation in the fire of Funchal 2016.

- Geometric shapes of some hedges help to accumulate pine needles, twigs, branches, pine cones and other vegetal debris on top of the flat shapes, contributing to flammability (in case of presence of fire embers) and combustibility (energy release).
- Size and geometry of hedges vary greatly. Large hedges can be up to 3 or 4 m of height and show from 80 to 200 cm width, running over several dozens —sometimes hundreds— of meters, connecting several lots in a settlement. These long line-ups act as 'fuses', effectively transferring flames through the settlement. Many others are mid-sized, typically of 1.5 to 2 m of height and 40 to 80 cm width.


Fig.89. Remarkable accumulation of pine needles over a cypress hedge.


Fig.90.Fire interaction between undeveloped lots and green hedges.

- Combination of undeveloped lots, packed with forest fuel load, and nearby green hedges commonly entail local intense fires which propagate inside a settlement, even in the case of a dense urban fabric.
- In many observed occasions, ornamental plants placed near or touching the walls, windows, roof or other parts of the house entails the eventual affectation of the structure. This is particularly true when it applies to flammable species, such as cypress and other conifers.


Fig.91.Local fuels entailing the destruction or affectation of houses.


Fig.92.A garden plot entailing local affectation of the house in Montesión, Toledo, Spain.

- Smaller hedges are commonly used as green screens to hide LPG tanks, garbage cans, little sheds, dog houses or other objects and materials. In case of combustion, fire radiation and flame contact is easily transferred to such elements.

4.12 Residential fuels, materials and objects

- Gardens and other open spaces immediately surrounding the house are generally populated by a wide variety of objects and materials. Most commonly, garden furniture is present in the horizontal places whether they are external to, attached to or an integral part of the house. Furniture materials vary greatly, according the general quality standards of the house, use and preferences of homeowners. These objects are rarely made of flashy or highly flammable materials and their ignition frequently is caused by other light elements or the presence of heat release in the nearby. As well as other objects in the garden, furniture may continue burning for minutes or hours after flame front impact.

- PVC furniture is commonly found in most of mid to low class housing lots, although it is becoming commonplace due to its durability and low price. Timber elements are less frequent, but found in some occasions made out of common and exotic woods (pine, beech, teak). Metal furniture is also found and commonly covered with clothes, mats, pads, cushions and other flammable materials and elements which frequently burn or are affected by landing fire brands.

Fig.93.The coach and other materials, ignited by flying embers, are behind the destruction of this house in the Monchique fire, 2018.

Fig.94. Garden furniture contributing to the destruction in Llutxent fire, 2018.

- Cars, motorbikes, bicycles, boats, gardening machinery amongst others can be also found in the exterior or stored in garages or sheds. When located in the exterior, it is also frequent to find these covered with canvas, fabric or plastics, and also with the presence of pine needles on top if they are placed under tree canopy.
- It is becoming a costume for some owners to pile up all kinds of materials and objects in their properties, particularly timber pallets, oil cans, metal and timber profiles, plastic containers, gas canisters, furniture, old cars and motorbikes, house trailers, machinery (chainsaws, moto cultivators, brushcutters), paint, thinner and varnish cans, mats, fabric, plastic canvas, cables, cardboard plates, electrical appliances, PVC and metal pipes, glass bottles, piles of books, magazines and other papers etc. This is a result of poor habits and carelessness of homeowners who frequently lay objects randomly on the ground, in the open, mixed with grass and other flashy fuels. It has been observed many times that, independently of the intensity of the approaching flame front, these objects and materials eventually catch fire (mainly due to firebrands) and keep on burning for hours, frequently entailing the affectation or destruction of the house.


Fig.95.A house severely affected in Benitatxell fire, due primarily to the combustion of the accumulated materials and objects.


Fig.96.A massive accumulation of objects entailed the destruction of the two houses in the grass fire of Búger, Mallorca (Spain), 2019.

- Accumulation of objects and materials in semi-enclosed spaces (such as in porches inside corners, open sheds and warehouses or under light structures) entail a remarkable accumulation of heat in case of combustion, sometimes creating hidden side risks for firefighters (such as explosion of gas canisters, emission of toxic gases etc.).


Fig.97.Warehouses and sheds with tools and materials completely destroyed in Monchique fire, 2018.


Fig.98.A garage in Neos Voutzas exposed to the passage of the fire and affection to the nearby vegetation, which were touching the structure.

4.13 Vehicles

- As observed in past forest fires, cars and other vehicles contribute to the local heat release and toxic gases emission in the vicinity of houses. Although ignition of cars is not immediate they require a sustained source of heat, particularly with the windows closed. Once they catch fire they continue burning for several minutes if not attended.
- Cars parked inside lots in the open are likely to burn and, eventually, to affect the nearby buildings. This is particularly true when other flammable materials are also located near, below or over the vehicle (plastic coverage, fabric, pine needles etc.).
- Although burning cars do not contribute to the overall flaming front propagation, they are local sources of heat. When burning vehicles are located in numbers along the street sides

they may block transit hence affect evacuation operations (as observed in Mati fire, Greece).

Fig.99. Burned vehicles near a house in Mati, Greece 2018.

Fig.100. Five cars were lost in this lot in Cadalso de los Vidrios, Spain, 2019.

Part III. About other structures

Other secondary structures may be present attached or detached from the main building. They are considered twofold, as structures potentially affected by fire but also as burning elements and potential sources of heat and firebrands. Indeed, more than frequently the affectation of these secondary structures entail the consequent affectation or destruction of the main house, especially if they are attached.

4.14 Secondary structures

- Structures, other than the main body of the house, maybe present in the microscale, such as warehouses, sheds or garages. These frequently show different construction materials and methods, particularly if they are detached from the house. In many occasions these secondary structures are sitting against the main volume or formed as extensions of it, with or without a connecting entrance (door, aley, corridor, etc.) to the main building.
- It is very frequent to observe secondary structures attached to the house but constructed in a rather poor way with light materials, many times erected by the homeowner, such as timber or metal pergolas, basic frames or simple concrete block walls, covered with fabric, plastic, canvas, corrugated metal panels (zinc, galvanised iron, aluminum), or fiber cement panels. In general, these spaces are open in one or several of their sides, potentially exposed to firebrands and flames.

Fig.101.A secondary structure in Funchal fire (2016) entailing the affectation of the main house to which was attached.

Fig.102.A self-made auxiliary building is completely destroyed due to the combustion of the many objects and materials stored. Cadalso de los Vidrios, Spain, 2019.

- Secondary structures very frequently are used as storage spaces of all kinds of materials and objects, more specifically construction materials (timber, laminated wood, cardboard, plastic panels, profiles, insulation panels, bricks), furbishing and maintenance materials and tools (paint, thinner, varnishes), fuel containers (gasoline, gas canisters, lubricants), books, fabrics, pool maintenance products (such as chlorine), garden furniture and tools, machinery, electric appliances and small to medium size vehicles (motorbikes, quads, small cars, electric bicycles).
- The combustion of these fuel complexes commonly occur minutes after the main fire front passage or after the landing of firebrands, and keep burning at different rates for minutes, hours or even days, providing a noticeable amount of total heat release. This combustion is common, and is the final cause of much of the observed affectation or destruction in buildings to which these improvised self-made storage spaces are attached. As mentioned before, the presence of light roofing contributes remarkably to the accumulation of heat in such a semi-enclosed combustion.
- Glass verandas and timber pergolas attached to the house may in certain cases drive their combustion towards elements in the main building, entailing affectation commonly minutes or even hours after the main front passage.
- Awnings attached to the house (for example, window or entrance awnings) very rarely conduct fire into the house, as they normally are made of fire-retardant or fire-resistant materials (they burn or degrade but do not propagate flames). It is observed however that most of the existing awning materials are affected by firebrands although they do not create sustained combustion (Figs.103, 104).

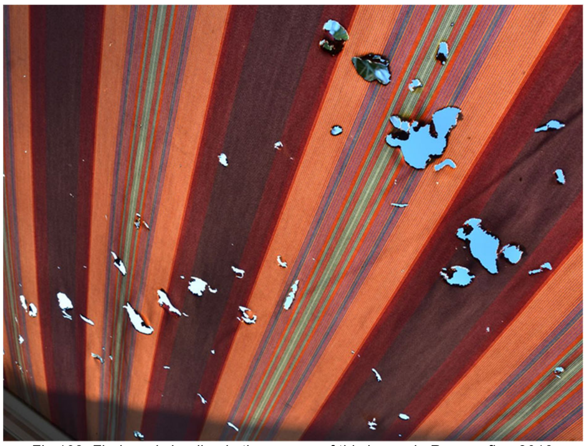


Fig.103. Firebrands landing in the canvas of this house in Rognac fire, 2016.

