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Document coordinator	Eulàlia Planas (UPC)
Contact	eulalia.planas@upc.edu
Authors	Elsa Pastor (UPC) and Eulàlia Planas (UPC)
Reviewed by	Frederic Heymes (ARMINES)

Abstract	The document provides the first structure of the WUI-PBD guidelines to be delivered at the end of the project. It reviews the contents of the classical PBD approach for fire protection design in buildings and highlights the needs in terms of data gathering and methodology development to be applied specifically in the WUI context.

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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 4 is devoted to review the state of the art in terms of building codes and regulations and to obtain quantitative information on thermal properties and fire protection characteristics of building materials and systems, both aspects specifically focused on the wildland-urban interface.

This document D.4.2 is part of task 4.2 'State of the art and gap analysis on WUI fire codes and regulations' dealing specifically with the performance-based approach. The document presents a first overview of the contents of the final WUI-PBD guide to be developed within the WUIVIEW project (deliverable D.7.1 of work package 7), and the associated needs in terms of data gathering and methodology development.

2. Introduction

Goal-oriented approaches for urban building design are nowadays used to cope with different design aspects, being fire safety one of them. In particular, performance-based fire safety design is a methodology to engineer fire safe building solutions based on three key aspects (Hurley and Rosenbaum, 2015):

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

Although the first evidence of PBD (performance-based design) applied to fire safety can be found more than 40 years ago (Custer and Meacham, 1997), its application is being irregular throughout different regions, mostly depending on the degree of innovative architectural designs, the building codes maturity in terms of performance-based provisions and on the fire engineering expertise. PBD is being significantly applied to i) face particular fire safety challenges related to prescriptive codes compliance when applied to singular constructions or new materials (e.g. high-rise buildings, atria, long tunnels, green buildings (e.g. Chu et al., 2007; Chow, 2015); ii) to update old prescriptions of existing codes (E. Ronchi, pers. comm., 16 March 2017), and iii) to design according to advanced goal-oriented building acts (e.g. Tavares et al. 2008, Borg et al., 2015).

In this context, PBD has taken root in several regions with a settled fire engineering culture (e.g. Northern Europe, Southeast Asia, New Zealand, Australia) and is being implemented at an accelerating rate in many others (e.g. Mediterranean Europe, North America). Moreover, PBD gives valuable insights of how a building performs in case of fire; it is a suitable methodology to address unique design characteristics and, finally, PBD outcomes are clearer and more targeted, meaning much ease of communication between stakeholders (Hurley and Rosenbaum, 2015).

Motivated by these reasons, we believe there is a need to increase the use and take advantage of PBD methods to address WUI fire safety challenges. Although its novelty, we are already aware of some evidences that support this idea, coming from regulatory bodies, research institutions, and practitioners. In one hand, the National Fire Protection Agency (NFPA) has already recommended considering a design fire scenario of an outside exposure fire –if appropriate– for PBD projects, that, although unspecified, it is recognized as a way to explore the performance of buildings facing a WUI fire (NPFA, 2018). In addition, PBD has recently been adopted as the approach to design private shelters in Australia (ABCB, 2014). On the other hand, CFD tools (Porterie et al. 2007) and other physics-based simpler models (Dietenberger and Boardman, 2017) have already showed potential to study the performance of structural elements challenged against WUI fires. Finally, it has already been highlighted by fire prevention agencies the need to provide homeowners with educational material containing updated scientifically based recommendations (e.g. distances to ornamental vegetation, safer building materials and configurations, etc.) to minimize fire risk at the WUI microscale (X. Navalón, pers. comm., 9 April 2015) which can be certainly grounded on sound CFD fire simulation studies.

In light of all these and considering the characteristics and specificity of WUI fires, the application of the performance-based design approach (i.e. focused on fire safety objectives and based on CFD modelling) can be of outmost importance to improve fire protection of building plots at the WUI. For this purpose, the development of a specific WUI-PBD guideline is fundamental. Moreover, the development of this guide and all the data and methodologies linked to it will also be of interest to tackle, among others, the following issues:

- Houses vulnerability assessment: building performance analysis for structure triage (i.e. defensible/indefensible houses).
- Sheltering: adequacy assessment of existing buildings as refuges and performance-based design of new shelters.
- 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.).
- Protection strategies evaluation: Performance analysis of suppression systems and other elements acting as heat barriers (e.g. backyard fencing, water mist systems, etc.).
- Fire-building interaction dynamics studies: Physical analysis of heat transfer enhancement mechanisms (i.e. re-radiation effects, local turbulences, flames entrainment) in systems with complex geometry.
- 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.
- Education: development of scientifically supported measures to be transferred into educational material about fire prevention and safety for homeowners, land managers and fire agencies.

