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Recommendations on structure survivability and sheltering capacity

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Abstract	This document reports the structure survivability and sheltering capacity analysis performed as core activity of the WUIVIEW WP6. Results from virtual experiments (FDS simulations) and literature review regarding pattern scenarios typical of WUI fires observed at microscale level are analysed and confronted with prescriptions from international codes and standards. The study involves the following topics: glazing systems exposed to fire, fuel packs burning in semi-confined spaces, fire exposure on LPG tanks, vulnerability of roofs, gutters and vents, residential vegetation management, fire hazard on hedgerows, vulnerability to wildfire exposure and sheltering. Recommendations from this analysis are distilled and translated into two simple (checklist type) self-assessment tools of structure vulnerability and sheltering capacity to be used as prototypes in WP7 study cases.
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Table of Contents

1.	About this deliverable	5
2.	Summary of lessons observed in past WUI fires.....	6
2.1.	Structure survivability in dwellings exposed to WUI fires.....	6
2.2.	Sheltering capacity in dwellings exposed to WUI fires	8
3.	Summary of key messages in WUI standards	10
4.	Structure survivability analysis	11
4.1.	Methodology and rationale	11
4.2.	Glazing systems exposed to fire	12
4.2.1.	Idealized Scenarios - experimental design.....	12
4.2.2.	Materials and fire characterization.....	13
4.2.3.	Performance criteria	15
4.2.4.	Simulations set-up	16
4.2.5.	Results and discussion	19
4.3.	Fuel packs burning in semi-confined spaces.....	23
4.3.1.	Idealized Scenarios - experimental design.....	23
4.3.2.	Materials and fire characterization.....	24
4.3.3.	Performance criteria.....	25
4.3.4.	Simulations set-up	26
4.3.5.	Results and discussion	28
4.4.	Fire exposure on LPG tanks	35
4.4.1.	Idealized Scenarios - experimental design.....	35
4.4.2.	Fire characterization	38
4.4.3.	Performance criteria.....	39
4.4.4.	Simulations set-up	40
4.4.5.	Results and discussion	43
4.5.	Vulnerability of roofs, gutters and vents	49
4.6.	Residential vegetation management.....	50
4.6.1.	Areas of management	51
4.6.2.	Fuel treatments	51
4.6.3.	Fire-resistant species	52
4.7.	Fire hazard on hedgerows	53
4.7.1.	Idealized Scenarios - experimental design.....	54
4.7.2.	Materials and fire characterization.....	54
4.7.3.	Simulations set-up	54

4.7.4.	Results and discussion	55
4.8.	Vulnerability to wildfire exposure	57
4.8.1.	Idealized Scenarios	57
4.8.2.	Solid Flame Model	58
4.8.3.	Results and discussion	58
4.9.	Summary of recommendations for structure survivability	63
5.	Sheltering capacity analysis.....	65
5.1.	Fire and smoke hazards	65
5.2.	Methodology and rationale	67
5.2.1.	Model	67
5.3.	Results and discussion.....	74
5.3.1.	Open vs. closed house 10 m away from the front	74
5.3.2.	Open house 5 m away from the front	77
5.3.3.	Radiative heat flux reduction inside the house	78
5.4.	Summary of recommendations for sheltering capacity.....	79
6.	References.....	80
7.	ANNEX A – V.A.T – Vulnerability Assessment Tool	88
8.	ANNEX B – S.A.T – Sheltering Assessment Tool.....	94

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 damage 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 6 is devoted to test pattern scenarios defined in previous WP5 in terms of structure survivability and sheltering capacity. The document at hand is the first deliverable of WP6. In this report, results from virtual experiments (i.e. FDS simulations) are analysed and confronted with prescriptions and recommendations found in codes and standards. From this discussion, insights on how to protect structures and minimize microscale vulnerability and on tenability conditions in typical dwellings exposed to WUI fires are gathered and structured in a rational basis. This information is later on translated into simple tools (checklists) to assist on structure survivability and sheltering assessment capabilities of WUI structures.

The document is organized as follows:

- In Section 2, a summary of lessons observed in past WUI fires regarding structure survivability and sheltering is provided along with the definition of several pattern scenarios that can be derived from these (collection of key messages from past D5.1 "Inventory of pattern scenarios"). Fault tree analysis technique is applied to define in a rational way the main causes leading to structure damage in European WUI settlements.
- Section 3 summarizes the main messages found in codes and standards at international level (collection of key findings from past D4.2 "State of the art and gap analysis on WUI fire codes and regulations").
- Section 4 reports the dwellings survivability analysis structured in a problem-oriented approach, i.e. following the pattern scenarios identified in past Section 2 (glazing systems exposed to fire, fuel packs burning in semi-confined spaces, fire exposure in LPG tanks, vulnerability of roofs, gutters and vents, residential vegetation management, fire hazard on hedgerows and vulnerability to wildfire exposure). Recommendations on structure survivability are distilled and presented in the form of a Vulnerability Assessment Tool (VAT) checklist (see ANNEX A).
- Section 5 reports the sheltering capacity analysis, with virtual experiments performed with synthetic cases at real scale (FDS simulations domain of 30 x 30 x 30 m). Recommendations on sheltering capacity of dwellings are distilled and presented in the form of a Sheltering Assessment Tool (SAT) checklist (see ANNEX B).

2. Summary of lessons observed in past WUI fires

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. In past WUIVIEW deliverable D5.1 "Inventory of pattern scenarios", a detailed analysis of past WUI fires in Europe was provided, from which several important lessons were extracted illustrating common factors, processes and scenarios 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 pre-impact, impact, fire transfer, and post-frontal combustion.

A second main consideration concerning lessons observed is that, **even though houses across Mediterranean Europe are built out of non-combustible 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) 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). 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. Non-natural fuels present at the WUI microscale vary significantly and include outdoor furniture, stored materials, gas canisters, small sheds, wood piles, etc., which have the potential to keep burning for a long time after the main fire front passes, and eventually reaching high intensities. Particular attention has to be paid at domestic Liquefied Petroleum Gas (LPG) infrastructure, whose exposure to fire may cause a dangerous escalation of the fire incident, eventually involving the ignition of the surrounding objects and, in the worst case, evolving into an explosion.

2.1. Structure survivability in dwellings exposed to WUI fires

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 Figure 1 reports the different observed patterns that can lead to the fire entering a structure during all of the abovementioned fire exposure phases. It clusters the pattern scenarios identified in Section 5 of D5.1 in a rational way so that a structured analysis can be later on performed.

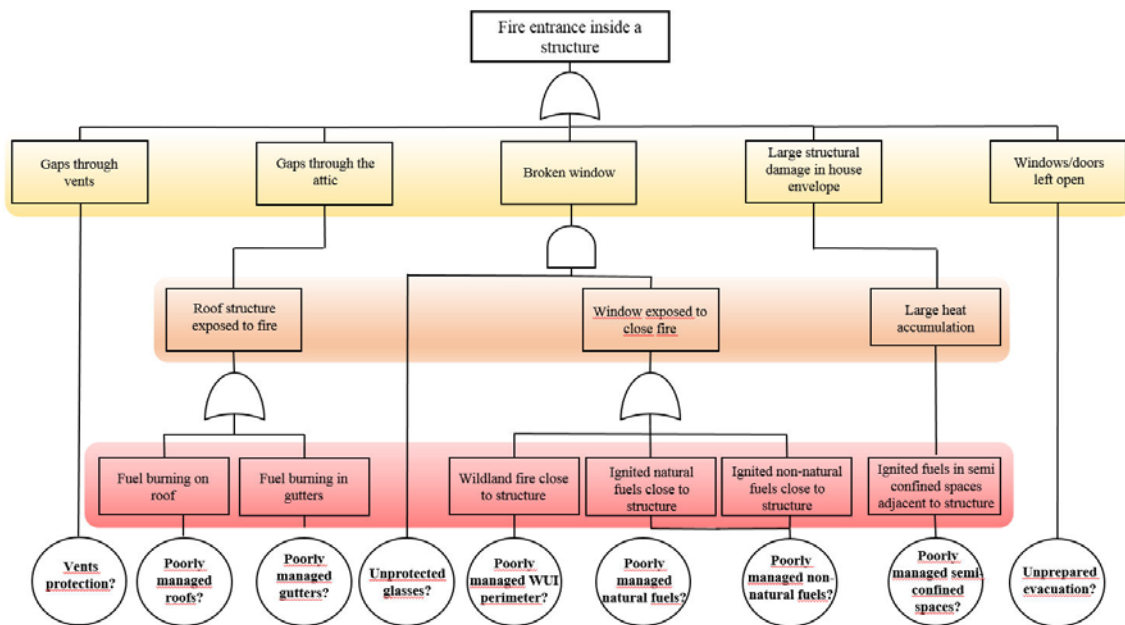


Figure 1. Fault tree describing observed patterns that lead to fire entrance inside a structure. The red area identifies the fire source, the orange one identifies the impact of the fire onto the structure, and the yellow one pinpoints the ways through which the fire can enter the structure.

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. 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.

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.

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.

2.2. Sheltering capacity in dwellings exposed to WUI fires

When threatened by a wildland fire, the safest option usually considered is an early evacuation. However, several factors may avert people from evacuating safely. The main reasons are the inability to provide or receive an early warning, or road networks that hinder rapid departure (Whittaker et al., 2017). It is under these circumstances that shelter may be the safest option.

Residential houses are common places to shelter during WUI fires. They are generally quite complex in terms of structure (having in-use and not-in-use compartments) and can have compartments that contain many combustible elements. However, a house can lose its integrity or can have a high air leakage rate so that it can fail to protect their occupants. The main factors that contribute towards this situation include house design, maintenance and fire severity.

The level of protection offered by a house in which people seek shelter can be correlated with its infiltration rate or frequency at which the indoor air is renovated (or air change rate, ACH). This frequency depends on the atmospheric conditions and the airtightness of the construction (Montoya, 2010). There is a direct correlation between the airtightness of a house and its building age. Houses built several years ago do not include ignition resistant qualities nor energy efficiency standards, so old constructions are likely to have higher infiltration rates than those recently built. In Catalonia there exists an airtightness model for single-family residences (Montoya, 2010). This is a multiple linear model that takes into account several characteristics of the residence, i.e. number of stories, floor area, age and structure type (heavy or light construction materials used).

During the extreme fire event that occurred in February 2009 in Victoria (Australia), known as Black Saturday (BS) bushfires, more than half of those who died were sheltering in house or other structures at the moment of their death. This represented an important change in wildfire fatality trends, owing to the fact that, previously, most fatalities occurred when inhabitants were attempting to protect their assets or to evacuate. A comprehensive study by Blanchi et al. (2015, 2018) examined 2009 BS bushfires to better understand the factors influencing safe sheltering.

According to Blanchi et al. (2018), residential houses represented the largest proportion (60%) of all shelter types in 2009 BS bushfires, followed far behind by commercial buildings. 65% of total fatalities were of people known to have sheltered in bathrooms, a room with poor visibility to the outside. The duration of the sheltering varied greatly; some sheltered only for a few minutes and others during one hour. In other situations, the duration of the sheltering extended substantially because consequential fire after the passage of the front took place over many hours.

Sheltering can be active or passive, each practice being characterized by the presence or absence, respectively, of attempts to regularly monitor conditions inside and outside the shelter, as well as taking actions to protect the refuge and its residents (Whittaker et al., 2017). In the study by Blanchi et al. (2018) the majority of residents who sheltered engaged in monitoring and in taking actions to protect occupants.

Blanchi et al (2015) also looked at distance to forest with respect to the cumulative percent of people who died or survived. Over 90% of the locations surveyed were within 100 m of forest and a greater proportion of fatalities occurred closer to forest (Figure 2). If only fatalities inside a structure are taken into consideration (Figure 3), percentages and distances are similar to those obtained considering all types of shelters (e.g. vehicles, open space).

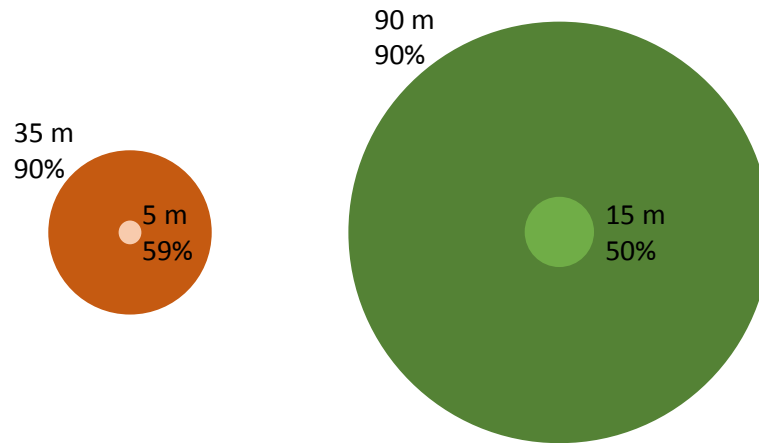


Figure 2. Orange circles: cumulative % of fatalities at sheltering locations within two distances (5 m and 35 m from the forest). Green circles: cumulative % of survivals at sheltering locations within two distances (15 m and 90 m from the forest) (data from Blanchi et al., 2015). Circles are scaled.

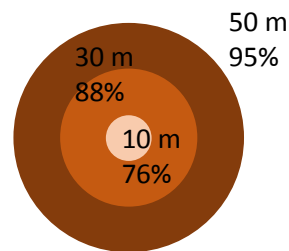


Figure 3. Cumulative percentage of fatalities within structures at three distances (10 m, 30 m and 50 m from the forest) (data from Blanchi et al., 2012). Circles are scaled.

To the best of our knowledge, **sheltering assessment guidelines based on scientific-research are missing at European level**. Although some references of best practices coming from other WUI realities (e.g. Australia, North America) can be inspiring, there are not any efforts in this sense applicable to typical Mediterranean dwellings, which are made of non-combustible materials and hence offer an inherent safe condition to shelter-in-place. WUIVIEW analysis of sheltering capacity (detailed in Section 5) corresponds to the first attempt of providing scientifically based guidance and recommendations of those preventive actions at the immediate surroundings of houses that have to be considered to create self-defensible spaces and increase safety in eventual shelter-in-place operations.

3. Summary of key messages in WUI standards

As discussed in past D4.1 “State of the art and gap analysis on WUI fire codes and regulations”, in the years to come, self-protected communities will be the first priority over fire suppression, entailing more and best prepared WUI scenarios grounded on solid and sound guidelines and legislation. However, the European Union is way behind this requirement, so do the Member States, which poorly have developed such regulations.

European standards are scarce and generally deficient when addressing the factors and processes that take place in the destruction of communities and human life. Furthermore, while the underlying WUI problem is a home ignition problem, **most legislation deals only with fuel management**, giving a wide variety of recommendations of how to manage a defensible space around structures, **some of them with a high degree of arbitrariness**. As such, current European standards set aside the structure itself, when reducing the vulnerability of structures against forest fires is a cornerstone to achieve a safer WUI.

International examples are available and may be inspiring to serve as baseline for policy making on building practices at the European WUI. Standards reviewed in WUIVIEW and used to discuss WP6 results are the Canadian Firesmart Guidebook for Community Protection (Partners in Protection 2003; Government of Alberta 2013); Standards NFPA 1141: Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural, and Suburban Areas (NFPA 2017a), NFPA 1144: Standard for Reducing Structure Ignition Hazards from Wildland Fire (NFPA 2018), California Fire Code Chapter 49: Requirements for Wildland-Urban Interface Fire Areas (State of California 2016); Australian standards: Construction of buildings in bushfire-prone area (NSW 2009); the New-Zealand Code of Building (Ministry of Business Innovation and Employment 2014) and the International IWUIC code 2015 International Wildland-Urban Interface Code (International Code Council Inc. 2015)

Requirements regarding structure survivability tackled in the mentioned standards are mainly focused on construction materials and design. They are mainly insisting in:

- The use of non-combustible materials for construction, the definition of which may vary depending on the country.
- Performing regular cleaning of combustible litter falling on roof, decks, balconies.
- Enclosure of vents, eaves, chimneys with non-combustible protective elements to prevent flying embers from entering the structure and starting a fire inside.
- Windows and glazing resistant to fire, with many options to fulfil this point (double-pane, tempered glass, small windows for smaller temperature gradients, etc.)

Detailed prescriptions gathered in these standards have been confronted with simulation results. From this discussion, insights on how to protect structures and minimize microscale vulnerability and on tenability conditions in typical dwellings exposed to WUI fires have been gathered and structured in a rational basis in Section 4.

4. Structure survivability analysis

4.1. Methodology and rationale

Following the event tree depicted in Figure 1 in which the pattern scenarios listed in past WUIVIEW D5.1 are clustered, a problem-oriented approach has been followed to structure the WUIVIEW dwelling survivability analysis. The overall problems studied are named as follows:

1. Glazing systems exposed to fire
2. Fuel packs burning in semi-confined spaces
3. Fire exposure on LPG tanks
4. Vulnerability of roofs, gutters and vents
5. Residential vegetation management
6. Fire hazard on hedgerows
7. Vulnerability to wildfire exposure

They have been approached by a scientific methodology in which problematic scenarios have been defined, idealized, analysed and discussed. This methodology has involved the use of numerical CFD modelling (problems 1, 2, 3, 6) analytical modelling (problem 7) and literature discussion (problems 4 and 5).

Regarding those problems analysed by CFD tools, a performance based approach has been followed. Scenarios have been idealized and simulated using FDS (Fire Dynamics Simulator), which is one of the most widespread CFD tools of open-source nature. It was developed by NIST (National Institute of Standards and Technology) and has been specially conceived and validated to analyse fire development in different sorts of fire scenarios. Physical characteristics of natural fuels studied in WP2 and burning dynamics of non-natural fuels studied in WP3 have been transformed into required inputs for CFD modelling. Building components have been modelled considering the thermal properties and configurations defined in WP4. FDS has provided time and space evolution of key variables for WUI risk management (e.g. temperatures and heat exposure) by the use of virtual monitoring sensors set accordingly to assess performance criteria achievement. Performance criteria of building elements, components and fire environment (e.g. thermal effects such as ignition, melting, smoke damage, structural integrity, damage to exposed items, etc.) have been established according to Performance-Based-Design (PBD) existing guidelines and scientific literature. Concerning fire exposure on LPG tanks, Ansys FLUENT CFD software has also been used to analyse the tank response to fire exposure. Criteria and key performance indicators for this type of scenarios were set in past WUIVIEW deliverable D3.1 “LPG infrastructure impact”.

Problems analysed through literature discussion, have been approached comparing results from available scientific literature research with prescriptions and recommendations gathered in standards. Gaps and inconsistencies have been detected and educated solutions have been proposed.

Finally, vulnerability to wildfire exposure (problem 7) has been studied by analytical models accounting for radiation heat transfer. Radiant heat flux exposure of WUI structures caused by the vicinity to a wildfire has been estimated by the Solid Flame Model. Simplified scenarios have been simulated to calculate safety distances and foresee consequences for abnormal heat radiation to people and assets.

4.2. Glazing systems exposed to fire

4.2.1. Idealized Scenarios - experimental design

Idealised scenarios include glazing exposure to radiation and flame impingement. Scenarios also include cases when shutters protect these glazing systems. Four different fire scenarios are analysed, with different window configurations and atmospheric circumstances. These are: i) a stack of wooden pallets with a height 0.9 m, ii) one Douglas fir tree (*Pseudotsuga menziesii*), iii) two Douglas fir trees in a row, iv) three Douglas fir trees in a row. The first fire scenario includes a typical non-natural fuel that could be present at the WUI. Douglas fir trees are very common in Northern countries where WUI fires are most prevalent (Pagni, 1993), and, given their size, they allow for a conservative approach for ornamental vegetation placed close to glazing systems. Moreover, burning characteristics of this tree specie are well known (Mell et al., 2009).

Two different window sizes are analysed: a small one, with the dimensions of 0.5x0.5 m, and a bigger one of 1.2x1.2 m. The window is further divided into single or double pane glazing, and the panes are either 3 mm or 6 mm thick. Two different materials for the frames are analysed as well: aluminium and uPVC.

For each scenario configuration, the fire is placed at different distances from the window in order to identify a distance at which the latter will not fail and the scenario can thus be deemed safe. Some scenarios are analysed in windy conditions, with a wind profile that peaks at 30 km/h at 10 m height, which can contribute to extreme fire behaviour and intensity (Stephens, 2016). Table 1 gives an overview of the different simulated distances between the window and the fire.

Table 1: Fire scenarios for glazing systems

Fire	Distance between window and fire [m]	Atmospheric conditions
Stack of wooden pallets 0.9 m high	2	Calm
	2.5	
	3	
	4	
	4.5	
1 Douglas fir tree	5	Calm
		Windy
	0.5	Calm
	1	Calm
		Windy
2 Douglas fir trees	2	Calm
		Windy
	0.5	Calm
	1	
	1.5	
3 Douglas fir trees	2	Calm
		Windy
	3	Calm
	Windy	
3 Douglas fir trees	1	Calm

1.5	
2	Calm
3	Windy
3.5	Calm
4	Windy

Once a safe distance is established for the fire scenario including the wood pallets, three other scenarios containing fuel packs are simulated, to identify if this safe distance is valid for other non-natural fuels. The first fuel pack contains a plastic table, 6 plastic chairs, each with its own cushion, and a parasol. The second one entails the combustion of 3 wooden pallets, 4 foam mats, 7 paint buckets and 11 cardboard sheets. The third fuel pack consists plastic toys, 3 bags of clothes (one containing cotton, one wool and one synthetic materials) and 2 boxes containing books and paper.

Three scenarios involving shutters placed in front of a window are also analysed. These scenarios consists of 2 Douglas fir trees burning 0.5 m from a 1.2x1.2 m window with a glass thickness of 6 mm. Shutters with a thickness of 4 cm made out of aluminium, uPVC and wood (yellow pine) are placed in front of the glass, at a distance of 10 cm, meaning that the shutters are located 0.4 m from the fire source.

4.2.2. Materials and fire characterization

The analysed window is composed of float glass, which is a very common glass type present at the WUI (FEMA 2008). As previously mentioned, frames and shutters in aluminium and in uPVC, as well as wooden shutters, are analysed. In accordance to the WUIVIEW database on material thermal properties, (see deliverable D4.3) the properties of these materials are given in Table 2.

Table 2: Material properties (Wang and Hu 2019), (Engineers EDGE 2020), (Thunderhead Engineering, 2020)

Property	Glass	Aluminium	uPVC	Yellow pine
Specific heat capacity [kJ/kgK]	0.82	0.9	1.29-1.59	2.85
Conductivity [W/mK]	0.95	236	0.134-0.192	0.14
Density [kg/m³]	2500	2700	1380	640
Emissivity	0.9	0.05	0.95	0.9

The combustion of the fuels inserted in the simulations can be characterized in different ways. The HRR curves of the scenarios containing non-natural fuels are prescribed in FDS with a RAMP. The fire is simulated as a flat surface in the first two fire scenarios and as a solid obstruction in the others. The HRR curves of the three fuel pack scenarios are data obtained during tests performed by CERTEC and ARMINES. The fire duration of the wood pallets scenario (Figure 4) is much shorter than the fuel pack scenarios (Figure 5, Figure 6, Figure 7), but its peak HRR reaches higher values.

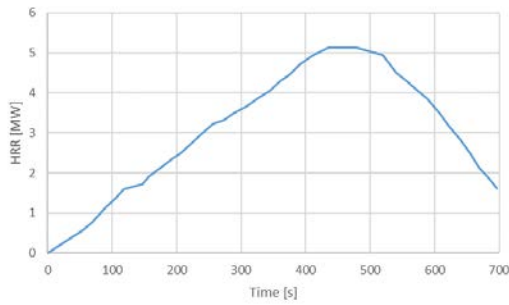


Figure 4: Heat Release Rate curve of stack of pallets (Karlsson, et al. 1999)

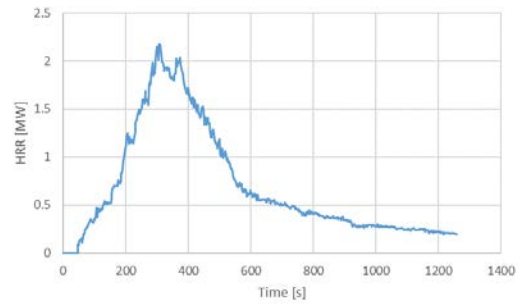


Figure 5: Heat Release Rate curve of the fuel pack containing the table, chairs and parasol

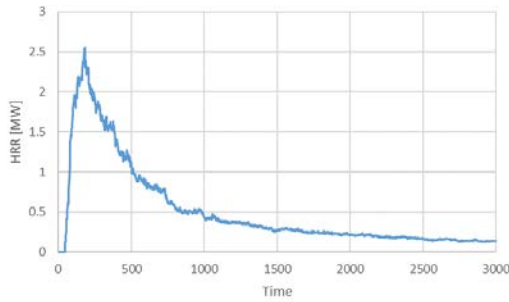


Figure 6: Heat Release Rate curve of the fuel pack containing pallets, mats, cardboard and paint

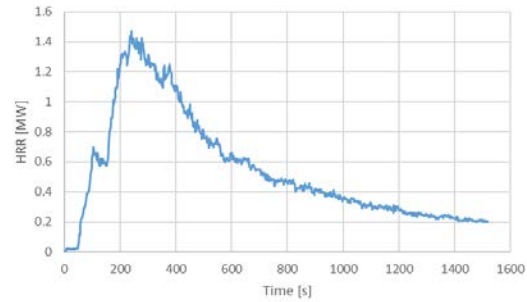


Figure 7: Heat Release Rate curve of the toys, boxes and clothes

As explained in Annex B, the HRR curve of the Douglas trees fires cannot be prescribed. Inputs about the vegetation are given to FDS, which then computes the HRR. The vegetation particles are ignited with other particles called ignitors, which burn for 10 s. The following figures (Figure 8, Figure 9, Figure 10) give the HRR curves for the scenarios with 1, 2 and 3 Douglas fir trees. As can be seen from the graphs, the wind has an effect on the HRR, because the wind will push the flames of the ignitors to one side of the tree, causing a delay of the ignition of the particles. This effect can especially be seen in Figure 10 where one of the trees will start burning when the other two have almost extinguished.

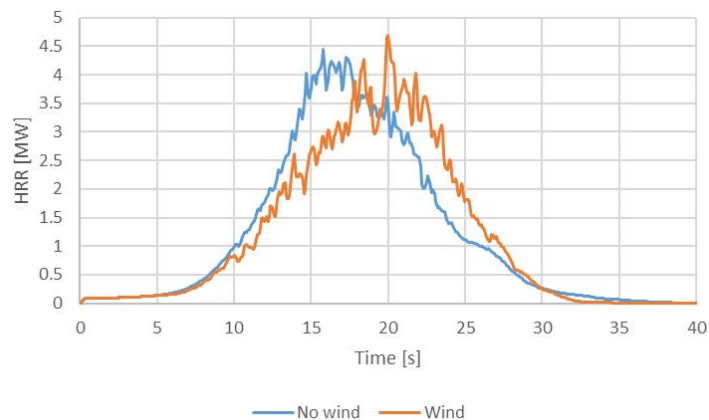


Figure 8: Heat Release Rate curve for one Douglas fir tree

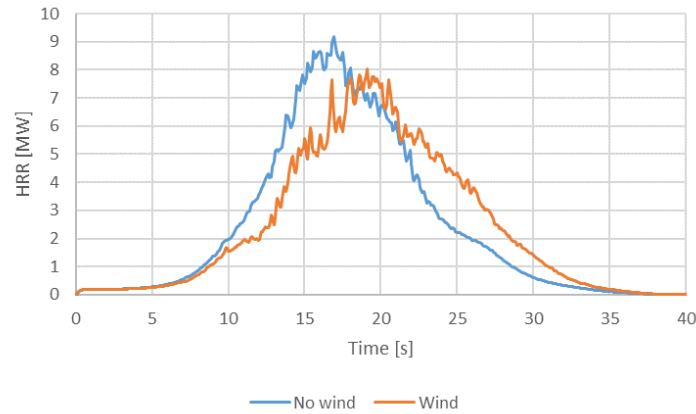


Figure 9: Heat Release Rate curve for two Douglas fir trees

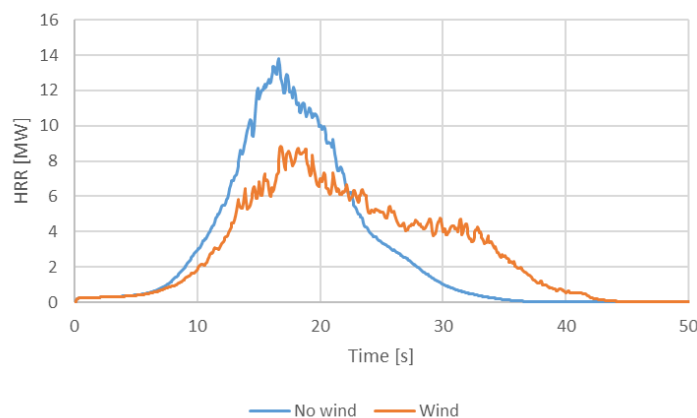


Figure 10: Heat Release Rate curve for three Douglas fir trees

4.2.3. Performance criteria

To identify when a glazing system will fail if exposed to radiation or flame impingement from a fire, performance criteria must be set for each material that composes a window.

Three different criteria have been identified for a glass pane, although one of them can only be applied to glass with a thickness of 3 mm. These are the surface temperature of the glass, the temperature difference between the unexposed and exposed area on the glass surface, and the heat dose received by the glass, which is calculated by obtaining the heat flux onto the glass over time. This last criterion can only be analysed for a glass pane of 3 mm, due to the limited information present in the literature. Table 3 gives the values of these performance criteria. Whichever criterion is reached first will indicate the failure of the glazing system.

Table 3: Performance criteria for float glass panes

Pane thickness [mm]	Surface temperature [°C]	Temperature difference ΔT [°C]	Received heat dose $[(\frac{kW}{m^2})^{\frac{4}{3}} \cdot s]$
3	150	58	1840
6	(Babrauskas, 1997)	(P .J. Pagni, 1988)	(Harada et al., 2000)
			-

The melting point of aluminium and uPVC is identified as the performance criterion for the frame. These are given in Table 4.

Table 4: Performance criteria for window frames

Material	Melting point [°C]
Aluminium	660 (Klein, 1997)
uPVC	200 (Chen et al. 2011) (AZoM 2001)

Wood is a material that chars on heating and will therefore build up a layer of char on its surface that will tend to shield the unaffected fuel beneath. When wood is burnt or heated above 450°C, 15-25% normally remains as char (Drysdale, 2011). Wood will start charring at temperatures of 280-300°C, and the average charring rate is 0.6 mm/min (Hurley et al, 2015). The criteria for ignition of wood are given in Table 5.

Table 5: Criteria for ignition of wood (Drysdale, 2011)

Critical radiant heat flux [kW/m ²]		Critical surface temperature [°C]	
Piloted ignition	Spontaneous ignition	Piloted ignition	Spontaneous ignition
12	28	350	600

To be conservative, piloted ignition is considered in the analysed scenarios.

4.2.4. Simulations set-up

The simulations are run with FDS. The different fire scenarios are placed at various distances from the window, as shown in Figure 11 to Figure 18. The initial outside temperature is set at 25°C, while the temperature on the other side of the glass, this inside the simulated room is set at 22°C.