Fig.104.Awning affected in the fire of Rognac, 2016.

4.15 LPG tanks and gas canisters

- Liquified Petroleum Gas (LPG) tanks are a popular, affordable and technically achievable way of providing fuel for house services by storing high-energy gases in a liquified form under high pressure. These are individual vessels placed near the buildings, whether in surface or underground installations, and of a variety of sizes according to user needs. Vessels are equipped with a set of service and safety valves, which ensure a safe operation. Overpressure entail safety valves opening and the release of gas, which vaporises instantly.
- LPG tanks are frequently placed in lots close to forest fuels, particularly in parcels located in the settlement fringe. In case of a forest fire, these are potentially exposed to radiant heat and, in some cases, to flame impingement. It has been observed in real fires that this heating entails the quick forced vaporisation of the liquified gas, increasing internal pressure and triggering the safety valve. The presence of flames or firebrands lit the exhaling gas thus creating a temporary jet fire (Figs.105,106).

Fig.105.

Fig.106.

- LPG jet fires affect the surrounding objects, especially ornamental plants and hedges, overhanging trees, walls and even windows, eaves and other exposed parts of a nearby house. This may entail a domino effect if the house or other elements catch fire.
- Other than that, LPG tanks exposed to a forest fire have never entailed a catastrophic explosion (BLEVE, Boiling Liquid Expanding Vapour Explosion). However, careful monitoring of the situation is required.
- More than frequently, homeowners decide to hide the LPG installation by surrounding it with green hedges, generally of flammable species. As a consequence, it has been observed that in case of landing firebrands igniting the hedge, the close combustion of it entails a quick increase of pressure and temperature in the interior of the gas vessel, triggering the appearance of a jet fire.
- In other occasions, objects and materials not related with the LPG installation are placed near or even below the tank which, in case of ignition and combustion, create again overpressure by heating and the appearance of a jet fire.
- More dangerous scenarios are observed when the heating source is placed above the tank, so affecting the gas phase (instead of the liquified phase); in such case not a proper cooling effect is achieved while, at the same time, overheating of the vessel wall may entail a reduction of its mechanical properties, more specifically when the heat source is continuous over a long period of time. This is the case, for example, of tree canopy or overhanging branches placed above the LPG tank.

Fig.107. A source of heat may have affected the nearby tank of LPG in Mati (2018).

Fig.108. Some objects and materials near this LPG tank and against the wall. In case of a jet fire, a degree of affectation of the house may be expected due to the proximity.

- Small gas canisters are also commonplace in houses affected by forest fires. Very rarely LPG tanks and gas canisters are seen together, as one replaces the other for the same use.
- Canisters are relatively safe when exposed to a heat source as far as they stay standing and the safety valve works properly. However explosions do relatively frequently occur in the WUI. These are observed when such containers are exposed to a long-period source of heat and they are sitting on one side. These explosions, frequently heard or reported after the fire passage, do entail a danger to firefighters operating in the microscale, even minutes or hours after the fire front passage. In other occasions, gas canisters show a

certain degree of affectation, oxidation and hollow parts, due to the combined action of overpressure and vessel wall weakening.

- It is a common practice by some homeowners to throw gas canisters into the pool before they leave the house threatened by an approaching fire.

Fig.109. This canister exploded hours after the passage of the fire, when exposed to nearby combustion in Funchal, Portugal (2016).

Fig.110. Semi-confined combustion creates a heat accumulation, as the evidence shows in the fire of Llutxent 2018. This lady left the empty canister in the porche, exposing them to sources of heat.

Fig.111. One of the many affected gas canisters in Mati, Greece (2018)i. Explosions were frequently reported.

Fig.112. Different degrees of affectation, from upper left to center low. No all the canisters have the same type and efficiency in protection against fires.

5. Microscale Pattern Scenarios

Following, a set of simplified scenarios extracted from the lessons learnt are presented. These are idealisation of particular situations at different scales, with a simplified geometry for its preliminary simulation in FDS. These descriptions have an associated 3D geometry, which is also provided in FBX format to be seamlessly imported and interpreted in the simulation software. All the dimensions are given in centimeters. Some other of the problems presented require a different approach to CFD modelling, such as the percolation and transportation of incandescent particles (firebrands); nevertheless, the geometries are provided as well for their use in other dedicated software. The presented simplified scenarios can be furtherly combined in more complex situations in order to test the possible interactions and domino effects.

The proposed microscale scenarios, which respond to the observed problems, are:

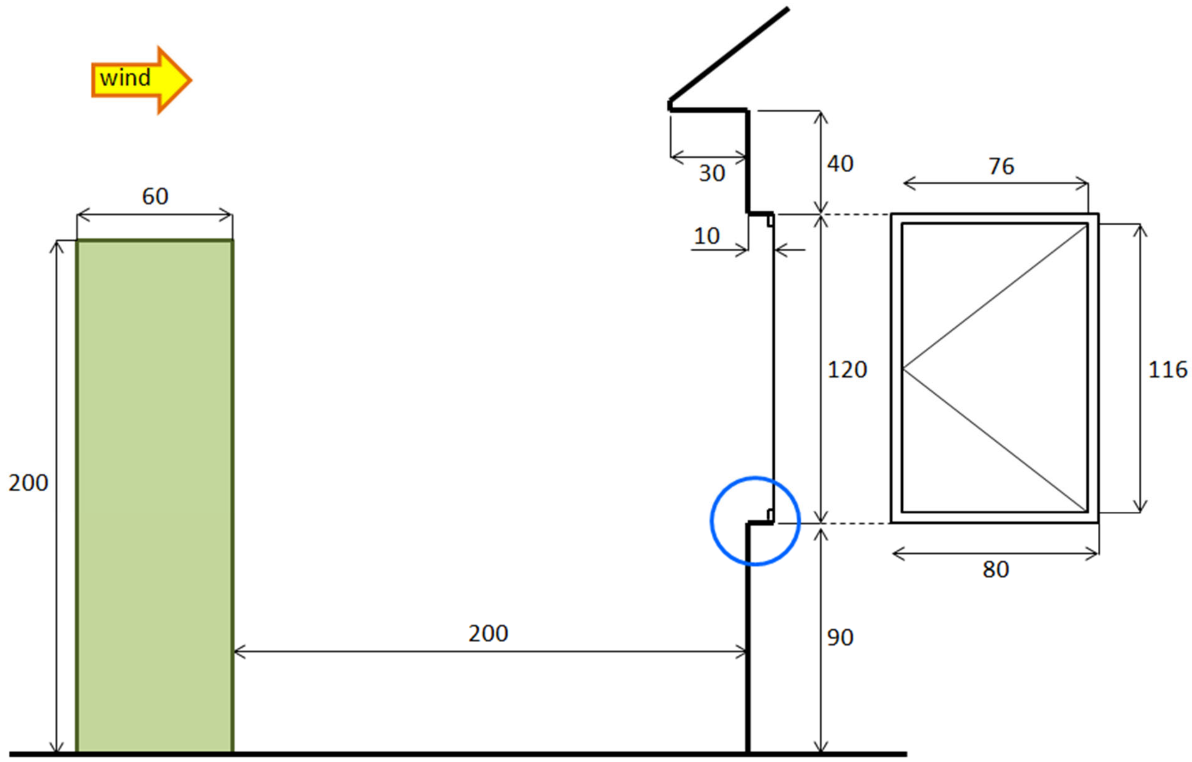
SC01. Glazing exposure to radiation
SC02. Glazing exposure to flame impingement
SC03. Fuel build-up and combustion in gutters
SC04. Fuel build-up and combustion on roofs
SC05. Firebrands entrance through openings
SC06. Blinds exposure to radiation and flame impingement
SC07. LPG tank exposure to nearby forest fire
SC07.1. LPG tank directly exposed to an incoming forest fire
SC07.2. LPG tank near a house wall exposed to incoming forest fire
SC08. LPG tank exposure to combustion of green hedges and ornamental
- *SC08.1. LPG tank near to green hedge type A*
- *SC08.2. LPG tank in a corner of green hedge type A*
- *SC08.3. LPG tank near a house wall and to a hedge type B*
- *SC08.4. LPG tank surrounded by a near hedge type B*
- *SC08.5. LPG tank under nearby tree canopy*

