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WUI fire risk mitigation in Europe: A performance-based design approach at home-owner level

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ABSTRACT

Fires at the Wildland-Urban Interface (WUI) are becoming increasingly hazardous for life safety and property protection. Guidelines and standards for fire practitioners are needed in order to help WUI communities face this threat and become fire-adapted. A performance-based design approach (PBD) is proposed to deal with the complex issues present at the WUI homeowner scale, which entails the use of Computational Fluid Dynamics (CFD) tools such as FDS in order to identify vulnerabilities in a quantitative manner. An analysis of recent European WUI fires is presented, along with the definition of several pattern scenarios that can be derived from these. Based on this analysis, examples of PBD fire scenarios specific for the Mediterranean WUI microscale are presented, involving glazing systems, roofing and gutters, external structures adjacent to the main building, and gaps present in the building envelope. A worked example to show the implementation of the proposed PBD method is provided in which the fire impact of residential fuel on a glazing system is quantitatively analysed.

1. Introduction

Wildfires approaching Wildland-Urban Interface (WUI) settlements have become a rising problem in Europe. Hot and dry seasons in southern European countries are lengthening due to global warming, and wildfires are presenting great intensities and large destructive potential [1]. Other consequences of climate change are the emergence of WUI fire-prone zones in northern countries, whose policies and communities are not designed to deal with large wildfires. Additionally, human pressure on European forests is continuously growing, with an increase in housing developments and thus ignition sources at the WUI [2,3]. Therefore, WUI fires are posing great management challenges in terms of civil protection and fire mitigation. Firefighters' capacities are often exceeded, since a simultaneous response to wildfire suppression, community evacuation, and structure protection is usually needed. Self-protection has hence become a growing necessity, and therefore in the years to come, the focus will have to be placed on creating fire-adapted communities, which can safely co-exist with wildfires.

The WUI fire problem is inherently complex, as it is characterized by the interaction of multiple phenomena of diverse nature occurring at different observation scales: the macroscale or landscape scale, the mesoscale or settlement scale and the microscale or homeowner scale. All three are interrelated and allow to rationalize and identify all WUI fire management aspects. For example, the macroscale is associated, inter alia, with large forestry and operational management strategies (e.g. landscape design, fuel reduction planning, management of strategic points for suppression, etc.); the mesoscale corresponds to the level where preventive and protective measures to keep settlements safe have to be planned and implemented (e.g. fuel reduced strips around communities, water supply points, etc.); and finally, the microscale, as extended concept of the well-known "home ignition zone" [4,5], where the specific phenomena threatening people and dwellings take place, is associated with preventive actions at the immediate surroundings of houses to guarantee structure integrity, create self-defensible spaces and increase safety in eventual shelter-in-place operations.

The WUI microscale is quite often characterized by the presence of all sorts of combustible elements that may jeopardize the main structure: ornamental vegetation, ground fuels, fences, stored material, outbuildings (e.g. garages, garden or storage sheds) or even adjacent structures. In case of ignition of these elements, and provided flames duration and intensity are significant enough, consequences might have a severe impact. On the other hand, regardless of building designs and practices, houses at the WUI always present elements that are weak to fire exposure (e.g. openings, glazing and flooring systems, decks and verandas or eaves and gutters). These types of elements are responsible for houses' vulnerability, either because they are combustible or made out of mate-

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rials sensitive to fire, or because their geometry enhances heat transfer. For example, ignition likelihood from embers might be increased by re-radiation mechanisms in re-entrant corners; and local turbulences and flames entrainment might be induced in angled and edgy facades [6]. In addition, fire at the WUI microscale also involves people's presence. Residents of some WUI areas have been encouraged to actively prepare, to stay and defend or shelter in place in case of fire. Therefore, the interaction of both structure vulnerability and surrounding fuels exposure is critical to guarantee safe sheltering conditions.

During these last years, a significant number of regulations and recommendations have been issued in WUI-fire prone countries to mitigate fire risk at the microscale level. Although some of them are highly elaborate (e.g. [7–9]) the analysis of vulnerabilities from which they are based relies on simple fire models and limited experiments and provide general solutions to very particular problems. In addition, it has already been recognized that some of these guidelines might be based on assumptions of flat ground, no wind, and radiative heating only [10], and fail in capturing real fire exposures [11]. There is thus a need for improving standards, guidelines and vulnerability analysis methods at the WUI microscale relying on frontline fire engineering research and tools that allow for safer building designs and better managed properties.

Yet, new modelling frameworks are already available for the scientific community, which are capable of handling the complexity of WUI microscale scenarios with a high degree of reliability, and therefore assist fire risk analysis and inform policy-making processes. They are physically-based CFD (Computational Fluid Dynamics) tools, which, relying on a proper characterization of fire energy released and building features, can provide information on key variables for WUI risk management (e.g. temperatures and heat exposure on people and assets, evolution of the smoke layer and toxic doses, etc.). FDS (Fire Dynamic Simulator [12]) has been validated in multiple fire engineering applications and it is nowadays the most popular CFD modelling tool for PBD (performance-based design) evaluations of complex fire scenarios. On the other hand, empirical observations from past fires can give valuable information on factors, processes and consequences responsible of fire damage at home-owner scale [13]. Analysis of past fires allow for the identification of complex interactions between fuels, fire and assets from which initial assumptions regarding structure damage can be drawn. These lessons learnt from WUI fires allow baseline scenario building that can be analysed by CFD tools through performance-based criteria to assess the degree of safety which meets the objectives of life and property protection.