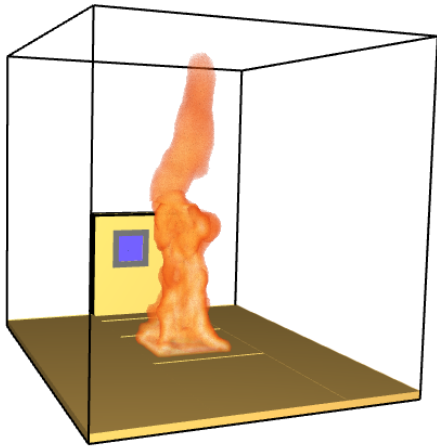


Figure 11: Wood pallet fire scenario with a distance of 2 m from a small window

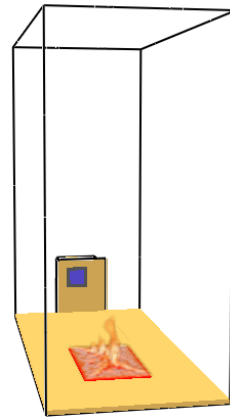


Figure 12: Fuel pack with a distance of 5m from the window – first scenario

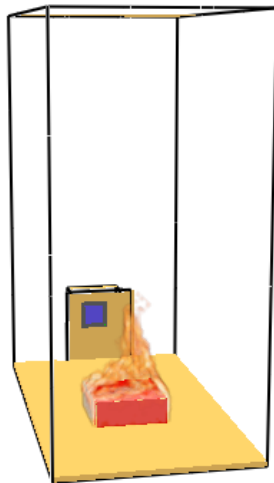


Figure 13: Fuel pack with a distance of 5m from the window – second scenario

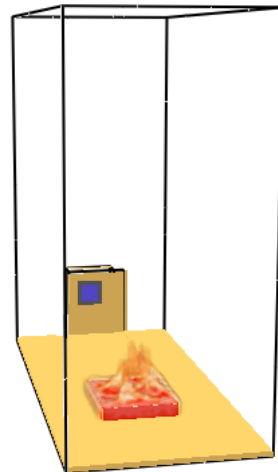


Figure 14: Fuel pack with a distance of 5m from the window – third scenario

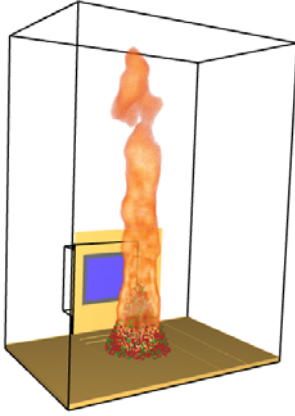


Figure 15: One tree fire scenario with a distance of 1 m from a big window

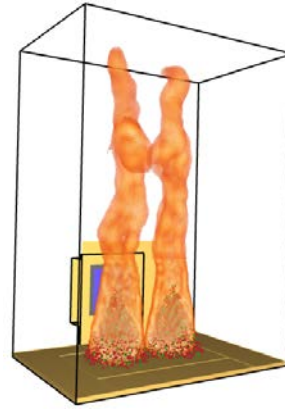


Figure 16: Two trees fire scenario with a distance of 1 m from a big window

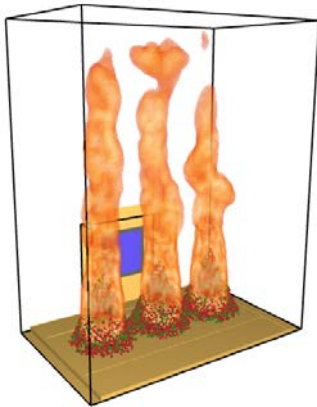


Figure 17: Three trees fire scenario with a distance of 1 m from a big window

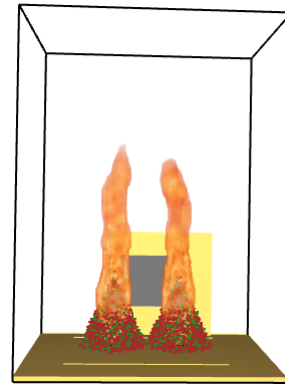


Figure 18: Shutters protecting the window

Wind profile

The wind profile is modelled by using the Monin-Obukhov similarity theory (McGrattan et al. 2016). The wind speed profile, u , varies with the height, z , according to Eq. 1.

$$u(z) = \frac{u_*}{\kappa} \cdot \left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right) \right] \quad (1)$$

Where u_* is the friction velocity, $\kappa = 0.41$ is the Von Kármán constant, z_0 is the aerodynamic roughness length, and L is the Obukhov length. The similarity functions are shown in Eq. 2.

$$\Psi_m\left(\frac{z}{L}\right) = \begin{cases} -5 \cdot \frac{z}{L} : L \geq 0 \\ 2 \cdot \ln\left(\frac{1+\zeta}{2}\right) + \ln\left(\frac{1+\zeta^2}{2}\right) - 2 \cdot \tan^{-1}(\zeta) + \frac{\pi}{2} : L < 0 \end{cases} \quad (2)$$

The value which characterizes the thermal stability of the atmosphere is the Obukhov length (L). When L is negative, the atmosphere is unstably stratified; when positive, the atmosphere is stably stratified (K. McGrattan et al. 2016). For the simulations, a value of L of 10^6 m was chosen, which indicates stable conditions, while a value of 0.5 m was chosen for the aerodynamic roughness length z_0 .

The friction velocity u_* can be computed using the following equation (Eq. 3):

$$u_* = \frac{\kappa \cdot u_{ref}}{\ln\left(\frac{z_{ref}}{z_0}\right)} \tag{3}$$

Where $u_{ref}=30\text{km/h}$ at a height of $z_{ref}=10\text{m}$.

Measuring devices

Devices measuring the surface temperature of the glass and of the frame are placed on the window as shown in Figure 19 and Figure 20. These devices are also placed on the second pane when analysing double pane windows. Five surface temperature devices are also placed on the shutters.

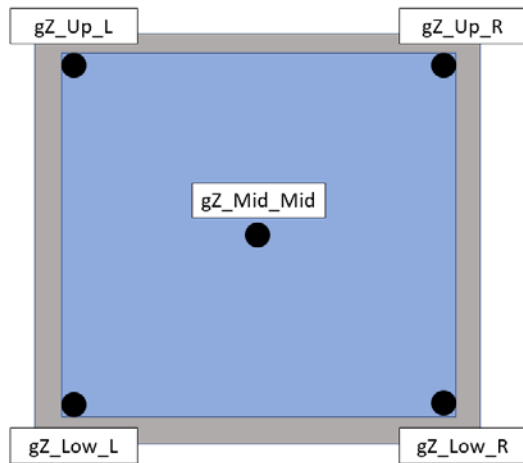


Figure 19: Location of devices on the glass

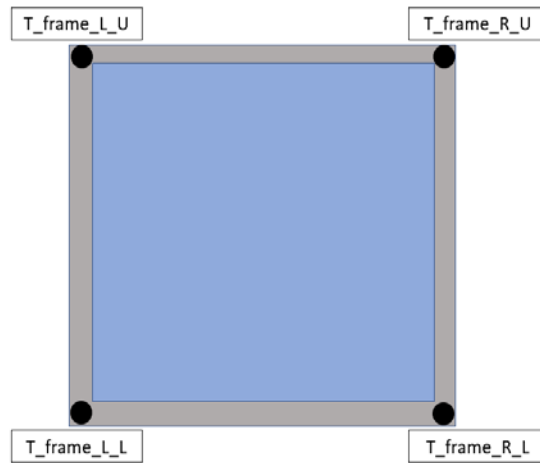


Figure 20: Location of devices on the frame

Devices measuring the incoming heat flux are placed on the four corners and in the middle of the glass pane and of the shutters. The measurements from these devices are used to calculate the heat dose the glass is subjected to and the radiative heat flux onto the shutters.

4.2.5. Results and discussion

The following tables present the distance between a window and a burning item needed for the window (glazing system and frame) not to fail. In all of the scenarios, the aluminium frame never reaches its melting point, therefore only uPVC frames are considered. Table 6 presents the results for calm atmospheric conditions, while Table 7 for windy conditions.

Table 6: Safe distances for windows in calm atmospheric conditions

Fire scenario	Window size [m]	Glass thickness [mm]	Safety distance glass [m]		Safety distance uPVC frame [m]
			Single pane	Double pane	
Wood pallets	0.5x0.5	3	4.5	4	3
		6	2.5		
Fuel pack	1.2x1.2	3	5	4.5	4
		6	4.5	3	
1 Douglas fir tree	0.5x0.5	3	1	0.5	2
		6			
2 Douglas fir trees	0.5x0.5	3	2	1	3
		6	1.5	1	
3 Douglas fir tree	0.5x0.5	3	2	1.5	3.5
		6			
1 Douglas fir tree	1.2x1.2	3	1	0.5	2
		6			
2 Douglas fir trees	1.2x1.2	3	2	1	3
		6	1.5	1	
3 Douglas fir tree	1.2x1.2	3	2	1.5	3.5
		6	2	1	

Table 7: Safe distances for windows in windy conditions

Fire scenario	Window size [m]	Glass thickness [mm]	Safety distance glass [m]		Safety distance uPVC frame [m]
			Single pane	Double pane	
Wood pallet	1.2x1.2	3	5	-	-
1 Douglas fir tree	0.5x0.5	3	2	1	2
		6			
2 Douglas fir trees	0.5x0.5	3	3	2	3
		6	2		
3 Douglas fir tree	0.5x0.5	3	3	2	4
		6	2		
3 Douglas fir tree	1.2x1.2	3	2	1.5	4

As can be seen in the tables here above, bigger distances are needed for single pane compared to double pane glazing systems, for 3 mm compared to 6 mm thicknesses, and for bigger windows compared to smaller ones.

In the scenarios including the trees it can be seen how the frame will fail at distances where the glass will not. This is due to the low thermal inertia of uPVC and the short duration but high intensity of the fire, which causes high temperatures at the surface of the frame and not as high at the surface of the glass.

When looking at the scenarios which include windy conditions, results show that flames are pushed towards the window, and for this reason larger distances are needed between the

window and the fire source in the tree scenarios. For the wood pallet scenario, the largest distance identified in calm conditions is also safe in windy conditions. Even though the flames are pushed toward the window, the distance is still great enough to not allow the glazing and frame system to reach their performance criteria.

The wood pallet scenario results thus in a safe distance of 5 m between the fire and the window. The scenarios including the fuel packs are therefore simulated at this distance, and results show that no failure of the glazing system occurs for all three scenarios, making 5 m a safe distance between the analysed glazing systems and the analysed WUI microscale non-natural fuels.

Regarding those scenarios with window protections, as can be seen in Figure 21, the surface temperature of the aluminium shutter barely reaches 26°C. The temperatures at the back of the shutter do not rise above 25°C, making these type of shutters a safe option for window protection.

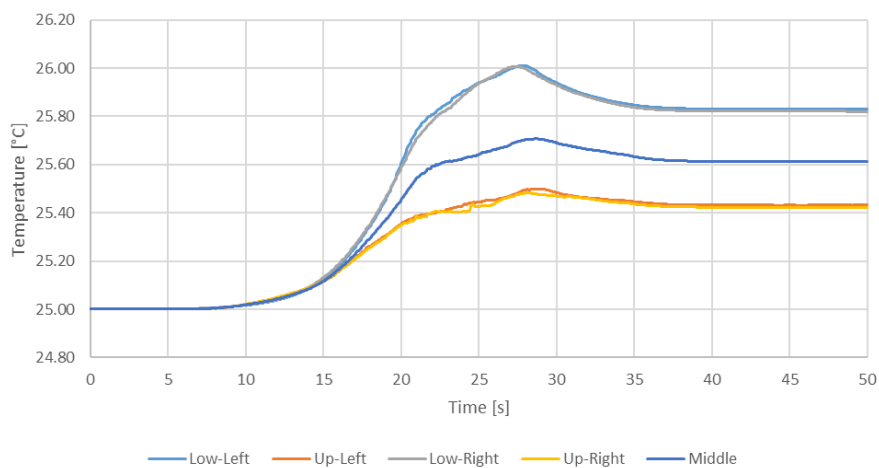


Figure 21: Surface temperature over time of the aluminium shutter

On the contrary, the uPVC shutter reaches its melting temperature at 16.5 s, as shown in Figure 22. This scenario cannot be deemed safe because the uPVC will melt, exposing the window to the heat coming from the fire.

The wooden shutter has similar surface temperature profiles as the uPVC one (Figure 23 and Figure 24). Both temperature and heat flux profile for this scenarios reach the critical values of wood, meaning that the shutter will ignite. However, given the burning and charring characteristics of wood, a char layer will be formed, which insulates the underlying layers, and the wood will eventually self-extinguish, because the external incoming heat flux which supports its ignition and burning will be null after 35 s.

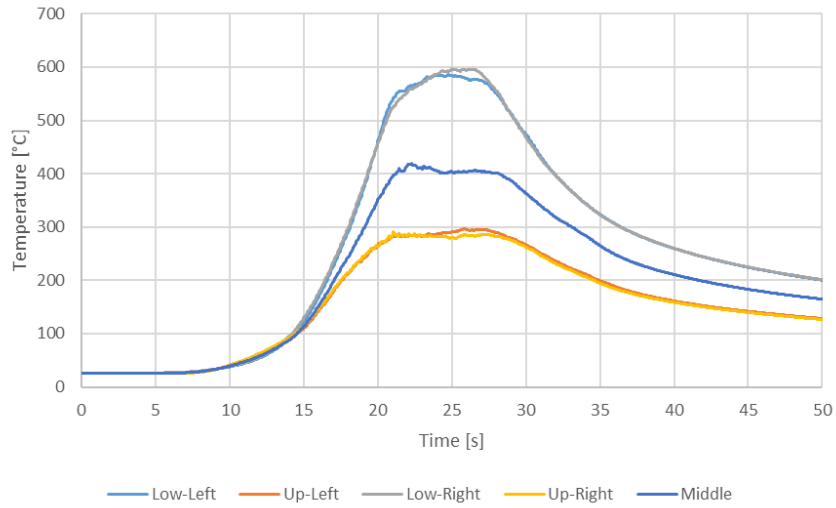


Figure 22: Surface temperature over time of the uPVC shutter

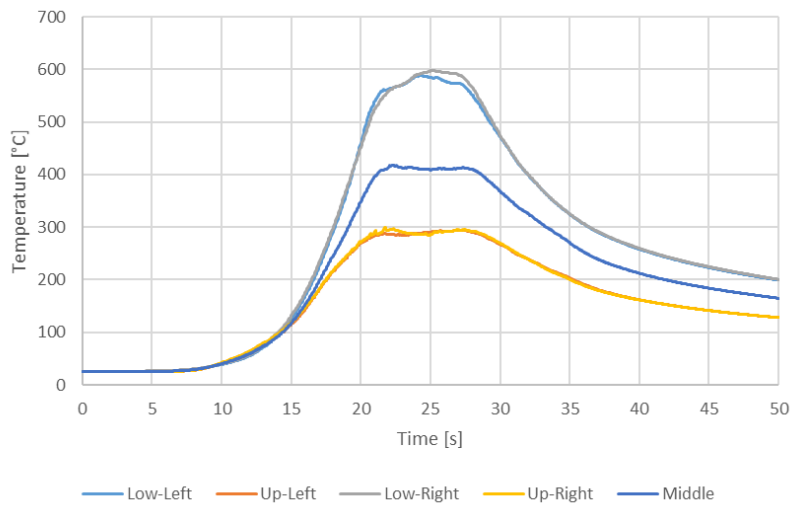


Figure 23: Surface temperature over time of the wooden shutter

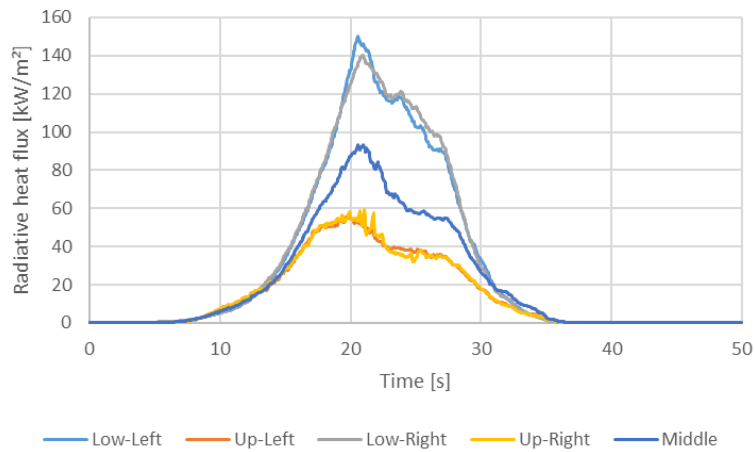


Figure 24: Radiative heat flux onto the wooden shutter

The following statements can be interpreted from the obtained results:

- The bigger the window, the less resistant it is to fire. Items must thus be placed further from a big window than from a small one.
- Double pane windows are more resistant than single pane windows, and a glass thickness of 6 mm is more favourable.
- Aluminium frames are more resistant than uPVC frames, given that the melting point of aluminium is much higher than the one of uPVC.
- Wind will push flames and heat coming from a burning item towards a window, and a greater distance is thus needed between the two in order to achieve safe conditions.
- Aluminium and wooden shutters can protect windows, if tightly closed, from fires located in their proximity.
- uPVC shutters are not recommended, since they will melt and expose the window to the fire.

The results obtained from the simulations of glazing systems go along with most recommendations present in international standards or prescriptions:

- Standards in Canada (Partners in Protection, 2003), USA (NFPA, 2018), France (Ministère de la transition écologique et solidaire 2011), as well as the International Wildland Urban Interface code (International Code Council Inc. 2015) recommend double or multi-paned glazing systems.
- The Canadian document *FireSmart : Protecting Your Community from Wildfire* (Partners in Protection, 2003) advises for small windows to minimize temperature gradients.
- Canadian guidelines (Partners in Protection, 2003) advise to equip windows with solid shutters made of 12 mm thick exterior graded plywood. New Zealand guidelines (Fire and Emergency 2017) recommend the use of solid shutters.
- In France (Ministère de la transition écologique et solidaire 2011), shutters should be made of non-combustible material (solid core wood or metal, no PVC). If solid core wood is chosen, they should be at least 3 cm thick, treated for fire-resistance, with no opening.

Regarding typical fuels generating fire exposure to windows, in Canada (Partners in Protection, 2003) and New Zealand (Fire and Emergency 2017), it is recommended to avoid vegetation within 10 m of glazing systems. Findings from the scenarios presented above show however shorter safe distances (of 4 m) between our simulated vegetation (three 1.9 m-tall Douglas Fir trees) and our windows (configured with the most representative characteristics), even in windy conditions.

Findings from the scenarios including non-natural fuels show that a distance of 5 m between the fuel pack and the analysed glazing systems does not compromise the integrity of the window.

4.3. Fuel packs burning in semi-confined spaces

4.3.1. Idealized Scenarios - experimental design

Four different scenarios (FPn) are analysed in order to identify structure survivability in case of the ignition and subsequent combustion of the fuels stored in these. The simulated semi-confined area has the dimensions of 2.5x2.5x2.5 m for the first three scenarios (Figure 25), while

for scenario 4 the floor area of this space is doubled. All walls are made of concrete, and the area has a big opening in the front.

- Scenario FP1 consists of the combustion of a fuel pack containing two different types of wood pellets, Chestnut and Oak, with the dimensions of 1x0.5x0.5 m. The fire is simulated in the semi-confined spaces with three different wall thicknesses: 15 cm, 20 cm and 25 cm.
- Scenario FP2 entails the combustion of a fuel pack containing 3 wooden pallets, 11 cardboard sheets, 4 foam mats and 7 paint buckets. The dimensions of the fuel pack are 1.6x1.3x0.63 m. Also in this scenario, simulations are performed with the three wall thicknesses specified in FP1.
- Scenario FP3 simulates a fuel pack consisting of a plywood wardrobe containing two polyester and two feather pillows and a plastic Christmas tree. The dimensions of the wardrobe are 1.22x0.61x1.78 m, while the tree has a diameter of 0.61 m and a height of 2 m. The tree wall thicknesses given in scenarios FP1 and FP2 are also simulated in this scenario.
- Scenario FP4 consists of simulating the fuel pack of scenario FP2 in a bigger area, with dimensions of 5x5x2.5 m. The walls are simulated with a thickness of 15 cm.

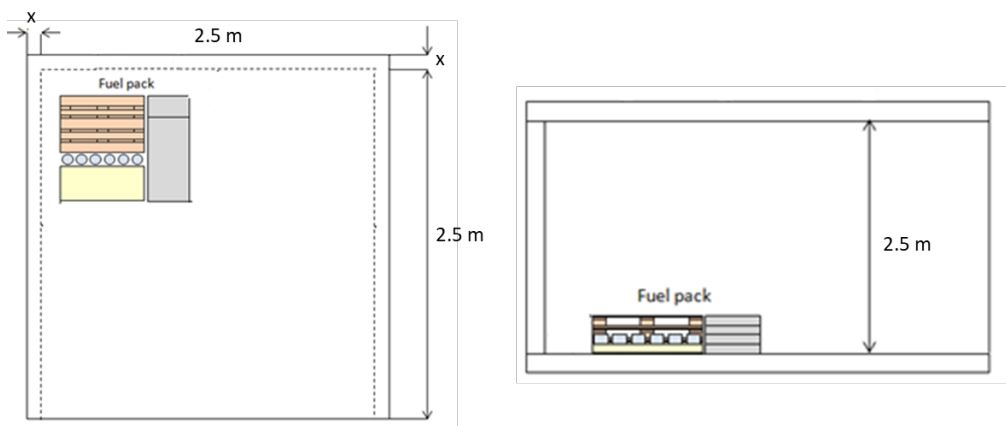


Figure 25: Configuration of the simulated semi-confined space

4.3.2. Materials and fire characterization

According to the WUIVIEW database (see deliverables D4.3), properties of concrete are summarized in Table 8.

Table 8: Material properties of concrete (Thunderhead Engineering, 2020)

Specific heat capacity [kJ/kgK]	Conductivity [W/mK]	Density [kg/m ³]
1.04	1.8	2280

The three different fuel packs are simulated as solid obstacles with an assigned Heat Release Rate Per Unit Area (HRRPUA) and Heat Release Rate (HRR) curve. The curves are obtained from the literature and from experimental tests performed within WP3. The HRR curves for each scenario are given in Figure 26 - Figure 28.

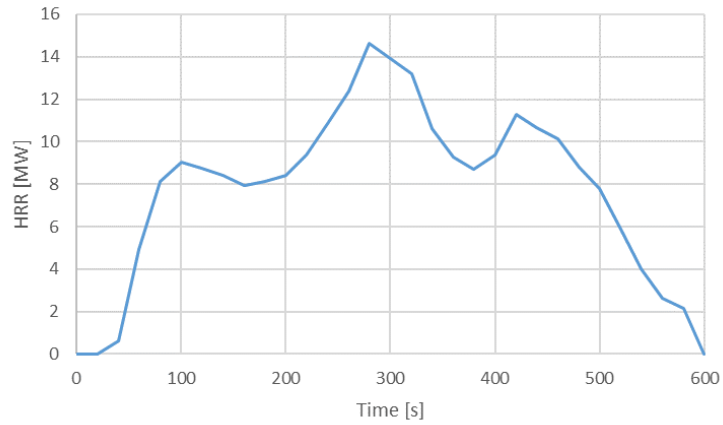


Figure 26: Heat Release Rate curve for scenario FP1 (Chung, 2010)

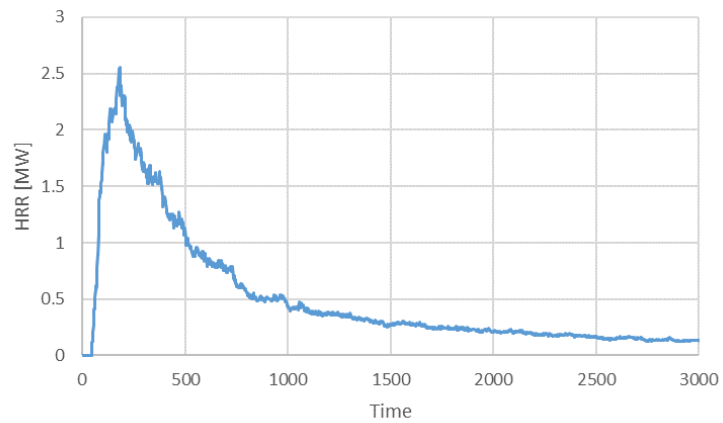


Figure 27: Heat Release Rate curve for scenario FP2 and scenario FP4 (experimental data from WP3)

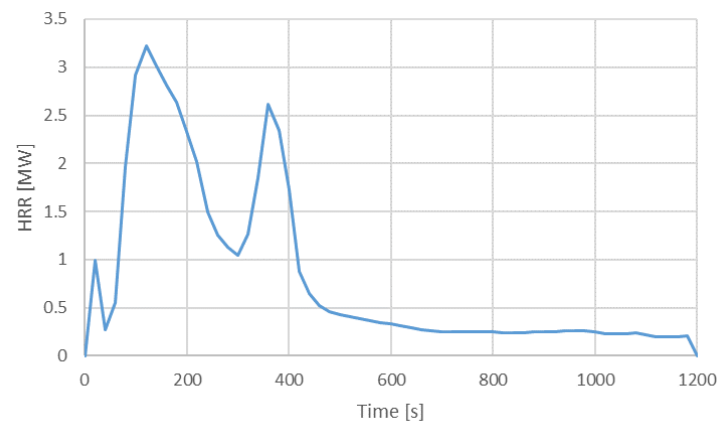


Figure 28: Heat Release Rate curve for scenario FP3 (Hurley et al, 2015)

4.3.3. Performance criteria

In order to be able to analyse the structural survivability of the concrete walls of the simulated space, performance criteria must be set. The walls are analysed based only on their compressive strength, since tensile strength only represents 10% of the value of the compressive one.

To assess the structural survivability or failure of the concrete walls, the live to dead load ratios are analysed. Following the procedure of Eurocode 1992-1-1 (EN 1992-1-1, 2004) and 1992-1-2 (EN 1992-1-2, 2004), an *ad-hoc* code has been developed to analyse the structural survivability of the concrete walls during the duration of a simulated fire. The code uses the temperature profile through the wall as input, and outputs a curve of the load bearing capacity of the wall over time.

The first failure point, represented in Figure 29 by the upper red line, is the point at which the concrete wall only has 74% of its original load bearing capacity. According to this threshold, it can be considered that if the load bearing capacity of the section of the concrete wall being analysed does not even cross the first red line, the wall will not fail.

The two green lines represent the range of usual live to dead load ratios found in concrete structures. The first one is at 62% of the original load bearing capacity, while the second one is at 55%. This line represents the standard failure boundary, at which realistic failure of the concrete wall could happen.

The bottom red line represents a load bearing capacity value is of 33 % of the original one, passing this line guarantees the collapse of the structure.

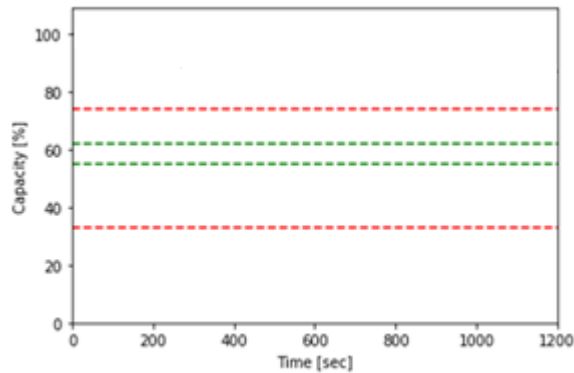


Figure 29: Performance criteria represented by the dotted lines for the load bearing capacity of a concrete wall

4.3.4. Simulations set-up

The simulations are run with FDS. The initial outside temperature is set at 25°C. The fuel pack is placed in the left corner, 5 cm from the walls. The following figures (Figure 30 - Figure 33) show the simulation geometry for each scenario.

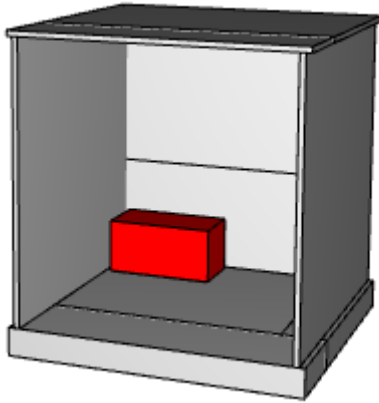


Figure 30: Scenario FP1

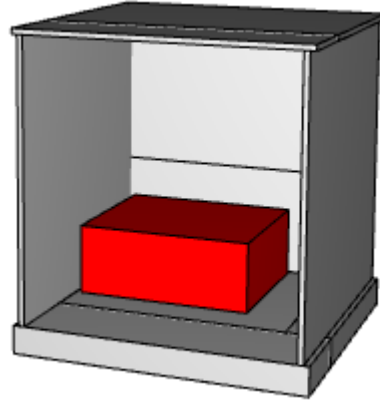


Figure 31: Scenario FP2

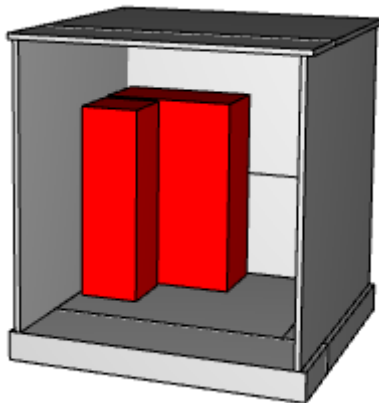


Figure 32: Scenario FP3

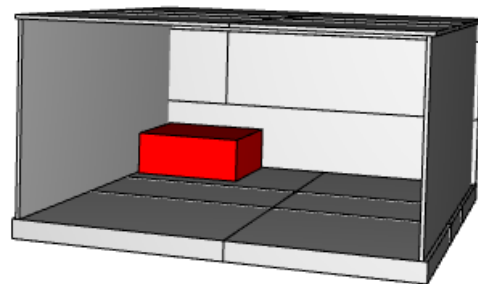


Figure 33: Scenario FP4

Devices

A total of 19 devices are spread across the surface of the simulated space in order to measure the temperature profile through the walls over time. Most devices are located at the internal corners of the space at different heights. These are the locations where the highest temperatures are obtained. Figure 34 shows the location of these devices (in yellow).

