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Using fuzzy logic to evaluate fire vulnerability of dwellings located at the wildland-urban interface

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Abstract

WUI fires are posing great challenges to firefighting services, which are overwhelmed by the need to not only suppress the fire, but also protect the community. The need for self-protection is therefore growing, as is the need for the creation of fire-adapted communities. A tool that can aid homeowners and residents of the WUI is therefore created, so that they can identify the vulnerabilities present on their properties and consequently reduce them in order to diminish the risk of damage due to a wildfire. This Vulnerability Assessment Tool is based on a fault tree analysis that includes possible structural vulnerabilities as well as the different ways a fire could spread on a property to finally enter and damage the building. The identification of the probabilities of the different events in the fault tree is obtained through the use of fuzzy logic, for which inputs, outputs and rules are identified. A questionnaire targeted to homeowners and based on the fault tree and linked to the probability identified with fuzzy logic is then developed. By filling in this questionnaire, homeowners at the WUI will be able to know what the probability of a fire entering their house is. The result of the questionnaire also indicates which are the issues on the property that need to be addressed in order to lower this probability. Finally, the tool is validated with a case study of several houses affected by a fire in Spain.

1. Introduction

Fires at the Wildland-Urban Interface (WUI) are annually expanding in frequency and severity, resulting in catastrophic events that take a heavy toll in human life and structure losses (Ganteaume et al. 2021). These events often overwhelm firefighters' capacities due to the need of a simultaneous response to wildfire suppression, community evacuation and structure protection, therefore highlighting the need of the creation of fire-adapted communities, which can safely co-exist with fire (Vacca et al. 2020). Risk reduction strategies which include preventive actions not only at the community scale, but also at the residents' scale (i.e., the WUI microscale) are needed to reach this goal, as case studies indicate that a home's structural characteristics and its immediate surroundings determine a home's ignition potential in a WUI fire, thus influencing its chances of survival (Cohen 2000), (Hakes et al. 2017).

The analysis of past fire events all over the world has resulted in the identification of the different pathways leading to building ignition, which have been summarized by Hakes et al. (2017). Consequently, some countries that have historically been affected by wildfires at the WUI have created standards and guidelines for new and/or existing buildings that include WUI microscale risk reduction strategies related to both building and property characteristics. These are mainly general rules based on experience, but frequently poorly supported by scientific evidence and studies, thus without taking into account the appropriate parameters and processes that explain fire behaviour and effects on assets at the relevant scale (Pastor et al. 2019). In the Mediterranean region, standards and guidelines do not always include building construction or maintenance, or it is not analysed with the appropriate detail.The focus of this work lies in creating a Vulnerability Assessment Tool (VAT) specific for Mediterranean WUI microscale settings, directed to WUI homeowners and residents that is supported by scientific evidence and studies and can give quantitative information on the vulnerability of a property to an incoming wildfire, and can thus identify the main issues that need to be addressed. The tool is presented in form of a checklist that can be easily filled in by the homeowners or residents themselves.

2. Methodology

In order to reduce the risk of home loss at the WUI, a coupled approach that reduces the vulnerability of a home to fire along with the probability of its exposure conditions is necessary (Calkin et al. 2014), (Caton et al. 2017). The causes of fire entrance inside a building located at the WUI can be summarized therefore in two intermediate events of a fault tree, as shown in Figure 1: one involving the exposure conditions and the other involving structural vulnerabilities typical of Mediterranean constructions. For the fire to enter a building, both of these events should occur. The different paths that lead to these two intermediate events in a Mediterranean environment, identified through a literature review of past events (Vacca et al. 2020), are further explored to develop the sketch model in Figure 2.

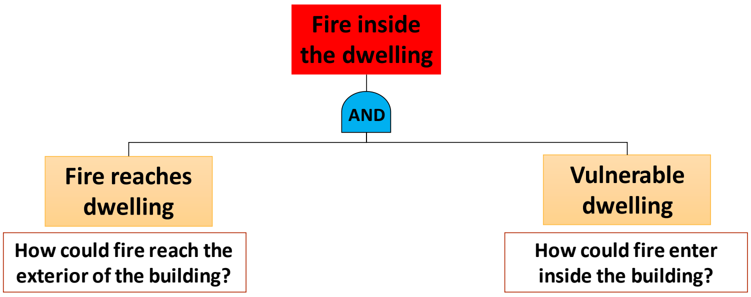

Figure 1: Events that lead to fire enetring a buidling at the WUI

When it comes to the ways the fire can reach the building, two areas around the dwelling have been identified: zone 1 includes the area within a radius of 10 m from the dwelling, while zone 2 consists of a 10 m to 30 m ring around the dwelling. In both zones, three types of fuels are considered: ornamental vegetation, artificial fuels (e.g., LPG tanks, garden furniture, sheds, etc.) and wildland vegetation. A set of fuel management guidelines (based on a review of existing guidelines as well as from observations from past fires and fire tests) has been established for each type of fuel. Failure occurs when compliance to these guidelines is not met.

The same method is applied to elicit the structural vulnerability of the dwelling according to the different paths through which fire could enter. According to Vacca et al. (2020), there are four main paths: glazing systems, roof, vents and structural damage to the dwelling's envelope due to heat accumulation in semi-confined spaces. The failure sequence for each one of these elements is identified as shown in Figure 2. For example, the failure of a glazing system depends on the thickness of the glass pane and the type of shutters, with different degrees of protection depending on the material.