In this paper, we present a PBD approach to assist fire vulnerability assessment at the WUI microscale. We provide the rationale of the method, highlighting advantages and challenges (Section 2). Based on analysis of past WUI fires, we summarize observed problems and vulnerabilities which have led us to identify pattern scenarios of structure damage in Europe (Section 3). From these lessons learnt, we outline design fire scenarios (Section 4) to be analysed by CFD tools, which can lead us to provide solid knowledge for better-informed fire safety design, property management and policy-making process.

2. Performance-Based design at the WUI microscale

Performance-based fire safety design is a methodology for the engineering of fire safe building solutions based on three key aspects [14]:

- The definition of the level and type of performance that the final solution has to guarantee to meet general and particular fire safety objectives related to life, assets and environment protection.
- The definition of the potential fire events that may occur (i.e. design fire scenarios), considering the interaction between occupants, building characteristics and fire.
- The quantitative assessment of the proposed design against the defined goals facing pre-defined fires scenarios, relying –when needed– on advanced CFD codes.

Although the first evidence of PBD applied to fire safety can be found more than 40 years ago [15], its application is irregular throughout different regions, mostly depending on the degree of innovative architectural designs, the building codes maturity in terms of performance-based provisions, and on the fire engineering expertise. PBD is being significantly applied to *i)* face particular fire safety challenges related to prescriptive codes compliance when applied to singular constructions or new materials (e.g. high-rise buildings, atria, long tunnels, green buildings [16,17]); *ii)* to update old prescriptions of existing code [18], and *iii)* to design according to advanced goal-orientated building acts (e.g. [19,20]).

In this context, PBD has taken root in several regions with a settled fire engineering culture (e.g. Northern Europe, Southeast Asia, New Zealand, Australia) and is being implemented at an accelerating rate in many others (e.g. Mediterranean Europe, North America). Moreover, PBD gives valuable insights on how a building performs in case of fire, it is a suitable methodology to address unique design characteristics and its outcomes are clearer and more targeted, meaning ease of communication between stakeholders [14].

When it comes to the WUI, regulatory bodies, research institutions and practitioners are starting to address its fire safety challenges with the aid of PBD methods. The National Fire Protection Agency (NFPA) has recommended considering a design fire scenario of an outside fire exposure for PBD projects involving WUI structures [21]. PBD has also been adopted as the approach to design private shelters in Australia [22]. CFD tools [23,24] and other physics-based simpler models [25] have already shown potential for studying the performance of structural elements challenged against WUI fires.

Considering the characteristics and specificity of WUI fires, a performance-based approach which focuses on fire-safety objectives is interesting to explore. The many variables and thus scenarios these problems present can be analysed with the help of CFD modelling tools such as FDS. Despite the inherent and unavoidable uncertainty of CFD, this modelling approach allows for great flexibility in the definition of different configurations, materials and fire loads present at the WUI microscale, which is otherwise very difficult to achieve in experimental tests.

With the proper characterization of the fire source and of the building features, FDS can provide information on key variables for WUI risk management. This tool allows for the analysis of a large number of scenarios and can cover the diverse fire safety needs of the WUI microscale, such as the quantification of the hazards associated to combustible materials placed close to structures, the assessment of the vulnerability of these structures, or the testing of current regulations. Results from these simulations can then be compared to previously set performance criteria, in order to obtain relevant and solid conclusions.

By following a PBD methodology, fire scenarios which involve the following issues can be analysed:

- Houses vulnerability assessment: building performance analysis for structure triage (i.e. defensible/indefensible houses).
- Subsystems hazard testing: hazard assessment of individual fuels (e.g. stored materials, ornamental and wildland vegetation, etc.) and performance evaluation of specific building components (e.g. openings, glazing systems, etc.).
- Post-fire investigation: quantitative analysis of past incidents to identify main causes of fire losses, illustrate lessons learnt and provide evidences to insurance covering assessment.
- Fire safety regulations improvements: design of PBD WUI-specific standards/codes and revision of prescriptive ones.

The analysis of these scenarios can lead to the development of scientifically supported measures to be transferred into regulation provisions, fire safety design guidelines and educational material about fire prevention and safety for homeowners, land managers and fire agencies.

Table 1
Summary of recent WUI fires in Europe.