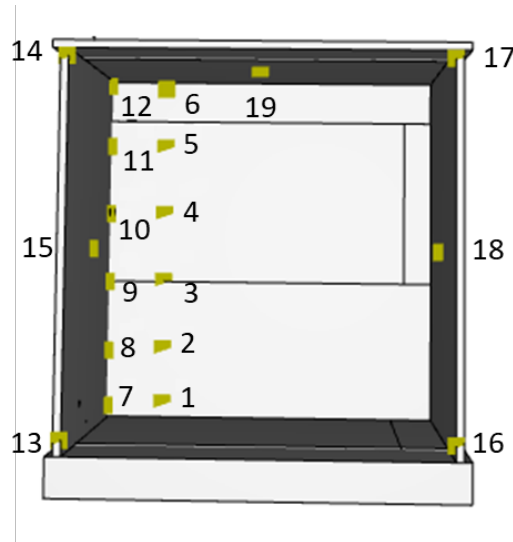


Figure 34: Location of wall temperature devices

4.3.5. Results and discussion

Scenario FP1

This scenario consists of simulating a fuel pack made of wooden sticks in a semi-confined space of 2.5x2.5x2.5 m (Figure 35). The devices giving the highest temperature values for each wall are the ones chosen to analyse the survivability of the concrete walls of the semi-confined space. For all of the wall thickness analysed in this scenario, the most critical sections of the wall are those measured by devices 5, 10, 14 and 17. Device 5 is placed on the back wall at 2 m height, while device 10 is placed at 1.5 m on the left wall. These devices are those placed very close to the fire. Devices 14 and 17 are placed at the upper front corners, respectively on the left side and on the right side. These are the locations where the flames and hot gases will exit the semi-enclosed space. Peak wall temperatures are recorded by device 5, where the temperature at the wall surface reaches 900°C.

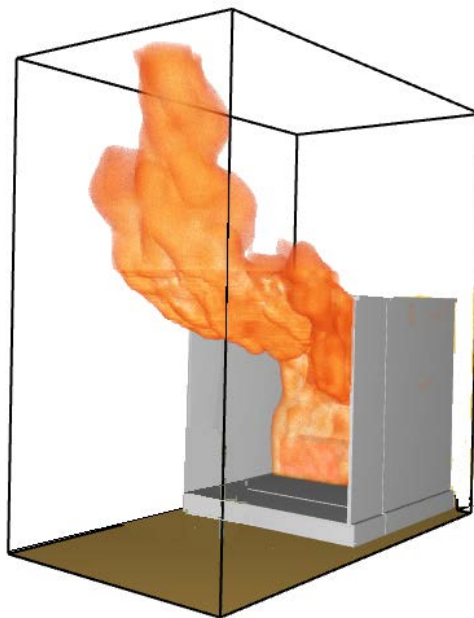


Figure 35. Scenario FP1 at 90.

As can be seen in the following figures (Figure 36 - Figure 38), the sections of the walls where devices 5, 10 and 14 are placed will fail if the wall thickness is 15 cm (the load bearing capacity in these points shown by the blue line passes the 74% line). The back wall fails at about 410 s, while the left wall fails at 440 s. Failure of the walls with a thickness of 20 cm and 25 cm does not occur, although the blue line gets very close to the 74% mark in some of the devices when walls are 20 cm thick. It is possible that the walls might fail once the fire is out, thus after the simulated 600 s.

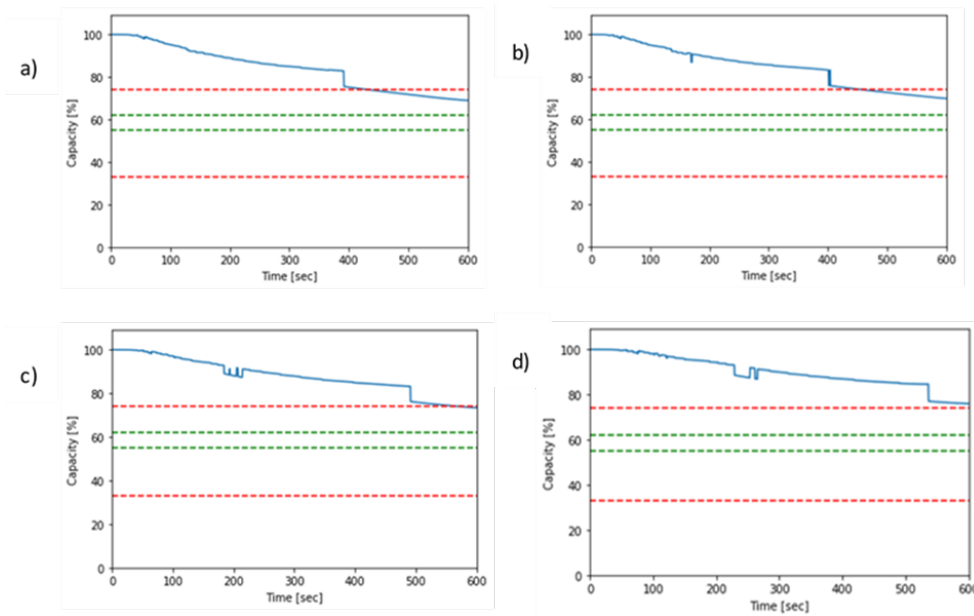


Figure 36: Variation of load bearing capacity of the wall section measured by a) device 5 b) device 10 c) device 14 and d) device 17 for walls with a thickness of 15 cm (scenario FP1)

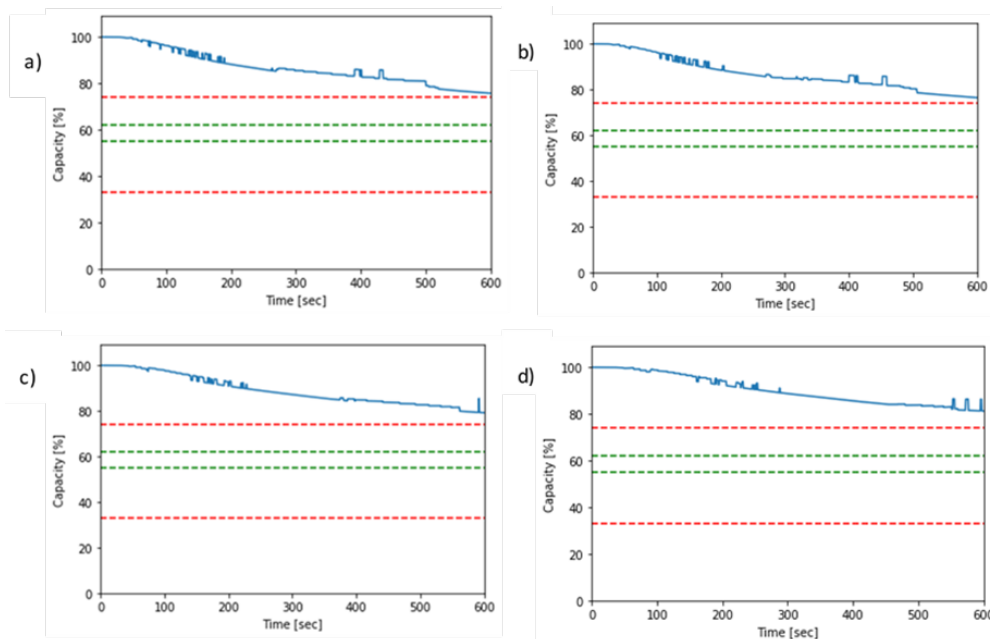


Figure 37: Variation of load bearing capacity of the wall section measured by a) device 5 b) device 10 c) device 14 and d) device 17 for walls with a thickness of 20 cm (scenario FP1)

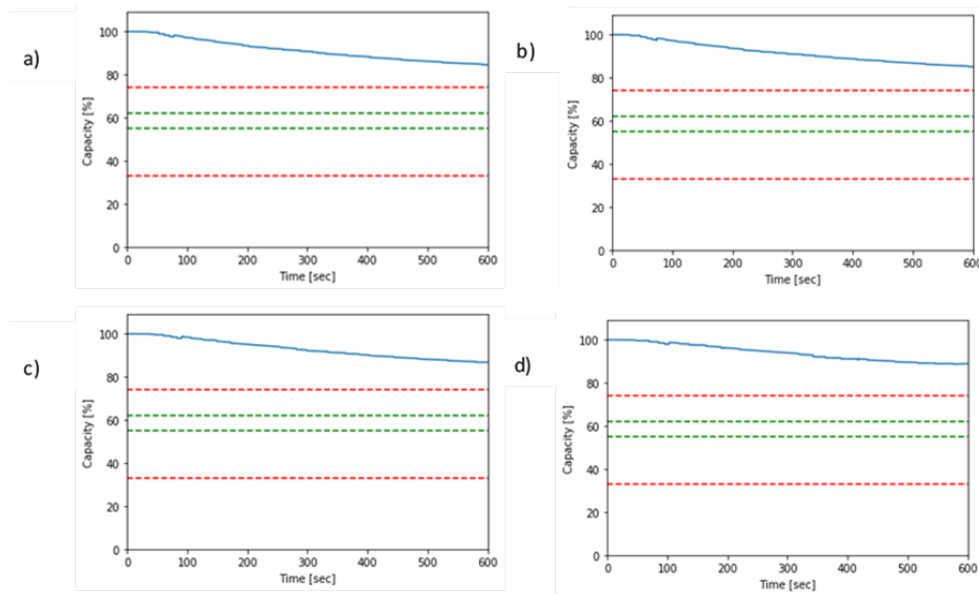


Figure 38: Variation of load bearing capacity of the wall section measured by a) device 5 b) device 10 c) device 14 and d) device 17 for walls with a thickness of 25 cm (scenario FP1)

Scenario FP2

This scenario entails the combustion of a fuel pack containing wooden pallets, foam mats, cardboard sheets and paint buckets (Figure 39). The dimensions of the semi-enclosed space are the same as those in scenario 1. The devices which measure the highest wall temperatures are device 2, 8, 14, and 17. The last two, as for the previous scenario, are located at the upper corners by the opening. Device 2 is located on the left wall at 0.5 m height, while device 8 on the back wall at the same height. The peak surface temperature is measured by device 2 with a value of 527°C.

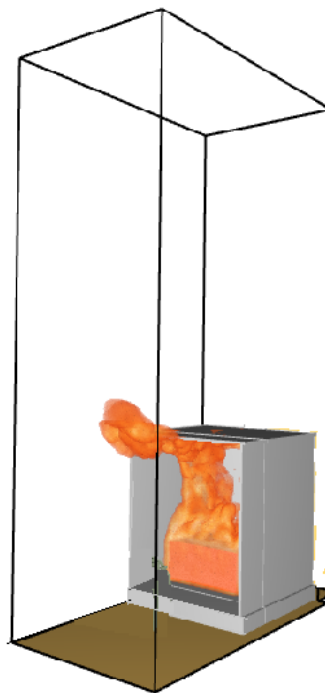


Figure 39. Scenario FP2 at 140 s

The HRR of this fire is much lower than the one of the previous scenario; however, the fire lasts much longer. As can be seen from the following figures (Figure 40 - Figure 42), the left and back wall of the structure will fail at all of the simulated thicknesses, because the load bearing capacity of the walls falls below 74%. With a thickness of 15 cm, the back and left walls fail at 900 s, with a thickness of 20 cm the back wall fails at 1450 s and the left one at 1500 s, while for a thickness of 25 cm the failure time for the left and back wall is about 1900 s.

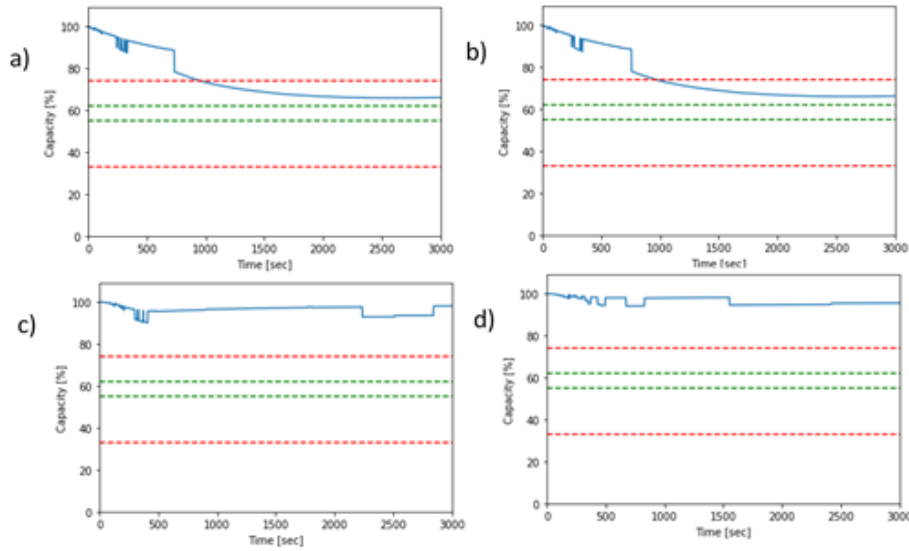


Figure 40: Variation of load bearing capacity of the wall section measured by a) device 2 b) device 8 c) device 14 and d) device 17 for walls with a thickness of 15 cm (scenario FP2)

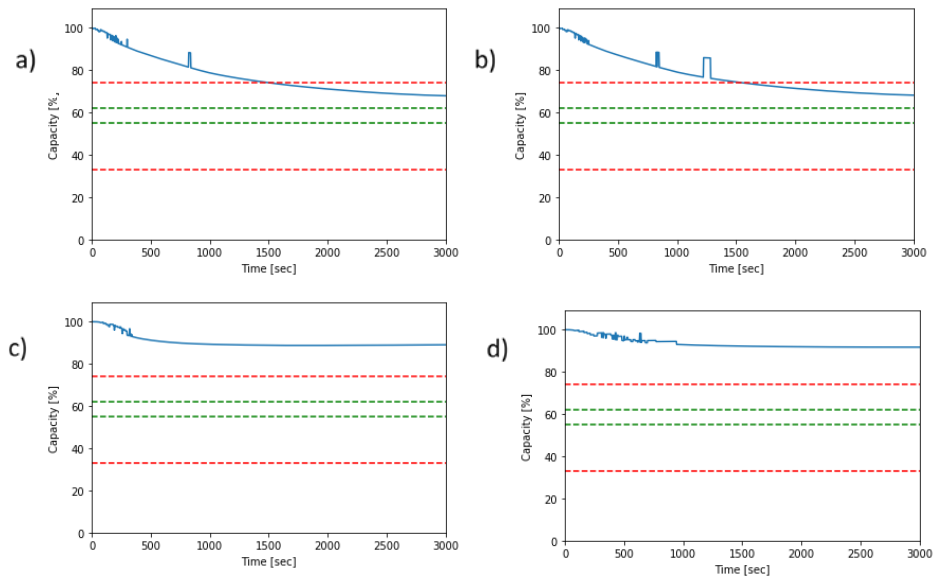


Figure 41: Variation of load bearing capacity of the wall section measured by a) device 2 b) device 8 c) device 14 and d) device 17 for walls with a thickness of 20 cm (scenario FP2)

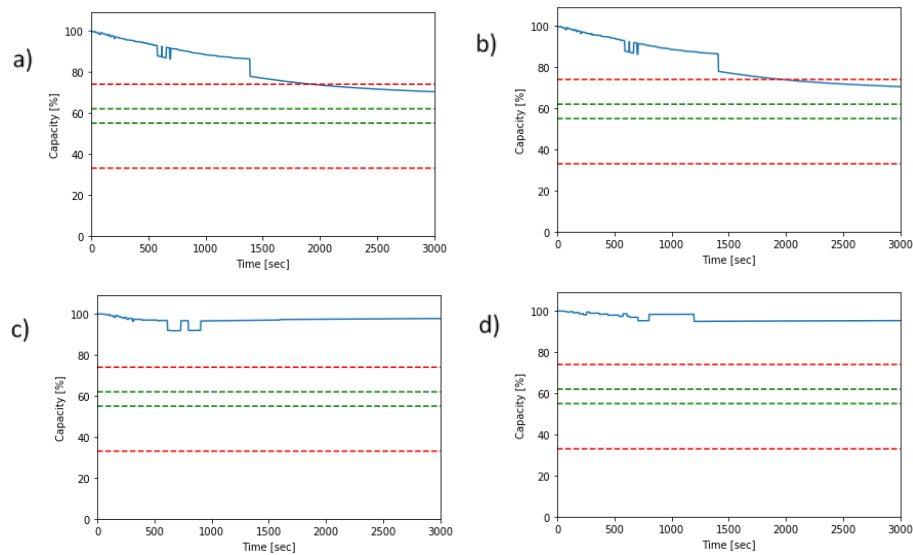


Figure 42: Variation of load bearing capacity of the wall section measured by a) device 2 b) device 8 c) device 14 and d) device 17 for walls with a thickness of 25 cm (scenario FP2)

Scenario FP3

This scenario consists of the combustion of a plywood wardrobe containing four pillows and of a plastic Christmas tree (Figure 43). The dimensions of the semi-enclosed space are the same as those in scenario 1 and 2. The devices which measure the highest wall temperatures are device 5, 11, 14, and 17. The last two, as for the previous scenarios, are located at the corners by the opening. Device 5 is located on the back wall at 2 m height, while device 11 on the left wall at the same height. Peak wall surface temperatures measure 529°C.

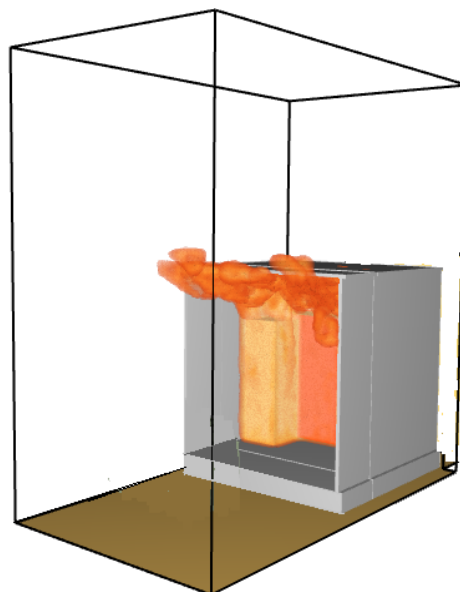


Figure 43. Scenario FP3 at 170 s.

As for scenario FP2, the HRR of this scenario is quite low. As can be seen from the following figures (Figure 44 - Figure 46), the left and back wall of the structure will fail at a wall thickness of 15 cm, because the load bearing capacity of the walls falls below 74% at the end of the simulation time (1200 s). The other two wall thicknesses can be deemed safe, since the load bearing capacity is maintained above 74%.

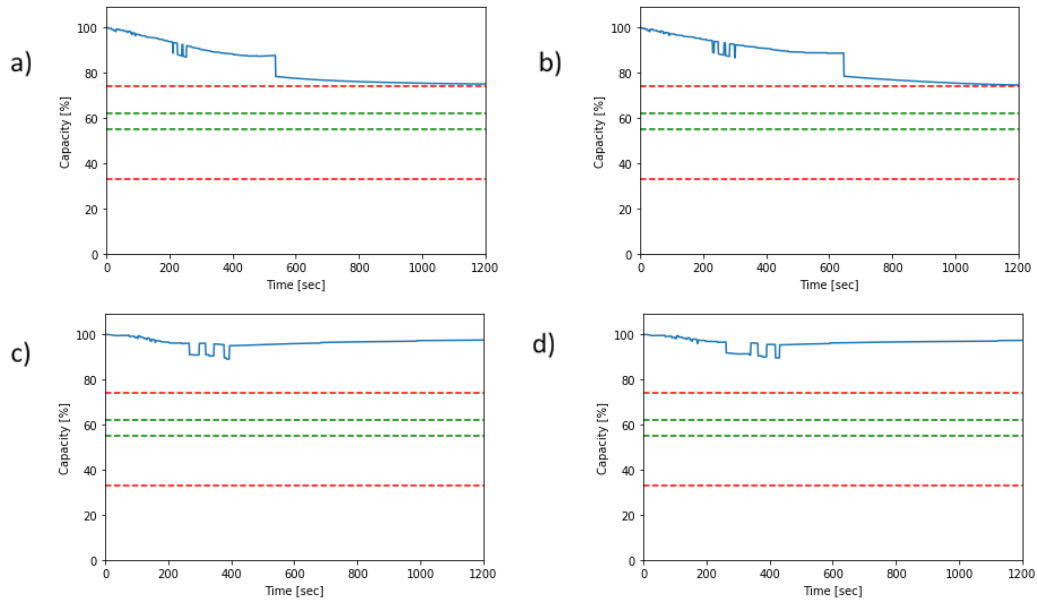


Figure 44: Variation of load bearing capacity of the wall section measured by a) device 5 b) device 11 c) device 14 and d) device 17 for walls with a thickness of 15 cm (scenario FP3)

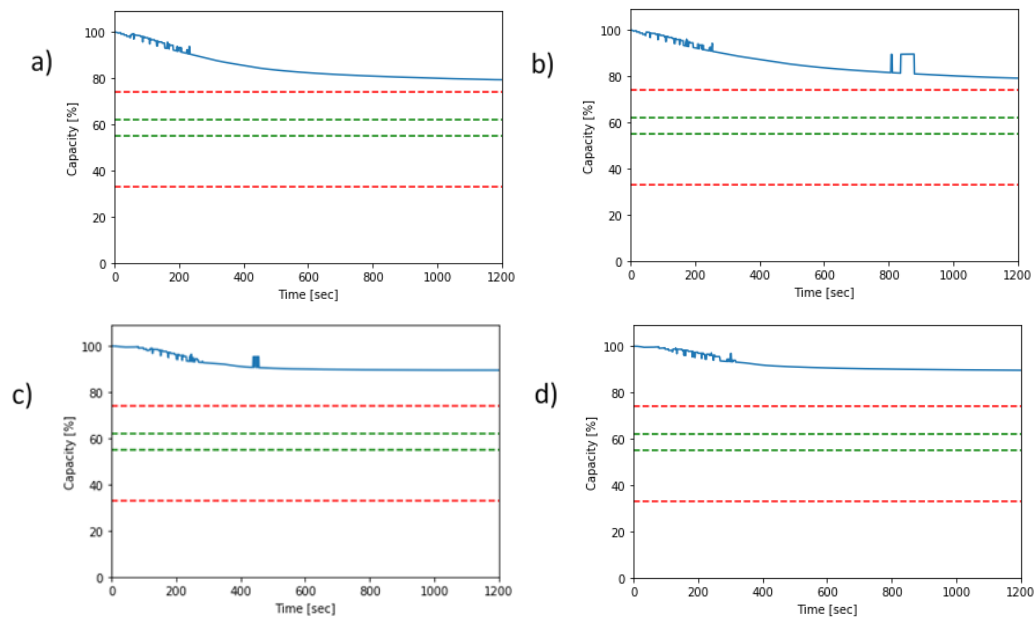


Figure 45: Variation of load bearing capacity of the wall section measured by a) device 5 b) device 11 c) device 14 and d) device 17 for walls with a thickness of 20 cm (scenario FP3)

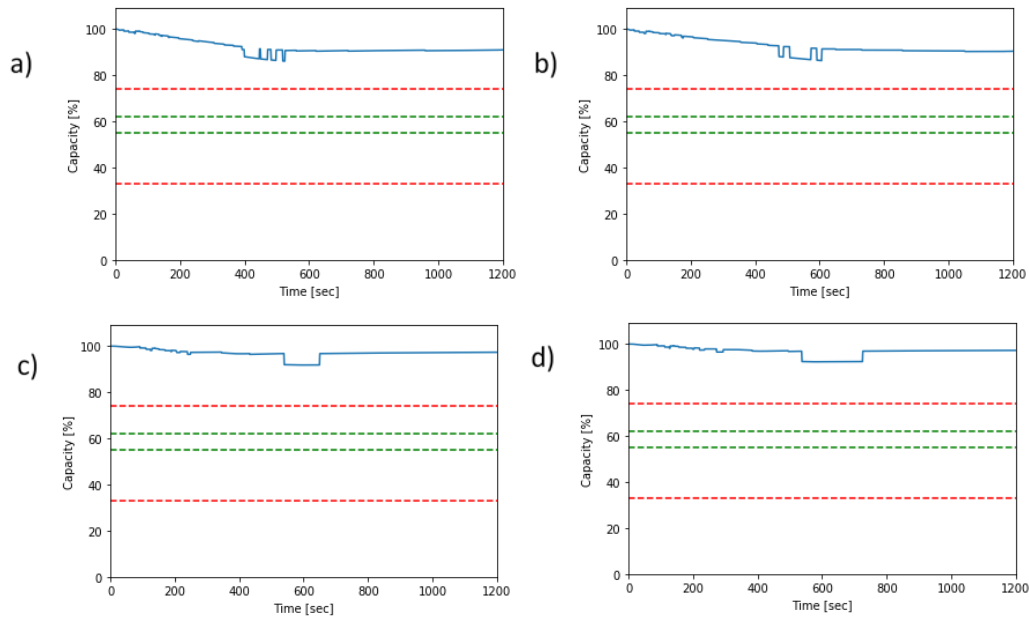


Figure 46: Variation of load bearing capacity of the wall section measured by a) device 5 b) device 11 c) device 14 and d) device 17 for walls with a thickness of 25 cm (scenario FP3)

Scenario FP4

The final scenario simulates the same fire as in scenario FP2, but in a semi-confined space with the dimensions of 5x5x2.5 m, thus with double the floor area as the other scenarios (Figure 47). The thickness of the walls is set at 15 cm. The maximum surface temperature is registered at the upper left front corner at 97°C. Temperatures far from the fuel pack are lower in this scenario in comparison with scenario 2. Failure time of the back and left wall is recorded at about 900 s, which is the same failure time as for scenario FP2.

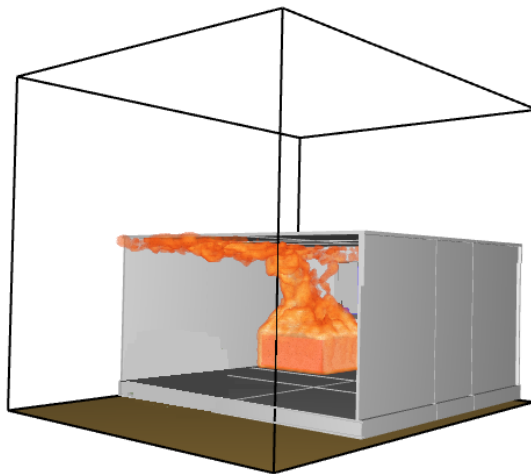


Figure 47: Scenario FP4 at 140 s

As can be seen in Figure 48 the devices located closer to the fire register the failure of the back and left walls. This is due to the fact that the fuel pack is placed very close to these walls, and temperatures in this location do not vary in comparison with scenario FP2.

The increase in room size affects the temperature distribution inside the semi-confined space, as lower gas temperatures reach the furthest areas of the space. The load bearing capacity of the walls located far from the burning fuel pack increases when the area of the semi-confined space increases.

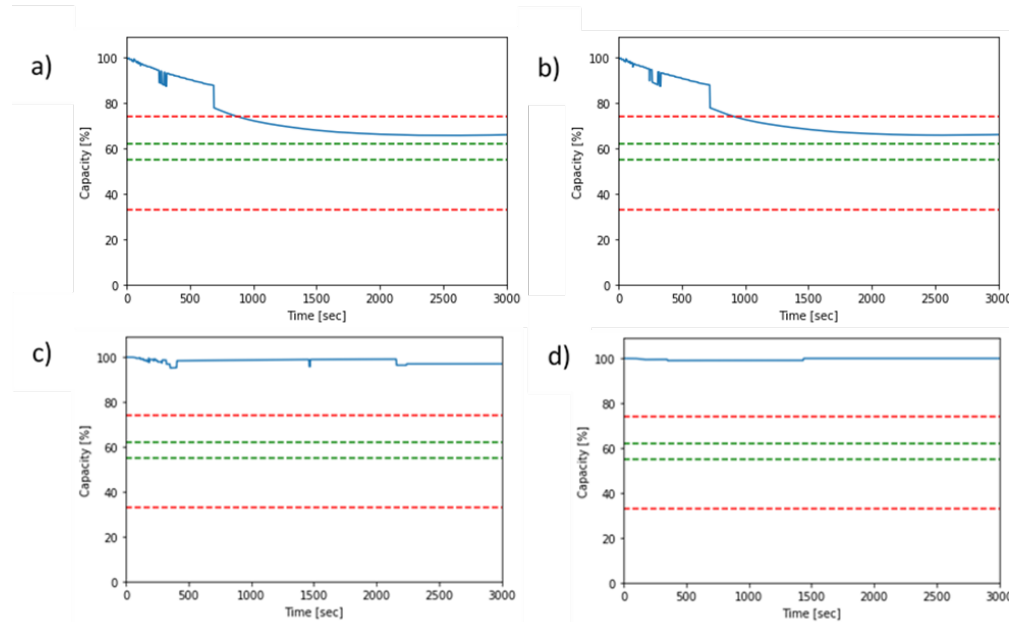


Figure 48: Variation of load bearing capacity of the wall section measured by a) device 2 b) device 8 c) device 14 and d) device 17 for walls with a thickness of 15 cm (scenario FP4)

Guidelines on structures adjacent to the main building in Canada (Partners in Protection, 2003) recommend not storing any combustible material under overhangs. In the USA (NFPA 2018) it is recommended to remove items underneath decks and porches, and firewood or combustible materials cannot be stored in enclosed spaces beneath buildings, nor on decks or under eaves, canopies or overhangs. In France (Ministère de la transition écologique et solidaire 2011), the structure of these spaces should be independent from the house frame.

All these guidelines or prescriptions are in line with the results coming from the analysed scenario. In all of the four analysed fires, the walls of the simulated semi-enclosed space will fail, with the exception of those spaces which have very thick walls subjected to a fire with low HRR values. The results show that increasing the thickness of concrete walls of semi-confined spaces used as storage areas does not guarantee that structural failure will not occur.

The area of the space influences the temperatures inside the semi-confined space: the bigger the area, the lower the temperatures. However, the bigger the area, the more space to store items, which creates a bigger risk for structural integrity.

4.4. Fire exposure on LPG tanks

4.4.1. Idealized Scenarios - experimental design

In line with the idealized situations reported in WUIVIEW deliverable D5.1, scenarios involving LPG tanks are analysed using the methodology presented in WUIVIEW deliverable D3.1. The first two fire scenarios consist of the burning of artificial fuels, while the other two involve the combustion of vegetation. These are divided in sub-scenarios as described here below.

- Scenario LPG1 entails the combustion of a stack of wooden pallets with a height of 0.9 m (Figure 49). The scenario is divided into two sub-scenarios:
 - Scenario LPG1.1, in which the pallets are placed 0.2 m from the tank.
 - Scenario LPG1.2, with the pallets placed at a distance of 1 m from the tank.

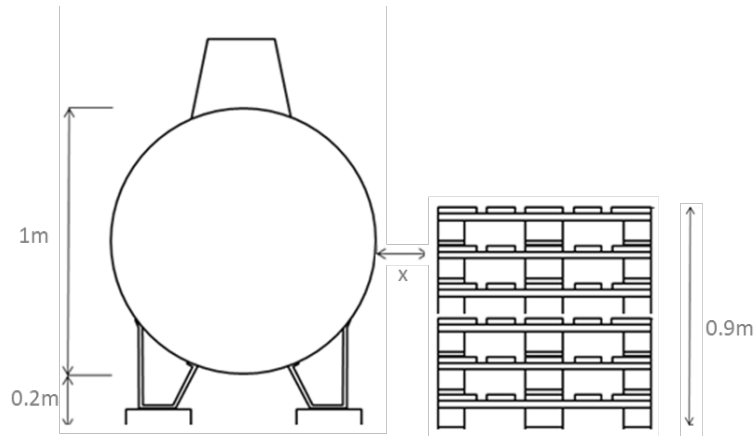


Figure 49: Scenario LPG1

- Scenario LPG2 consist of a fire burning in a semi-confined space located 1 m from an LPG tank (Figure 50). The three different fires analysed in the previous section create three sub-scenarios:
 - Scenario LPG2.1 (see Scenario FP1 for fuel packs in semi-confined spaces).
 - Scenario LPG2.2 (see Scenario FP2 for fuel packs in semi-confined spaces).
 - Scenario LPG2.3 (see Scenario FP3 for fuel packs in semi-confined spaces).