3. Framework for Performance-Based approach at the WUI

Performance-based fire protection is usually carried out when the building unique characteristics makes very difficult or impossible to comply with prescriptive-based codes. Commonly, prescriptive-based codes provide the requirements to protect people and structures from fires that start inside the building and eventually propagate through it or to adjacent buildings, but they do not take into consideration the case when a wildland fire threatens the building. Some exceptions are specific prescriptive codes developed to deal with the WUI problem, such as NFPA 1144 or IWUIC, which provide a methodology to assess wildland fire ignition hazard and provide minimum requirements to reduce the potential of structures ignition from wildland fires. Although very useful, as any prescriptive code it may not be able to take into account all the particularities and specificities of a given situation or, in some cases, the proposed distances may not be well justified. Therefore, when dealing with buildings' fire protection design at the wildland-urban interface (WUI) prescriptive codes do not always provide design guidelines for all kind of situations and it becomes somehow natural to follow a performance-based approach. Nevertheless, from our knowledge, this approach has never been applied at the WUI, and requires to be adapted in order to be fully effective. The objective of this deliverable is thus to analyse the PBD classical approach and provide guidelines on the changes required and on the set of steps to follow, to finally be able to develop a WUI-PBD guide.

3.1. Classical approach to performance-based fire protection design

The classical approach when doing a performance-based fire protection design in buildings follows a well-known process (see Figure 1) that requires go through several steps, beginning with the definition of the project scope (SFPE, 2006).

According to Hurley and Rosenbaum (SFPE, 2016) "*project scope identifies the portions of a building or facility that will be considered by the design, the desired features of the design, the intended characteristics of the building, and the regulations that are applicable to the design. The scope also includes identification of the project stakeholders—those that have an interest in the success of the design. Stakeholders may include building owners or their representatives, regulatory authorities, insurance providers, building tenants, fire officials, or other parties*"; which could perfectly be applicable to a WUI-PBD approach too, without the need of further development.

After the scope has been defined, the next steps include the definition of goals (Step 2) and objectives (Step 3) of the design project. Goals and objectives provide the desired overall safety outcome but in a rather different way. Goals are expressed in such a broad and qualitative way that any person without engineering expertise can easily understand it. The objectives have to provide detail on the maximum allowable levels of damage and on the maximum or minimum acceptable fire conditions. Goals and objectives are not enough to evaluate quantitatively the performance of a given design; consequently, the next step is the development of the performance criteria (Step 4), which have to be predictable using fire models. Performance criteria are threshold values that, when surpassed, point out that unacceptable damage occurs.