Fire	Date	Structure damage	Effects on humans
Västmanland, Sweden	July 31st 2014	35 structures with light or no damage 32 structures destroyed or severely damaged	1 fatality 1 civilian seriously injured 9 firefighters injured
Funchal, Portugal	August 9th 2016	37 structures completely destroyed 117 structures severely damaged	3 fatalities 200 injured
Rognac, France	August 10th 2016	24 houses completely destroyed 15 structures moderately damaged 117 structures lightly damaged	No fatalities 6 injured
Benitatxell, Spain	September 4th 2016	3 structures severely damaged 197 houses lightly damaged	No fatalities
Pedrógão Grande, Portugal	June 17th 2017	153 structures with light or moderate damage 427 with remarkable damage 457 structures destroyed	65 fatalities 200 injured
Mati, Greece	July 23rd 2018	1713 structures with light or no damage 794 structures with remarkable or severe damage 998 structures destroyed	101 fatalities 200 injured
Llutxent, Spain	August 7th 2018	30 structures with remarkable damage 13 structures completely destroyed	No fatalities

3. Building fire scenarios

To illustrate the potential of the approach mentioned here above, fire scenarios will be defined according to observations from past WUI fires. Recent fires and their consequences are described in this section, along with a summary of the lessons observed from these fires. Fault tree analysis is subsequently applied to describe the main fire-structure interactions leading to a fire entering a structure, being hence responsible to house damage.

3.1. Survey of recent WUI fires in Europe

One of the main sources of information about the factors and processes responsible of houses' vulnerability is the systematic survey, data gathering and detailed study of forest fires in the WUI [13]. Information about meteorological conditions, fire behaviour, firefighting 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, from which valuable lessons have been extracted, are briefly presented in Table 1. Information about these fires was gathered through site visits and interviews to the local fire authorities. The degrees of damage vary from *no damage* to *complete destruction* as described by Pastor et al. [26].

On the 31st of July 2014, around 13:29 a call was received by 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 region was suffering from a long and deep drought period, affecting live and dead forest fuels, including moss on the ground. The fire front progressed over several days with several wind changes, but on the 4th of August, in the afternoon, a phenomenal run towards North-Northwest took place, with the generation of a dense plume which created an out of control scenario. The average rate of fire spread was 48 m/min (almost 3 km/h) with peaks of 100 m/min (6 km/h), and projection of fire embers was observed at distances over 2 km ahead of the fire front. The fire ran over several housing areas, particularly in the town of Stabäck, which was in the main path of the fire run. There were a total of 67 structures damaged. One person was reported dead and another one was seriously injured.

On August 8th 2016, a fire was set by an arsonist in the San Roque parish, not far from the city of Funchal on the Island of Madeira (Portugal). Madeira was suffering a heat wave as never seen before, with sustained minimum temperatures of 28 °C. Two large fires started almost simultaneously. The fire in the Funchal area spread quickly sideward, under winds abnormally blowing from the North at 20–30 km/h, with gusts of 50–80 km/h. Early in the afternoon, the fire front reached a water treatment plant, devoid of any prevention measure or protection installation. The second day (9th of August) the fire front increased its activity in two of the many ravines running in parallel to the wind direction, packed with fuel and with almost vertical walls, which eventually caught fire laterally and affected the many houses on top. Three deaths are attributed to the wildfire and over 200 people were injured. Eighty people needed medical assistance in several hospitals, suffering from burns and smoke inhalation. All the fatalities occurred inside structures. A total of 154 houses were severely damaged or completely destroyed. Most of them presented evidence of combustion on the inside, with collapsed roofs. Many were surrounded by residential fuels, little orchards, unmanaged vegetation or eucalypt forests.

On August 10th 2016, a fire ignited at 15:09 in the municipality of Rognac, not far from the Marignane airport of Marseille, France. The cause of the fire was a cigarette negligently casted onto a pile of dry vegetal debris in an area under construction. Mistral wind blowing from the Northwest with gusts of 50–80 km/h quickly impelled the fire towards a densely populated area. The flame front spread at phenomenal speeds, with registered peaks up to 7 km/h, projecting flying embers and generating spot fires at reported distances up to 1 km ahead. No fatalities were reported in this fire. However, 33 people suffered smoke intoxication. This fire affected 156 structures, out of which 24 were completely lost, 15 moderately damaged and 117 suffered light damage.

On September 4th of 2016, a forest fire started at 15:31 in the municipality of Poblenou de Benitatxell, Alicante (Spain) as a consequence of arson, in a day with record temperatures of 35 °C and low relative humidity below 25%. At that time, the wind was blowing at a speed of 24 km/h from Southwest, with gusts of 52 km/h, pushing the fire along the ridge towards the Northeast and threatening several settlements in the area. On the same day, two other important fires were happening in Bolulla and Moixent, which were requiring a good number of firefighting forces. Although the fire was rapidly attended, a reactivation by a spot fire projected a massive shower of fire embers into the nearby settlements, percolating in the Valle del Sol and Pinosol settlements up to 2.5 km ahead. Evacuations of the affected settlements were ordered, which involved nearly 1400 people. No fatalities were reported in this event. Around 200 structures were affected by the fire, most of them due to the spotting that happened on the first day. Only 3 were reported to be severely damaged, mostly due to the accumulation of residential fuels close to the structures and, in other cases, because windows were left open.