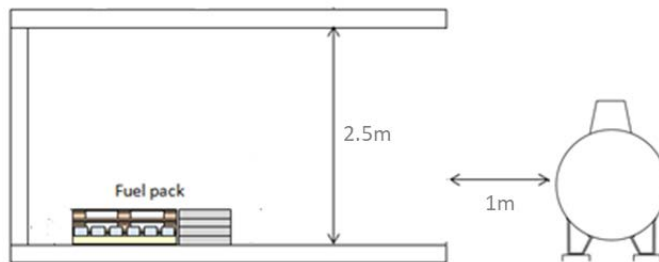


Figure 50: Scenario LPG2

- Scenario LPG3 simulates a LPG tank exposed to the combustion of a 3x3x0.4 m bed of cured grass (Figure 51). The following sub-scenarios are analysed:
 - Scenario LPG3.1, in absence of wind.
 - Scenario LPG3.2, with a wind profile (20 km/h at 10 m height) blowing from left to right.

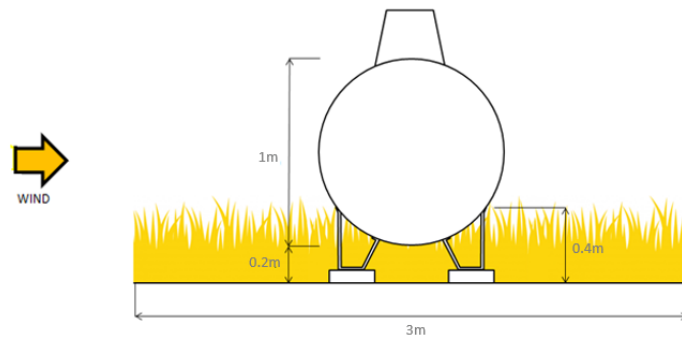


Figure 51: Scenario LPG3.1 (without wind) and Scenario LPG3.2 (with wind)

- Scenario LPG4 simulates a tank placed next to a 3 m-height hedge of *Cupressus Arizona* (Figure 52 and Figure 53). The configuration of the hedge and the distance between the hedge and the tank will vary, thus creating four different sub-scenarios. Scenarios simulating windy conditions will have a wind profile with a peak velocity of 20 km/h at 10 m height.
 - Scenario LPG4.1, with a hedge placed 2 m from the tank in calm conditions.
 - Scenario LPG4.2, with the same hedge as in the previous sub-scenario, but in windy conditions.

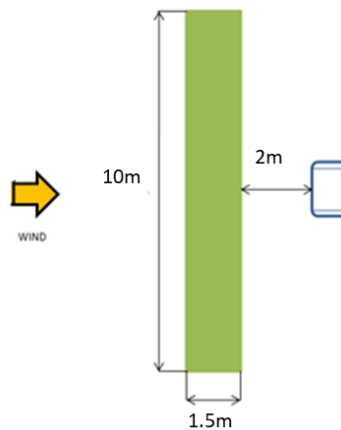


Figure 52. Scenario LPG4.1 (without wind) and Scenario LPG4.2 (with wind)

- Scenario LPG4.3, in which the hedge is simulated in a L shape with calm conditions.
- Scenario LPG4.4, in which the hedge is simulated in a L shape with windy conditions.

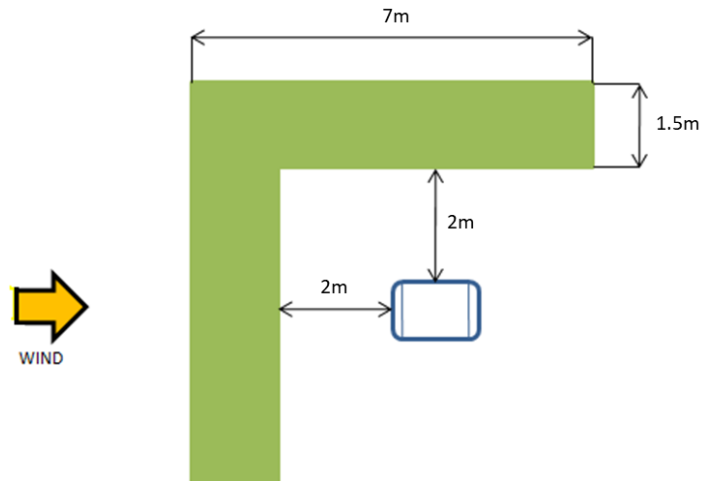


Figure 53: Scenario LPG4.3 (without wind) and Scenario LPG4.4 (with wind)

4.4.2. Fire characterization

For all sub-scenarios, with the exception of the last four, the burning items are simulated as solid shapes with an assigned HRR curve (following option 3.1 of the methodology described in WUIVIEW deliverable D3.1). The curve for scenario LPG1 (stack of wood pallets burning) was presented in Figure 4, while the curves for scenarios LPG2.1, LPG2.2 and LPG2.3 (fuel packs burning in semi-confined spaces) were shown respectively in Figure 26, Figure 27 and Figure 28.

In scenario LPG3 (grassfire) the fire is simulated by creating a 3x3 m vent on the ground with an assigned HRRPUA of 574 kW/m² and a spread rate of 0.9 m/s, taken from experimental data on cured grass (Cheney et al., 1993; Cheney and Gould, 1995). The resulting HRR curve is given in Figure 54.

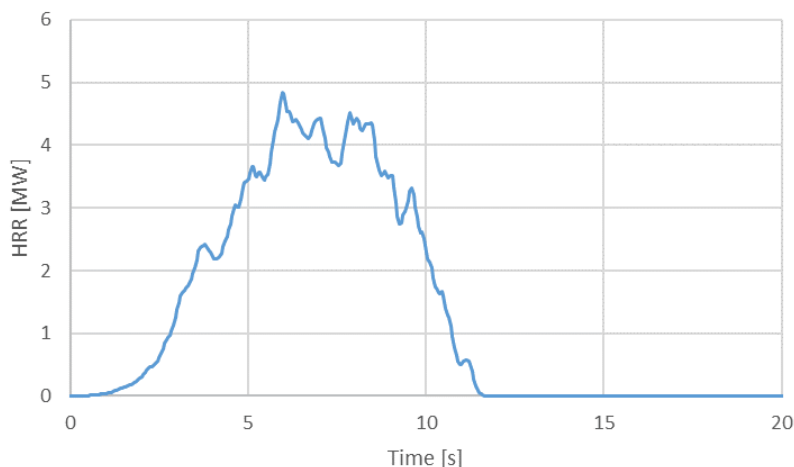


Figure 54: Heat Release Rate curve for scenario LPG3

In scenario LPG4 (hedgerow fire exposure) the fire is simulated following option 3.2 of the methodology described in WUIVIEW deliverable D3.1, thus by introducing solid particles belonging to five size classes: foliage, wood with a diameter (d) smaller than 3 mm, wood with $3 < d < 6$ mm, wood with $6 < d < 10$ mm, and $d > 10$ mm (see D2.2 "Natural fuels database" for detailed description of fuel loading). The wood is divided further in two sub-classes: live wood

and dead wood. The bulk density of the live particles is 12.94 kg/m³, while the one for the dead wood is 4.1 kg/m³. The foliage is concentrated in the outer parts of the hedge, the dead roundwood in the centre. The live roundwood is distributed evenly across the entire volume of the hedge. Ignition is piloted by particles called ignitors, which are placed at the bottom and will burn for 10 seconds. The HRR curve is not prescribed as in the previous scenarios, but it is calculated in the simulation. With this type of fire characterization, the wind can have an effect on the resulting HRR curve, as can be seen in the following figures (Figure 55, Figure 56). In the windy scenarios the flames are pushed sideward and not upwards, so many of the particles located at the top of the hedge do not ignite.

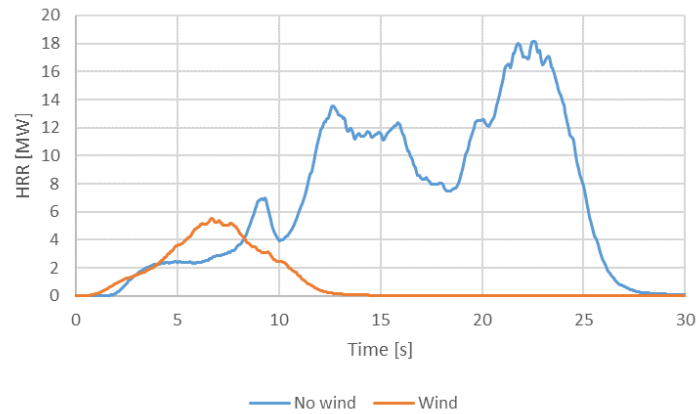


Figure 55: Heat Release Rate curves for scenarios LPG4.1 (no wind) and LPG4.2 (wind)

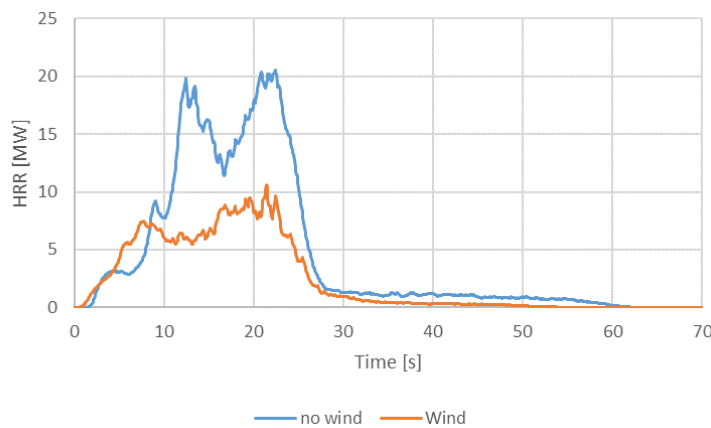


Figure 56: Heat Release Rate curves for scenarios LPG4.3 (no wind) and LPG4.4 (wind)

4.4.3. Performance criteria

According to the API 2510 (American Petroleum Institute, 2001), the integrity of an LPG tank exposed to fire is not compromised as long as: i) the tank is equipped with a properly designed pressure relief valve (PRV), i.e. the PRV prevents the vessel pressure from rising more than 21% above the design pressure and ii) the incident radiation is below 22 kW/m².

The first performance criterion that is considered in these scenarios is thus the value of 22 kW/m² for the incident radiation onto the tank. If the value of the incident radiation stays below this threshold, the tank will be deemed safe. If this value is however larger than the threshold, further investigation on the integrity of the tank will be needed.

As presented in the WUIVIEW deliverable D3.1, two different indicators are used as performance criteria in case the incident heat flux onto the tank passes the threshold value. These are the Weakened Surface Index (WSI) and the Pressure Release Valve Index (PRVI) given in Table 9. The first one aims at assessing the extension of mechanical weakening of the tank steel structure due to high temperature, while the second one highlights how close the pressure reached in the tank is to the PRV set point. Although opening of the PRV represents a safety measure to prevent tank rupture, the jet fire resulting from the ignition of the fluid released by the valve increases the heat load onto the tank and its surrounding and may contribute to worsen the consequences of the fire. Fire scenarios resulting in values WSI and PRVI higher than 1 have the potential to compromise tank integrity and/or to result in an escalation of consequences. In this work however, a safety coefficient of 0.9 is applied to identify scenarios not having the potential to compromise the integrity of LPG installations.

Table 9: Indicators for the assessment acceptability of the LPG tank response to fire

Indicator	Definition	Notes
WSI: Weakened Surface Index	$WSI = \frac{S_{a,max}}{S_c}$	<p>$S_{a,max}$: maximum (over simulation time) surface area where the temperature is higher than 400°C</p> <p>S_c: critical surface area (0.48 m²)</p>
PRVI: Pressure Relief Valve Index	$PRVI = \frac{p_{max}}{p_{PRV}}$	<p>p_{max}: maximum pressure reached in the tank</p> <p>p_{PRV}: PRV set point (18 bar)</p>

4.4.4. Simulations set-up

In all of the simulated scenarios, the reference target is a 1 m³ steel LPG tank (diameter = 1000 mm, length = 1470 mm, wall thickness = 6 mm, with semi-elliptical ends) containing propane. In the FDS simulations, boundary files are used to record surface quantities at the tank. The measurements recorded are the incident heat flux, the heat transfer coefficient and the gas temperature. Should the incident heat flux onto the tank be higher than 22 kW/m², the response of the tank is then further modelled in ANSYS® Fluent® to identify the WSI and PRVI indicators.

The wind was inputted as a profile coming from one of the vent of the mesh boundaries, with the aid of a ramp. The wind profile needed about 10 s to stabilize, so ignition of the fuel for scenarios including wind is 10 s after the start of the simulation.

Scenario LPG1

The fire in Scenario LPG1 is simulated as a flat surface with an assigned HRR curve (Figure 4). The distance between the tank and this surface is 0.2 m for Scenario LPG1.1 (Figure 57) and 1 m for Scenario LPG1.2 (Figure 58).

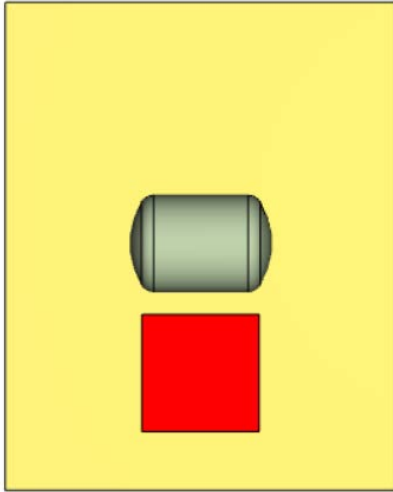


Figure 57: Scenario LPG1.1 set-up

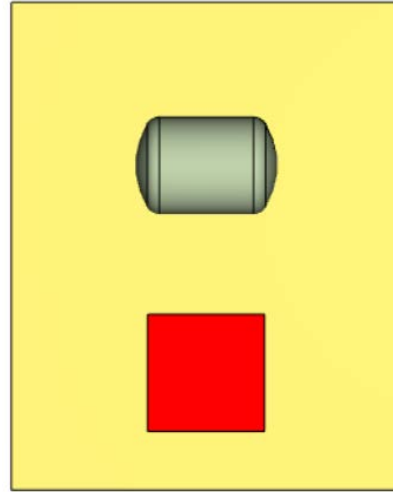


Figure 58: Scenario LPG1.2 set-up

Scenario LPG2

In all the sub-scenarios of Scenario LPG2, the fire is simulated as a solid obstacle. Each surface of this obstacle, with the exception of the bottom, is covered by a vent with an assigned HRRPUA and an HRR curve. The following figures (Figure 59 - Figure 61) show the setup for each sub-scenario. The dimensions of the storage area is 2.5x2.5x2.5 m.

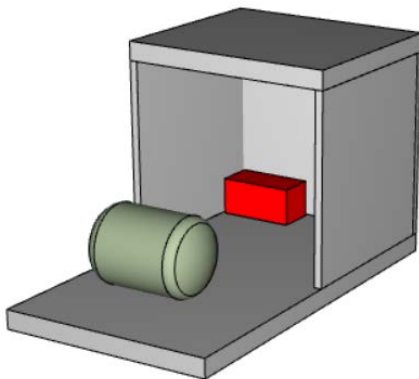


Figure 59: Scenario LPG2.1

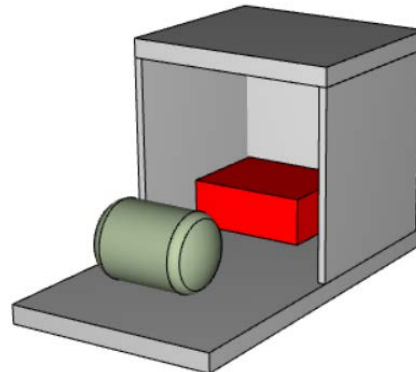


Figure 60: Scenario LPG2.2

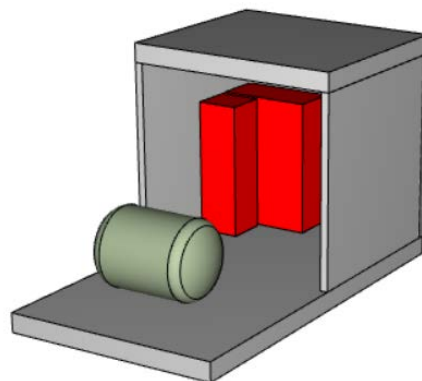


Figure 61: Scenario LPG2.3

Scenario LPG3

The grass is simulated as a flat surface (Figure 62), and ignition happens in its lower right corner. Scenario LPG3.2 includes the analysis of the effects of this type of fire in windy conditions. A wind profile has thus been inserted, which reaches its maximum velocity of 20 km/h at a height of 10 m.

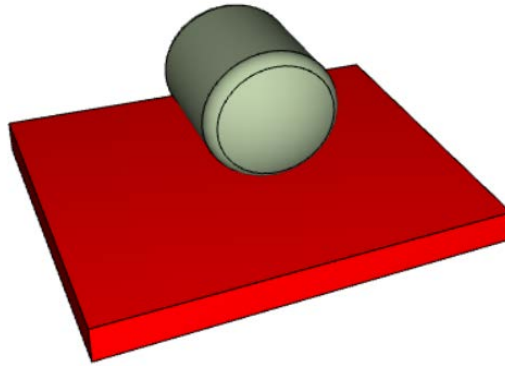


Figure 62: Scenario LPG3.1 and LPG3.2

Scenario LPG4

This scenario consists of the simulation of different hedge configurations placed at diverse distances from a tank (Figure 63, Figure 64). As previously stated, the HRR curve is calculated by FDS. Windy conditions include a wind profile with a maximum velocity of 20 km/h at 10 m.

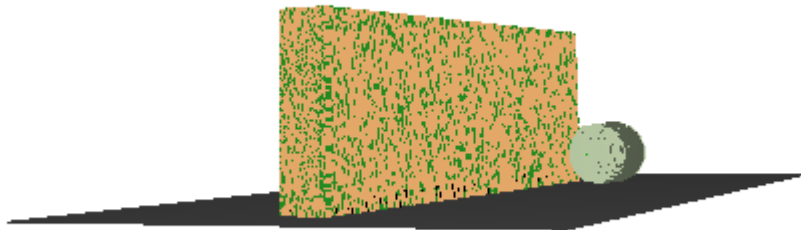


Figure 63: Scenario LPG4.1 and LPG4.2

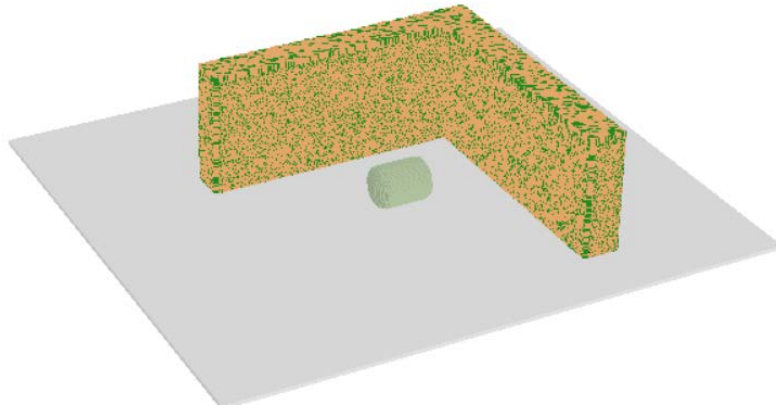


Figure 64: Scenario LPG4.3 and LPG4.4

4.4.5. Results and discussion

Scenario LPG1

Scenario LPG1.1 gives an incident heat flux onto the tank higher than 22 kW/m^2 , as can be seen in Figure 65. This indicates that further investigation is needed to identify the tank's response to the fire.

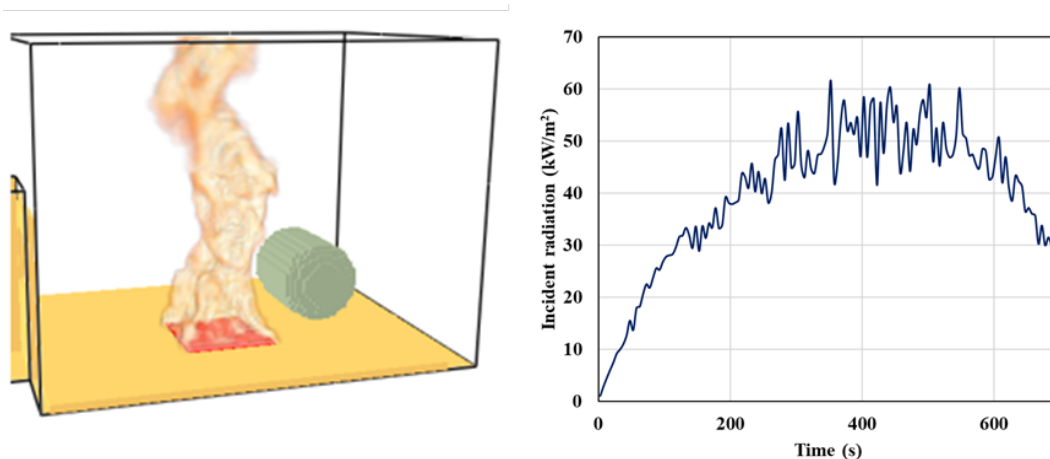


Figure 65: Simulation for scenario LPG1.1 and incident radiation onto the tank as a function of time

The tank response step is carried out using the Ansys Fluent setup and computational grid described in the WUIVIEW deliverable D3.1, with a filling degree of 80%. Figure 66 depicts the results of this step in terms of pressurization curves and maximum wall temperature. The wall temperature never reaches 400°C , resulting in a null WSI, while the PRVI is 0.9. It can be concluded that this scenario does not have the potential to compromise the integrity of the LPG tank. However, it may lead to the opening of the PRV, which, for the reason stated above, should be considered an unwanted situation.

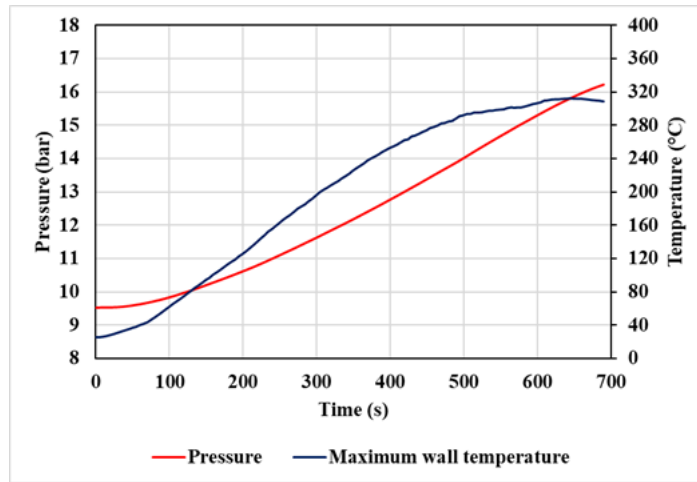


Figure 66: Results for the tank response in scenario LPG1.1

In scenario LPG1.2 the tank is placed 1 m from the fire. This results in a much lower incident radiation onto the tank, as can be seen in Figure 67. The incident radiation has values between 22 kW/m² and 27 kW/m² for about 100 s. This time is too short to cause a large pressure rise inside the tank nor a significant temperature increase of the tank’s wall temperature.

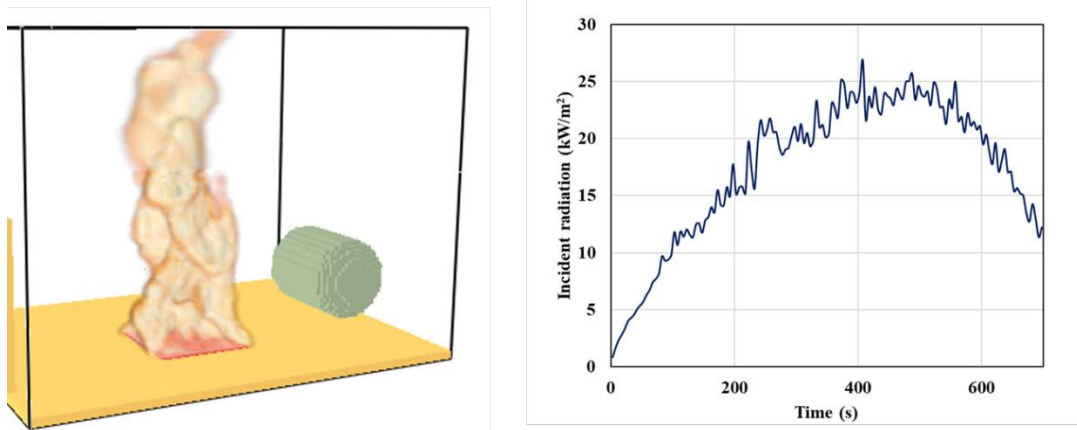


Figure 67: Simulation for scenario LPG1.1 and incident radiation onto the tank as a function of time

Scenario LPG2

The incident radiation onto the tank in scenario LPG2.1, as can be seen in Figure 68, is higher than 22 kW/m² and further investigation is therefore needed to identify the tank’s response to the fire.

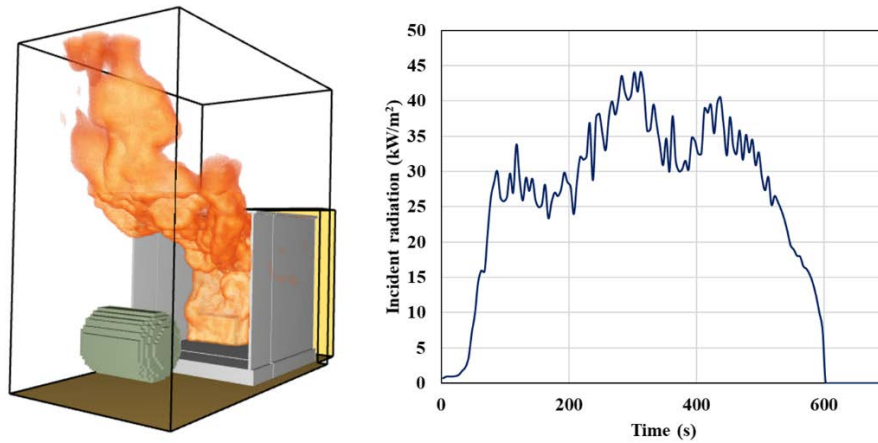


Figure 68: Simulation for scenario LPG2.1 at 120 s and incident radiation onto the tank as a function of time

As for scenario LPG1.1, the tank response step is executed using the setup and computational grid described in the WUIVIEW deliverable D3.1, with a filling degree of 80%. As can be seen in Figure 69, the tank’s wall temperature rises above 400°C, resulting in WSI of 0.04, while the PRVI is 1. This scenario does not have the potential to compromise the integrity of the LPG tank, however it leads to the opening of the PRV, which is an unwanted situation.

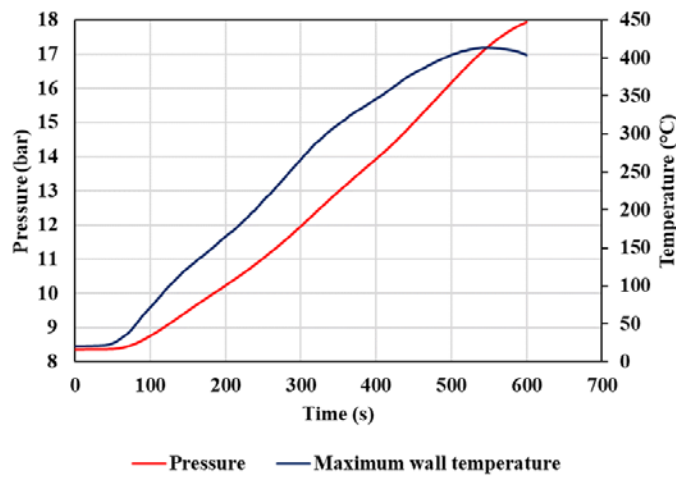


Figure 69: Results for the tank response in scenario LPG2.1

As can be seen in Figure 70 and Figure 71, the incident radiation onto the tank in scenarios LPG2.2 and 2.3 is well below 22 kW/m². These two scenarios can therefore be deemed safe and no further analysis is needed.

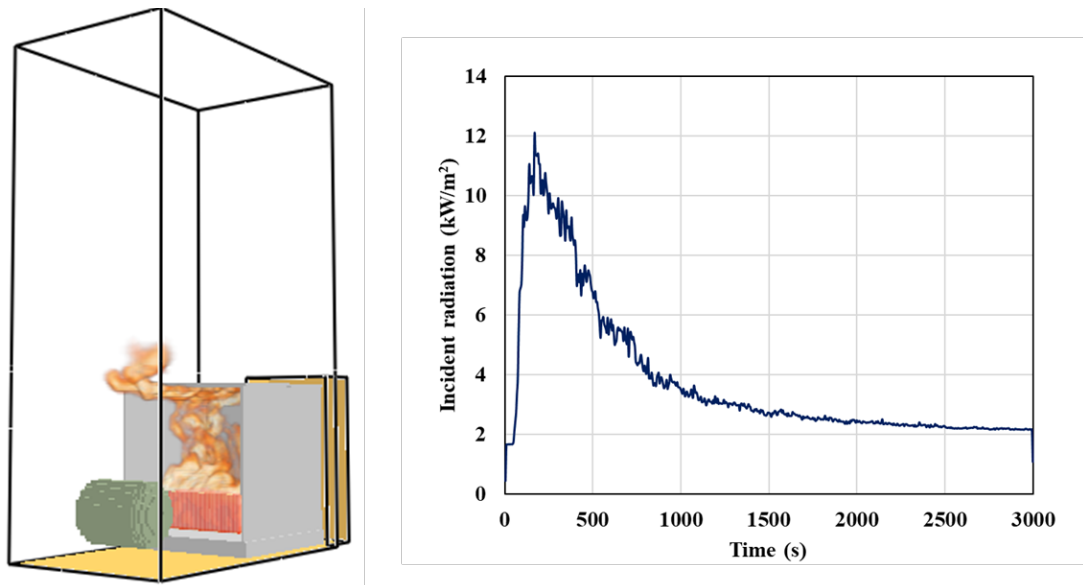


Figure 70: Simulation for scenario LPG2.2 at 230 s and incident radiation onto the tank as a function of time

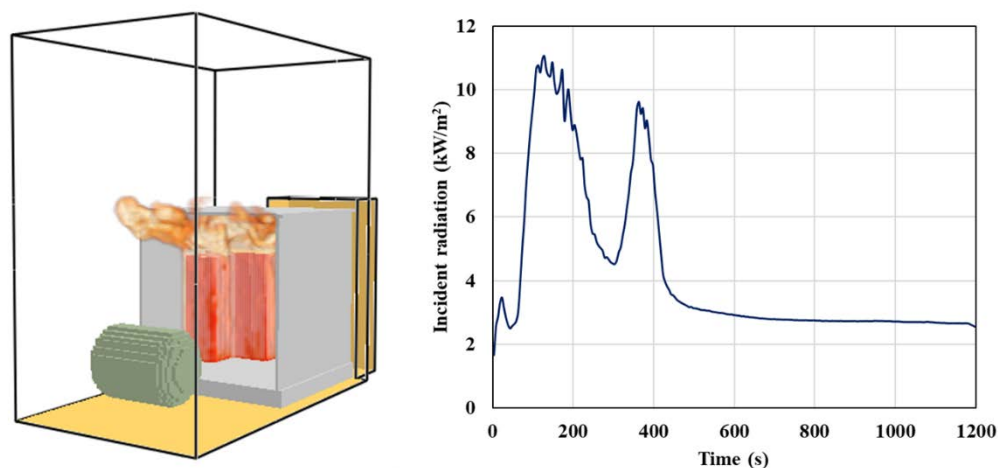


Figure 71: Simulation for scenario LPG2.3 at 100 s and incident radiation onto the tank as a function of time

Scenario LPG3

Results are shown in Figure 72 - Figure 74. In both sub-scenarios, the fire extinguishes in less than 15 s. Although the fire duration is very limited, the incident radiation onto the tank is high. As given in Figure 73, a peak of around 100 kW/m² is reached in windy conditions. It must be taken in mind that this represents only a fraction of the total heat flux to the tank. In fact, the curves do not take into account the convective contribution of the flame that is in contact with the tank wall. This scenario is representative of those situations in which the tank is exposed to a quite strong fire for a very small amount of time. Given the very high heat fluxes, further investigation about the conditions of the tank are needed.