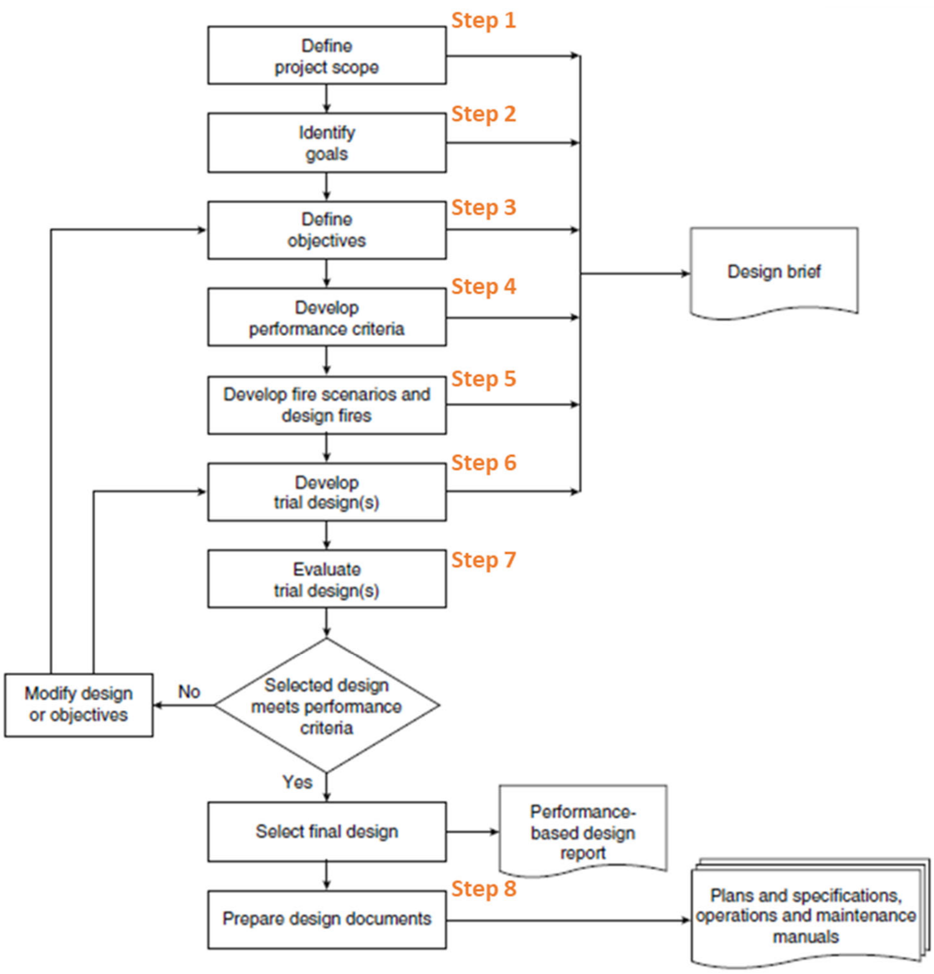

Figure 1. Performance-based design process adapted from (SFPE, 2006).

Diverse reference sources provide examples of goals, objectives and performance criteria that can be used when doing a classic PBD (e.g. NFPA 101, NFPA 5000, ICC Performance Code, NZ C/VM2, SCDF-Fire Safety engineering guidelines). Later in this document we analyse which ones can also be applicable to a WUI-PBD and the eventual need for developing specific goals, objectives and performance criteria for WUI projects.

Next step of the methodology is the definition of the set of design fire scenarios (Step 5) that will be used to evaluate if the building design meets the performance criteria. A design fire scenario is defined by three sets of characteristics: building characteristics, occupant characteristics and fire characteristics. The building characteristics describe the physical features, contents, and internal and external building's environment. Occupant characteristics have to be defined when life safety or occupant response is considered in the scope of the project. Finally, the fire characteristics are provided quantitatively as design fire curves. Design fire curves give the evolution of the heat release rate (HRR) as a function of time and are meant to be a representation of anticipated fires but do not need to be exact predictions of what will happen in case of fire.

Once the scenarios have been defined, one can proceed to develop the trial designs (Step 6). Trial designs are the fire protection strategies that might allow achieving the goals of the project, which can include: i) methods to reduce the likelihood of ignitions, ii) systems to control the spread and management of smoke, iii) systems for fire detection and notification, iv) fire suppression systems, v) methods for occupants behaviour and egress control, and vi) methods for passive fire protection.

Finally, the trial designs can be evaluated in order to determine if they meet the performance criteria (Step 7). In this step, engineering tools such as fire models of diverse degree of complexity can be used to quantitatively demonstrate whether the performance criteria have been accomplished or not.

Finally yet importantly, detailed documentation of all the design process has to be prepared (Step 8), including all the quantitative description of the evaluation with the models and data used as well as the justification of why they have been chosen and they are appropriate.

3.2. New approach to performance-based fire protection design at the WUI

The idea behind this new approach is to analyse which parts of the classical PBD approach have to be modified, complemented or adapted to apply it for the analysis of the wildfire protection design of buildings at the wildland urban interface. The guideline to be developed will only consider the threats coming from wildland fires but not from other kind of fires already included in the classical approach. That is, every step in the classical approach will be reviewed to provide a guide on how to consider the new scenarios typical of the WUI, which are not currently being considered.