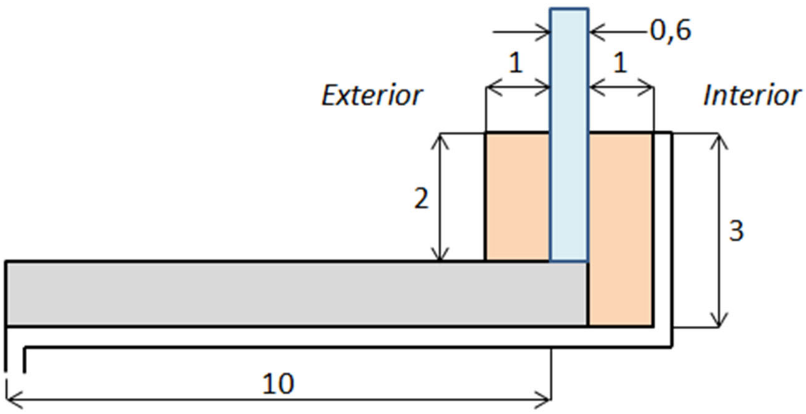
SC09. LPG tank exposure to combustion of other elements
- *SC09.1. LPG tank placed over light flammable grass*
- *SC09.2. LPG tank with a fuel pack underneath*

SC10. Fuel pack combustion in semi-confined arrangements
SC11. Combustion of materials inside warehouses, garages
SC12. Smoke entrance and diffusion inside the house
SC13. Fire propagation over green hedges and ornamental elements

SC01. Glazing exposure to radiation

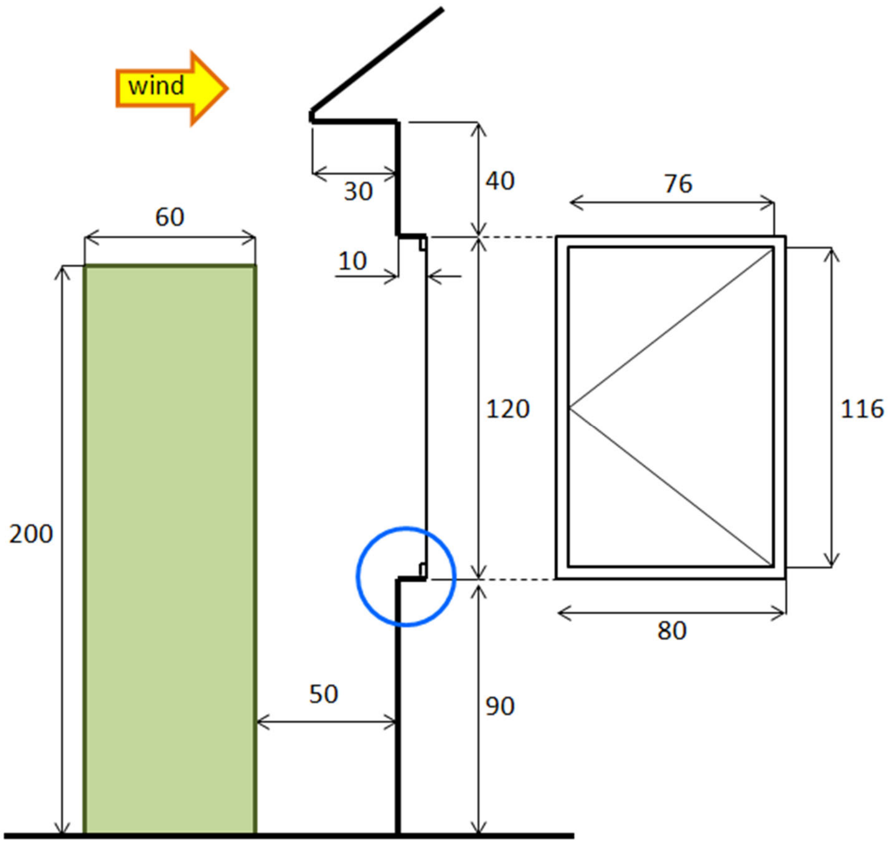
- A 120x80x0.6 cm glazing single pane mounted on a metal (iron) frame of 2x1 cm in a window box with a rebate of 10 cm, at a height of 90 cm from the floor.
- Separated 2 m from a 200x60x300 cm green hedge.
- Hypothesis of no wind and 20 km/h wind at 10 m in the direction of the structure.

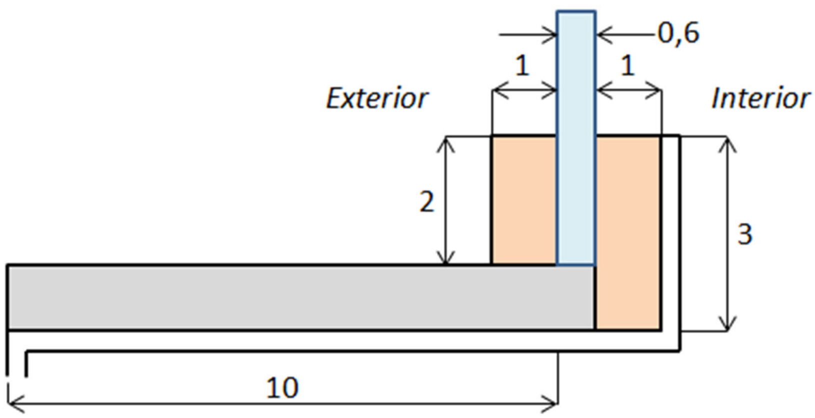




SC02. Glazing exposure to flame impingement

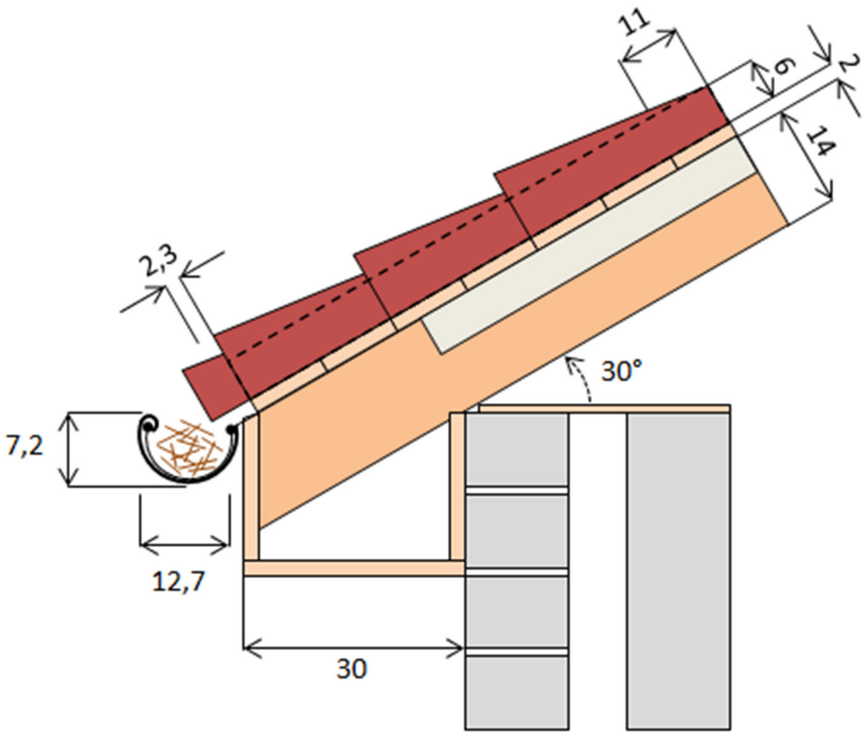
- A 120x80x0.6 cm glazing single pane mounted on a metal (iron) box frame of 2x1 cm in a window case with 10 cm rebate, at a height of 90 cm from the floor.
- Separated 50 cm from a 200x60x300 cm green hedge
- Hypothesis of no wind and 20 km/h wind at 10 m in the direction of the structure.