On the 17th of June 2017, a battery of dry thunderstorms passed across central Portugal, with lightning strikes which entailed fire outbreaks. That day, five fires ignited 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 drought period, and that day was a record in temperatures, reaching 46 °C and relative humidity below 25%. The Pedrógão fire started around 14:30, allegedly by electrical failure of a medium-voltage power line without protective strip. Around 20:00 a downburst was observed due to the collapse of the plume, which eventually caused a dramatic change in the fire behaviour, which allowed the fire to spread in all directions at extraordinary speeds. This event triggered the evacuation of many of the villagers in the area. Simultaneously, this rapid spread outran a group of people in their vehicles on the E236 road connecting Castanheira da Pera and Figueiró dos Vinhos, causing a major entrapment and killing 34 people. This complex wildfire claimed the lives of 65 people. More than 200 people were injured. More than 1000 structures were damaged 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; 91 structures were completely destroyed.

On July 23rd 2018, a fire started at 16:38 in Daou Penteli, a small residential area within the Northeast part of Attica region (Greece), 30 km from Athens, due to reported negligence by a man burning some vegetal debris. On the same day, around noon, another wildfire started in the West Attica near the city of Kinetta, potentially threatening its population and an oil refinery. The fire in Daou Penteli rapidly spread towards the Neos Voutzas settlement, in the main axis of propagation, pushed by 80–100 km/h winds unusually blowing from West for that time of the year. The fire front continued a down slope fast run through ravines, engulfing dense pine stands and jumping perpendicularly over Marathon Avenue, a four lane highway which separates Neos Voutzas from the densely populated area of Mati. Showing indicators of extreme behaviour, the fire continued burning through a mixed pattern of houses and vegetation, mostly and particularly thanks to the projection of massive showers of firebrands. As no evacuation order was given, many of the people found themselves trapped between the approaching fire and the seashore, fringed by a cliff. Two main entrapments involved the killing of 78 people, 3 of which were inside structures, and severely injuring many others. Twenty-three people died later in hospitals, resulting in a dead toll of 101. This fire accounted for nearly 2000 houses damaged, 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. All types of buildings were present in the area: 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.

On the morning of the 6th of August 2018, a lightning strike from a thunderstorm started a forest fire around 15:00 in an inaccessible slope in the municipality of Llutxent, Spain. East winds favoured a rapid and intense evolution of the incipient fire heading towards the West. At that time, on the same day, five other fires erupted, many of them as cause of lightning strikes. The existing atmospheric instability helped to quickly create a massive convection column. The towns of Barx and La Drova were preventively evacuated (2500 people). The next day the winds started rolling in the Northeast and by afternoon the fire was conducted towards the settlements already evacuated the day before, engulfing the houses. Around 50 structures were damaged in 3 of the settlements. Out of them, 13 houses were completely destroyed. No victims were reported.

3.2. Summary of lessons observed

A number of observed lessons are extracted from these wildfires in European WUI areas, which involve factors and processes that seem to be repeated when it comes to the interaction between fire and structures.

A first lesson is that, in all of the reported forest fires at the WUI, structures are affected by fire in one or several phases at different moments in time and at different rates, with various consequences. These could be seen as ‘fire exposure phases’, which entail one or more of the following:

- Pre-impact. 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 will reach the property, well before any flame is on sight. These firebrands are capable of setting fire to cured grasses, pine needles, hedges and ornamental plants and several other combustible materials and objects present in the garden near the house, or even to the house itself [27–29]. 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. The phase in which a flame front is directly facing the house at such a distance at which flame impingement and radiant heat may affect —and eventually ignite— the components of the house [27], the vegetal elements of the garden and the several other objects and materials that are present on the property. This is particularly true for the properties and houses at the border of the settlement, directly facing a forested land.
- Fire transfer. The phase in which fire propagation occurs through the elements on a property, commonly green hedges, trees and other vegetal elements, into the neighbouring parcels along the settlement. Fire propagation may also happen through the new production and emission of firebrands from the burning elements on the property into other remote parts of the settlement, particularly undeveloped unmanaged lots with cured grass and dense vegetation.
- Post-frontal combustion. The phase in which all the objects, materials and house components that ignited in any of the previous phases continue burning for longer periods and which eventually can cause further damage or chained events (domino effect). In this phase, quite an amount of energy and combustion gases can still be released.

A second main consideration in regard to lessons observed is that, even though houses across Mediterranean Europe are built out of noncombustible materials such as stone, bricks, clay stone, mortar or iron, these structures still can be destroyed if the fire gets through. A first reflection based on observation underlines the many complexities and subtleties lay behind houses’ destruction. In fact, many of the observations point at little details in the structure design and maintenance, elements, materials, or configurations as well as the relative position, size and type of the potential heat sources. These are responsible for the fire initiation inside the house and for the degrees of structural damage.