The guideline aims at being applicable as a standalone methodology for the WUI context, even if the building meets all the requirements of the prescriptive provisions of a given building code. It has to be highlighted that most of the general building codes (not those mentioned at the beginning of section 3 that are WUI specific) do not provide particular prescriptive provisions for the protection of buildings against wildfires, although some of them can mention that buildings should be protected against potential external fires (without mentioning explicitly wildfires) (CTE-DBSI, 2010).

Next sections provide a first analysis of the work that has to be developed during the WUIVIEW project in order to provide a final version of the Guideline at the end of the project.

4. Definition of the project scope in WUI-PBD projects

The definition of the project scope in a WUI-PBD will not highly differ from the scope of a classical PBD or even from that of a prescriptive-based design. It will identify clearly the needs of the project and includes:

- The parts of the building or plot facilities that will be considered by the design
- The intended characteristics of the building or plot facilities
- The regulations applicable
- The identification of the project stakeholders (i.e. building owners, regulatory authorities, insurance providers, fire officials, etc.)

The final version of the WUI-PBD guidelines will provide examples of project scopes, taken from the study cases.

5. Goals, objectives and performance criteria in WUI-PBD projects

5.1. Goals

In the classical PBD approach (SFPE, 2006) four fundamental goals for fire safety are identified:

- Life safety
- Property protection
- Mission continuity
- Environmental protection

Usually one of them becomes the primary goal of the project, although in some cases more than one can be considered. In a WUI-PBD approach, any of those can also be applied depending on the scope of the project. If the scope is to design a safe family building, then the goals will probably be life safety and property protection. If the scope is the design of an automated warehouse in the vicinity of a forest, the goals would likely be property protection and mission continuity or even environmental protection if for example it stores hazardous materials.

Some existing codes identify more specific goals. They will be analysed and the final version of the WUI-PBD guideline will provide a set of more specific goals that can be used in the WUI context.

5.2. Objectives

Usually two types of objectives are considered, the stakeholder objectives and the design objectives. Stakeholders' objectives provide more information than goals do, with detail on the maximum allowable level of damage. Design objectives describe the maximum acceptable fire conditions necessary to achieve the stakeholders objectives. In a WUI-PBD project the stakeholders objectives can be very similar to those considered in a classical PBD project, but the design objectives required to meet the stakeholders objectives will need to be defined from scratch.

Existing codes like NFPA 101 provide a list of stakeholders objectives that can be considered. These will be reviewed and analysed for its inclusion in the WUI-PBD final guideline. Moreover a list of design objectives will be developed.

5.3. Performance criteria

Performance criteria may vary significantly depending on the specific design situation, which is why most of the performance-based codes do not provide explicit threshold values. Moreover, performance criteria depend on fire protection goal. In the case of life safety goal, threshold values corresponding to exposure of people to high gas temperatures, thermal radiation, toxicity of fire products or visibility through smoke are required. These values might even vary depending on the physical and mental conditions of people considered and on the length of exposure. In the case of the other goals (property protection, mission continuity and environmental protection) threshold values will be related, for instance to thermal effects (ignition, melting or charring), fire spread, smoke damage, structural integrity or damage to the environment.

Values of performance criteria for life safety and property protection can be found in diverse reference sources (see some examples in Table 1). They will be reviewed and the WUI-PBD final guideline will provide a list of selected performance criteria specifically applicable to the WUI context.

Table 1. Example of performance criteria for life safety available in some codes and references.

Reference	Smoke layer height	Radiation heat	Convection heat	toxicity	visibility	Smoke layer temperature
CPFSB 2011	2 m[(a)]	2.5 kW/m^2 [(b)]	n.s.	[CO] < 1000 ppm [(c)]	10 m	< 60 °C
GU n. 192 del 20/8/2015 – S.O. n. 51	2 m	Occupants: < 2.5 kW/m^2 Firefighter: < 3 kW/m^2	Occupants: T < 60 °C Firefighter: T < 80 °C	Occupants: FED and FEC < 0.1 (at a height of 1.8 m) Firefighter: n.s.	Occupants: > 10 m (for premises with a surface area > 100 m^2) and > 5 m (For premises with a surface area < 100 m^2) Firefighter: > 5 m. (for premises with a surface area > 100 m^2) and > 2,5 m (for premises with a surface area < 100 m^2) Always measured at 1.8 m height	< 200 °C
NZ-C/VM2. (2017).	n.s.	FED_T < 0.3 Measured at 2 m height		FED_{CO}[(h)] < 0.3 Measured at 2 m height and including CO, CO_2 and O_2	> 10 m (for premises with a surface area > 100 m^2) > 5 m (for premises with a surface area < 100 m^2)	n.s.
SCDF.(2015)	n.s.	< 2.5 kW/m^2 Measured at 1.8 m height	FED_T <0.3	FED < 0.3	> 10 m Measured at 2.5 m height	Upper layer < 200 °C Measured at 2.5 m height Lower layer < 60 °C