The tank response step is carried out using the Ansys Fluent setup and computational grid described in the WUIVIEW deliverable D3.1. The filling degree is set to 80%. Figure 74 reports

the results of this step in terms of pressurization curves and maximum wall temperature. It clearly appears that, regardless of the presence of the wind, both sub-scenarios produce a negligible increase in both pressure and wall temperature. It can thus be concluded that Scenario LPG3 does not represent a threat for the tank’s integrity. This is reflected by the values of the indicators: the PRVI is 0.47 both for calm and windy conditions, whereas the WSI is always null. This result is a direct consequence of the very short duration of the fire.

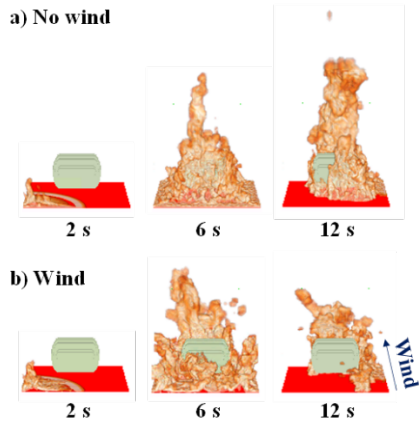


Figure 72: Fire evolution for scenario LPG3.1 (a) and LPG3.2 (b)

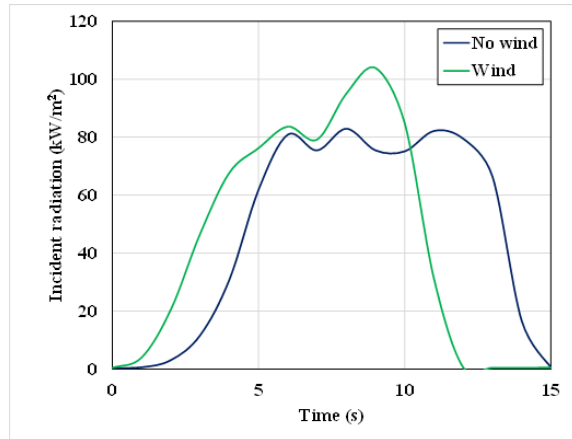


Figure 73: Incident radiation onto the tank for scenario LPG3.1 (no wind) and LPG3.2 (wind)

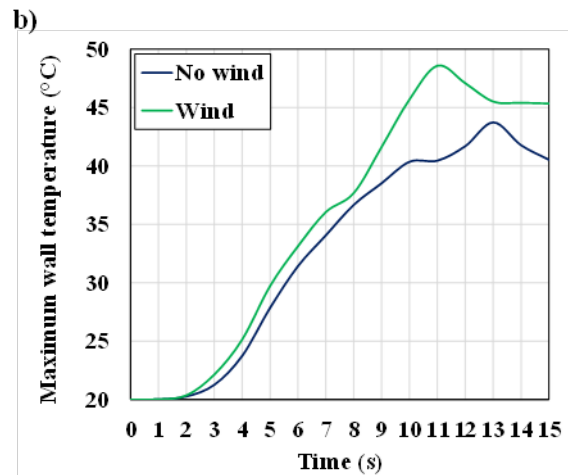
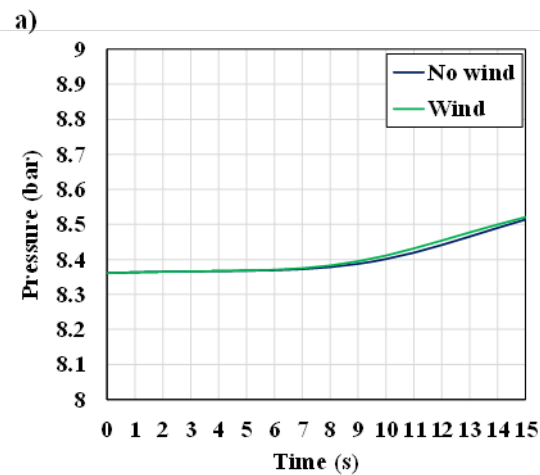


Figure 74: Pressurization curves (a) and maximum wall temperature (b) obtained in calm (scenario LPG3.1) and windy (scenario 3.2) conditions.

Scenario LPG4

In all of the sub-scenarios which analyse different geometry of hedges, the fire extinguishes quickly.

Scenarios LPG4.1 has a fire duration of 27 s and scenarios LPG4.2 of 12 s. As can be seen in Figure 75, the incident radiation onto the tank is always lower than 22 kW/m², and the scenarios can be deemed safe without the need of performing a CFD simulation of the tank response.

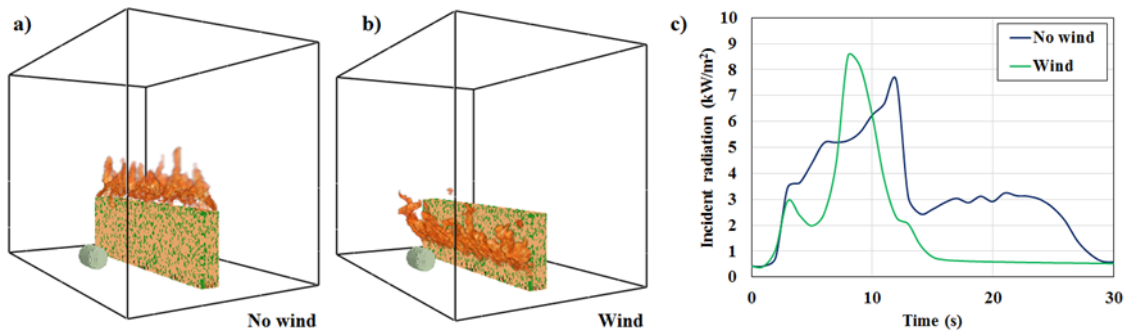


Figure 75: Simulation for scenario LPG4.1 (a) and LPG4.2 (b); incident radiation onto the tank as a function of time (c)

Both scenario LPG4.3 and LPG4.4 have a fire duration of about one minute. As can be seen in Figure 76, also in these scenarios the incident radiation onto the tank is always lower than 22 kW/m². Tank integrity can thus be considered to not be compromised by these fire scenarios.

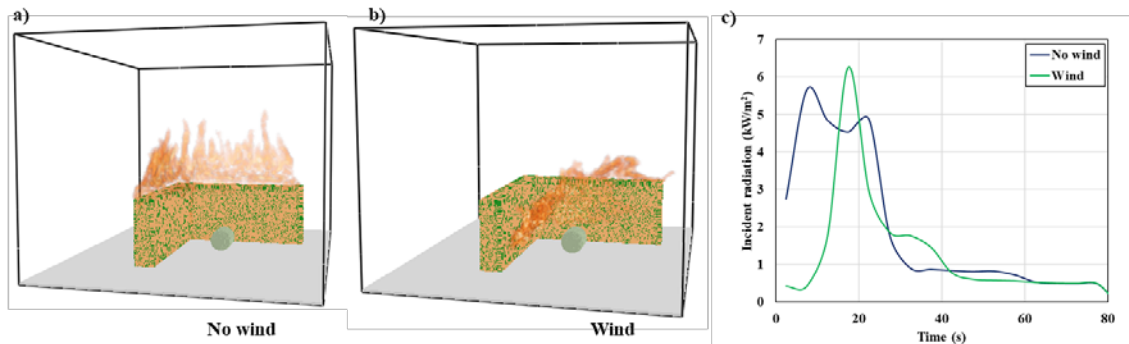


Figure 76: Simulation for scenario LPG4.3 (a) and LPG4.4 (b); incident radiation onto the tank as a function of time (c)

Safety distances for LPG tanks vary depending on their volume (Figure 77). Within the European Union these distances are not harmonized.

Country	Volume Range (m³)	Minimum Safety Distance (m)
France	$V < 8$	3
	$8 \leq V < 11$	5
Greece	$V < 0.5$	3
	$0.5 \leq V < 9$	5
Italy	$0.15 \leq V < 3$	3
	$3 \leq V < 5$	5
Portugal	$V < 0.5$	3
	$0.5 \leq V < 5$	5
Spain	$0.15 \leq V < 1$	3
	$1 \leq V < 5$	5
UK	$0.15 \leq V < 0.5$	3
	$0.5 \leq V < 2.5$	5

Figure 77: Minimum safety distances as a function of tank volume (in m³) for different European countries

In Canada (Partners in Protection, 2003) and USA (NFPA 2004), propane tanks should be 3 m away from any vegetation and 10 m away from any building.

The simulations performed with ornamental vegetation placed 2 m from the tank show no risk for the tank’s integrity nor for the opening of the PRV, due to the short duration of these fires.

Results from the simulations with the stack of wood pallets show that a distance of 1 m between the fuel and the LPG tank can be deemed safe.

Scenarios with LPG tanks located at a distance of 1 m from the opening of a semi-confined space with the dimensions of 2.5x2.5x2.5 m and containing fuel packs with a fire load of less than 2000 MJ can be deemed safe.

4.5. Vulnerability of roofs, gutters and vents

The roof (with its accessories) is one of the most vulnerable elements against WUI fires in dwellings (Quarles et al., 2010). The direct contact of a flame or the firebrand activity can drive a fire underneath the roofing materials, starting a new combustion process that opens new gaps and weakens the structure, being even able to lead into its collapse (fire damage in roofing starts to appear above the 200-300 °C temperature threshold (Dietenmerger & Boardman, 2017)). Several research studies (e.g. Foote, 1994; Davis, 1990; Howard et al., 1973) have found that fire-resistant roofs improve the chances that a home has to survive in case of a forest fire. Because of this, many risk surveys include roofs in their evaluation of vulnerabilities (e.g. Cohen, 1995; Dietenmerger & Boardman, 2017).

To avoid flame contact from the outside, it is paramount to reduce the fuel load around the structure (See next Section 4.6) and ensure that there is no vegetation (tree branches) above the roof (Penman et al., 2015). On the other hand, direct flame contact may also occur if there are debris, twigs, leaves, needles or branches accumulated on the roof, suitable to ignite. Several works stress the importance of cleaning the roof from these accumulated fuels (e.g. Penman et al., 2015), and also point out the existence of sink areas where roofs tend to accumulate fuel, like corners, nooks (Nowicki, 2002) or complex shapes (Quarles et al., 2010). Regarding gutters, it seems to be more important to maintain them clean, than the material used in their construction (Quarles et al., 2010). There exist devices designed to prevent gutters from debris accumulation, but their effectiveness has not been tested (Hakes et al., 2017); Quarles et al. (2010) go further and expose the idea of substitute gutters for a proper subsurface drainage system, thus directly eliminating the hazard.

Other important source of risk, jeopardizing homes during WUI fire events, is the firebrand activity over the roof (Cohen, 2000; Nowicki, 2002; Dietenberg, 2010; Quarles et al., 2010; Calkin et al., 2013). These firebrands act as a heat source, being able to ignite the fuels accumulated over the roof or even the roofing materials if they are combustible. Being able to recognize the situations in which firebrands interact with the roof is a key factor in order to prevent ignitions. Manzello et al. (2008) studied the ability of firebrands to accumulate and ignite fuels on roofs as a function of the angle between two sections of a roof (e.g. roof valleys or interactions with dormers). Tests showed that the larger the angle between these surfaces, the lower the probability of an ignition, observing flaming combustion with valley angles of 60°, but just smoldering combustion over 90°. With angles over 135°, no ignitions were observed. On the other hand, firebrands that sneak into the roof or the attic through vents, gaps or holes could lead into inner ignitions. Manzello et al. (2007) studied how firebrands passed through meshes of different sizes (6, 3 and 1.5 mm size gaps). They found that firebrands were always able to penetrate the mesh, no matter the size. However, in meshes with larger gaps the firebrands were directly able to go through while in finer meshes firebrands remained blocked until combustion make them small enough to cross. Small firebrands were not be able to release

as much energy as the larger ones concluding that smallest meshes hindered ignitions. Tests performed by Manzello et al. (2011) involved flame ignitions by firebrands getting through certain materials with apertures of 2 mm, but recorded no-ignitions and smoldering ignitions with smaller meshes (up to 1.04 mm). Finally, Manzello et al. (2010) proved that in non-maintained roofs and in roofs where debris have sneaked inside the structure, the risk of ignition increased.

It is worth to note that most of these works are focused on wood-based constructive techniques (wood, OSB boards, plywood, etc.). Despite these constructive materials are widespread in northern European countries, Pastor et al. (2019) indicate that modern buildings in the Mediterranean basin (with an extended use of concrete and clay tiles, among others non-combustible materials) have a significantly lower vulnerability. It is also necessary to take into account the rural areas, where traditional buildings techniques are still present in ancient dwellings (e.g. Muñoz & López, 2008).

Regarding international standards, most prescriptions and recommendations agree with the need of fire-proof or non-combustible roofs, with different levels of performance and specified requirements (Intini et al., 2019). However, the shape of the roof does not have any type of consideration in standards, when it has been scientifically proved to be a key factor in firebrand accumulation and ignition likelihood (Manzello et al., 2008). Most standards also stress the need of avoiding the accumulation of fuels over the roof by cleaning and removing close trees and overhanging branches, but just a few of them claim a proper maintenance of the roof itself (proper seams between shingles, plug holes, cover gaps, etc.).

The need of cleaning also applies to gutters, to which some standards (ICC, 2015; CBSC, 2016) also require setting up specific devices to avoid fuel accumulation. However, the effectiveness of gutter guard systems have not been proved in case of fires. Regarding the constructive material of gutters, there is not a clear consensus across standards of whether gutters should be non-combustible or rather, plastic materials (i.e. PVC) should be allowed. If accumulated material is ignited, non-combustible gutters may drive the fire through the roof. On the other side, PVC gutters may melt and fall in case of fire, carrying the fire to the ground level (Quarles et al. 2010).

According to standards and scientific research, to avoid fire intrusion, vents in roofs and the building envelope should be screened with corrosion-resistant, non-combustible wire meshes, with diameters' size little enough to prevent the pass of firebrands. International codes recommend different diameters for meshes (between 2 and 6 mm), but scientific studies provide evidences that firebrands can penetrate meshes of these diameters with indoor fire ignition potential.

4.6. Residential vegetation management

Residential vegetation is a key aspect when analyzing fire risk at the WUI. It must be properly selected, located and managed to minimize impact at homeowner level in case of fire. In the following subsections, we provide discussion on the critical ring to be fuel-managed around structures and on the fuel treatments and species providing more fire resistance.

4.6.1. Areas of management

All standards dealing with the WUI fire problem include prescriptions regarding residential vegetation management within a certain area around the structure. Recommendations to reduce fire hazard are generally established within at least two rings: 1) an inner ring, from the building out to a given distance, where the area should be maintained to a minimal fuel load to avoid a fire path to the building; 2) an outer ring, from the limit of the inner ring up to a given distance, where fuel loads are maintained at a level where the intensity of an approaching wildfire would be significantly reduced. The limit between the two rings is generally set around 10 m while the limit of the outer rings is more variable (from 30 m up to 100 m depending on standards and countries).

The prescription of 30 m, mentioned as a baseline in Spain by the National Forestry Act (BOE, 2013), is based on assumptions of flat ground, no wind, and radiative heating only, according to the results from the International Crown Fire Modeling Experiment (ICFME) undertaken during the late nineties (Alexander et al., 2004, Cohen, 2004). However, recent research studies (e.g. Rigolot et al., 2004; Zárata et al. 2008 and Rossi et al. 2011, Rahman & Rahman, 2019) recommend using larger distances, especially in case of wind, adverse orography or fuel models. Indeed, regulations in France and Portugal establish 50 m as the limit of the outer ring in which fuel management is prescribed (or even up to 100 m if the municipality decides so, in case of France).

Therefore, while in some scenarios the 30 meters safety buffer might be larger than needed, in the majority of situations this distance might be not enough. In addition, this is of special concern in situations where firefighters are expected to stay and defend properties (e.g. external borders of a WUI settlement) and for *shelter-in-place* designed structures, from where inhabitants are expected to go out to extinguish incipient fires. In these areas, the safety distances must be set also for people and not just for structures, being 30 m most likely insufficient (see section 4.8 for further details).

4.6.2. Fuel treatments

Standards also indicate the fuel treatments to be performed within the two management areas (inner and outer ring). Regarding the outer ring, accepted knowledge on wildfire behavior indicates that, to achieve a significant reduction of a fire-front intensity, it is necessary to avoid any type of crowning activity and to reduce the surface fuel load up to a certain level.

Accordingly, prescriptions and recommendations indicate that it is necessary to separate crowns from trees or canopies from big shrubs to a certain distance to avoid crown-to-crown propagation. This distance varies from 3 m to 9 m, depending on the conditions and the standard. This separation distance might avoid crown fire spread in most of the scenarios, but should be checked for steep slopes and wind-prone areas, in which flame contact between crowns is most likely to occur (Finney et al., 2010; 2013).

On the other hand, to enable vertical discontinuities and avoid fire transition from the ground to the fuel canopy, many standards recommend pruning lower branches up to a certain height. Standards propose different levels, from 2 m to 4 m (some of them considering 1/3 of the tree height as a reference) and different ways of measuring those. While some standards refer this height from the soil, others measure it from the surface fuel layer. Setting this safety vertical distance measuring it from the ground (i.e. not taking into account the deep of the surface fuel)

makes little sense. This distance must be always set from the surface fuel layer. In Morvan (2007), physically-based simulations showed that fire transition could still happen with a 2 meters pruned height for high surface fuels loads. Morvan (2007) set a threshold of 10 cm surface fuel layer depth, to guarantee no fire vertical transition. This fuel depth value of 10 cm could work as a rule of thumb to help owners to manage the surface fuel load in their properties.

The vegetation in the inner ring must also meet some additional requirements, according to standards. Dead vegetation removal (e.g. tree trunks, smaller branches and needles, litter, etc.) is a common recommendation together with the use of fire-resistant species as ornamental vegetation close to structures.

4.6.3. Fire-resistant species

Flammability tests are often used to determine the degree of fire-resistance of wildland and ornamental vegetation (e.g. Martin et al., 1994, Long et al., 2006). These tests usually involve the analysis of small samples using laboratory equipment (e.g. oxygen bomb calorimeters, epiradiators and cone calorimeters). While these types of techniques have been proved simple and efficient for comparative purposes (e.g. Long et al., 2006; Della Roca et al., 2015; Molina et al., 2019), they are not suitable to evaluate the real burning behavior of individuals (Fernandes & Cruz (2012). During WP2, flammability of four species (*Cupressocyparis leylandii*, *Cupressus arizonica*, *Prunus laurocerasus* and *Thuja occidentalis*) was tested at real scale in a combustion bench, using individuals and groups of individuals (see WUIVIEW deliverables D2.1 and D8.1 for further details). In these experiments, we proved that other characteristics of fuel not captured in small-scale flammability tests (fuel treatment and maintenance, draught condition, structure, dead-live fuel ratio, bulk density, etc.) play a key role in the way ornamental vegetation burning can have an impact on structures.

According to that, fire-resistant species should have three main characteristics to guarantee low fire hazard at the microscale level:

- Low flammability according to laboratory tests and low flammability at the clustering level (i.e. at real scale, integrated with other gardening elements).
- Low maintenance requirements. This is of special concern in second residences, where maintenance is usually performed scattered in time. Low maintenance species do not easily die, accumulate dead fuels or generate fuel beds under the canopy.
- Resistance against the drought, being able to store moisture even after long periods without water.

Table 10 gathers some species that generally meet this requirements. They have been selected from several sources, including WUI design guidelines and research papers (White & Zipperer, 2010; FireSmart, 2013; Ganteaume et al., 2013; Dalmau-Rovira et al., 2019). Species gathered in this table must not be considered as an ultimate list, but as an indicative one. Furthermore, while some species are adapted and fire-resistant in some regions, in others regions with different conditions and environments could present lower performance. It is thus important to use species adapted to local conditions.

Table 10: List of some species recommended for gardening in the WUI. If not the species but the genus is specified, then the genus is recommended. In this case, in the common name column an example of possible species is given; (a.o.) stands for “Among others” and indicates that there are more species of the genus recommended. (f) fruit tree; (h) valid for hedgerows; c: climbing plant valid for fences.

Scientific name	Common name	Characteristics (to be remarked)
<i>Acer</i> spp.	Maple (a.o.)	
<i>Alnus</i> spp.	Alder (a.o.)	
<i>Aloe</i> spp.	Aloe	
<i>Atriplex halimus</i>	Mediterranean saltbush	
<i>Betula</i> spp.	Birch (a.o.)	
<i>Ceanothus</i> spp.	Buckbrush (a.o.)	
<i>Celtis</i> spp.	Mediterranean hackberry (a.o.)	
<i>Chaenomeles japonica</i>	Japanese quince	
<i>Citrus</i> spp.	Orange and lemon (a.o.)	f,h
<i>Eleagnus angustifolia</i>	Russian olive	
<i>Fagus sylvatica</i>	European geech	
<i>Fraxinus</i> spp.	Ash (a.o.)	
<i>Ginkgo biloba</i>	Ginkgo	
<i>Ipomea</i> spp.	Morning glory (a.o.)	c
<i>Juglans regia</i>	Persian walnut	f
<i>Larix</i> spp.	Larch (a.o.)	
<i>Ligustrum lucidum</i>	Chinese privet	
<i>Lonicera japonica</i>	Japanese honeysuckle	c
<i>Morus alba</i>	white mulberry	
<i>Nerium oleander</i>	Oleander	h
<i>Olea europaea</i>	Olive	f,h
<i>Pistacia lentiscus</i>	Chios	
<i>Pittosporum tobira</i>	Japanese pittosporum	h
<i>Plumbago auriculata</i>	Plumbago	c
<i>Populus</i> spp.	Poplar (a.o.)	
<i>Prunus</i> spp.	Cherry laurel (a.o.)	f,h
<i>Pyracantha coccinea</i>	Scarlet firethorn	h
<i>Rhagodia spinescens</i>	Spiny Saltbush	
<i>Rosa</i> spp.	Dog rose (a.o.)	c
<i>Solanum jasminoides</i>	Potato vine	c
<i>Tamarix</i> spp.	Tamarisk (a.o.)	h
<i>Teucrium</i> spp.	Wall germander (a.o)	

4.7. Fire hazard on hedgerows

Hedgerows are commonly used in gardening because of their aesthetic value and their capacity to give privacy acting as *green walls* around properties. However, this gardening element may play a double role in case of fire: i) like any other vegetation, once a hedgerow is burning, it acts as a heat source that helps fire to spread to nearby fuels and to break into the structures and ii) its systematic use by owners promote fire percolation, connecting distant places of the WUI. In this section, fire hazard of hedgerows will be analyzed from these two points of view.

4.7.1. Idealized Scenarios - experimental design

To study fire propagation characteristics in hedgerows, simulations with FDS have been set under calm and windy conditions. The hedgerow simulated is linear, with a rectangular cross-section artificially-shaped area, as in common WUI settlements (e.g. Figure 78).



Figure 78: Burning hedgerow in a WUI fire. Source: Bombers de la Generalitat de Catalunya.

4.7.2. Materials and fire characterization

Following the pattern scenarios stated in the WUIVIEW Deliverable 5.1, a hedgerow ranked as type B has been simulated and studied. It consists on a shaped hedgerow of *Cupressus arizonica* with a cross-sectional area of 0.6 m wide by 1.50 m high. The characteristics and burning behaviour of the fuel have been adjusted following observations from WP2 experiments (D2.1). Allometry has been set according to data recorded in the WUIVIEW Technical Note 2.3. The fuel has been represented in FDS with a cloud of particles that follows the distribution in diameter and physiological state of the tissues stated in the WUIVIEW Deliverable 3.1. The bulk density of the live particles is 12.94 kg/m^3 , while the one for the dead wood is 4.1 kg/m^3 . The ignition has been set with a burning ground surface at one end of the domain.

4.7.3. Simulations set-up

The simulations consisted in an outstretched environment, wide and high enough to allow the entrance of air from the outside of the domain and to avoid interferences between the borders of the domain and the flame. This resulted in a $9 \times 2.6 \times 8 \text{ m}^3$ domain composed by cubic cells of 0.05^3 m^3 in volume. The wind vectors in the windy simulation were aligned with the longitudinal axis of the hedgerow, with a vertical wind profile following the Monin-Obukhov similarity theory for stable conditions and a roughness of 0.5 m, typical of WUI environments. The reference wind was of 20 km/h at a height of 10 meters. HRR and a profile of the temperatures in the longitudinal axis have been obtained as outputs. Figure 79 shows a scheme of the simulated scenario.

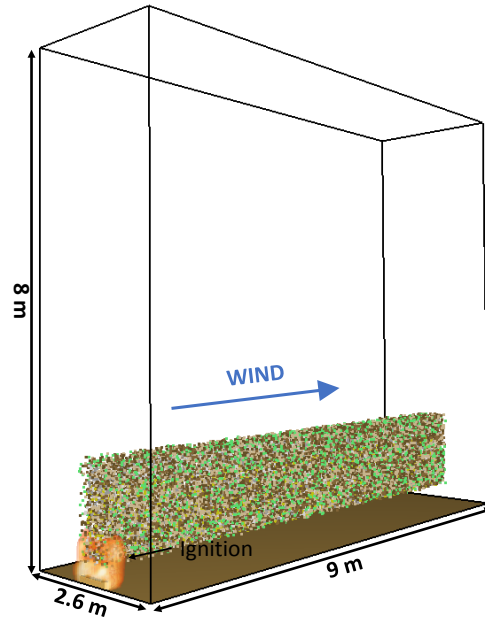


Figure 79: Scenario set in FDS

4.7.4. Results and discussion

FDS has been used to evaluate the rate of spread and the HRR of a flame front in a hedgerow (Figure 80 - Figure 82). As can be seen in Figure 80, the HRR raises during the first minute in both simulations, reaching a peak of about 4000 and 4500 kW for the simulations with calm and windy conditions, respectively. After this peak, the HRR decreases until the stabilization of the rate of spread is achieved, around 100 seconds after the ignition. In this period the HRR ranges between 2500 and 3000 kW for the simulation in calm conditions and between 3000 and 3500 kW for the simulation with windy conditions. After approximately 200 seconds, the tilted flame of the simulation with wind starts to interact with the border of the domain. Representative steady-state data is hence considered to be comprised between 100 and 200 seconds of the simulation.

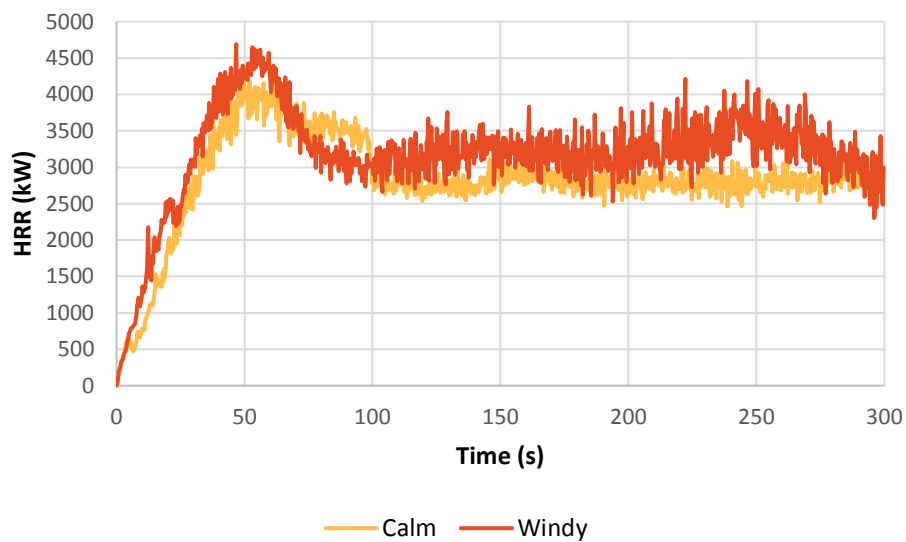


Figure 80: Heat Release Rate (kW) emitted by the burning hedgerows under calm and windy conditions.

These differences in the HRR are due to the different rate of spread of the fire front in both scenarios: under calm conditions, the flame front spreads slower than with the wind pushing the flame. In the absence of wind, the fire front spreads at 1.5 m/min, generating straight flames that raise 6.5 meters above the hedgerow. On the other hand, the rate of spread of the fire front pushed by the wind raises up to 1.85 m/min, with a flame length of 5 meters from the top of the hedgerow, tilted 45°. It is worth to note that the cloud of fuel particles set in these simulations with FDS remain after the passage of the fire front (composed now by unburned fuels, char and ashes), maintaining their capacity to act as obstacles against the wind force. However, in real burning experiments, thinner fuels were observed falling down or being dragged by the convective effect of the smoke plume. This means that in real conditions, the wind might encounter a lower amount of obstacles, having more capacity to push the flame leading to an increase of the expected rate of spread.

