Wildland-Urban Interface Virtual Essays Workbench
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PBD Virtual Lab WUIVIEW

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PBD WUI-specific final guideline

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Abstract	The document provides a WUI specific Performance-Based Design (PBD) guideline, based on the needs and findings presented in previous work packages. The steps of the PBD approach are described focusing on the WUI environment. The guideline will aid fire safety practitioners in the design and evaluation of WUI fire scenarios.

(1) Draft / Final

(2) Public / Restricted / Internal

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1. About this deliverable

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

The project is divided into 8 work packages, out of which work package 7 is devoted to showcase the methods and findings of the WUIVIEW virtual laboratory by analysing real WUI settlements. The document at hand is the first deliverable of WP7. It provides a specific Wildland-Urban Interface (WUI) Performance Based Design (PBD) guideline, in line with the overview presented in the Deliverable 4.2 of the project. The guideline has been developed based on the foundations detailed in D4.2 and through continuous feedback from preliminary implementation on 4 case studies: 2 dwellings in Madrid region (Spain), 1 community shelter in central Portugal and 1 dwelling in Goteborg area (Sweden) (see Deliverable D7.2 for details on these).

2. Performance-Based Design framework

Performance-based fire safety design is a methodology for the engineering of fire safe building solutions based on three key aspects (Hurley and Rosenbaum 2016):

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

When it comes to the WUI, regulatory bodies, research institutions and practitioners are starting to address its fire safety challenges with the aid of PBD methods (Vacca et al. 2020).

The complexity of the different interactions that can occur between fire, structures and residents can be analysed through a PBD approach for both new and existing buildings located at the WUI.

As explained in WUIVIEW Deliverable 4.2, by following a PBD methodology, fire scenarios which involve the following issues can be analysed:

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

This document follows the classic PBD process, as shown in Figure 1.

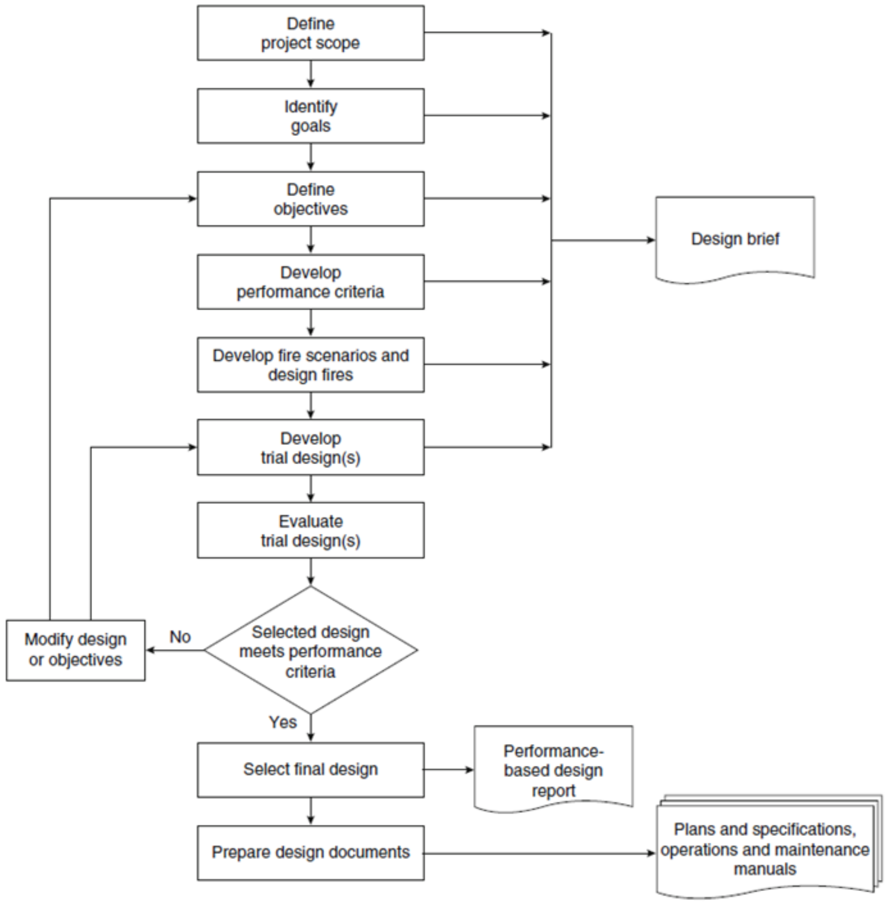

Figure 1:Performance-Based Design process (Hurley and Rosenbaum 2016)