n.s: Not specified; FED: Fractional effective dose (the fraction of the dose of carbon monoxide or thermal effects that would render a person of average susceptibility incapable of escape); FEC: Fractional effective concentration (the fraction of the irritant gas concentration that would render a person of average susceptibility incapable of escape)

[(a)] *Unless otherwise justified by the authorized person*

[(b)] *For a short period of exposition*

[(c)] *If toxicity can become an issue.*

6. Fire scenarios and design fires in WUI-PBD projects

One of the most important aspects of a PBD is the selection of the design fire scenarios that will be used to evaluate whether a trial design is acceptable or not. In the classical PBD approach, most PBD codes provide a set of fire scenarios that need to be considered. Nevertheless, these are obviously very specific for compartment fires and will not be useful for the WUI context. What is useful though is the idea behind the proposed design fire scenarios, which is that at least three types of scenarios should be considered:

1) High-frequency, low-consequences (typical)
2) Low-frequency, high consequence (high challenge)
3) Special problems scenario

In the frame of WP5 (see D 5.1 *Inventory of pattern scenarios*) an extensive work has been carried out to make an inventory of typical pattern scenarios for the WUI situation, which will also be tested and simulated with FDS. This work will be essential to, later on, defining a specific set of fire scenarios to be included in the WUI-PBD final guideline.

As explained in section 3.1 a design fire scenario includes three types of information: building characteristics, occupant characteristics and fire characteristics. Concerning the building characteristics, in the classical approach it mostly relates to the physical features, contents and ambient environment within the building. In the WUI approach, this may have some importance but we will be mostly interested in providing the external features of the structure and the contents and ambient conditions of the building plot. Concerning the occupants' characteristics, we do not expect much difference between the classical approach and the WUI approach, although a careful analysis of the two most common situations in WUI fires, i.e. evacuation and "stay and defend", will have to be performed. Both aspects will be detailed in the WUI-PBD final guideline.

Finally, concerning the third type of information that has to be provided in a design fire scenario -the fire characteristics- this will be one of the most challenging parts of the development of the WUI-PBD final guideline. In the classical approach, the fire characteristics describe the history of a fire scenario including first item ignited, fire growth, flashover, full development and decay and extinction; generally expressed as the heat release rate as a function of time (what is also called the fire curve, see Figure 2). A quite significant amount of information exist on fire curves for individual items (see) commonly found inside buildings (SFPE, 2016) but it is practically inexistent for wildland and ornamental fuels and items found outside buildings in, for instance, a typical family plot.

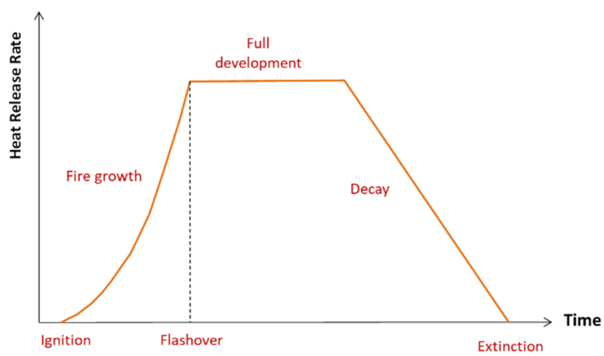

Figure 2. Example of a typical fire curve.