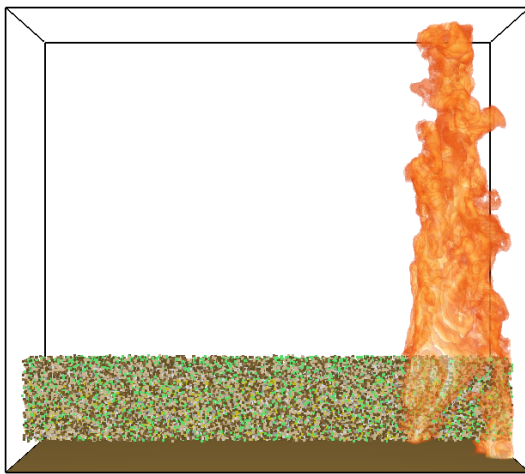


Figure 81: Simulation with calm conditions

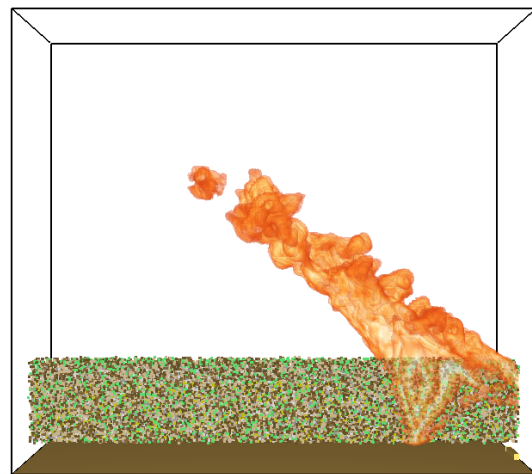


Figure 82: Simulation with windy conditions

Many species commonly used to grow hedgerows trend to store fine dead fuels when they are shaped (Fernandes & Cruz, 2012) (e.g. *Cupressus* spp., *Cupressocyparis* spp., *Thuja* spp., etc), helping fire propagation (Ryu et al., 2006) as seen in our simulations. As such, these can hardly match with the fire-resistance conditions set in the Section 4.6. Because of this, it is key to isolate them, to prevent their ignition and to impede their role as ignitors (cleaning periodically fine fuels from the ground, ensuring safety distances with other fuels and removing overhanging branches). Furthermore, it is necessary to limit the horizontal continuity by creating interruptions which will hamper fire spread. For this purpose, it could be helpful to profit existing elements in the property, such as doors or walls, to separate sections of a hedgerow.

In addition, our results show how the wind can dangerously push the fire front. It is key to avoid hedgerows aligned with frequent or strong winds and steep slopes. In general, hedgerows are not specifically referred in WUI guidelines despite its proved fire hazard. Just some standards mention in general terms the need to avoid the alignment of the vegetation with main winds.

Regarding the species, some of these guidelines and recommendations offer a list of fire-resistant species, some of which can be used to conform hedgerows, as seen in section 4.6.3. As mentioned before, flammability (understood as real fire behavior) of hedgerows has to be analysed at real scale, to account for all the properties playing a key role on fire dynamics.

4.8. Vulnerability to wildfire exposure

Knowledge of the geometry and other characteristics of fire fronts allows us to analyze the WUI fire problem from a physically-based perspective, evaluating the radiative and convective heat fluxes. Radiative heat fluxes can be relatively easily calculated by applying the Solid Flame Model (Eisenberg et al., 1975), which is a physical model frequently implemented with complementary empirical and semi-empirical sub-models, as well as considering some simplifications (e.g. Australian Standard 3959, 2009; Zarate et al., 2008; Rossi et al., 2011). Convective heat fluxes however involve complex mechanisms hard to model. This is why its calculation is usually performed by means of CFD simulation techniques and tools (Zykanov, 2019) such as FDS software (Mell et al., 2009). CFD tools have a high potential when estimating the wildfire exposure at the WUI. However, the large computational cost and the complexity of the inputs needed by these simulators could limit their use. However, the farther a structure is from the fire, the lower the effect of convective heating. In previous sections, FDS has been used to evaluate the fire hazard and related vulnerability at short distances (e.g. effect of ornamental vegetation or fuel packages burning close to the dwellings). If the rings around the structure are managed and maintained according to our results and recommendations, flame impingement and convective heating due to fuels burning close to the structure will be avoided in most situations.

In this section, Radiant Heat Flux (RHF) exposure of WUI structures caused by the vicinity to a wildfire has been estimated by the Solid Flame Model. Simplified scenarios have been simulated to showcase the potential of this method to assess safety distances and foresee consequences for abnormal heat radiation to people and assets.

4.8.1. Idealized Scenarios

The scenarios defined in this section deal with the wildfire exposure from a simplified point of view. The wildfire is represented by a static fire front that is burning at the edge of the WUI, i.e. the external limit of the fuel-managed area that usually surrounds the settlement. The RHF calculations allow predicting the wildfire exposure for different widths of these fuel-managed areas. Here the RHF has been calculated for 36 different scenarios that differ in their slope, wind speed, flame tilt angle and fuel model (see Table 11). All scenarios share the same ambient conditions (30°C and 30% RH) and a 100 meters long fire front, with a flame temperature of 817 °C and an emissivity of 0.95 (as established by the Australian Standard 3959, 2009). A general scheme of the scenarios can be seen in Figure 83. A representative flame length and fire front intensity for each fuel type have been extracted from the valid range of the models presented in Alexandre & Cruz (2012), specifically from Clark (1983) for grasslands, Catchpole et al. (1998) for shrublands and Butler et al. (2004) for crown fires in forests. In order to estimate a Thermal Heat Dose (THD; Purser & McAllister, 2016) received in the WUI, the residence times set in Alexander et al. (2007) for grasslands (10 s), shrublands (20 s) and forest stands (45 s) have been used.

Table 11: Fire scenarios for wildfire exposure

Variable	Units	Option 1	Option 2	Option 3
Fuel type	-	Grassland	Shrubland	Forest
Residence time	[s]	10	20	45
Flame length	[m]	3	5	20
Fire front intensity	[kW/m]	4515	8100	38550
Distance to the structure	[m]	10	30	50
Slope	[deg ₃₆₀]	0	15	30
Wind Speed _{10m}	[m/s]	0	4.5	9
	[km/h]	0	16.2	32.4

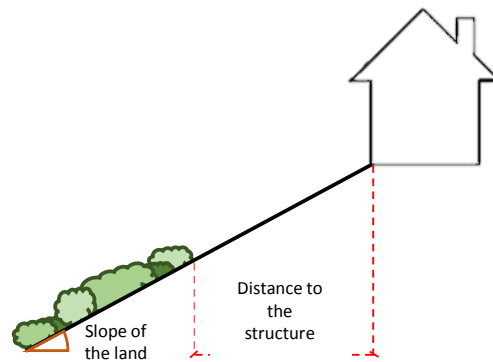


Figure 83: Schematic scenario for wildfire exposure

4.8.2. Solid Flame Model

The radiant heat flux has been calculated here with the Solid Flame Model tool developed in Muñoz et al. (2019). The flame tilt angle has been determined from the equilibrium between the wind drag force, using a wind velocity power profile with a Hellman's exponent of 0.3, and the flame buoyant force (Nelson et al., 2012). Besides, a set of 'worst case scenarios' have been calculated. In these worst case scenarios the wind speed is not used to estimate the flame tilt angle, instead the angle that maximizes the RHF is directly used for each distance. The atmospheric transmissivity has been determined using the model from Bagster & Pittbaldo (1989). The Thermal Heat Dose has been later calculated according to (Eq. 4.4).

$$THD = RHF^4 \cdot t_r \quad (\text{Eq. 4.4})$$

4.8.3. Results and discussion

The radiant heat fluxes for the different scenarios evaluated can be seen in Figure 84 and in Figure 85. The prescribed flames have an emissive power of 75 kW/m² approximately, because all the flames have identical temperature and emissivity, independently of the scenario evaluated. This is therefore the radiant energy received by a structure if the flames impinge on its walls (i.e. the view factor will be equal to one and a null amount of energy will be absorbed by the atmosphere). If the WUI is surrounded by fuel-managed areas that avoid flame

impingement, the RHF received by the structures is lower as the fuel-managed area is wider, being a function of this distance, the flame geometry and the slope of the terrain.

As explained, if the prescribed flame is in contact with the structure, the RHF is equal to the emissive power. Just when the flame is not in direct contact with the structure, the RHF starts to decrease. For instance, in the absence of wind, the flames are expected to stay completely straight and the RHF starts to decrease immediately with increasing the distance. On the other hand, if a strong wind pushes a 3 meters length flame against the ground, the RHF will start to decrease only for fuel-managed areas wider than 3 meters. Flames with large tilt angles (Table 12) and large lengths will remain in contact with the structure more easily, and thus the modelled RHF will need wider fuel-managed areas to start to decrease. Steeper slopes will shield the structure from the flame, and the RHF will be lower.

Table 12: Flame Tilt Angles (deg_{360}) expected for the different scenarios (fuel types, wind speeds and slopes). The values are set from the surface of the terrain. WCS: Worst Case Scenario.

Fuel type	Grassland			Shrubland			Forest			
	Wind Speed [m/s]	0	4.5	9	0	4.5	9	0	4.5	9
Slope [deg_{360}]	0	90	59	52	90	61	53	90	65	55
	15	75	44	37	75	46	38	75	50	40
	30	60	29	22	60	31	23	60	35	25
	WCS	Variable			Variable			Variable		

It is worth to note that, while this model takes into account the direct flame contact solely from a geometrical perspective, it does not take into account the convective heating that occur when there is flame impingement. The Australian Standard 3959 (2009) estimates that this convective heating might occur when the RHF is over the 40 kW/m² threshold (i.e. considered in this section as the flame impingement threshold).

As it can be seen in Figure 84 and Figure 85, 10 meters seem to be enough distance to avoid flame impingement for grasslands and shrublands, even in the worst case scenarios. However, this 10 meters safety distance could not be enough to avoid convective heating in case of crown fires. Nonetheless, with 20 meters of safety distance the RHF goes under the 40 kW/m² threshold in all the scenarios.

Flame impingement over the structure must not be the only parameter to evaluate the wildfire exposure danger. It is also necessary to take into account that the RHF may produce ignitions (e.g. in polymers or in wooden elements) even with no flame contact. It is thus important to know which constructive materials are facing the fire front in the structure. It is also important to take into account the presence of inhabitants or firefighters during the design of the fuel managed area. Table 13 shows values of RHF that are able to lead into ignitions or injuries. As it can be seen, a RHF of 10 kW/m² is able to ignite certain polymers and wooden elements if there are pilot flames, like flaming embers. 12.5 kW/m² seem to be enough to ignite some wooden materials without any pilot flame. Looking at these RHF thresholds, a safety distance of 10 meters seems to be enough to prevent ignitions in grassland fires, while safety distance should be enlarged up to 20 and 50 meters in case of shrubland and crown fires, respectively. According to this results, in line with other research and guidelines (e.g. Zarate et al. 2008, Rossi et al. 2011, Cordier & Prin-Derre. 2017) it can thus be recommended that the safety distances should be enlarged beyond 30 meters.

Table 13: Effect of different Radiant Heat Fluxes (RHF) for different flame residence times (t_r) and subsequent Thermal Heat Dose (THD). Long exposure times have been denoted with “-”.

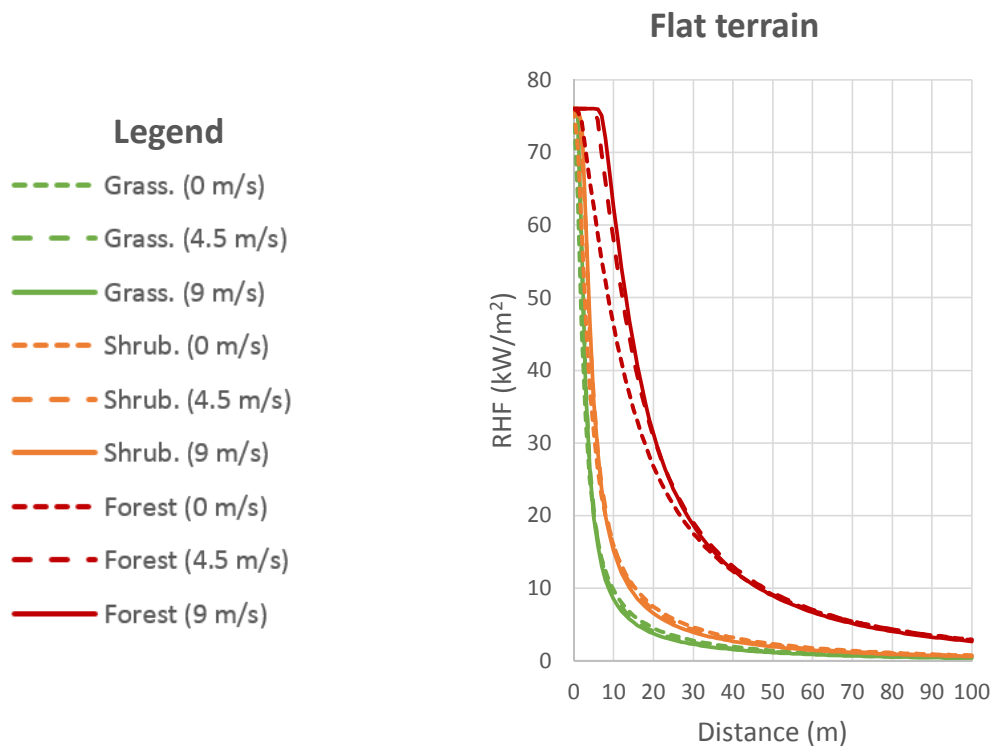
Target	RHF [kW/m ²]	t_r [s]	THD [(kW/m ²) ^{4/3} .s]	Expected consequences	Source
Human	1.4	-	-	Harmless	Casal (2018)
	1.7	-	-	Pain threshold	Casal (2018)
	2,1	60	[70 - 160]	Pain in bare skin	Casal (2018)
	4,2	10			Butler et al. (2010)
	4,7	15			Casal (2018)
	6,4	8			Drysdale (2011)
	10	5			Butler et al. (2010)
	10,4	3			Drysdale (2011)
	30	1			Butler et al. (2010)
	4,7	30			[200-240]
	16	5	Stoll (1969)		
	25	10	720	Severe pain in bare skin	Butler et al. (2010)
	30	10	930	Full burn	Butler et al. (2010)
	7	90	1200	Max. tolerable for firefighters	Cohen and Butler (1998)
	25	60	4340	100% fatality	Butler et al. (2010)
Assets	10	-	-	Certain polymers ignite	Zarate et al. (2008)
	10	-	-	Piloted wood ignition	Spearpoint & Quint. (2001)
	12.5	(long exposure)-	-	Unpiloted wood ignition	Casal (2018)
	15	-	-	Ignition of polyester	Mouritz (2007)
	25	-	-	Ignition of phenolic laminate	Mouritz (2007)
	45	20	3200	Unpiloted wood ignition	Cohen and Butler (1998)

In some cases however, these thresholds for certain expected consequences have been determined after long exposure times (i.e. large flame residence times). Despite long exposure times could be expected with some heavy fuels common in the WUI (e.g. logging slash, firewood piles, vehicles, furniture or dwellings), natural fuels surrounding the WUI are expected to burn no longer than 45 seconds (Table 11). It is thus necessary to evaluate the safety distance taking into account both data, the RHF and the expected residence time. Nonetheless, this is not an easy task, because ignition time varies not only with RHF but also with other variables related to the receiving element characteristics (Lin et al., 2019) and, there is very few data available in the literature. As an example, available data show that wood can be ignited without pilot flame for long exposures to a RHF of 12.5 kW/m² while for RHF of 45 kW/m², it just needs around 20 seconds to ignite. However, the required time to ignite is missing for intermediate values of RHF. One possible solution to deal with this lack of data is the Thermal Heat Dose (THD) concept, which merges RHF and residence time in a single value. Despite this is a useful concept, it must be used just as an indicative value.

Figure 86 shows the expected Thermal Heat Dose for the scenarios analyzed in this section. Indicative THD ignition thresholds of 10000 and 20000 (kW/m²)^{4/3}.s have been estimated by Zhou & Fernandez-Pello (2000) and Lin et al. (2019) for composite materials and piloted wood respectively. Considering these thresholds, neither the grassland scenarios nor the shrubland

ones might produce ignitions by radiation in the dwellings. In the crown fire scenarios, ignitions could be expected by radiation in composite materials of the dwelling for safety distances lower than 13 meters, while no ignitions are expected in the wooden materials just by radiation.

As a conclusion, the lower limit value of 30 meters width fuel-managed areas explained in Section 4.6 is expected to be enough to prevent ignitions by radiant heat fluxes in the WUI in case of wildfire exposure if proper fuel treatments have been performed. However, these safety distances could not be enough if the presence of inhabitants or firefighters is expected. Furthermore, while these safety distances seem to be enough for natural fuels exhibiting flames no taller than 20 m and with residence times no longer than 45 s, conditions leading to taller and more persistent flames (presence of heavy fuels, very tall trees with high crown bulk densities, etc.) could pose additional risk of ignitions. For this reason, a general recommendation extracted from past section 4.6 and the present section is to leave a fuel managed area of 50 m, to guarantee assets and peoples safety in a larger variety of conditions.



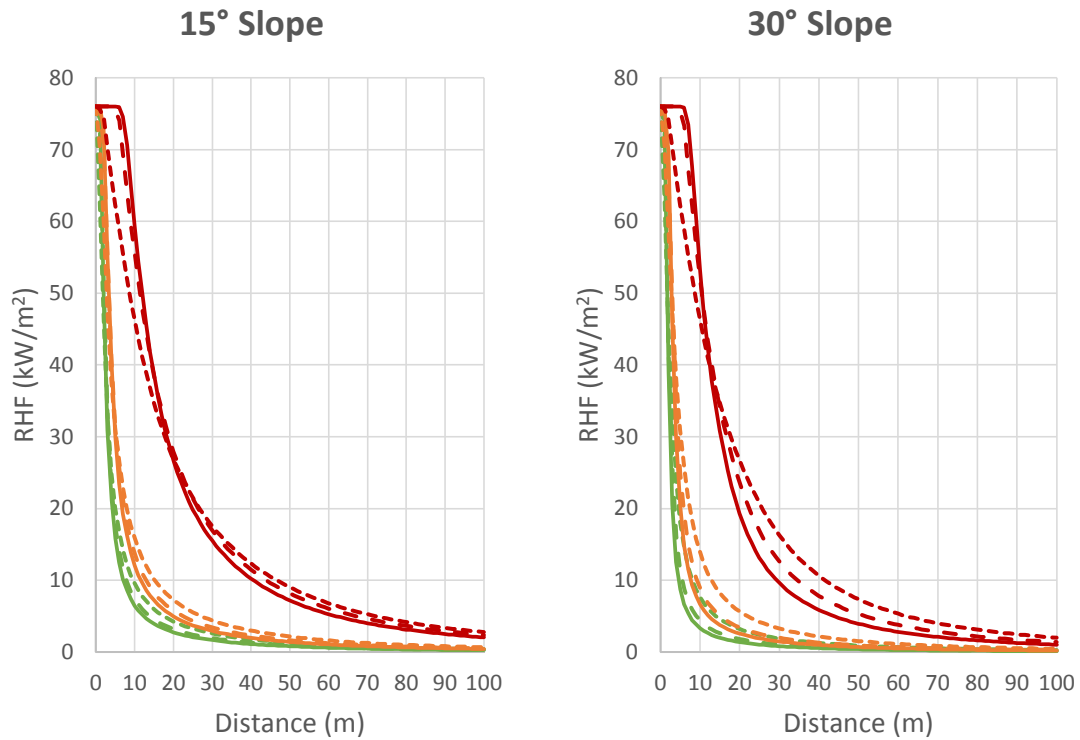


Figure 84: Radiant Heat Fluxes expected as a function of the distance from the dwellings for different fuel models (Grasslands, Shrublands and Forests), wind speeds (0, 4.5 and 9 m/s) and slopes (0°, 15° and 30°).

Worst case scenario

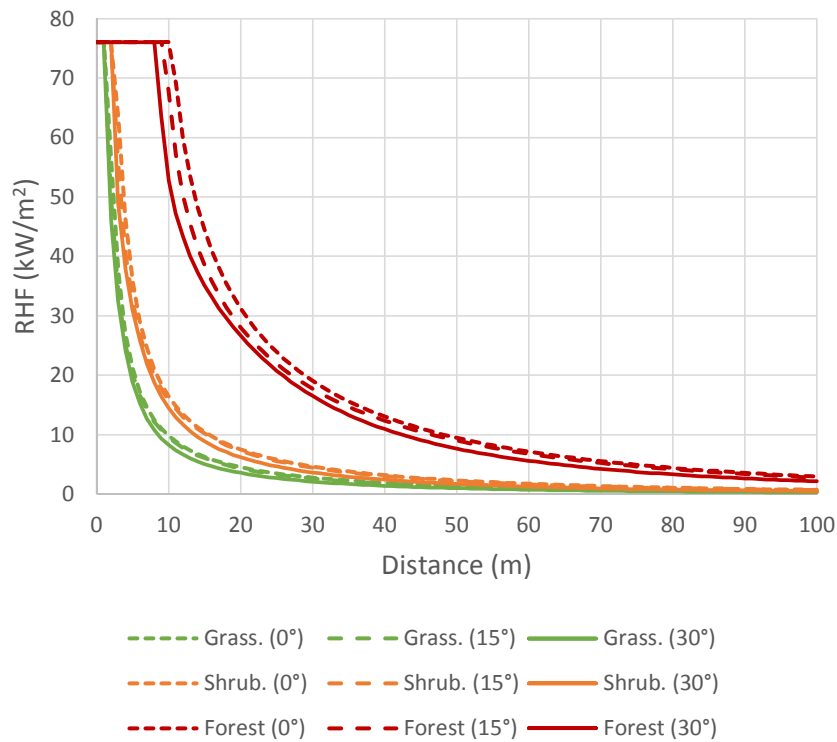


Figure 85: Radiant Heat Fluxes expected as a function of the distance from the dwellings for different fuel models (Grasslands, Shrublands and Forests) and slopes (0°, 15° and 30°). The flame tilt angle has been adjusted to obtain the worst-possible radiant heat fluxes.

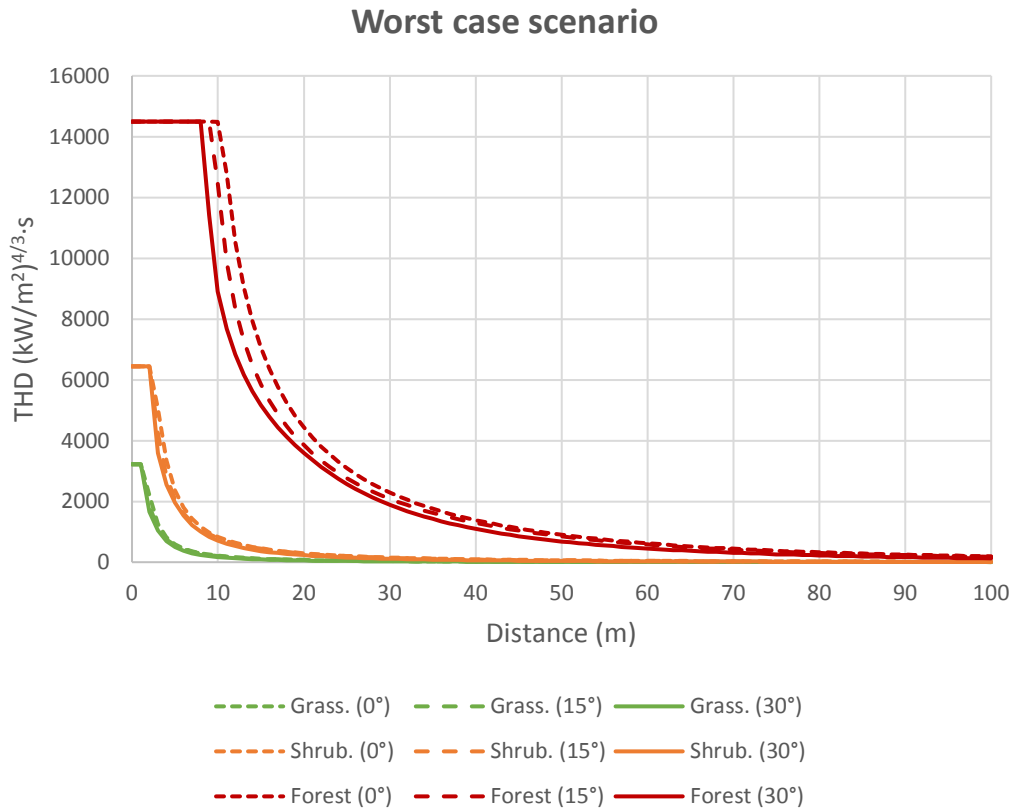


Figure 86: Thermal Heat Dose expected as a function of the distance from the dwellings for different fuel models (Grasslands, Shrublands and Forests) and slopes (0°, 15° and 30°). The flame tilt angle has been adjusted to obtain the worst-possible Thermal Heat Dose.

4.9. Summary of recommendations for structure survivability

This section summarizes the main points, previously analysed, that must be followed to maximize a structure's survivability at the WUI homeowner scale, and that will be the base of our **Structure Vulnerability Assessment Tool (VAT)**, detailed in ANNEX A. Here it is important to take into account not just the structure itself but also its surrounding elements (e.g. wildland vegetation, ornamental fuels, non-natural fuels, LPG tanks, etc).

Regarding the constructive characteristics of the structure and its maintenance:

- Prefer smaller windows to large ones, since they can resist better against incoming radiation or flame impingement. Frame materials with a high melting point, such as aluminium, should be preferred to plastic materials such as uPVC.
- Double or multi-pane glazing systems are better suited to withstand the radiation or flame impingement coming from a fire. Glass thickness of 6 mm is advised.
- Shutters made out of wood or aluminium can protect glazing systems from breaking in case of fire. uPVC shutters are not advised, since they will melt and expose the window to the incoming fire.
- Semi-confined spaces used as storage areas should be independent from the frame of the main building, in order to avoid causing its structural failure. No items should be stored under overhangs of the main building.

- The roof and its accessory elements must be built with fire-resistant materials and with shapes that hinder the accumulation of debris and firebrands. Roofs must be able to face direct flame contact and firebrand showers.
- To ensure an adequate maintenance, the roof and its accessory elements must be periodically cleaned of flammable debris. Furthermore, a proper maintenance of the roof must be periodically scheduled to ensure that there are no new flaws that could weaken it (e.g. broken tiles, fissures, etc.).
- To prevent inner ignitions by firebrand activity, all the vents and gaps must be sealed with a suitable technique (e.g. covered with adequate meshes or clogged with non-combustible materials).

Regarding the surroundings of the dwellings, it is necessary to manage the hazardous fuels around the structure to minimize risk:

- There cannot be vegetation over the roof or very close to the building. Ornamental vegetation (preferable fire-resistant) should be located at least 4 m from any glazing system.
- Fuels which have the potential to burn for longer than 5 minutes (usually artificial fuels) should be placed at least 5 m from any glazing system.
- Combustible materials should not be stored under overhangs, since combustion of these materials might cause structural failure.
- The distance between an LPG tank of 1 m³ and any type of fuel should be at least 2 m.
- Fire-resistant species must be prioritized in the closest ring around the dwellings (approx. 10 meters around the structures), avoiding fuel continuity in the litter layer.
- In the outer ring, it is necessary to i) ensure a low surface fuel load (Max. 10 cm in depth), ii) separate trees so that the crowns are distanced 6 meters and separate the base of the crown from the ground fuels at least 2 m. 50-m radius of the outer ring is recommended, particularly if the structure is on slope and wind is frequent.
- Hedgerows must be isolated from the surrounding vegetation and periodically cleaned from ground fuels. If aligned with the main wind or slope, hedgerows should be substituted by low-flammable species if possible or their horizontal continuity must be interrupted to avoid long fire runs.

5. Sheltering capacity analysis

It has already been stressed that when threatened by a wildfire progressing towards a WUI area, the safest option is an early evacuation. However, several factors may avert people from evacuating safely (late awareness, traffic jams, etc.). It is under these circumstances that sheltering in place may be an option.

In this section, a preliminary review of fire and smoke hazards is provided together with the performance criteria established in the scientific literature for tenability and survivability conditions in case of sheltering. Following, the methods and rationale to assess sheltering capabilities of dwellings by means of CFD simulations are summarized. Results from simulations are discussed and distilled into basic recommendations that have been gathered within a form of a checklist as a Sheltering Assessment Tool (See Annex B).

5.1. Fire and smoke hazards

Fire effluents consist of a highly complex mixture of liquid and solid smoke particulates and vapors, many of which are toxic (SFPE, 2016). The production of toxic substances depends on the composition of the burning fuel and the decomposition conditions (SFPE, 2016). Toxic substances can affect human health instantaneously, after a short period or after a long period of exposure. In this work, the toxicological hazard assessment focuses only on the sheltering period.

The toxic potency of a substance depends on the amount needed to impair a given toxic effect. Two major types of incapacitating effects are considered in fires (SFPE, 2016):

1. *Incapacitating effects due to irritant fire products*

Two effects of irritants are identified: sensory irritation (painful effects to the eyes and upper respiratory tract) and acute pulmonary irritant response (potential for edema and lung inflammation). For sensory irritation the effects do not depend on an accumulated exposure dose (i.e. the integrated area under each concentration-time curve) but occur immediately on exposure. On the contrary, irritants likely to cause death through lung edema and inflammation after the fire depend on the accumulated exposure dose. They are not normally expected to have a direct impact on tenability (ISO, 2012) because their effects can be observed several days after exposure.

The most important irritants are hydrogen fluoride, hydrogen chloride, hydrogen bromide, nitrogen oxides, phosphoric acid, sulfur dioxide, acrolein and formaldehyde (SFPE, 2016).

2. *Incapacitating effects due to asphyxiant fire products*

An important aspect that needs to be considered for asphyxiant gases is the time when a sufficient exposure dose has been inhaled to cause incapacitation through confusion and loss of consciousness. The most important gases causing asphyxiation are carbon monoxide, hydrogen cyanide, and reduced oxygen concentration. Carbon dioxide is important mainly because it increases the rate of uptake of CO and HCN (SFPE, 2016).

Interactions between individual asphyxiant gases or between asphyxiants and irritants are normally considered to be approximately additive (SFPE, 2016).

Fire victims are also exposed to heat leading to incapacitation and death, and the most important sources of heat exposure are radiation from hot areas and convection from hot gases. There are three basic ways in which fire victims are exposed to heat: (1) hyperthermia, (2) body surface burns, and (3) respiratory tract burns.

Performance criteria

Performance criteria within a shelter during a WUI fire may be based on two considerations (Brown et al., 2003):

- Tenability – people sheltering are able to occupy the house during the passage of the fire front, and also after the fire front has passed if surrounding elements burn in the vicinity of the house (consequential fire), without experiencing non-tolerable irritation, significant loss of alertness, or irreversible health effects.
- Survivability – people sheltering are able to occupy the house during the passage of the fire front, and also after the fire front has passed if fires in adjacent structure or heavy fuels occur, without loss of consciousness or loss of life.

Provision of tenable conditions within a shelter for people exposed to fire or fire products during shelter-in-place practice have been selected in two areas: 1) thermal effects to people (e.g. exposure to high gas temperatures or thermal radiation); 2) toxicity of fire products. The “visibility through smoke” criterion, normally used in compartment fires, has not been considered in this study because it is assumed that occupants know well the structure of the house. Although performance criteria might vary depending on the physical and mental conditions of the occupants, in this work only length of exposure has been considered.

At temperatures below 120°C tolerance is limited by hyperthermia, whereas above this temperature pain followed by burns become important (SFPE, 2016). Pain from the application of heat to the skin occurs when the skin temperature at a depth of 0.1 mm reaches 44.8°C (SFPE, 2016). For the design and construction of private shelters (ABCB, 2014), a maximum interior air temperature of 45°C has been established to set a tenable environment within a shelter. Also, a maximum 70°C has been set for interior walls which occupants would be able to touch.

Superficial 2nd degree burns vary according to two skin properties: initial skin temperature and epidermal thickness. There exist a critical radiant heat flux (1.7 kW/m²) below which no pain would be experienced, no matter the time duration.