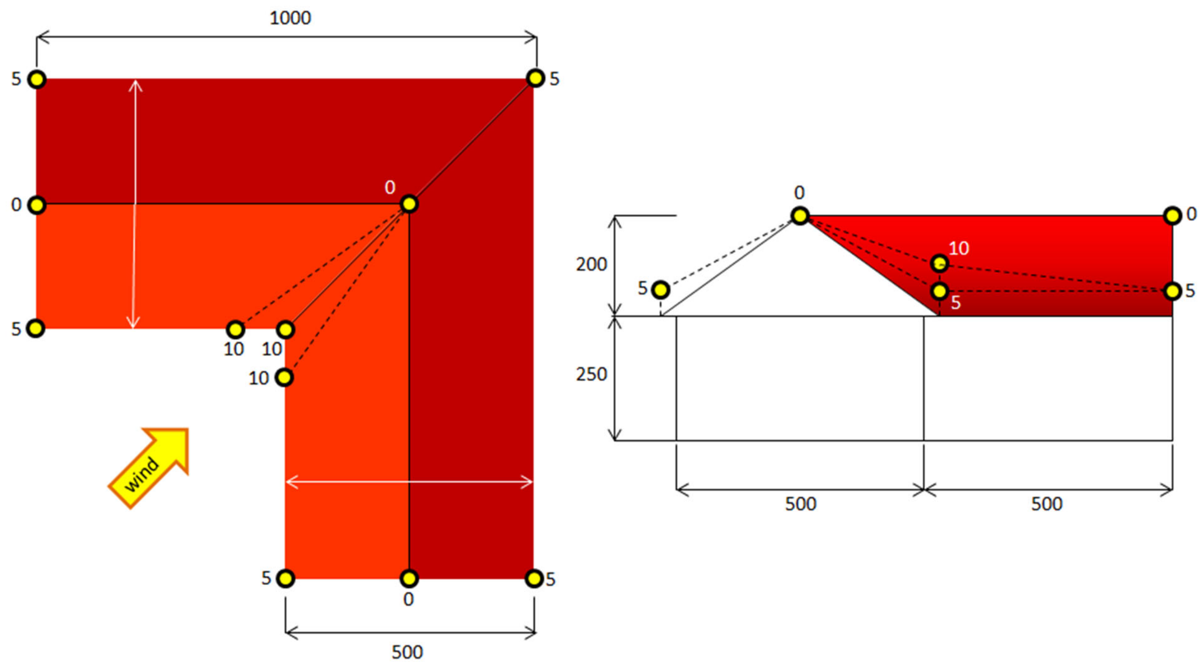
SC03. Fuel build-up and combustion in gutters

- Eave in a typical clay tile and timber structure configuration, section 1 meter long.
  - Rafter 14x80x7 cm, timber.
  - Sheathing 11x2x100 cm, nailed on rafters, timber.
  - Batten 6x80x6 cm, timber.
  - Fascia 20x2x100 cm, timber.
  - Soffit 30x2x100 cm, timber.
  - Roof angle 30º, open eave.
- Semi-circular zinc gutter 7.2 cm depth, 12.7 cm width and 100 cm long, with roof hung brackets nailed onto the rafter.
- Pine needles (*Pinus sylvestris*) covering all the available volume in the gutter over 1 m, under combustion simultaneously.
- The model assumes that the gutter is not degraded with the combustion.
- Hypothesis of no wind.



SC04. Fuel build-up and combustion on roofs

- A cross gabled roof house with four sides of 5 m and two of 10 m, forming an 'L' shape with 35º of pitch inclination, with a valley in the intersection.
- Spanish clay tiles, metal flashing in the intersections (zinc).
- Covered with a layer of pine needles (*Pinus sylvestris*) with different fuel depths depending upon the position:
  - Ridge and crossing, 0 cm.
  - Eaves, 5 cm.
  - Lower part of the valley, 10 cm.
  - Both sides of the eave, one meter apart, 10 cm.
  - The rest of the points in the main slopes have a linear variation.
- Hypotheses of no-wind and 20 km/h wind speed at 10 m, with 45º wind direction lined up with the valley axis.
- Combustion starts in the base of the valley and randomly across the roofing.
- Some of the tiles are displaced, broken or removed, so the roof sheeting is exposed.



SC05. Firebrands entrance through openings

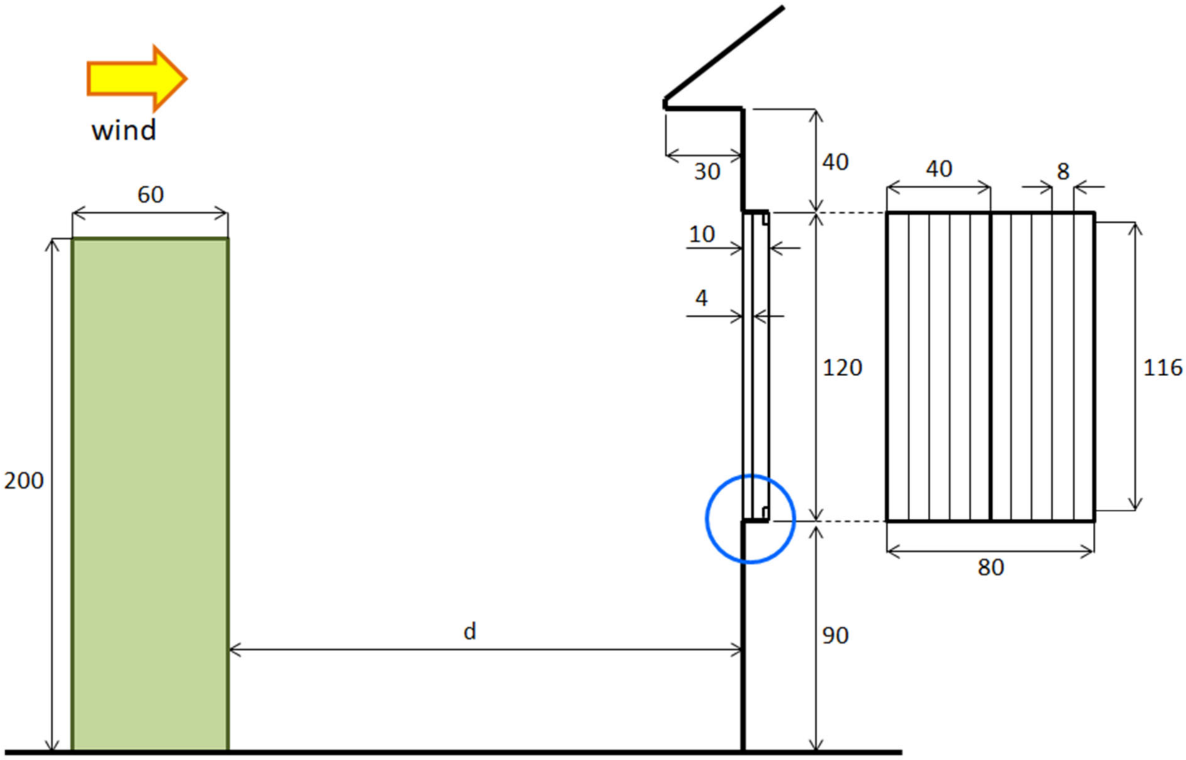
- A single family structure, gable roofing, with clay tiles
- Eaves with open configuration in the edge, leaving entrance to particules.
- With one 80x120 window in the winwards (W) and the other in the opposite wall (L)
    - Completely open (both, L/W; only L; only W)
    - Half open (both, L/W; only L; only W)
    - Completely closed (both, L/W; only L; only W)
- A 100x200 entrance door, also facing winward, with a separation with the floor of 5 cm.
- In one of the sides, little vents of 20x10 at ground level, without protection or glazing.
- Exposed to a source of incandescent particles
- Wind blowing towards the house, 20 km/h at 10 km/h.

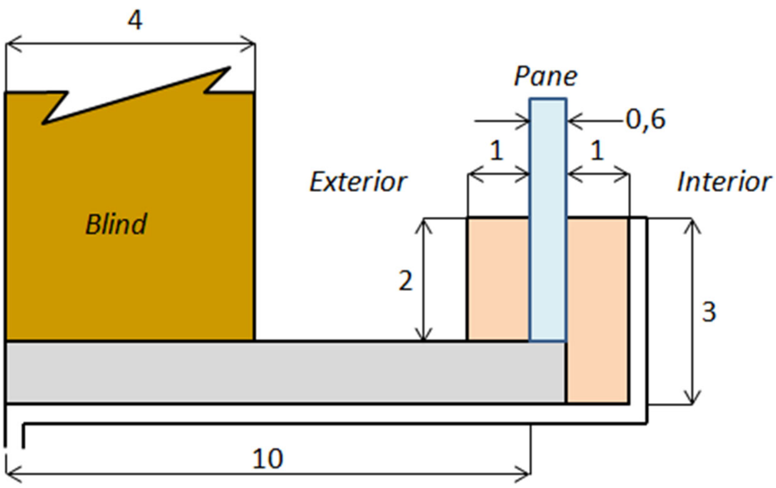
Purpose of the simulation

- Analysis which of the configurations is more effective in letting the particles enter the house.
- Analysis which of the eventual entrances (roof tiles, eaves, vents, windows, door space) allows most of the particles entrance.
- Analysis of how the configuration of open/closed windows affects the circulation, hence the transport, of flying embers inside the house.

SC06. Blinds exposure to radiation and flame impingement

- A timber blind of double swing sheet of 120x40x4 cm each, placed in the border of a window case with 10 cm rebate, at a height of 90 cm from the floor.
- Separated by a distance *d* of 50 and 200 cm from a 200x60x300 cm green hedge
- Hypothesis of no wind and 20 km/h wind at 10 m, in the direction of the structure.