Three main fire sources which can approach a WUI microscale structure have been identified: the wildfire front, the burning of natural fuels and the burning of non-natural fuels present at the microscale. The threat posed by all three fire sources depend on the residence time of the fire (i.e. the length of time for the flame front to pass a given point [30]) and on the flames’ geometry. For wildfires, these characteristics vary greatly depending on the type of fuels (e.g. grassland, shrub land, forest stand, logging slash) [31]. Natural fuels placed around the house consist mostly of ornamental vegetation. The intensity at which this vegetation burns as well as the duration of the flaming phase depend on the species and its level of maintenance (i.e. trimming, pruning, watering), which conditions the fuel load, the density and the moisture content of the vegetation. For example, hedges of *Cupressus arizonica* can ignite quickly, have a very rapid fire growth and a short fire duration, while hedges of *Prunus laurocerasus* have lower combustibility and are much harder to ignite (Ribeiro et al., WUIVIEW Deliverable D2.1, unpublished work). Non-natural fuels present at the WUI microscale vary significantly and are composed mostly out of plastic or wooden materials. Their Heat Release Rates (HRR) and burning times are also substantially variable, as can be seen from Fig. 1, where the HRR curve of a stack of 6 chairs

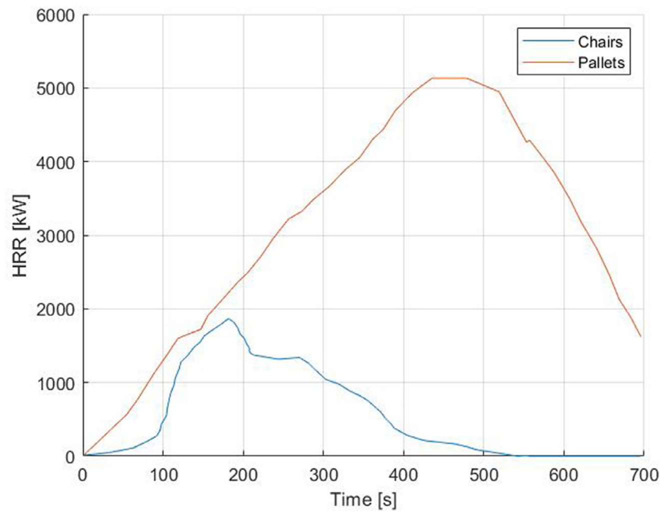

Fig. 1. HRR curve of a stack of 6 chairs [32] compared to the one of a stack of pallets [33]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

made out of plastic and steel is compared to the one of a stack of wooden pallets with the height of 0.9 m.

As pointed out in other surveys [13,28,34] we have observed that the likelihood of house loss is mostly related to the interaction of firebrands attack with surrounding combustible elements, which results in flames too close to the structure, excepting those cases of houses particularly adjoining the wildland which might then be exposed to shrub land or forest fire.

The fault tree in Fig. 2 reports the different observed patterns that can lead to the fire entering a structure during all of the abovementioned fire exposure phases.

One of the observed ways of a fire entering a house is through windows or doors that are left open due to sudden and unprepared evacuation, or through poorly designed or maintained vent ducts (Fig. 3). Flames or flying embers can enter the house and start indoor ignition of curtains, furniture, papers or any other light fuels. This may progress into full involvement of a room and the eventual burning of the whole house, if left unattended.

If a property is poorly managed, and the combustible elements commonly present at the WUI microscale are placed too close to a structure, they can be responsible of severe impact. The same is plausible in case of a settlement located too close to forested land. The combustion of aforementioned fuels, if placed close to unprotected glazing elements, can cause cracking or collapsing of the glass, hence giving way to the entrance of smoke, firebrands and flames. Direct flame impingement onto windowpanes or other weak points within the house envelope can greatly affect structures' integrity (Fig. 4).

Confined or semi-confined spaces such as garages, sheds, or storage areas, which contain non-natural fuels, are also vulnerable to fire embers, radiation exposure and flame impingement. These secondary structures are often placed close to the main structure or are extensions of it. A large accumulation of heat in those areas due to the ignition of their contents could lead to fire spread to the main structure through internal doors, passageways, or windows, as well as to structural damage to the house envelope (Fig. 5).

In a wildfire, roofing is directly exposed to flying embers, radiation and even direct flames. 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 through the attic, the involvement of the roofing structure and its eventual collapse (Fig. 6).

4. Definition of fire scenarios

As previously mentioned, homes ignition at the WUI is associated with embers, heat exposure or flame impingement [27]. Embers coming from the main fire front can deposit on combustible building elements or enter the building through gaps in its envelope. They can also ignite other fuels placed in the surroundings of the main structure, such as ornamental vegetation or non-natural fuels, which subsequently pose a threat to the building. Heat exposure, mainly radiant, may occur when large flames are close to exposed structural elements, and it may create damage to sensitive areas of a structure (e.g. glazing systems). Finally, flame impingement occurs when flames from either close burning items or from the surrounding wildland are in contact with adjacent structural elements. This represents the most hazardous ignition mechanism because it provides the highest heat fluxes transferred onto structures.

Protection of structures must thus incorporate these potential sources of ignition by including them in design fire scenarios which are specific for the WUI. Currently, NFPA 101 [21] describes a WUI design fire scenario as *i)* an outside fire exposure and *ii)* it addresses the concern regarding a fire starting at a location remote from the area of interest and either spreading into the area, blocking escape from the area, or developing untenable conditions within the area. There is thus clearly a lack of guidelines on how to develop WUI microscale design fire scenarios which address the diverse weaknesses of WUI structures when exposed to the different pathways of ignition.