The ‘fractional effective dose’ (FED) concept is normally used to calculate the length of time an individual can be exposed to a particular toxicant before succumbing to its effects. The dose of gas inhaled is calculated as the product of concentration (C) and time (t); then, FED is expressed as shown in Eq. 5:

$$FED = \frac{\text{Dose received at time } t}{\text{Effective dose to cause incapacitation or death}} \quad (5)$$

Sensory irritation is a toxic effect that depends on the immediate concentration of an irritant to which a subject is exposed, rather than the dose. So the concept of fractional irritant concentration (FIC) is used (Eq. 6).

$$FIC = \frac{\text{Concentration of irritant to which subject is exposed at time } t}{\text{Concentration of irritant required to cause impairment of escape efficiency,}} \quad (6)$$

So, time to loss of tenability from the effects of toxic gases is calculated as the time at which the 'fractional effective dose' or 'fractional irritant concentration' reach a value of 1.

5.2. Methodology and rationale

Our attempt to evaluate the sheltering capacity was performed using a particular dwelling and the Fire Dynamics Simulator (FDS), as in the above mentioned studies dealing with structure survivability. The visualization program that is used to display the output of FDS, Smokeview, was also employed. According to the authors' knowledge, a similar approach has not been done before.

Linear and static flame fronts located 10 m or 5 m away from the house were simulated. The house was set open (i.e. most of the windows were open and inside doors too) or completely closed (i.e. all the windows were closed, but inside doors were kept open).

We took only into account the possibility of reaching untenable conditions inside a particular house due to toxic gases and/or thermal effects derived from radiative heat transfer. Only radiative heat transfer was considered because databases and equations derived over the years to evaluate human injury due to thermal effects consider only radiation hazards (SFPE, 2016).

Potential ignitions of material around the house or inside the house were not considered. Therefore, pollutants resulting from the combustion of structural material were not taken into account, although some of them (e.g. HCl, acrolein) could potentially impair the judgement and behavior of residents (Blanchi et al., 2012).

The specific objectives of this work include the detailed analysis of the following points: temporal evolution of thermal and toxic conditions within the house; differences between individual rooms; differences due to fireline position; and differences between open and closed house.

5.2.1. Model

Ambient conditions

An ambient temperature of 30°C has been set to simulate more realistically common ambient conditions registered during wildfires. Wind velocity has been set at 4.55 m/s at 10 m height, similar to the wind velocity registered during the wildfire that impacted on the house used here (see subsection *House*).

As in simulation studies reported in section 4, a wind profile has been defined in FDS following the Monin-Obukhov similarity theory. Here a neutral stability has been considered, which corresponds to $L = 10^6$. Moreover, the aerodynamic roughness length has been taken $z_0 = 0.5$, corresponding to a very rough terrain, such as one having mixed farm fields and forest clumps, orchards and scattered buildings.

Domain

The dimensions of the simulation were: 30 m x 29.2 m x 30 m. Thus, the simulated domain covered a volume of 262800 m³. Twenty-one meshes were defined within the domain and the cell size was set uniform within each one. The smallest cell size (cubic; 0.2 m) was used in those meshes that included the fire front and the house. The rest of the meshes had a cell size of 0.4 m (Figure 87).

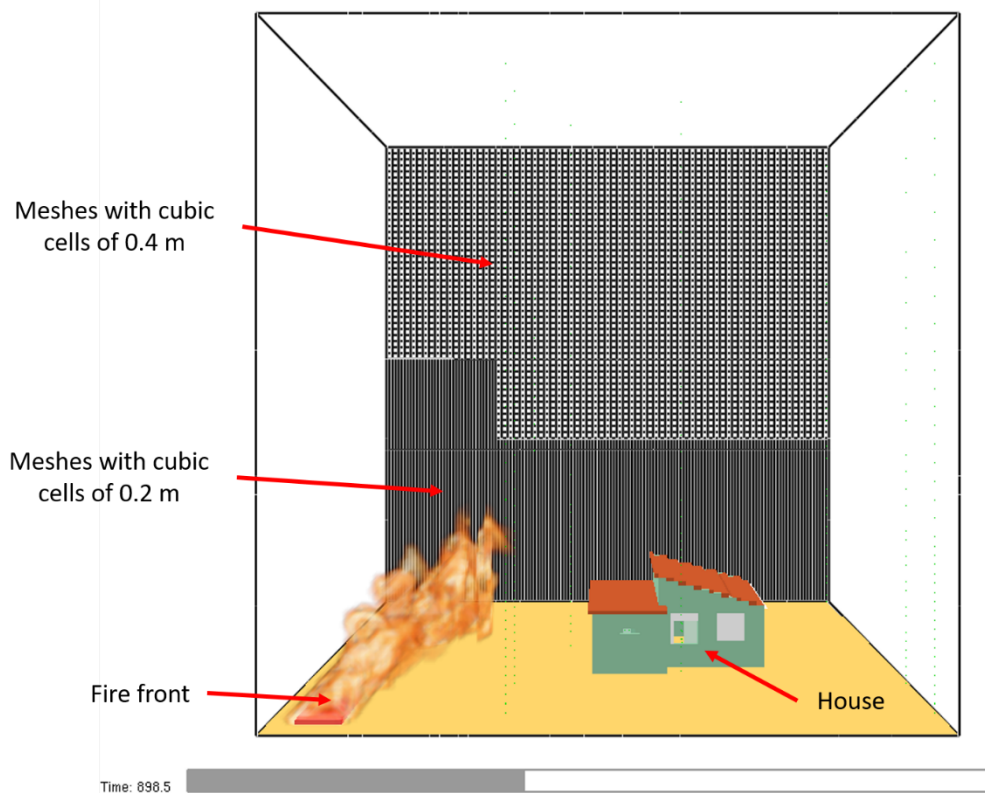


Figure 87. Main elements of the simulation performed considering a distance of 10 m between the fire front and the open house. The domain is discretized using several meshes of 0.4 m and 0.2 m cubic cells.

House

Dimensions and construction design of the dwelling (Figure 88) corresponded to those of a real house that received the impact of a wildland fire in 2015 in Òdena, Catalonia, Spain. This construction was modelled to be used with FDS in a previous work (Fanlo, 2016). It had one habitable story, it was built with air-bricks and had an area of about 67 m².

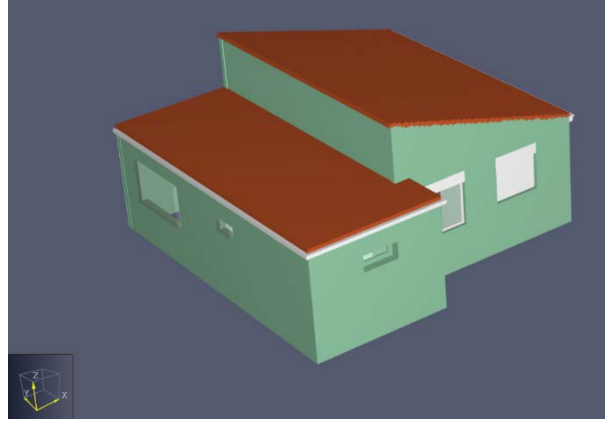


Figure 88. The house selected for the simulations.

The distribution of rooms, windows and doors is shown in Figure 89. Only two of the seven windows of the house were set to be closed in the simulations that we identify as “open house simulations”. The other windows were open, as well as the door located on the right side according to Figure 89. All internal doors were also set open.

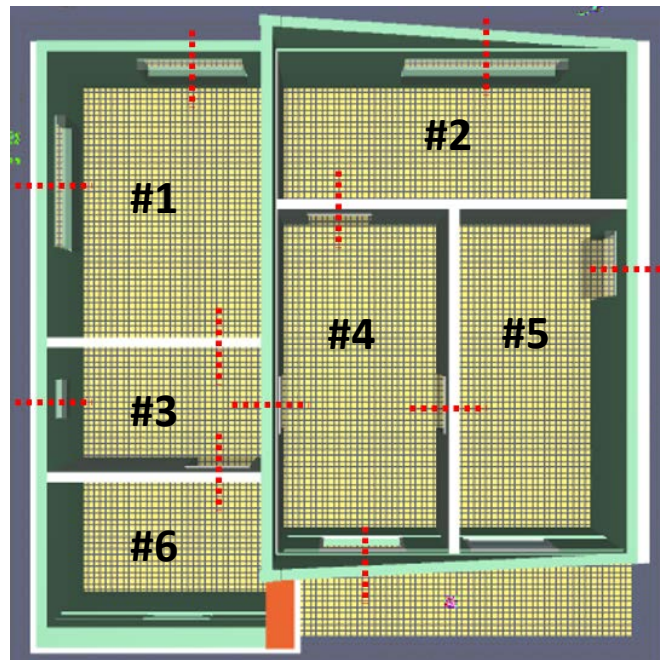


Figure 89. Top view of the distribution of rooms, windows and doors. Dashed red lines indicate which openings were left completely open. Rooms are numbered from #1 (top-left) to #6 (bottom-left).

The simulation performed considering a closed house was set by including shutters and a dual-pane glass on each open window of the house. A wooden door was also included. No air change ratio was taken into account in this scenario. Although in reality it is difficult to fulfill this condition, we wanted to test an extreme situation in terms of sheltering.

If an air change (ACH) value were considered, an equivalent air leakage area would be calculated according to Eq.7.

$$A_L = Q_r \frac{\sqrt{\rho/2\Delta p_r}}{C_D} = V_{house} \cdot ACH_{\Delta p_r} \frac{\sqrt{\rho/2\Delta p_r}}{C_D} \quad (7)$$

Where: A_L = equivalent air leakage area (m^2); Q_r = predicted airflow rate (m^3/s); ρ = air density (kg/m^3); Δp_r = reference pressure difference (Pa); C_D = discharge coefficient; V_{house} = volume of the house; $ACH_{\Delta p_r}$ = air leakage rate at reference pressure.

In this case the calculated area assuming an ACH value of $1 h^{-1}$ is extremely small ($0.0057 m^2$) in comparison with grid cell resolution ($0.2 m$). However, this area could be broken up through the house using several localized leakages and one approach from FDS could be set (i.e. two VENT inputs should be linked via an HVAC input with $TYPE_ID='LEAK'$). The distribution of leakages should be set according to the state of maintenance of the house and some verification analysis should be done against analytical solutions. This approach, however, could not be tested yet.

Fireline

The fire front specified had the following area: $2 m \times 27 m$. It was created by defining a very thin solid obstruction with a heat release rate per unit area (HRRPUA) of $2700 kW/m^2$ and a front temperature of $1000 K$. The HRRPUA ramped up quickly ($1 s$ ramp) once the wind field was stabilized (approximately $250 s$ after the beginning of the simulation).

The HRRPUA value was set based on the works from Nelson and Adkins (1998) and Alexander and Cruz (2019). Nelson and Adkins (1998) concluded that the width of the front from laboratory and field fires driven by wind can be correlated with information on fuel consumption and wind speed by dimensional analysis (Eq. 8):

$$S_f = 0.39 \cdot m_c^{0.25} \cdot u_w^{1.51} \tag{8}$$

Where: S_f stands for the width of the front [m]; m_c stands for the fuel consumption [kg/m^2]; u_w stands for the wind velocity [m/s].

Fireline intensity can be calculated according to Eq. 9, and represents the rate of energy released per unit time and length of fire front [kW/m] (Byram, 1959).

$$I_B = \Delta H \cdot m_c \cdot r \tag{9}$$

Where: I_B stands for fire line intensity [kW/m]; ΔH stands for fuel low heat of combustion [kJ/kg]; m_c stands for the fuel consumption [kg/m^2]; r stands for the linear rate of fire spread [m/s]

If we consider a low fireline intensity for a conifer forest, according to Alexander and Cruz (2019) we can set a fuel consumption value of $m_c = 1.8 kg/m^2$ and a rate of spread of $10 m/min$. Thus, according to Eq. 8, we obtain a width of the front of around $2 m$ (considering a wind velocity of $3 m/s$ at $2 m$ height given that the velocity imposed at a height of $10 m$ is $4.55 m/s$).

The fireline intensity is calculated according to Eq. 9 assuming a net fuel low heat of combustion of $18000 kJ/kg$ (Alexander and Cruz, 2019) ($I_B = 5400 kW/m$). Then, the HRRPUA is calculated considering the dimensions of the front ($2 m \times 27 m$) according to Eq. 10.

$$HRRPUA = \frac{I_B \cdot Length}{Area} = \frac{I_B}{S_f} = \frac{5400}{2} = 2700 \frac{kw}{m^2} \tag{10}$$

Combustion reaction

Wildland fires generate a great number of different species. The characterization of the chemical composition of wildland fire smoke and its quantification through emission factors (EF) (i.e. grams of a gas species produced per unit kilogram of vegetation burned on a dry mass basis) have made considerable progress over the last decade. Since the fundamental review of Andreae and Merlet (2001) many publications have summarized existing EFs by vegetation type or region. Two recent works from Andreae (2019) and Prichard et al. (2020) have been considered in this work.

The work from Prichard et al. (2020) has been used to establish which compounds could affect human health during sheltering-in-place. These authors selected 23 compounds from an online database of existing EFs of 276 known air pollutants (Smoke Emissions Repository Application (SERA) database). These pollutants were selected because they had a minimum of 100 record counts in the database. Most of the 23 air pollutants are designated as EPA criteria air pollutants (CAP), greenhouses gases (GHG), hazardous air pollutants (HAP) or known air toxins (TX).

From the 23 compounds listed by Prichard et al. (2020), nine were selected in this work considering their toxicity to human health (e.g. formaldehyde), or their capacity to displace oxygen concentration creating risky situations (e.g. CO₂).

The EFs of the chemical species selected are shown in Table 14. These values were extracted from Andreae (2019) to take into consideration differences between fuel complexes. The main impairing effect of each compound is also included in Table 14.

Table 14. Emission Factors of first selection of pollutants (EF from Andreae, 2019) and main impairing effect. SD: Standard deviation.

POLLUTANT	FORMULA	ID	IMPAIRING EFFECT	EF [g/kg]	
				MEAN	SD
Acetic acid	C ₂ H ₄ O ₂	64-19-7	Irritant	2.74	1.60
Ammonia	NH ₃	7664-41-7	Irritant	0.98	0.69
Carbon dioxide	CO ₂	124-38-9	Asphyxiant	1570.00	130.00
Carbon monoxide	CO	630-08-0	Asphyxiant	113.20	50.00
Formaldehyde	CH ₂ O	50-00-0	Irritant	2.08	0.70
Hydrogen cyanide	HCN	74-90-8	Asphyxiant	0.64	0.39
Methanol	CH ₃ OH	67-56-1	Irritant	2.16	0.87
Particulate matter	-	-	Others (carcinogen)	18.36	8.31
Phenol	C ₆ H ₆ O	108-95-2	Irritant	0.25	0.09

Combustion products were set according to the results of a weighting average that was calculated using EFs, atmospheric lifetime values and immediately dangerous to life or health (IDLH) values (Table 15).

Atmospheric lifetime was considered to take into account that substances emitted during a wildfire may be removed close to the emission point, while others might be transported before they are ultimately removed.

The immediately dangerous to life or health concentration is a condition that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment (NIOSH, 2017).

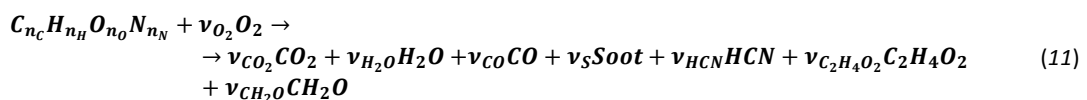
EFs, atmospheric lifetime values and IDLH values were considered to have the same weighting factor. Large EFs and atmospheric lifetime values imply more negative impacts on tenability because there would be a larger amount of product for longer. On the contrary, a large IDLH value implies a positive impact on tenability, because it means that the hazard of the chemical is relatively lower.

Finally, the selected substances were: acetic acid, carbon dioxide, carbon monoxide, formaldehyde and hydrogen cyanide. Compounds with EF+LF-IDLH values ≤ 0 were not considered, except particulate matter. In this case it is not an immediate component dangerous to life but it has a very high EF that has to be taken into consideration to correctly formulate the combustion reaction balance.

Table 15. Normalization of emission factor (EF), atmospheric lifetime (LT) and immediately dangerous to life or health (IDLH) values for each component.

COMPONENT	EF mean [g/kg]	EF norm	LIFETIME [day]	LT norm	IDLH [ppm]	IDLH [mg/m3]	IDLH norm	EF+LF-IDLH
Acetic acid	2.74	0.0017	6.00	0.0014	50.00	123.05	0.0017	0.0005
Ammonia	0.98	0.0006	10.00	0.0024	300.00	208.97	0.0029	0.0000
Carbon dioxide	1570.00	1.0000	4234.00	1.0000	40000.00	71998.36	1.0000	0.3333
Carbon monoxide	113.20	0.0721	90.00	0.0213	1200.00	1374.72	0.0191	0.0248
Formaldehyde	2.08	0.0013	0.15	0.0000	20.00	24.56	0.0003	0.0003
Hydrogen cyanide	0.64	0.0004	912.50	0.2155	50.00	55.26	0.0008	0.0717
Methanol	2.16	0.0014	16.00	0.0038	6000.00	7863.07	0.1092	-0.0347
Particulate matter	18.36	0.0117	7.00	0.0017	-	1750	0.0243	-0.0037
Phenol	0.25	0.0002	0.02	0.0000	250.00	962.27	0.0134	-0.0044

The combustion reaction was balanced considering the species selection made before and their corresponding emission factors according to Eq. 11.

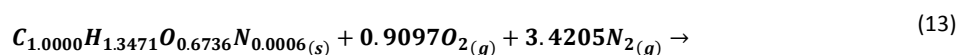


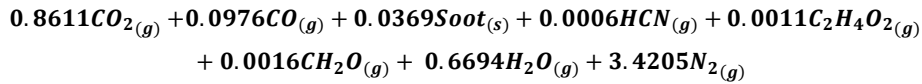
Where ν_j refers to the yield of a given substance j , and is calculated according to Eq. 12.

$$\nu_j = \frac{MW_F}{MW_j} EF_j \cdot 10^{-3} \forall j \quad (12)$$

Where MW means molecular weight and subscripts j and F refer to a given compound and the fuel, respectively, and EF is the corresponding emission factor.

Obeying the law of conservation of mass, we balanced the reaction according to Eq. 13.





Duration

Each simulation was set to be running for at least 600 s (10 min). However, simulations performed with the house open had a longer duration; i.e. 3600 s (60 min) for the front located 10 m away from the house, and 1000 s (17 min) for the front located 5 m away from the front. For comparison reasons, all simulations were checked at most after 600 s, meaning that the fire impact was checked for approximately 6 min (= 600 s - 250 s), given that the first 250 s were set to generate a stable wind profile and there was no fire then.

Outputs

Planar slices of temperature, pressure, velocity, volume fraction and density were saved at different locations outside and inside the house to visualize flow patterns. In Figure 90 we can see the slices corresponding to the house (or very close to it) at the x- and y-planes. Z-plane slices were also defined inside the house from 0.6 m up to 3.0 m with intervals of 0.2 m.

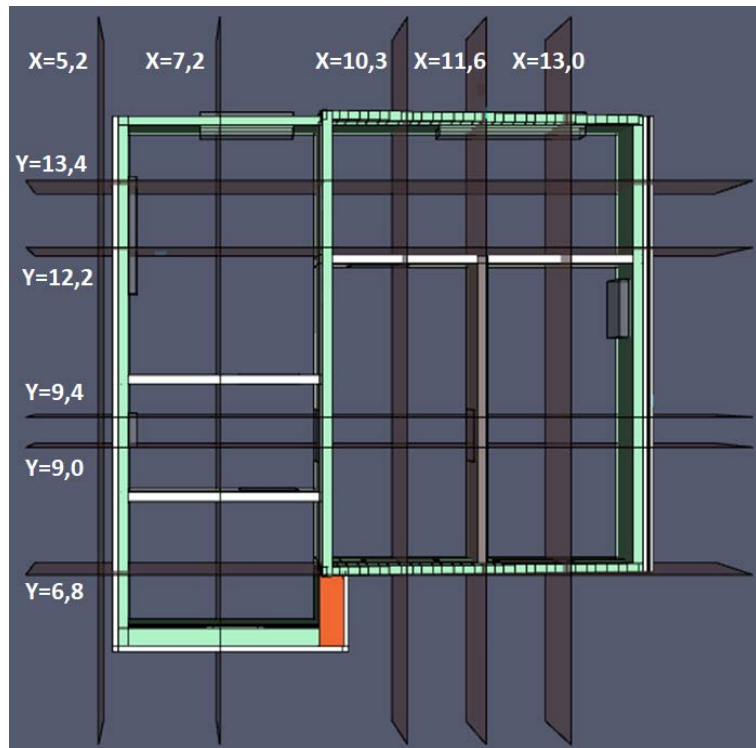


Figure 90. Slices defined next to and through the house in the X- and Y-planes.

Devices for each variable mentioned above, and also for radiative heat flux gas, were set at different heights and locations inside the house. We can see in Figure 91 that each room had four devices defined in the corners, and another one in the center. Furthermore, there was also one device located in the middle of each opening (windows or doors).

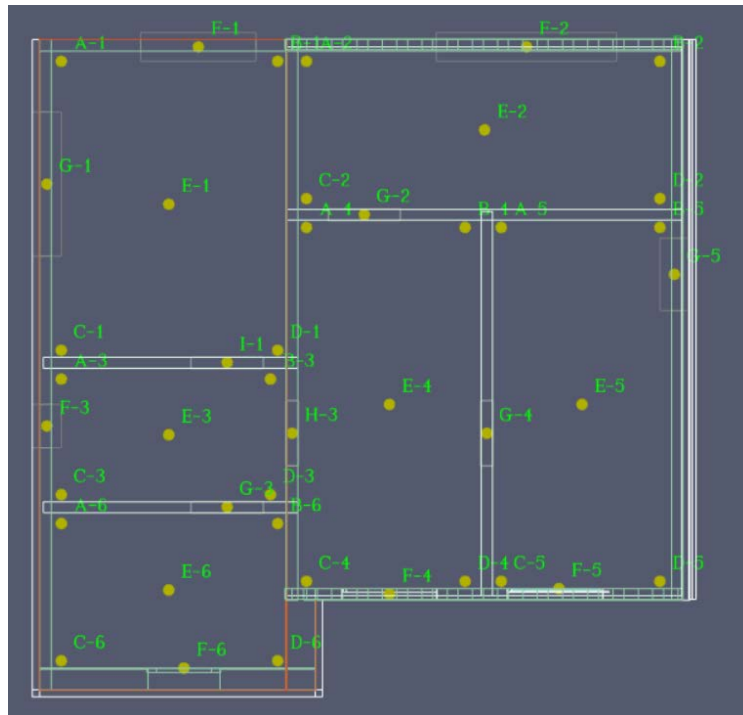


Figure 91. Location of devices defined inside the house. Rooms are numbered from #1 (top-left) to #6 (bottom-left).

5.3. Results and discussion

5.3.1. Open vs. closed house 10 m away from the front

Concentrations registered by the devices located inside the open house positioned 10 m away from the front line indicate that hydrogen cyanide, acetic acid, and formaldehyde concentrations were almost constant (0 ppm) for the complete period of the simulations (both open and closed house). Therefore, irritant concentrations associated to acetic acid and formaldehyde were not an issue for tenability 10 m away from the front.

FED slices were computed by Smokeview using only CO₂, CO and O₂ quantities obtained from the slice files generated by FDS (see Eq. 14).

$$FED_{tot} = FED_{CO} \cdot HV_{CO_2} + FED_{O_2} \quad (14)$$

Where FED_{tot} is the total FED, FED_{CO} is the FED due to CO, HV_{CO_2} is a hyper-ventilating factor applied to CO and FED_{O_2} is the FED due to O₂.

No FED values higher than 1 were calculated inside the house both if the house was open or closed (Figure 92).

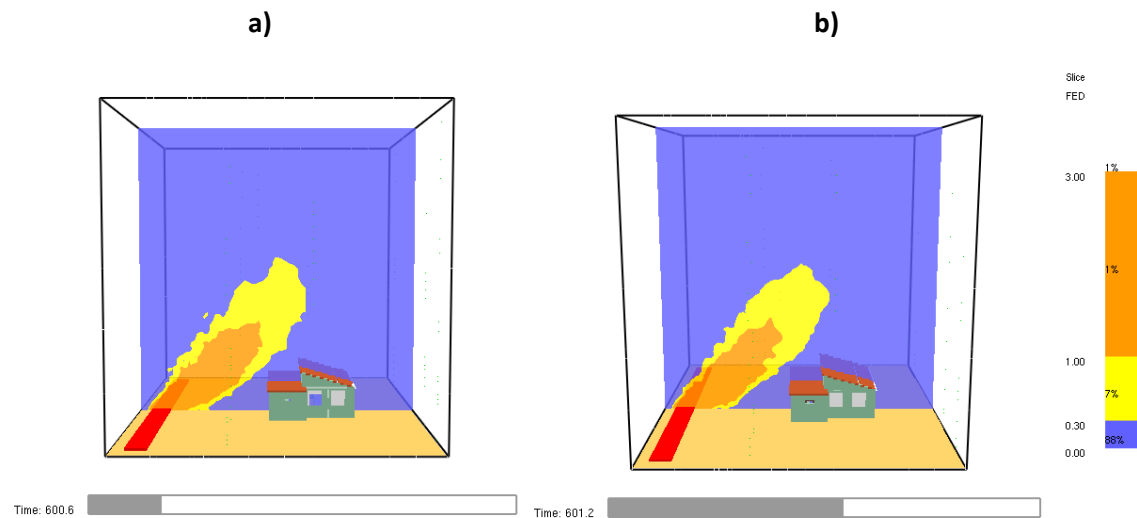


Figure 92. Fractional Effective Dose calculated with Smokeview (Y -slice = 9.4 m; fire-house distance = 10 m) for a residence time of 6 min: a) Open house; b) Closed house.

Comparing an open house scenario (Figure 93a) against a closed one (Figure 93b) for a residence time of 6 min, we can observe that the highest temperatures are reached in room #1 (top-left) in both cases. Moreover, the maximum interior air temperature set for tenable environments by ABCB (2014), i.e. 45°C, is reached only for the open house scenario.

Room #1 has a wall with a large window (2 m wide x 1.2 m high) parallel to the fire front, and a second window on the wall perpendicular to the fire front (1.6 m wide x 1.2 m high). Rooms #3 and #6 have also a wall parallel to the fire front but, in the case of room #3 it has only a small window (0.6 m wide x 0.3 m high) parallel to the fire front and the only window from room #6 is located on the wall perpendicular to the fire front and it was set closed in all simulations.

Moreover, according to Figure 93a, room #2 (the top-right one) presents the lowest temperatures for a residence time of 6 min. This indicates that this room would be the preferable option to be used as shelter under the conditions simulated in this case (fire line at the left side and wind blowing from the same side). This is probably due to the configuration of the house under study, i.e. hot gases entering the house through room #1 circulate inside the house going through open interior doors and looking for the easiest way to reach the outside; in this case, following the flow direction (x -direction) created by the two doors in room #4 and the outside door in room #5. This indicates that rooms used for sheltering-in-place should be selected taking into consideration possible propagation paths generated inside the house due to its design.

In the corresponding closed house scenario the room with the lowest temperatures is #6, which is closer to the fire front than room #2. However, temperature differences between these two rooms are not as large as in the open scenario. Both rooms have windows located on the wall perpendicular to the fire front, but the window in room #2 is much larger than the one in room #6. Thus, heat transfer through conduction is more predominant in room #2. Moreover, in the open scenario room #6 was getting warmer than room #2 because very hot gases were flowing inside it through the open interior doors. Under a closed scenario, this heat transfer mechanism is not present any more.

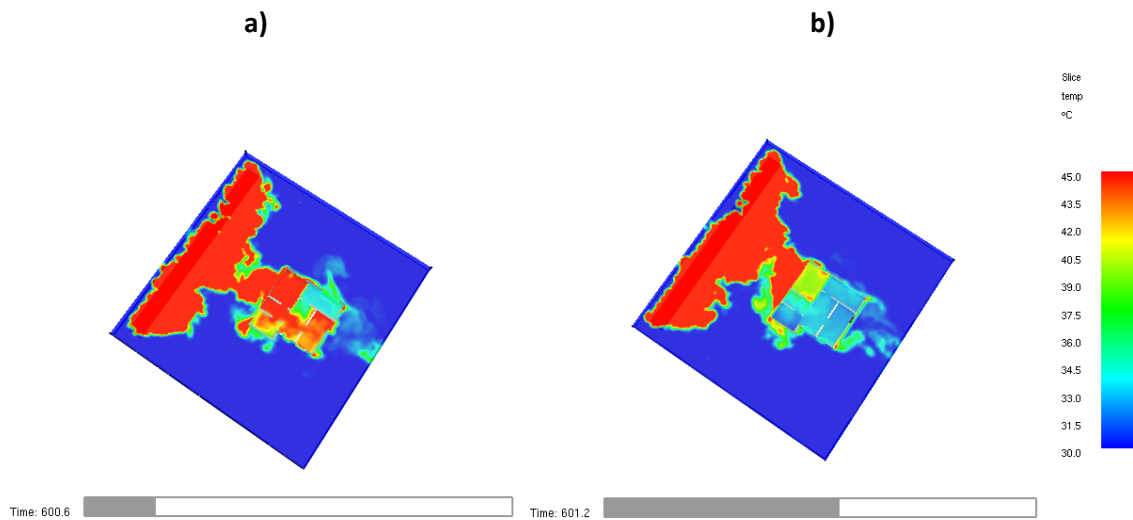


Figure 93. Top view of temperatures (Z-slice = 1.6 m) for a residence time of 6 min: a) Open house; b) Closed house.

Figure 94 is included to show that no smoke was getting into the house when it was set closed (a) and that temperatures higher than 45°C can be reached inside the house for residence times of around 12 min (b).

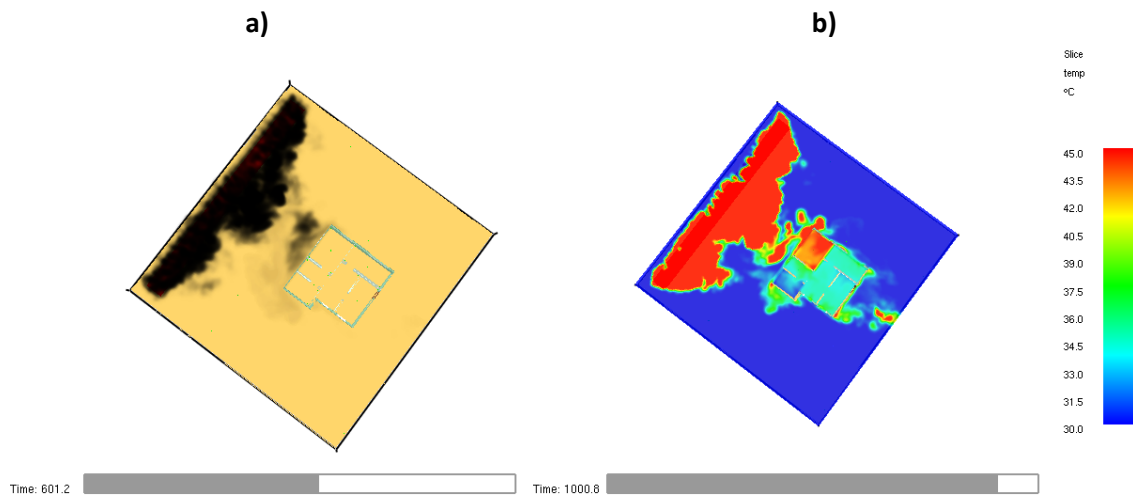


Figure 94. Closed house, fire front at 10 m, top view (Z-slice = 1.6 m) of: a) Smoke; residence time = 6 min; b) Temperatures, residence time = 12 min.