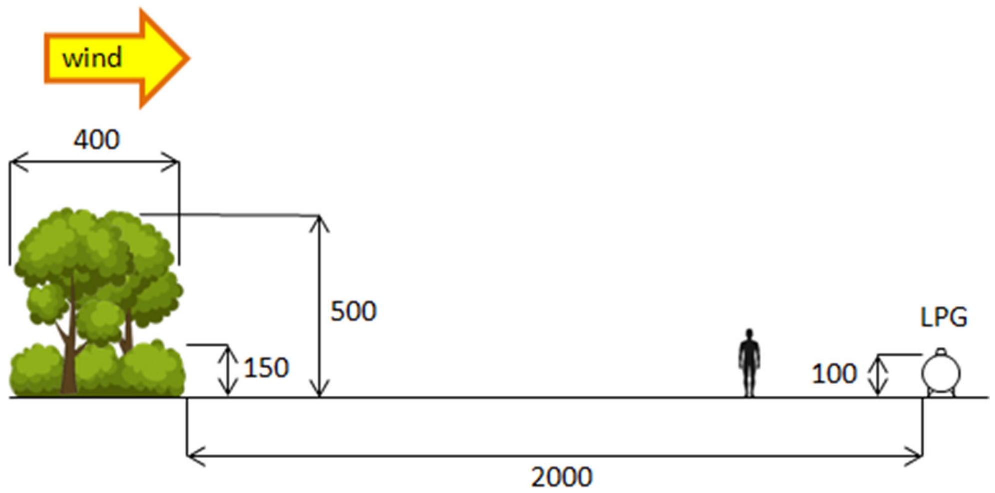




SC07. LPG tank exposure to nearby forest fire

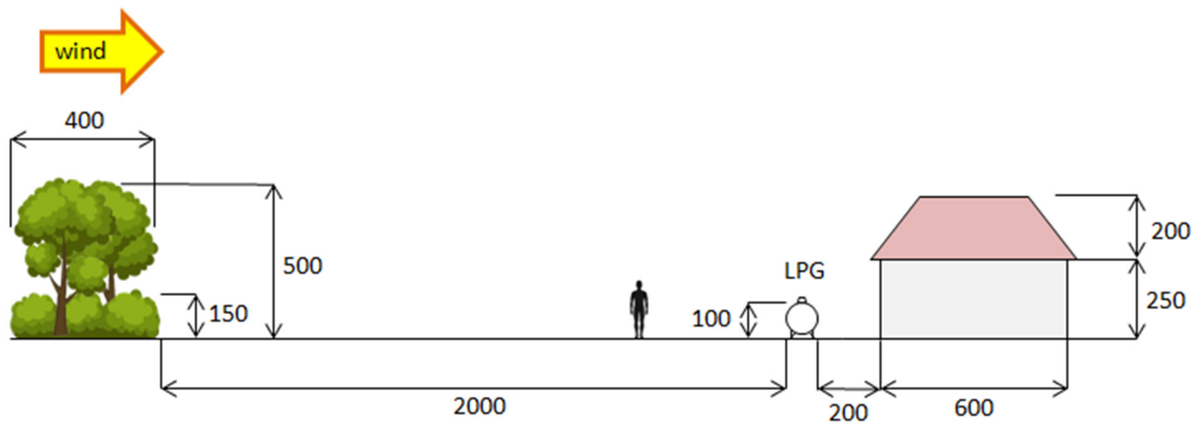
SC07.1. LPG tank directly exposed to an incoming forest fire

- A1 LPG tank (1 m^3) exposed to the combustion of a forest fuel composed by a pine stand of 5 m tall and a shrub (model 4) of 1.5 m tall, at a distance of 20 m.
- Hypotheses of no-wind and a 20 km/h wind at 10 m.
- The length of the section is 20 m, the LPG tank is centered.



SC07.2. LPG tank near a house wall exposed to incoming forest fire

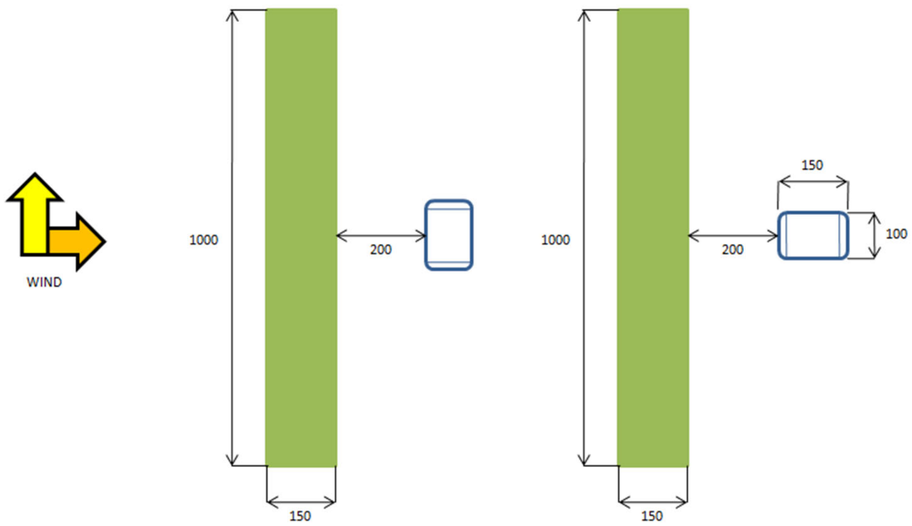
-
- A1 LPG tank (<1 m^3) exposed to the combustion of a forest fuel composed by a pine stand of 5 m tall and a shrub (model 4) of 1.5 m tall, at a distance of 20 m.
- House of 5x6x4.5 m is located at a distance of 2 m from LPG tank on the opposite side.
- Hypotheses of no-wind and a 20 km/h wind at 10 m.
- The length of the section is 20 m, the LPG tank and the house are centered.

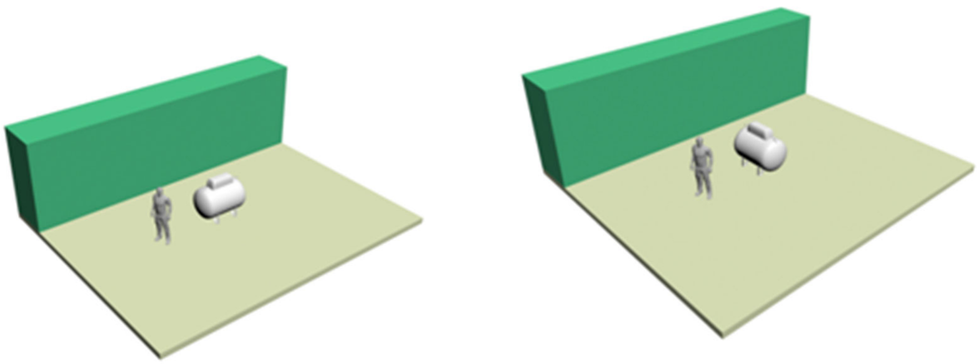


SC08. LPG tank exposure to combustion of green hedges and ornamental

SC08.1. LPG tank near to green hedge type A

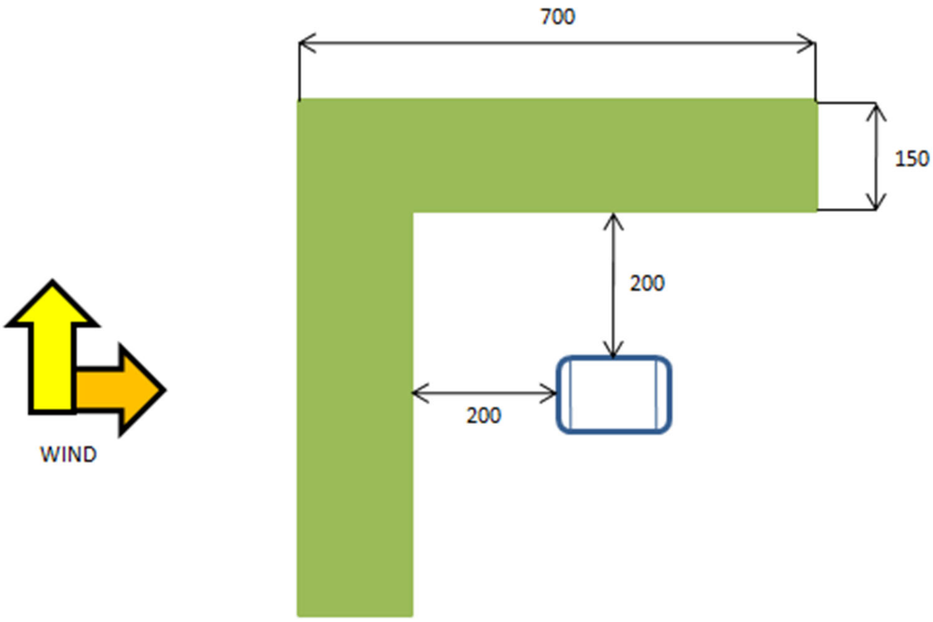
- A1 LPG tank (1m^3) exposed to the combustion of a type A hedge
- Type A: *Cupressus arizonica* 300x150x1000 cm
- Wind hypotheses:
    - No-wind
    - 20 km wind, parallel to the lot.
    - 20 km wind, orthogonal to the lot.
- Vessel shell set at a distance of 200 cm, according to safety specifications (UNE 60250 in Spain), placed in the centre
- Two hypotheses of tank arrangement
    - A) Major axis of the LPG tank parallel to the hedge
    - B) Major axis of the LPG tank orthogonal to the hedge