As previously stated, structures at the Mediterranean WUI are built out of non-combustible materials, which means that a fire can enter the structure only through potential gaps. The pattern scenarios outlined from past fires and given in Fig. 2 identify the weaknesses of south European WUI structures. Design fire scenarios that deal with these weaknesses are presented in the following sections. These scenarios deal with subsystem hazard testing, with the scope of evaluating the vulnerability of specific building components to a particular WUI fire exposure (e.g. wildfire front, burning ornamental vegetation and burning of non-natural fuels). The assessment of these scenarios has to be addressed considering the goals of life safety (for buildings with sheltering purposes) and property protection. Subsequently, specific objectives have to entail the prevention of structural damage to the building and the avoidance of fire or smoke entering the structure.

4.1. Glazing systems exposed to a close fire

As observed in recent fires, windows are frequently one of the most exposed elements of a structure. Cracking or collapsing of window panes is observed as a consequence of flame impingement or heat exposure coming from the wildfire front or from close objects or vegetation previously ignited mainly by flying embers. Once the window has failed, flying embers can also enter the structure and cause the ignition of the inside elements.

Windows vary greatly in size, framing, glazing type, thickness, and casing. Double glazing, reinforced glass, tempered glass and reflective glass are more resistant to radiation than laminated single pane glass. Performance criteria set to avoid cracking of the glass or melting of the frame will thus vary depending on the typology of the window.

The following variables must be considered when setting up a scenario involving glazing systems:

- Type of fire the window is exposed to and its distance from it. If the building is placed close to the forested land, the window might directly be exposed to the radiation coming from the wildfire front. Otherwise, flying embers could ignite the natural and non-natural fuels present on a property. If these fuels are located closely enough to a window, they can pose a threat to its integrity as well.