3. Scope

This PBD guideline can be applied to properties located at the WUI in their entirety, which can include one or more buildings, or sections of these properties. These buildings and their surroundings must comply with local regulations. Buildings may include dwellings, commercial and industrial structures, and public buildings.

Stakeholders must be identified in order to set the goals and objectives of the design. The stakeholders at the WUI can for example be the homeowners, the local firefighters, or anyone that has an interest in the protection of the property.

The guideline has been developed to quantify hazards and vulnerabilities of buildings taking in mind their sheltering capacity or just their ability to withstand the passing of a wildfire.

4. Goals and objectives

4.1. Goals

Goals must be selected for each project depending on the aims of the stakeholders. They are the desired outcome expressed in qualitative terms. The classic PBD goals of life safety, property protection, mission continuity and environmental protection (Hurley and Rosenbaum 2015) can be applied at the WUI level as well.

4.2. Objectives

Design objectives must be set by taking the previously selected goals into account. These can include for example the creation of a sheltering area for occupant protection, limiting the fire spread through a property, or maintaining a building's structural integrity. If fire protection systems are included in the design, an objective should be set for their effectiveness.

5. Performance criteria

Performance criteria are threshold values set to quantify the hazards posed by each scenario. They can be divided into two categories: life and non-life safety. These criteria have been identified in WP6.

5.1.1. Life safety criteria

Life safety criteria include threshold values for tenability conditions inside a building, when it can be used as a shelter. In this case, also non-life safety criteria must be met. Recommended life safety criteria are given in Table 1.

Table 1: Recommended life safety performance criteria

Criteria	Threshold Values
Fractional Effective Dose	FED < 1 (Hurley et al. 2016)
Interior air temperature	T < 45°C (Australian Building Codes Board 2014)
Interior wall temperature	T < 70°C (Australian Building Codes Board 2014)
Radiant heat flux	$\dot{q}'' < 1.7$ kW/m^2 (Casal 2017)

5.1.2. Non-life safety criteria

These criteria include the structural requirements of a building, which should be met when the building is used as a shelter, as well as when the goals of the project include property protection. Criteria must be set for the vulnerable structural elements of a building, as well as for other vulnerable elements located on a property (i.e. LPG tanks).

Threshold values for different structural elements are given in Table 2.

Table 2: Recommended non-life safety performance criteria

Criteria	Threshold Values
Window breakage	Surface temperature < 150°C (Babrauskas 2010) ΔT < 58°C (Pagni 1988) For 3 mm panes: Received heat dose < 1840 $[\left(\frac{kW}{m^2}\right)^{\frac{4}{3}} \cdot s]$ (Harada et al. 2000) Aluminium frame – surface temperature < 660°C (Mitchell 2003) uPVC frame – surface temperature < 200°C (Chen et al. 2011)
LPG tank integrity	Incident heat flux < 22 kW/m^2 (American Petroleum Institute 2001) Pressure Relief Valve Index < 0.9 Weakened Surface Index < 0.9 (Scarponi et al. 2019)
Concrete walls load bearing capacity	> 74%

6. Design fire scenarios

6.1. Development of scenarios

Identification of scenarios can be performed via failure analysis, historical data, checklists, statistical data, fault- or event-tree analysis, etc. (Hurley and Rosenbaum 2015). An example of a fault tree analysis is given in Figure 2. Five different events which can cause fire entrance inside a structure have been identified:

- Through windows or doors that are left open due to sudden and unprepared evacuation, or though 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.
- Through broken windows, in case of a poorly managed property or settlement where combustible elements are placed too close to unprotected glazing elements. The combustion of these fuels can cause cracking or collapsing of the glass, giving way to the entrance of smoke, firebrands and flames.
- Due to the presence of semi-confined spaces such as garages, sheds, or storage areas containing non-natural fuels that are located 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.
- Through gaps created in the attic due to poorly maintained roofs and gutters, which are directly exposed to flying embers, radiation and even direct flames.