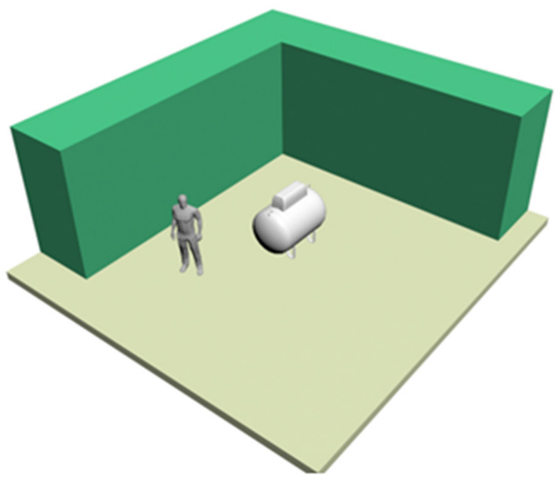




SC08.2. LPG tank in a corner of green hedge type A

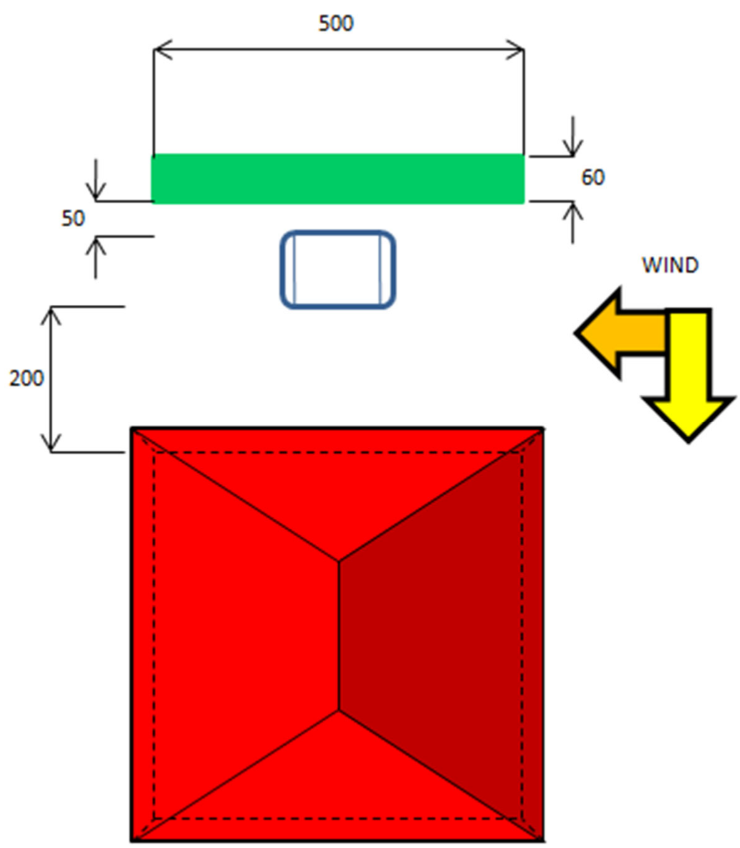
- A1 LPG tank (1m^3) exposed to the combustion a corner of a type A hedge
- Type A: *Cupressus arizonica*, 300x150x700 per block
- Wind hypotheses:
    - No-wind
    - 20 km wind at 10 m height, parallel to the lot.
    - 20 km wind at 10 m height, orthogonal to the lot.
- Vessel shell set in the corner at a distance of 2m to each of the sides, according to safety specifications (UNE 60250 in Spain)





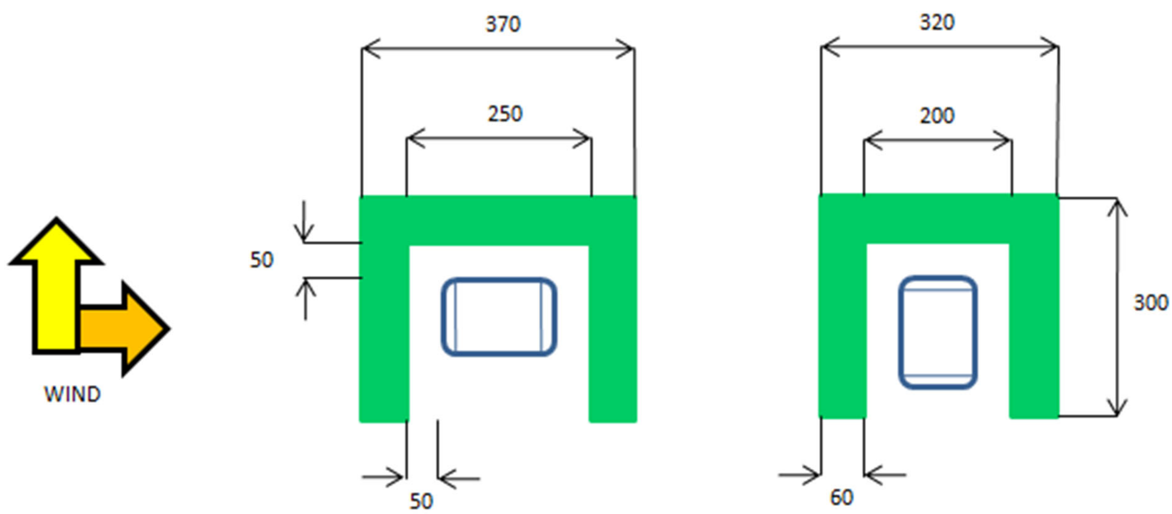
SC08.3. LPG tank near a house wall and to a hedge type B

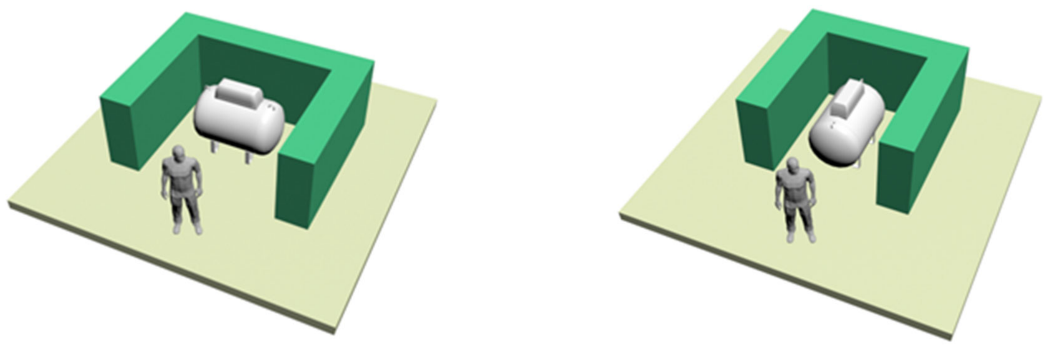
- A1 LPG tank (1 m^3) exposed to the combustion of a type B hedge
- Type B: *Cupressus arizonica*, 150x60x500 cm
- Wind Hypotheses:
    - No-wind
    - 20 km wind at 10 m height, parallel to the hedge axis.
    - 20 km wind at 10 m height, orthogonal to the hedge axis, towards the house.
- A hip roof house of 5x5 m and eave overhang of 30 cm, with 2.5 m walls in parallel to the LPG tank and green hedge main axis, separated by 2 m from the tank vessel.