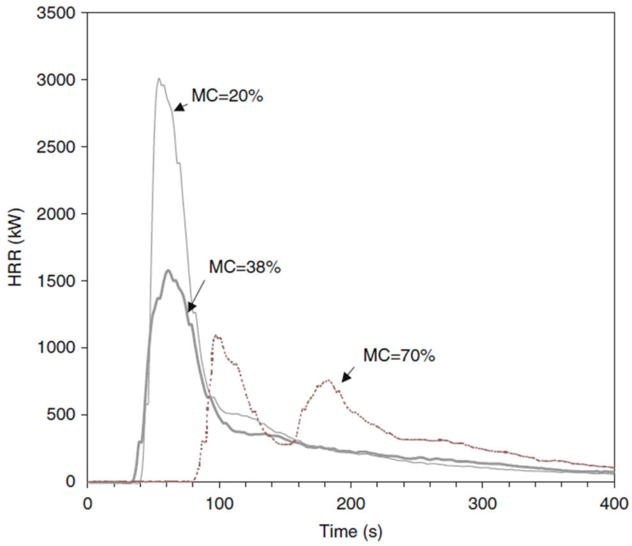

Figure 3. Typical heat release rate curves of Christmas trees (SFPE, 2016).

The work carried out in WP2 and WP3 will provide the baseline information concerning the burning characteristics of both wildland fuels, and residential fuels (either natural or artificial) commonly present at the WUI microscale. This information will be key to provide fire curves that will be used in the WUI-PBD final guideline to define the fire characteristics of the proposed design scenarios.

7. Methods for evaluating the trial designs in WUI-PBD projects

The classical approach to PBD identifies three possible levels of evaluation: subsystem, system and whole building. The same idea can be applied to the WUI approach with some considerations, taking into account that the type of components or subsystems considered in the classical approach (egress, detection, suppression, fire resistance, etc.) could differ from those considered in the WUI approach.

To evaluate trial designs engineering tools -fire models of diverse complexity level- need to be used to determine if the performance criteria are meet. Although in some cases simple algebraic equations might be used, the WUIVIEW project will take advantage of the potential of CFD tools, such as FDS, to develop a methodology to verify the trial designs. These tools offer a great perspective in the WUI context for their three-dimensional modelling capacity, which allows taking into account the spatial and temporal variability of WUI scenarios. The work in WP5 and WP6 will help developing the procedure that will be later included and detailed in the WUI-PBD final guideline.

The use of advanced simulation tools requires a significant amount of data related to building, fire and occupant behaviour. The works developed in WP2 (*WUI natural fuels hazard characterization*), WP3 (*Artificial fuels characterization*) and WP4 (*Building and protective materials characterization*), and their outcomes in terms of databases on natural fuel burning characteristics (WP2), on artificial fuel burning characteristics (WP3) and on thermal properties and fire protection characteristics of building materials and systems (WP4), will provide all the required information to run the models.

8. Documenting the design process in WUI-PBD projects

After carrying out the evaluation and selection of the final design, a detailed performance-based design's report has to be prepared. This will not be different in the case of the WUI-PBD. The report should describe all the quantitative parts of the design and evaluation and should inform about the models and calculation methods used, including the reasons of their selection and the rationale of why the data used are appropriate for the situation being modelled. The WUI-PBD final guideline will provide enough information to help fire safety engineers documenting the WUI-PBD projects.

9. Uncertainty

In fire protection engineering there is obviously some uncertainty. Uncertainty is defined (SFPE, 2006) as "the amount by which an observed or calculated value might differ from the true value". The major sources of uncertainty are mainly:

- Theory and model uncertainties due to the incomplete or not perfect understanding of the underlying science to the problem.
- Data and model inputs uncertainty.
- Calculation limitations due to the numerical approximations done to solve the models.
- Design fire scenario selection could not eventually represent the range of fires that might occur in reality.
- Uncertainties in risk perceptions, attitudes and values. Linked to the selection of objectives and performance criteria, as sometimes it can be difficult to assess the level of safety desired or the tolerable risk to life.
- Uncertainty in human behaviours. Where human behaviour is considered, uncertainty is introduced due to its highly stochastic nature.

Currently there is no single accepted methodology to deal with the uncertainty of the PBD process (Hurley and Rosenbaum, 2015). Nevertheless, it is important to verify that for reasonably foreseeable variations in the input variables and inaccuracies in the predictive models, predicted outcomes of the PBD could not change from an acceptable solution to an unacceptable solution. To do that several tools or combination of tools can be used such as sensitive analysis, to decide which parameters add more uncertainty to the system, or safety factors to provide a higher degree of confidence in the overall result.

The WUI-PBD final guideline will give some insights into the uncertainty associated to the overall process and provide means to deal with it.

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