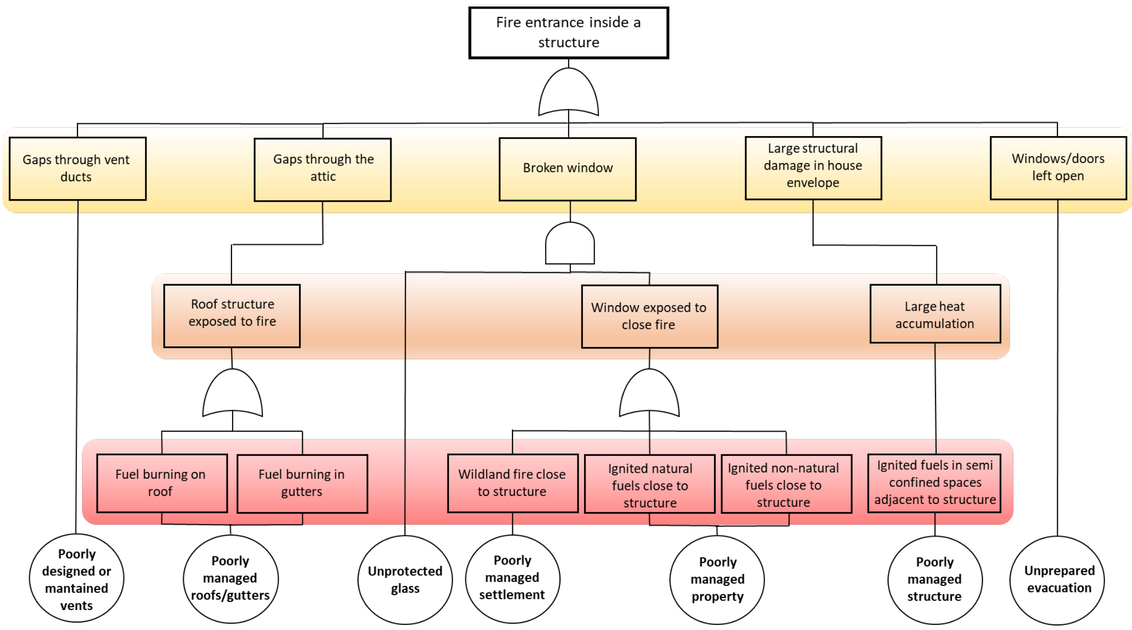

Figure 2: Example of a fault tree analysis at the WUI (Vacca et al. 2020)

Scenarios can be selected on the assumption that ignition of residential fuels will happen by firebrands coming from the main front or from the wildfire itself, should the property be located at the perimeter of a settlement or in case of an intermix scenario.

Once scenarios have been identified, a reduction of their population might be needed. This can be done by identifying those scenarios with:

- **High-frequency, low-consequences**: these are scenarios that are most likely to happen, which will have lower consequences on the property. An example of these types of scenarios is the ignition of a hedgerow in one point with fire spread through the hedge, with average environmental conditions (i.e. temperature, wind direction and speed, humidity).
- **Low-frequency, high-consequences**: these are scenarios that are less likely to happen, but can create large damage to a property. For example, the ignition of a hedgerow in multiple points, with extreme environmental conditions (i.e. high temperatures, low humidity, worst-case wind speed and direction).
- **Special problems**: these scenarios include specific issues of a property which can be addressed individually, such as the presence of combustible items close to a LPG tank or the storing of fuel packs in semi-confined spaces.

6.2. Fire characteristics

Fire characteristics must be selected for each scenario. When analysing the WUI, the most common type of design is a full burnout, meaning that the fire is not suppressed but decays according to the available fuel. If suppression systems are present and assumed to function, then they should also be inserted in the scenario, by cutting the fire curve at the time they are expected to activate.

The fire characteristics include the evolution of the Heat Release Rate (HRR) or of the Mass Loss Rate (MLR) over time, along with the products of the combustion, the area/location and the spread rate of the fire. More information on how to define these characteristics in a model is given in Appendix A.