SC08.4. LPG tank surrounded by a nearby hedge type B

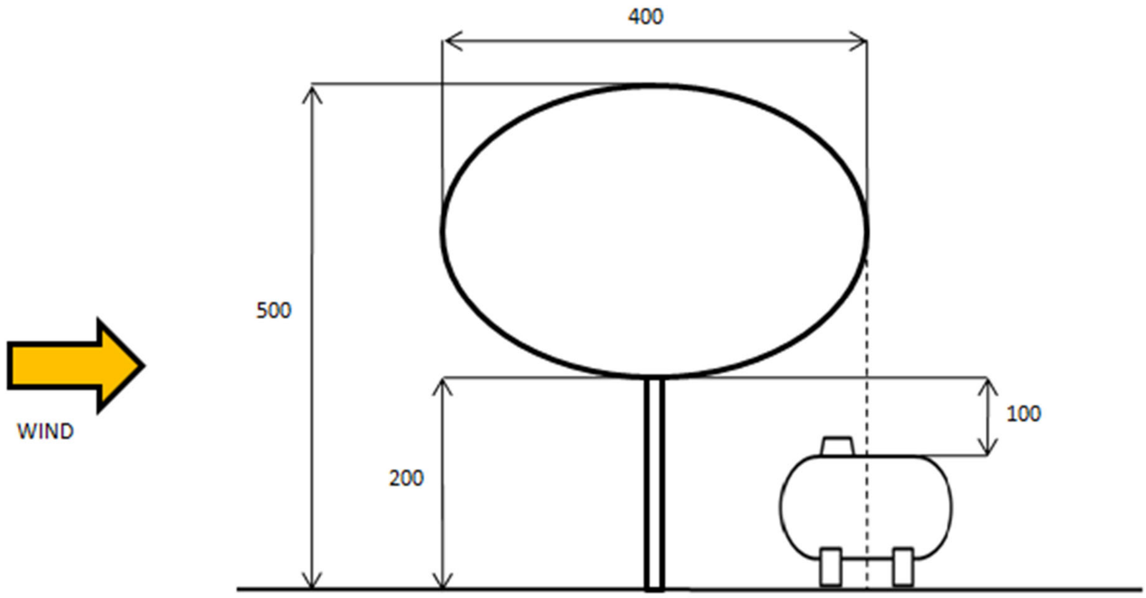
- A1 LPG tank (1 m^3) exposed to the combustion of a surrounding type B hedge
- Type B: *Cupressus arizonica*, 150x60x300 cm per block
- Wind Hypotheses:
  - No-wind
  - 20 km wind at 10 m height, parallel to the lot.
  - 20 km wind at 10 m height, orthogonal to the lot.
- Vessel shell set in the corner at a distance of 50 cm to each of the sides, according to what has been generally observed in real cases
- Hypotheses of tank arrangement:
  - A) Major axis of the LPG tank parallel to the hedge
  - B) Major axis of the LPG tank orthogonal to the hedge

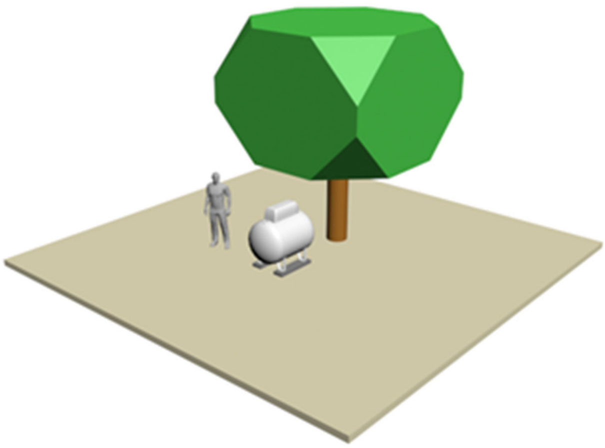




SC08.5. LPG tank under nearby tree canopy

- A1 LPG tank ($1m^3$) exposed to the combustion of a tree (pine) hanging over the tank
- Canopy covering 50% of its length.
- A pine tree (*Pinus halepensis*) of 5 m height, crown diameter of 4m, CBH at 2 m.
- Hypotheses of no-wind and 20 km/h (10 m) wind blowing towards the LPG tank
- Upper part of the vessel shell is at a vertical distance of 1m from tree crown base

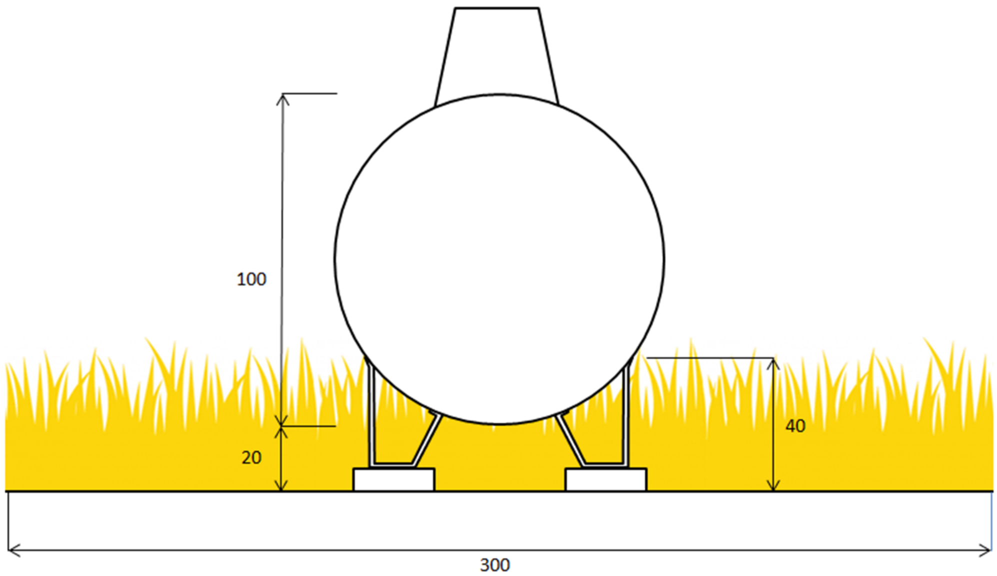




SC09. LPG tank exposure to combustion of other elements

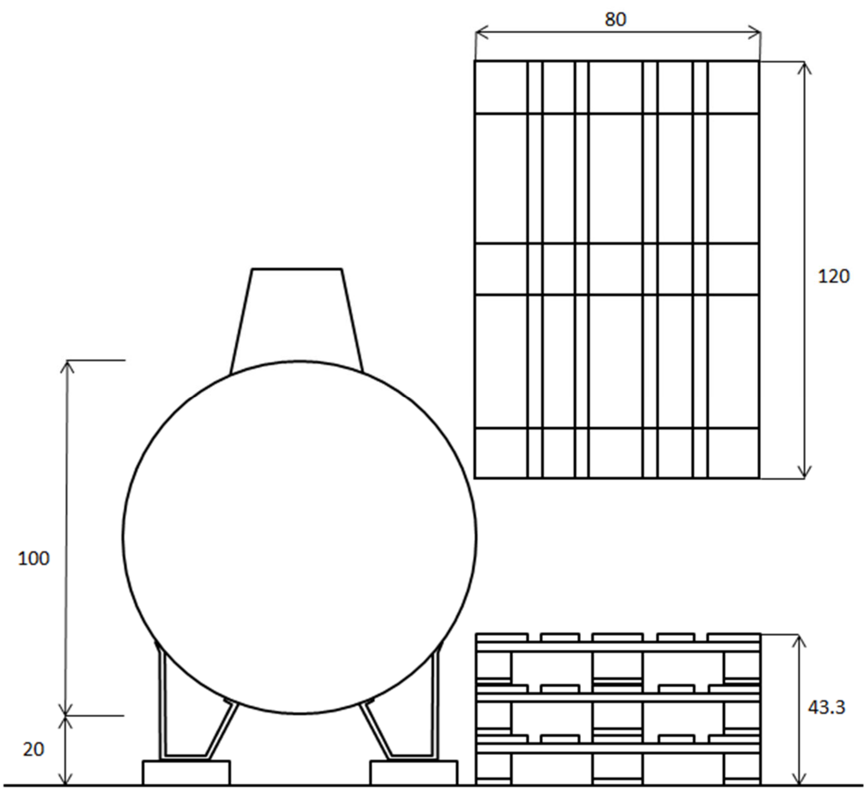
SC09.1. LPG tank placed over light flammable grass

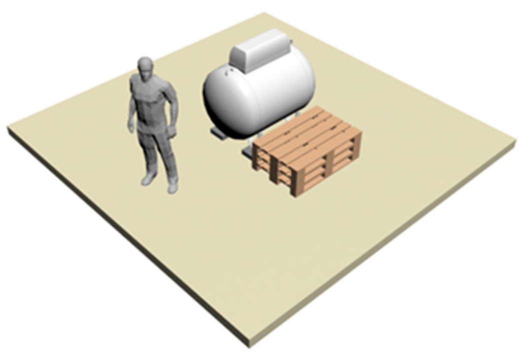
- A1 LPG tank (1m^3) exposed to the combustion of flashy cured grass with a fuel bed of 40 cm.
- Located in an area of 3x3 m^2 and LPG is centered
- Hypotheses of no-wind and 20 km/h wind (10 m) perpendicular to the main axis of the LPG tank.
- Lower part of the vessel shell is located at 20 cm from the ground.