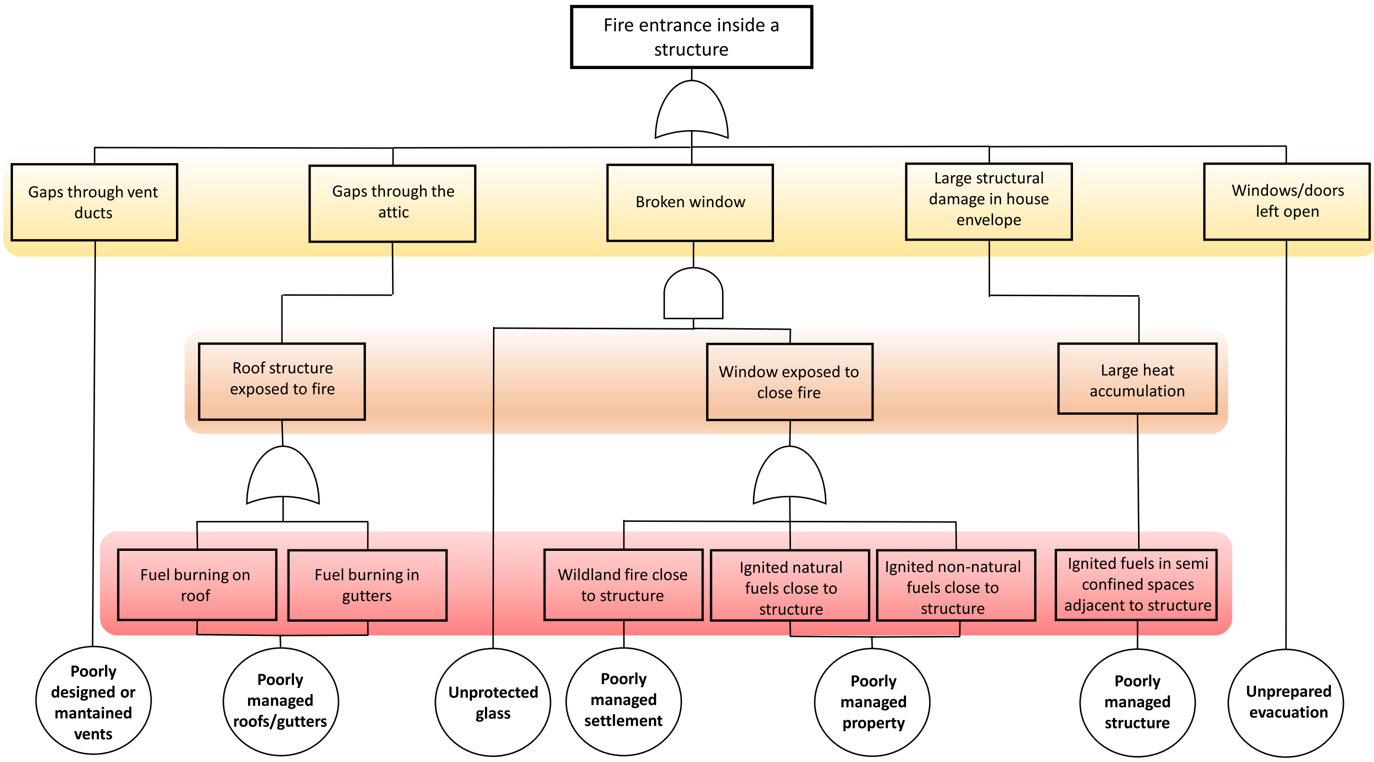

Fig. 2. Fault tree describing observed patterns that lead to fire entrance inside a structure. The red area identifies the fire source, the orange one identifies the impact of the fire onto the structure, and the yellow one pinpoints the ways through which the fire can enter the structure. The bottom events are identified as basic events, while the others are intermediate events, which lead the main one, thus to the entrance of fire inside a structure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Vent placed in the attic of a house in Neos Voutzas-Mati (Greece, 2019).

Fig. 4. Glazing collapse in Neos Voutzas-Mati (Greece, 2018) due to the combustion of a pine tree.

- Location of the lot where the house is installed in the landscape. This plays a key role in the type, extension and intensity of exposure to flame fronts, fire embers and smoke. Houses located in midslopes, ridges or hilltops are potentially more exposed than those located in the lower parts, wide valleys or flat terrain.
- Window characteristics. In order to set the performance criteria for the window as well as the inputs for the simulation, its geometry must be known, along with the typology and thickness of the glass, the amount of panes, and the frame material.
- Wind conditions. Wind direction and speed can be critical variables, since flames coming from a close by fire could impinge onto the window due to the wind.

4.2. Roofing and gutters exposed to a wildfire front

Roofing is one of the components mostly related to house survivability in case of a forest fire, since it is one of the parts of the house most exposed to an incoming flame front. The most common types of roofing observed in the European WUI are gable roof, hip roof, intersecting roof and shed roof. In some countries (i.e. Greece) flat roofs are also common. Roofs located under overhanging tree branches tend to accumulate fine fuels such as pine needles, particularly in the valleys and other convex shapes or on flat roofing. These points also accumulate

Fig. 5. A house severely damaged in Benitatxell (Spain, 2016) due to the combustion of fuels in a semi-confined space.

Fig. 6. Clay tile roofing severely affected by spot fires in the Funchal wildfire (Portugal, 2016).

flying embers and provide local combustion which may entail the involvement of the roof structure. Clay tiles are very frequent 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. Eaves are protruding parts of the roof particularly exposed to radiation and flame impingement. Eaves' soffit vents are eventual entrances of embers or flames, which can subsequently reach the attic structure.

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) have a better resistance to 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.

When setting up a scenario involving roofing and gutters, the following variables should be considered:

- Fuel load configuration, which involves the type of fuel, its packing ratio and moisture content, and its depth along the eaves or gutters. This scenario entails the ignition of the accumulated fuel by flying embers coming from the wildfire front.
- Geometry of eave and gutter and distance between them, in order to detect possible fire spread from the gutters to the roof.
- Roof and gutter characteristics, including the roofing angle and the material composition, in order to identify the possible weaknesses in the structure and thus set performance criteria.
- Wind conditions. Wind speed and direction can vary the direction and rate of fire spread along the roof or gutters.

4.3. Fire in secondary structures

In Europe, and particularly in Mediterranean countries, secondary structures such as sheds, garages, or other types of storage areas are common. These can be attached to the main building, and are populated with many different non-natural fuels. Generally, these spaces are semi-confined, and thus open on at least one side. The objects stored in these structures can therefore be exposed to flying embers and to flames which could cause the ignition of these items, which will subsequently burn for long periods of time.

If one of these secondary structures is connected to the main buildings and the elements present in these areas are ignited, the great heat build-up created by the fire could cause great damage to the main structure's envelope.

The following variables must be considered when setting up a scenario in these type of structures:

- Geometry and composition of the fuels present in the structure. This scenario entails the ignition of these fuels by embers or close flames. The heat release rate of these fuels can be derived from experimental data or from theoretical methodologies.
- Location of the fuels within the secondary structure.
- Structure characteristics. The geometry of the secondary structure and its location in respect to the main building must be set, as well as the material composition of the two structures. If the composition and thicknesses of the elements creating the constructions are known, performance criteria to avoid structural failure can be identified.

4.4. Gaps in building envelope exposed to wildfire

Vents are openings designated to facilitate air circulation. Most common vents are located on the roof, while others 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. These are ways through which embers, smoke and eventually fire can enter a building, particularly if there is no screening, along with other gaps such open windows or doors. Performance criteria for this scenario will vary depending on the goals (i.e. life safety or property protection).

The following variables must be considered when setting up a scenario involving these gaps in the building envelope, assuming an incoming wildfire front:

- Distance of fire front from the building. This will determine if the building is subjected to flying embers, radiated heat, flame impingement, or smoke coming from the fire front.
- Configuration of openings (open, semi-open) and their location within the building envelope.
- Location of the lot within the landscape, as described in Section 4.1.
- Wind conditions. Wind speed and direction can vary the location of the deposition of flying embers, the flames' tilting angle, and the speed and direction of the smoke spread.