6.3. Environmental characteristics

Environmental characteristics can greatly influence the outcome of a scenario, and must thus be included in the design. These include the location of the property within the landscape, as well as the one of the building within the property, along with meteorological information such as outdoor temperature, humidity, and wind direction and speed.

6.4. Property characteristics

Physical features of the building (i.e. the geometry of the structure) and of the landscape or property can affect phenomena such as the fire entering the building or the way the smoke spreads through the property and inside the building. They also affect fire spread and growth through the property.

Property characteristics such as the proximity of vegetation to a building, the presence of other combustible materials or structures, or the construction materials of the building, along with possible leakage areas which would allow for smoke to enter a building must thus be taken into account during the design.

6.5. Occupant characteristics

Occupant characteristics that must be taken into account are their ability to respond in case of spot fires, to evacuate when needed and to shelter in place, if the building is considered as a shelter.

7. Trial designs

Once the fire scenarios have been selected, trial designs should be established. For existing buildings and properties, the design can include the situation *as-is* for the analysis of the current vulnerabilities.

Trial designs can also include fire protection strategies for the achievement of the goals of the project, such as methods to reduce likelihood of ignition or fire growth (e.g. presence of fire resistant species or non-combustible items) or suppression systems. Also passive fire protection strategies should be taken into account.

If the trial designs do not achieve the set performance criteria, they should be redefined and re-evaluated.

8. Trial design evaluation

The evaluation of the trial designs involves determining if a design meets all of the set performance criteria.

Fire modelling with diverse degree of complexity can be used for the quantitative evaluation of the designs. Computational Fluid Dynamics modelling tools such as FDS (NIST 2020) can be used to simulate complex geometries where a more detailed spatial resolution is required (Hurley et al. 2016). This tool offers a great perspective in the WUI context, allowing to take the spatial and temporal variability of WUI scenarios into account.

The use of these tools requires a significant amount of information related to the building and the fire, along with the occupant's behaviour in case of the analysis of the sheltering capacity of a building. The data needed as input for the simulation setup is described in Appendix A.

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Appendix A – Fire inputs

When evaluating a trial design, fire inputs are needed. Within the FDS tool there are different ways to simulate the combustion of items located at the WUI. These are described in the tool's user guide (McGrattan et al. 2020), and are here briefly summarized.

The first method is the one that considers a known HRR or MLR curve. In this case, the Heat Release Rate Per Unit Area (HRRPUA) in kW/m^2 or the MLR of the items of which the combustion is simulated must be known, along with the time dependency of the variable. There are no standard values for these inputs when it comes to the WUI environment. Information on the burning behaviour of some items, especially for artificial fuels, can be found in the literature. Information is also needed for the products of the simulated reaction. For artificial fuels, CO and soot yields can be defined by taking pre-flashover design values used for the PBD of buildings (e.g. Y_{CO} = 0.04 kg/kg, Y_{soot} = 0.07 kg/kg (Ministry of Business Innovation and Employment 2013)), should more specific data be unavailable.

This method can also be used for an approaching wildfire front. The width of the front can be correlated with information on fuel consumption and wind speed by dimensional analysis (Nelson and Adkins 1988):

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

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 the following equation, and it represents the rate of energy released per unit time and length of fire front $[\mathrm{kW/m}]$ (Byram 1959):

$$\boldsymbol{I_B = \Delta H \cdot m_c \cdot r}$$

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 $[m/s]$. These values can be found in Alexander and Cruz (2019).

Once the width of the front and the fireline intensity are known, than the HRRPUA can be calculated as follows:

$$\boldsymbol{HRRPUA = \frac{I_B \cdot Length}{Area} = \frac{I_B}{S_f}}$$

When simulating the combustion of vegetation, a second method can be used. This entails the representation of vegetation with Lagrangian particles. In this case, a pyrolysis model will predict the fire spread rate through the vegetation. The needed inputs for this model are the moisture content or moisture fraction determined on a dry weight basis, the bulk density and the density of the dry vegetation. Fuel sampling might be needed to retrieve these data.