Maximum radiant heat flux (RHF) values measured at the devices located in room #1 (around 6.5 kW/m²) (Figure 95a) indicate that superficial 2nd degree burns would be reached only about 15 s after ignition if the windows and door were open (SFPE, 2016). On the contrary, in the closed house scenario 2nd degree burns or pain would not be reached (maximum RHF ~ 1 kW/m²).

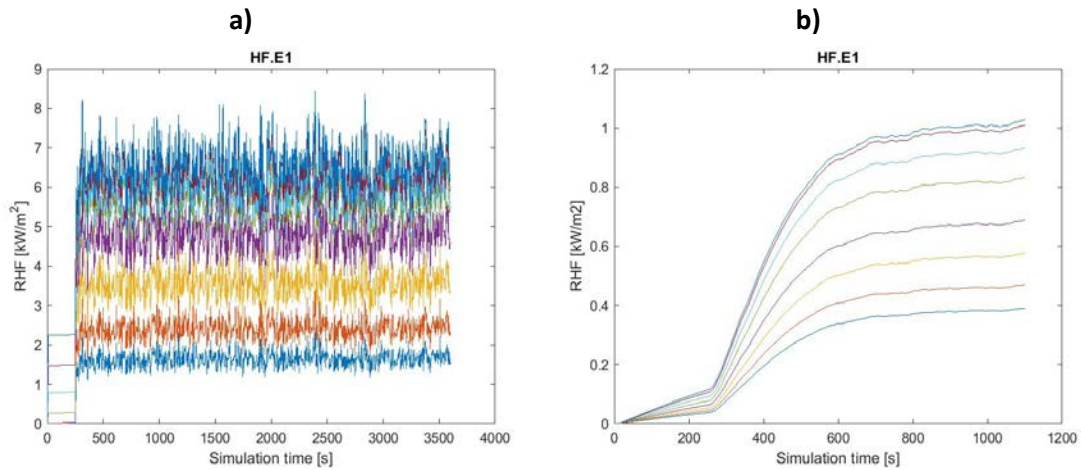


Figure 95. Radiative heat flux (RHF) received by a device located in the middle of room #1 (E1) at different heights facing the fire. Height intervals = 0.2 m; lowest height = 0.5 m (lowest RHF values series); highest height = 1.9 m (highest RHF values series): a) Open house; b) Closed house.

These results are in agreement with Blanchi et al. (2012), who suggested that fatalities within structures could be associated with high radiant heat and possible flame contact circumstances potentially resulting in a rapid rate of tenability loss of the structure.

5.3.2. Open house 5 m away from the front

FED results at $z = 1.6$ m obtained at three different residence times (Figure 96) indicate that loss of tenability would not yet be reached due to toxic doses for a residence time of 9 min, although values higher than 0.3 would be reached in all the rooms at this time. However, this is a critical temporal value because afterwards FED values higher than 1 would be obtained inside the house already. According to Figure 96 only 3 minutes after the critical temporal value is reached the first row of rooms closer to the fire front (rooms #1, #3 and #6) reach untenable conditions. This time interval is quite small, meaning that untenable conditions can be reached rapidly inside the house. Finally, after 26 min of residence time the complete house is under untenable conditions.

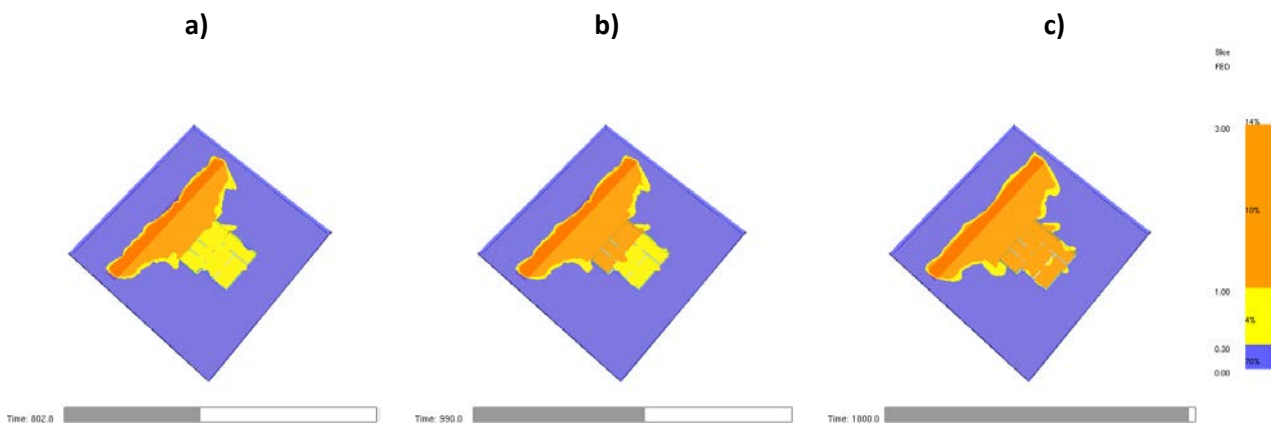


Figure 96. Evolution of Fractional Effective Dose calculated with Smokeview (Z-slice = 1.6 m; open house 5 m away from the front): a) residence time = 9 min; b) residence time = 12 min; c) residence time = 26 min.

Regarding temperatures, it is observed in Figure 97a that temperatures higher than 45°C are reached inside all the rooms after a residence time of 6 min. This indicates again that thermal effects are also important factors resulting in tenability loss. On the contrary, with the front located 10 m away from the house room #2 temperatures are still below 45°C after residence time of 6 min (Figure 97b).

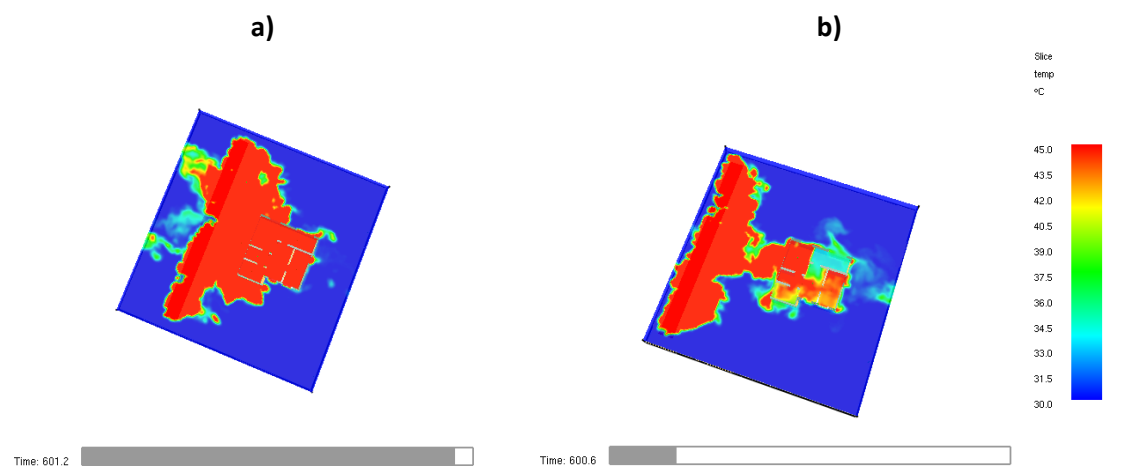


Figure 97. Top view of temperatures (Z-slice = 1.6 m; open house; residence time = 6 min): a) fire-house distance = 5 m; b) fire-house distance = 10 m.

5.3.3. Radiative heat flux reduction inside the house

The average radiative heat fluxes (RHF) measured by a device located outside the house at a height of 2 m and 10 m or 5 m away from the fire front are shown in Table 16. These values are in agreement with those calculated using the solid flame model described in section 4.8.2 (only 4-19% difference). Average radiative heat flux measured inside the house, in the middle of the room where the worst conditions are observed (room #1; Figure 95), indicate that a reduction larger than 70% with respect to the outside RHF can be observed inside. Although a value of 70% seems quite large, it would not be enough to hinder radiative thermal effects on people sheltering at this location if the house (the window in this case) is open and the fire front is at 10 m or less (see 5.3.1).

Table 16. Radiative heat flux (RHF) calculated outside and inside the house, and reduction percentage of RHF. FDS results are validated against those obtained using the solid flame model (SFM) explained in section 4.8.2. RHF sensor is positioned at a height of 2 m and at a distance of 10 m or 5 m from the fire front. Open and closed house scenarios are considered.

	Distance	RHF (kW/m ²)			
		Outside (FDS)	Inside (FDS)	Reduction	Outside (SFM)
OPEN	5 m	58.9	9.8	83%	56.36
	10 m	24.2	6.5	73%	28.50
CLOSED	5 m	-	-	-	56.36
	10 m	23.9	1	96%	28.50

The solid flame model can be used to estimate the minimum distance between the flame front and the open house required to avoid thermal injuries (i.e. RHF inside < 1.7 kW/m²). According to the results from Table 16, a conservative value for the radiative heat flux reduction would be 70%. This would mean that the RHF sensed outside the house should be $1.7/(1-0.7) = 5.7$ kW/m² or less. According to the solid flame model results shown in Table 17, a distance of 27.7 m would be enough to avoid thermal injuries under an open house scenario tested here, according to the simulated fire front. This value is similar to the minimum threshold value of 30 m commented before, although this implies that there is no other radiation source in between the flame front and the house (i.e. no isolated trees, no non-natural fuels burning close to the house).

Table 17. Radiative heat flux estimated with the solid flame model at a height of 2 m for a flame front similar to the one described in section 5.2.1.

Distance	RHF (kW/m ²)
27 m	5.99
28 m	5.59

5.4. Summary of recommendations for sheltering capacity

Based on the results of the simulations performed so far, loss of tenability due to toxic effects can be reached rapidly if the front is only 5 m away from the dwelling and it is open. Also, thermal effects can be noticed rapidly.

Under the atmospheric conditions tested here a distance of 10 m seems to be enough to avoid tenability loss due to toxic effects. However, thermal effects seem to pose a high level of risk for large residence times.

Based on the information reviewed in this section and according to the results obtained, RSF (2008) recommendations can be used regarding sheltering capacity:

People sheltering-in-place should:

- Be physically fit to fight spot fires in and around their home for more than 10 hours.
- Be mentally, physically and emotionally able to cope with the intense smoke, heat, stress and noise of a wildfire while defending their home.
- Be able to protect their home while also caring for members of your family, pets, etc.
- Have the necessary resources, training, clothes, and properly maintained equipment to effectively fight a fire.
- Know the configuration of the shelter (house) to be able to estimate which openings may influence at most hot gases propagation pathways inside the house to be able to control smoke movement through compartmentation.

On the other hand, structures where people may shelter-in-place should meet recommendations listed in past section 4.9 to guarantee structure survivability in case of fire impact. Moreover, in case of shelter-in-place, home-owners should prepare their property by closing all openings (including window protections), taping window edges from inside to ensure windows remain in place if broken, remove combustible materials close to windows inside the house and made available plenty of water supply for hydration.

This recommendations are structures within a form of a checklist as a **Sheltering Assessment Tool (SAT)** for self-evaluation at homeowner level. Details can be found in **Annex B**.

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7. ANNEX A – V.A.T – Vulnerability Assessment Tool

In line with the fault tree analysis commented in section 2 and according to the summary of recommendations for structure survivability (section 4.9), a simple methodology for quick self-assessment of structures survivability is now presented.

In a form of a **checklist**, eight blocks of questions are arranged following the structure of the fault tree depicted in Figure 98. As it can be recognised, this fault tree is a simplified version of the tree shown in past Figure 1. The checklist structured and weighted as shown, provides a normalised Fire Vulnerability Index (FVI, ranked from 0 to 100) that gives an idea of the **likelihood of fire entrance inside a WUI structure** in case of a forest fire.

As explained in section 2, fire can get inside a structure by five different causes (gaps through vents, gaps through the attic, broken windows, large damage in house envelope and windows left open). Weighting has been given in the same proportion to all causes in the vulnerability assessment methodology (20 points) meaning that, should these events occur individually, the chance of having fire inside a structure is the same, no matter the cause. The larger the number of possible events leading to gaps or openings, the more vulnerable the structure will be, as the probability of ember, flames or smoke entrance will be higher. For this reason, we have set a maximum value of FVI of 100, resulting from the sum of the five different possible causes set in our method. Therefore, after going through the checklist, obtaining a FVI value of 100 will be a sign of very poorly managed property, whereas a FVI value of 0 will reflect an optimum management.

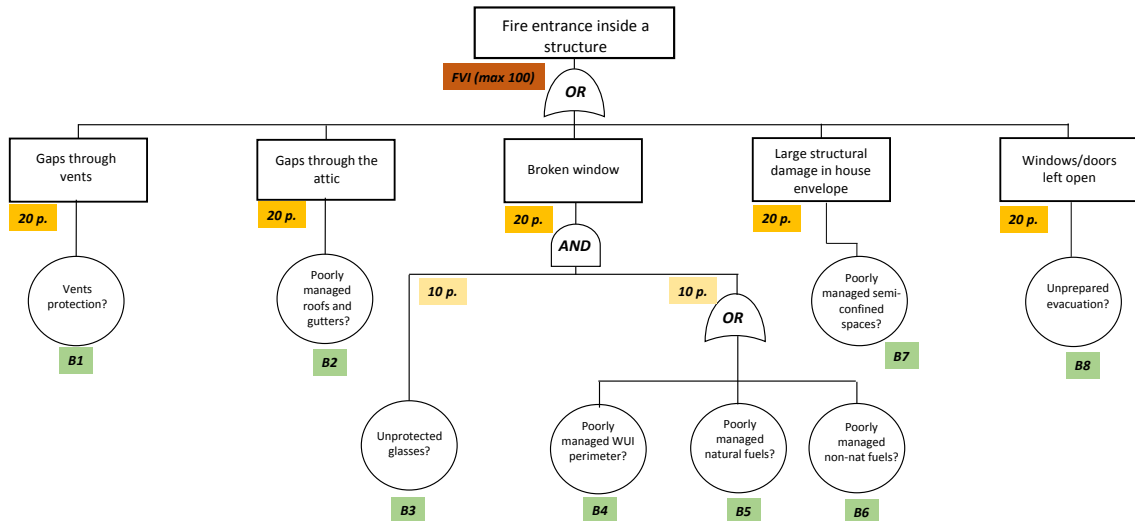


Figure 98. Logical structure of the Vulnerability Assessment Tool in the WUI microscale. Bn: Block of questions #n; FVI: Fire vulnerability index; p.: points.

The considered blocks ask about the state of vents (B1), roofs and gutters (B2), glasses (B3), wildland around houses (B4), fuels management at the property (B5 and B6), structure management in semi-confined spaces (B7) and evacuation procedures (B8).

Unsatisfactory answers of B1 will show a situation in which having fire entrance through vents will be probable. This situation will hence provide a preliminary FVI of 20 points. Equally, unsatisfactory answers of B2, B7 and B8 may also lead to preliminary FVI of maximum 20 points in every case, due to possible gaps through attic, large structural damage and windows left open,

respectively. Note that the logic gates driving the path towards a broken window by fire exposure, implies weighting B3, B4, B5 and B6 with a FVI of maximum 10 points each. Without the required level of protection in glazing systems (B3 negative evaluation) and any of the blocks B4-B6 with 10 points (note an OR logic gate among them), there will be most likely a chance of a broken window.

The checklist is made of the 8 different blocks, together with auxiliary comments and images to provide better understanding of questions and the points associated to every positive (YES) or negative (NO) answer are provided in the following tables. The number of maximum points associated to each block are also reflected in the last row.

B1: Are your vents well protected in case of fire exposure?

- Ventilation openings are potential entry points for flying embers that could ignite the building from inside. Typical types of vents found in houses are roof openings for attic ventilation (e.g. vent tiles, ridge closer vents), vents in eaves, weep holes, baseboard vents and vent pipes.

- To avoid fire intrusion, vents should be screened with corrosion-resistant, non-combustible wire meshes, with a diameter little enough to prevent the pass of firebrands.

- International codes recommend different diameters for meshes (between 2 and 6 mm), but scientific studies provide evidences that firebrands can penetrate meshes of these diameters leading to indoor fire ignition potential.




Photo source: D. Caballero; <https://ucanr.edu/sites/fire/Prepare/Building/Vents/>

ID	Question	YES	NO
B1.1	Do you have unprotected ventilation openings (i.e. vents without any type of screening or vents not accepted as ember- and flame-resistant)?	20	0
B1.2	Is your protection of vents made of non-combustible corrosion-resistant materials/meshes?	0	10
B1.3	Are your fire-resistant mesh openings less than 2 mm in diameter?	0	5

MAX = 20 points
(If question B1.1 is affirmative, B1.2 and B1.3 are non-applicable)

B2: Is your roof-gutters system protected in case of fire exposure?

- The roof is one of the parts of the house most exposed to the fire front radiation and eventually the landing firebrands. Roof under overhanging tree branches, particularly in the valleys or flat roofing, tend to accumulate fine fuel that can be ignited by firebrands causing undesired damage. To avoid fire damage at the roof, scientific studies and regulations agree that fire-rated materials are required for roof covering, however, roof cover is in most cases inherently safe (i.e. made of non-combustible materials) in Europe. In addition, good sealing of gaps between roof covering and decking, particularly in roof edges is also required. The shape of the roof does not have any type of consideration in standards, however, it has been scientifically proved to be a key factor in firebrand accumulation and ignition likelihood.

- Roof and gutters maintenance and cleaning are also key aspects when analysing vulnerability. Non-maintained roofs and gutters with accumulated fine fuel (e.g. debris, pine needles) increase the likelihood of fire entrance inside a structure. Burning debris in a gutter will provide a flame contact exposure to the edge of the roof.

- Regarding the constructive material of gutters, there is not a clear consensus across standards of whether gutters should be non-combustible or rather, plastic materials (i.e. PVC) should be allowed. If accumulated material is ignited, non-combustible gutters may drive the fire through the roof. On the other side, PVC gutters may melt and fall in case of fire, carrying the fire to the ground level. Gutter covers are required in all codes; however, effectiveness of these type of devices has not been scientifically proven. Research indicates that it seems to be more important to maintain gutters clean, than the material used in their construction.



Photo source: <https://ucanr.edu/sites/fire/Prepare/Building/Vents/>

ID	Question	YES	NO
B2.1	Is your roof covering or your roof assembly made of fire-rated material (e.g. clay tiles, concrete tiles, asphalt glass fibre composition singles, slate, etc.)?	0	20
B2.2	Is your fire-rated roof covering in good state? (Are there missing, displaced or broken tiles? Is the underlying roof sheathing exposed? Are there unsealed spaces between the roof and the external walls or between the roof covering and the roof decking, particularly in roof edges?)	0	4
B2.3	Do you perform periodic roof maintenance?	0	4
B2.4	Does your roof present geometry favourable for the deposition of fuels and firebrands? (Is your roof flat? Are there roof valleys? Are there intersections between roofs and external vertical walls/sidings?)	4	0
B2.5	Are your roof or gutters exposed to overhanging tree branches?	4	0
B2.6	Do you perform regular cleaning of debris piling up on roof or gutters?	0	4
MAX = 20 points (If question B2.1 is negative B2.2-B2.6 are non-applicable)			

B3: Are your glasses protected in case of fire exposure?

- Windows are frequently one of the most exposed elements in a house to a source of heat in a forest fire, together with roofing. Broken windows and glazing systems are entry points for flying embers, potentially triggering ignition inside the house.

- Windows vary greatly in size, materials, framing, casement, glazing and opening systems. It is observed that double-glazing, reinforced glass, tempered glass and reflective glass are more resistant to radiation than laminated single pane glasses.

- If glasses are protected, screens/blinds or shutters will absorb some of the incident energy, resulting in less energy being absorbed by the glass. Shutters should be made of non-combustible material (solid core wood or metal, no PVC).



Photo source: D. Caballero

ID	Question	YES	NO
B3.1	Do you have protection for all your windows/glazing systems (i.e. shutters, blinds) made of non-combustible materials (solid core wood fire-resistant, metal like aluminium)?	0	5
B3.2	Are your glazing systems double or multi-paned or made of fire-resistant tested material (e.g. tempered glass) and thickness equal or larger than 6mm?	0	5
MAX = 10 points			

B4: How vulnerable is your structure due to the vicinity of wildfuels? (*)

(*) Answer this block if your property is located at the fringe of a WU-interface or at the WU-intermix

- 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. Houses placed midslope, ridges or hilltops are potentially more exposed than those located in the lower parts, wide valleys or flat terrain.

- All standards dealing with the WUI fire problem include prescriptions regarding wildland fuel management around WUI settlements or structures to reduce fire intensity. Accepted knowledge on wildfire behaviour indicates that, to achieve a significant reduction of a fire-front intensity, it is necessary to avoid any type of crowning activity and to reduce the surface fuel load up to a certain level.

- Recommended treatments focus on breaking vertical and horizontal fuel continuity with different levels of demand depending on how and where the structure is installed in the landscape.



Photo source: D. Caballero

ID	Question	YES	NO
B4.1	Do you have a fuel-managed area around your settlement (in case of WU-interface) or your property (in case of WU-intermix) well maintained? (In case of structures located midslope, ridges or hilltops: fuel-managed ring of at least 50 m from the foundation of the structure, separation between crown trees/high shrubs of at least 8 m, lower tree branches pruned at 1/3 of tree height, low surface fuel load of 10 cm depth maximum. In case of structures located in flat terrain: fuel-managed ring of at least 30 m, separation between crown trees/high shrubs of at least 6 m, lower tree branches pruned at 1/3 of tree height, low surface fuel load of 10 cm depth maximum)	0	10
MAX = 10 points			

B5: Do you have your residential vegetation properly managed?

- Ornamental vegetation must be properly selected, placed and managed to minimize impact at property level in case of fire. Recommendations to reduce fire hazard of residential vegetation are generally established within the first 10 meters around the house.

- Management actions focus on breaking litter layer continuity, maintaining separation distances between ornamental trees and selecting fire resistant species.

- Special attention is devoted to ornamental hedgerows, that if aligned with slopes and main winds, can drive the fire through neighbouring properties



Photo source: D. Caballero

ID	Question	YES	NO
B5.1	Do you have a 10-m wide area around your structure well managed? (scattered residential vegetation fire-resistant or separated 6 m, all trees/hedges separated at least 4 m from any glazing system, non-continuous litter layer, hedges not aligned with wind or main slopes, no presence of dead fuels)?	0	10
MAX = 10 points			

B6: Do you have your non-natural fuels properly managed?

- Non-natural fuels are all type of materials and objects located around the house which may eventually entail combustion. These include outdoor furniture, stored materials, gas canisters, small sheds, wood piles, etc., which have the potential to keep burning for a long time after the main fire front passes, and eventually reaching high intensities.

- Particular attention has to be paid at domestic Liquefied Petroleum Gas (LPG) infrastructure. When exposed to a fire, LPG tanks will heat up and pressurize. If the tank pressure reaches the Pressure Relief Valve (PRV) set point, this will open, releasing LPG that will immediately ignite forming a jet fire, which will worsen the heat load to the tank and its surroundings. In the worst case it may evolve into an explosion (BLEVE) and the ignition of surrounding objects.



Photo source: D. Caballero

ID	Question	YES	NO
B6.1	Are there any non-natural fuels located within 5 m from vulnerable structure elements (e.g. doors or windows, gutters)?	0	5
B6.2	Are there any combustible materials (including ornamental vegetation, storage spaces, or combustible eaves) located within 2 m from LPG tanks?	0	5

MAX = 10 points

B7: Do you have semi-confined spaces properly managed?

- Semi-confined spaces are areas that are partially open, such as those located under terraces, porches, decks, eaves or canopies, or the spaces enclosed in open sheds and warehouses.

- The storage of combustible materials in such spaces entails large heat accumulation should these materials be ignited, leading potentially to structural damage of the envelope of the semi-confined space.



Photo source: D. Caballero

ID	Question	YES	NO
B7.1	Do you store combustible materials in semi-confined spaces adjacent to your house?	10	0
B7.2	Are there openings (e.g. windows, doors) which connect a semi-confined space used as a storage area to the house?	5	0
B7.3	Are the walls of the house connecting to the semi-confined space used as a storage area made out of concrete or bricks (20 cm thick minimum)?	0	5

MAX = 20 points

B8: Are you properly prepared for an evacuation?

- When threatened by a wildland fire, the safest option usually considered is an early evacuation, if it is possible and the evacuation route is not cut-off by smoke or flame front. But before leaving the house, some precautions may be observed

- Houses left with open windows, which is frequent in last-minute, unprepared evacuations, are exposed to the entrance of fire embers and flames, potentially entailing the destruction of the house. Windows must be shut and taped from the inside, so that they may remain in place if broken. Also, inner fuels close to windows have to be removed to minimize risk.

ID	Question	YES	NO
B8.1	Would you be capable of shutting all the doors and windows before leaving, tape your windows from the inside so that they remain in place if broken and remove inner curtains and furniture close to windows?	0	20
MAX = 20 points			

Further work

This VAT checklist will be tested, refined and improved in WP7 study cases (Spanish and Portuguese WUI settlements). Moreover, an adapted version for Northern European WUI will be also developed through the WUIVIEW study cases set in Sweden.

8. ANNEX B – S.A.T – Sheltering Assessment Tool

As for the structure survivability assessment, a simple method for sheltering assessment (SAT: Sheltering Assessment Tool) is herein provided. This method is in line with results and recommendations gathered in Section 5 of the present document.

It has already been stressed that when threatened by a wildfire progressing towards a WUI area, the safest option is an early evacuation. However, several factors may avert people from evacuating safely (late awareness, traffic jams, etc.). It is under these circumstances that sheltering in place may be an option.

Mediterranean type of houses may offer enough sheltering capabilities provided their degree of survivability is high when exposed to fire. In our simulation study reported in Section 5, we have demonstrated how a house with good air-tightness may be an effective barrier against *i*) smoke toxic compounds and *ii*) thermal radiation from the flames if glazing systems and other openings are protected, and if the area surrounding the structure is well managed. However, for a successful shelter-in-place action, homeowners should have a certain physical and mental fitness to cope with the situation that sheltering in case of an approaching fire may represent (e.g. stress, anxiety, heat, smoke, noise, etc.). In addition, actions to get immediately prepared and respond accordingly have to be feasible and well known for successful sheltering.

These three requirements (i.e. **structure endurance, physical and mental fitness and preparedness/response**) represent the basis of our sheltering assessment logic (Figure 99). For a successful sheltering, the assessment of three blocks of questions related to each requirement (B1-B3 in Figure 99) has to be individually affirmative, i.e. if any of these requirements cannot be reached, sheltering will most likely be an unreliable option.

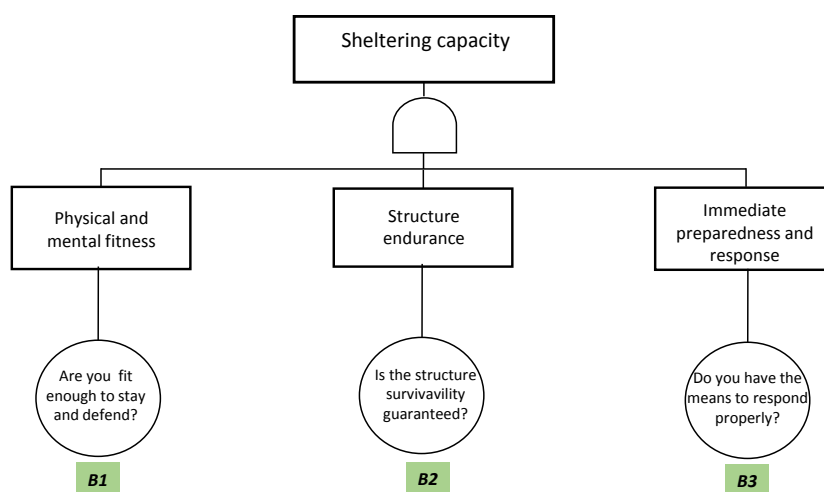


Figure 99. Logical structure of the Sheltering Assessment Tool in the WUI microscale. Bn: Block of questions #n.

Therefore, the **checklist conforming the SAT tool** is made of three blocks of questions put together with auxiliary comments to provide better understanding of questions. The following three tables gather the corresponding blocks of the SAT tool.

B1: Are you fit enough to stay and eventually defend your property?

- Population deciding to stay in place in case of fire should have a certain physical and mental fitness to cope with the situation that sheltering in case of an approaching fire may represent (e.g. stress, anxiety, heat, smoke, noise, etc.)

- Sheltering in place may eventually involve active defence actions (e.g. firefighting of spot fires) and protective actions towards family and pets.

ID	Question	YES	NO
B1.1	Are you mentally, physically and emotionally able to cope with the intense smoke, heat, stress and noise of a wildfire while defending your home?	✓	
B1.2	Are you physically fit to fight spot fires in and around your home?	✓	
B1.3	Will you be able to protect your home while also caring for members of your family, pets, etc.?	✓	

B2: Is your structure survivability guaranteed?

- Mediterranean type of houses may offer enough sheltering capabilities provided their degree of survivability is high when exposed to fire. This block is linked to the WUIVIEW Vulnerability Assessment Tool (VAT).

ID	Question	YES	NO
B2.1	Does your structure have a high chance of survivability according to VAT (vulnerability assessment tool) checklist (FVI \leq 20)? (*)	✓	

(*) A threshold value of Fire Vulnerability Index (FVI) \leq 20 is considered in here for an affirmative answer. An FVI of 20 means that there is at least 1 out of 5 possibilities of fire entrance inside the structure due to possible gaps. If Blocks 1 and 3 are affirmative, a value of FVI = 20 is considered manageable.

B3: Do you have enough means to respond properly when the fire is approaching?

- Actions to get immediately prepared and respond accordingly have to be feasible and well known for successful sheltering.

ID	Question	YES	NO
B3.1	Can you patrol the inside of the home as well as the outside for embers or small fires?	✓	
B3.2	Can you prepare the inside of your home (e.g. remove curtains, move furniture away from windows, tape windows from inside so they remain in place if broken)?	✓	
B3.3	Do you have a supply of fresh water available to keep hydrated?	✓	
B3.4	Are you able to estimate which openings (windows, doors) may influence at most hot gases propagation pathways inside the house depending on fire front position?	✓	
B3.5	Do you have the necessary clothes and properly maintained equipment to effectively fight a fire?	✓	

Note that the checklist includes basic questions whose answer gives a general idea of the chances of a successful sheltering. Questions related to auxiliary fire protection systems that enhance structure endurance (e.g. sprinklers, water canyons, etc.) have not been included due to the marginal use of those. However, properties having this type of systems installed will obviously have a complementary structure endurance leading to better sheltering conditions.