5. Worked example

As a worked example, a scenario involving a glazing system exposed to a fire from residential fuel burning is analysed. Performance criteria

Table 2
Performance criteria for 3 mm single pane glass [35,36].

Surface temperature [°C]	ΔT between middle and edge [°C]	Received heat dose $[(kW/m^2)^{4/3}\ s]$
150	58	1840

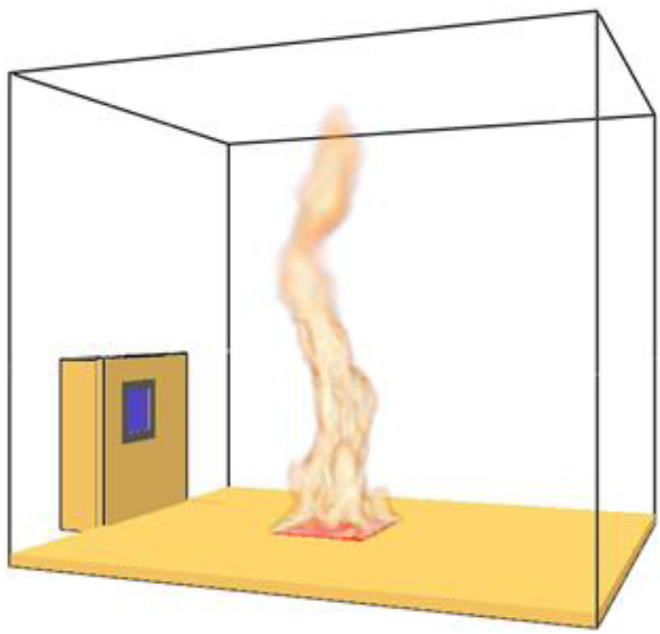

Fig. 7. FDS geometry.

Table 3
Time of glass failure for the different performance criteria.

Performance criteria	Time of failure [s]
Surface Temperature	215
ΔT	–
Heat Dose	206

for unprotected glass, single pane and with a thickness of 3 mm are given in Table 2. Failure of the glazing system will happen when one of these criteria is met.

The heat dose is a function of the received heat flux and the exposure time, as indicated in Eq. (1) [37].

$$Heat\ dose = I^{\frac{4}{3}} \cdot t \left[\left(kW/m^2\right)^{\frac{4}{3}} s \right] \tag{1}$$

Taking as example the basic event of a poorly managed property, a fire scenario of non-natural fuels is here analysed. A stack of pallets of a height of 0.9 m is placed at a distance of 2 m from a 3-mm thick single pane window. The Heat Release Rate curve of this fire is given in Fig. 1. The size of the window is 0.5 m x 0.5 m. This scenario involves calm conditions (no wind).

The scenario is simulated in FDS (Fig. 7), where the surface temperatures of the glass and the heat flux onto the glass are measured. The heat dose is then calculated from the obtained heat flux over time curve.

Table 3 shows the different failure times according to each performance criterion.

The glass will thus fail due to the received heat dose after about 3.5 min from the ignition of the pallets. At this time the HRR of the fire reaches 2.5 MW. The ΔT criterion between middle and edge of the glass is in this case never reached. This is due to the small size of the window, which allows for a more uniform temperature increase across the whole surface of the glass.

Given the results, such a fire source as the one simulated must be placed further than 2 m from the window. Simulations must thus be performed at greater distances, in order to identify the distance at which such a fuel can be safely placed in front of a window.

6. Concluding remarks

The need for a PBD approach for the WUI microscale is highlighted by the complexity of the different interactions that can occur between fire, structures and residents. A procedure for the extraction of lessons observed in real fires and for the identification of pattern scenarios has been presented, from which four design fire scenarios specific for the Mediterranean WUI microscale have been derived, namely: *Glazing systems exposed to a close fire; Roofing and gutters exposed to a wildfire front; Fire in secondary structures; Gaps in building envelope exposed to wildfire*. By utilizing CFD tools such as FDS to analyse these scenarios, vulnerabilities can be identified in a quantitative way, since results can be compared to performance criteria set for specific scenarios, as shown in the worked example on glazing systems. This approach offers thus a powerful and flexible tool to explore, analyse and derive robust conclusions by repeating scenarios under non-limited virtual laboratory conditions. This will allow for the creation of a PBD WUI-specific guideline applicable both to new and existing structures.

It is recommended to continue the systematic survey, data gathering and analysis of real fires as main source of information to drive and focus the research activities and to broaden the pool of WUI design scenarios. Future work should include the quantification of the different fire sources described in the scenarios (i.e. heat release rate curves), along with the recommendations on the wind conditions to adopt for each scenario. The presented approach can also be used for the assessment of existing and new buildings as adequate sheltering places, the analysis of suppression systems and other elements which could act as heat barriers (e.g. backyard fencing, water mist systems, etc.), and the analysis of heat transfer mechanisms in building structures with complex geometries.

Declaration of Competing Interest

Authors declare no conflict of interest.

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