SC09.2. LPG tank with a fuel pack underneath

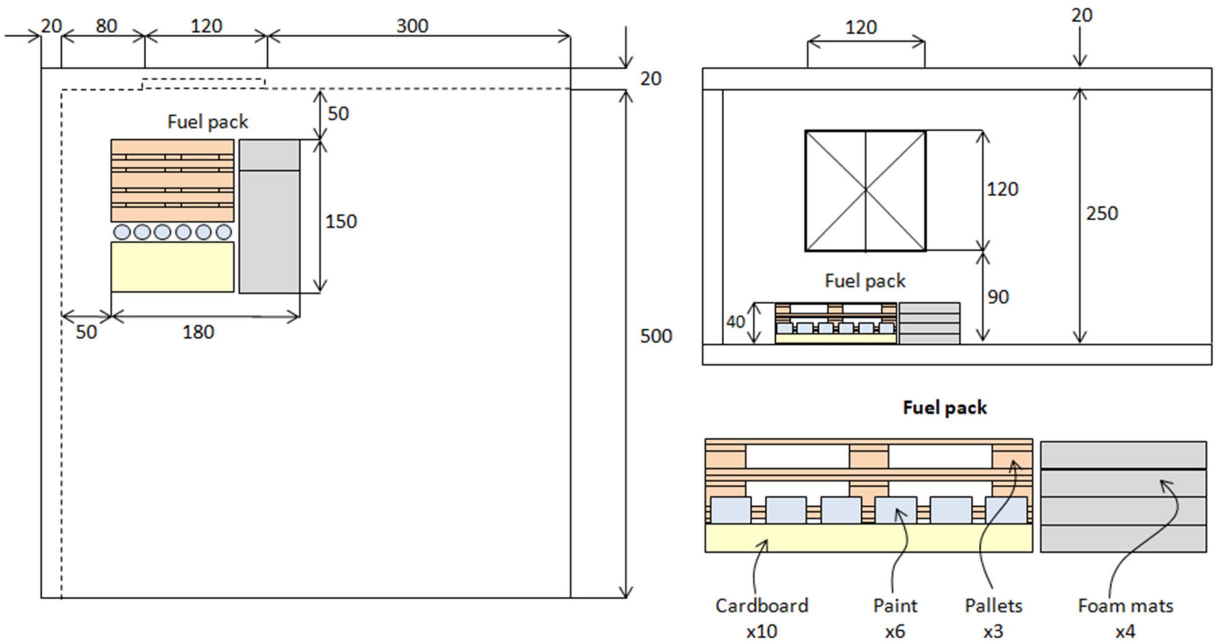
- A1 LPG tank (1m3) exposed to the combustion of three timber pallets, 80x120 cm each.
- Located below the LPG tank over 1 m2
- Hypotheses of no-wind and 20 km/h wind (10 m) blowing from the fuel pack towards the LPG tank
- Lower part of the vessel shell is located at 20 cm from the ground.





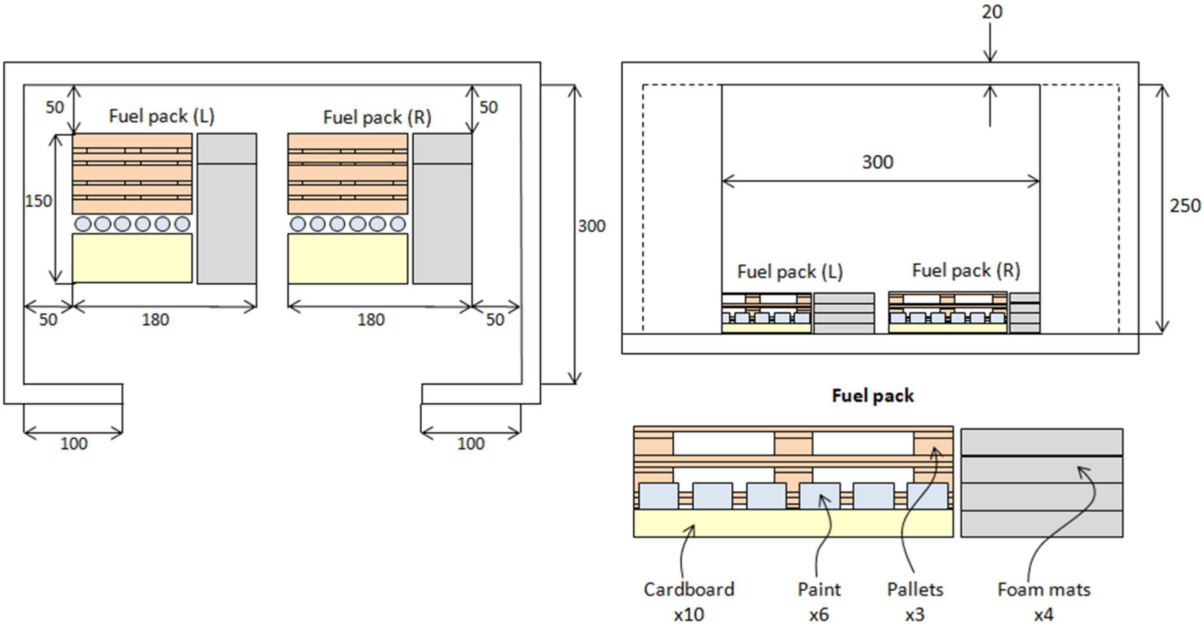
SC10. Fuel pack combustion in semi-confined arrangements

- A house porche corner, offering a 25 m^2 of overhanging ceiling in a 5x5 m^2 surface, flanked by two walls 2.5 m height which limit the air intake in case of combustion.
- A window is located in the North wall, with two swinging single panes, 60x120x0.6 cm each, with timber frame of 3x1 cm. The window box has a rebate of 10 cm.
- A fuel pack is placed 50 cm away of each wall, the window axis is lined up with the fuel pack center. The fuel pack is composed by:
  - 6 paint cans of Ø15x20 cm, holding 14 liters each.
  - A pile of cardboard of 10 pieces, 120x50x0.1 each.
  - 3 timber pallets 80x120 each, piled up.
  - 4 foam mats, 150x60x10 each.



SC11. Combustion of materials inside warehouses, garages

- A small warehouse, is composed by three walls 20 cm thick made of masonry, a ceiling, and a partially enclosed opening of 300x250 cm without any door. The internal floor surface offers a free space of 300x500 cm^2.
- Two fuel packs (left and right) are placed 50 cm away of each wall of the walls.
- Each fuel pack is composed by:
  - 6 paint cans of Ø15x20 cm, holding 14 liters each.
  - A pile of cardboard of 10 pieces, 120x50x0.1 each.
  - 3 timber pallets 80x120 each, piled up.
  - 4 foam mats, 150x60x10 each.



SC12. Smoke entrance and diffusion inside the house

- A single family structure, gable roofing, with clay tiles
- Eaves with open configuration in the edge, leaving entrance to particules.
- With one 80x120 window in the winwards (W) and the other in the opposite wall (L)
  - Completely open (both, L/W; only L; only W)
  - Half open (both, L/W; only L; only W)
  - Completely closed (both, L/W; only L; only W)
- A 100x200 entrance door, also facing winward, with a separation with the floor of 5 cm.
- In one of the sides, little vents of 20x10 at ground level, without protection or glazing.
- A forest fuel composed of two layers, crowns at 5m height of Pinus halepensis and a layer in the understory of 1.5 m of fuel bed, separated 20 m from the house.
- Wind blowing towards the house, 20 km/h at 10 km/h.
- Exposed to a concentration of gases produced in the combustion of the approaching forest fire and the surrounding ornamental vegetation.

Purpose of the simulation

- Analyse the eventual diffusion of gases inside the house in the 'all-closed' configuration (windows closed)
- Analyse the influence of the different window configurations in the entrance and circulation of gases inside the house.
- Evaluate the feasibility of the house as shelter or not, due to the entrance and accumulation of gases.

SC13. Fire propagation over green hedges and ornamental elements

- Hedge Type A *Cupressus arizonica*, 300x150 in a 'T' shaped hedge with a 5 m leg placed perpendicular to the main length of 10 m).
- Wind hypotheses:
  - No-wind.
  - 20 km wind at 10 m height, parallel to the main length axis.
  - 20 km wind at 10 m height, 45º from the main length axis.
- An ignition point located in the axis of the main length at a distance of 250 cm from the lower border.
- This configuration refers to the intersections that exist in the settlements, precisely in the border between two lots, were interesting flame interactions have been observed.