Quantification of the probability of failure of each of these events has proven to be difficult, as information on paths that lead to ignition during past fires is not always available or reliable, as it is mostly collected without the possibility of thorough investigation due to lack of information or resources. To deal with this difficulty, a model that combines fuzzy logic with classical logic has been developed, that uses fuzzy sets that provide means to model the uncertainties associated with lack of information (Sivanandam et al. 2007).

2.1. Model Description

The structure of the developed model is given in Figure 2. Note that, according to Figures 1 and 2, two system variables lead to the final output of the model (i.e., fire inside the dwelling) through a classical logical AND gate, these are: (i) Probability of fire reaching the dwelling (POF_1) and (ii) Probability of failure of the dwelling due to its vulnerabilities to fire (POF of the dwelling). In the same way, this last variable (ii) is obtained through a classical logical OR gate according to the values obtained for the probabilities of failure of the four elements that constitute pathways for the fire into the house, i.e. glazing systems, roof, vents and semi-confined spaces that can suffer structural damage due to heat accumulation. The probability (i) (POF_1) depends on the compliance to different rules set for fuels located in the two considered zones previously described. All the probabilities of failure are obtained through the use of fuzzy logic. Seven fuzzy inference systems (FIS) are defined, as shown in Figure 2.

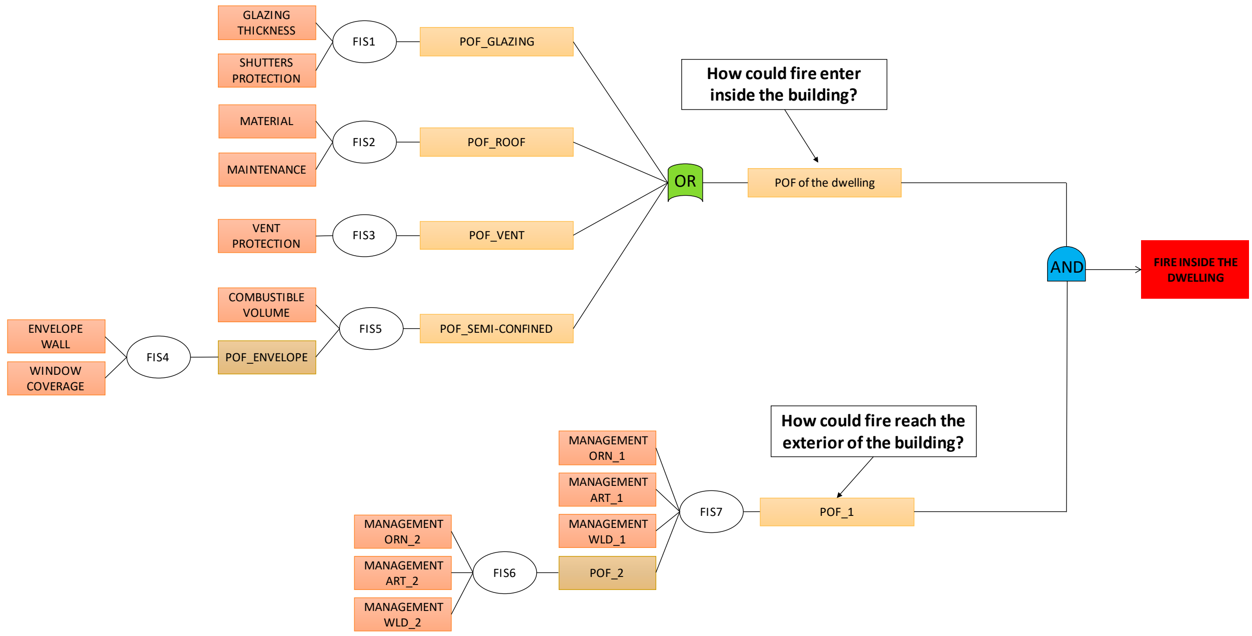

Figure 2: Scheme for vulnerability assessment to wildland fires for dwellings at the WUI. FIS: Fuzzy Inference System; POF: Probability Of Failure; ORN: Ornamental; ART: Artificial; WLD: Wildland; _1: Refers to zone 1; _2: Refers to zone 2.

When a FIS is defined, the generic process shown in Figure 3 must be followed. Initially, the variables that are relevant in the system must be identified (inputs and outputs). These variables must then be fuzzified, meaning that they need to be defined as fuzzy sets by identifying their universe of discourse and selecting a set of linguistic terms (i.e., fuzzy subsets) that accurately describes them. Subsequently, a membership function for each fuzzy subset must be defined to quantify the degree of belonging of any value in the universe of discourse to each fuzzy subset (Sivanandam et al. 2007). Then the inferring process is performed by using a set of rules that connect antecedents (input variables) with the consequent (output variable). These rules usually have a structure such as: "IF …, THEN …". An aggregation process is required to take into account the different rules that activate according to the inputs. Then, since the output is also defined as a fuzzy set, a defuzzification process is necessary in order to transform the fuzzy results into a precise output.

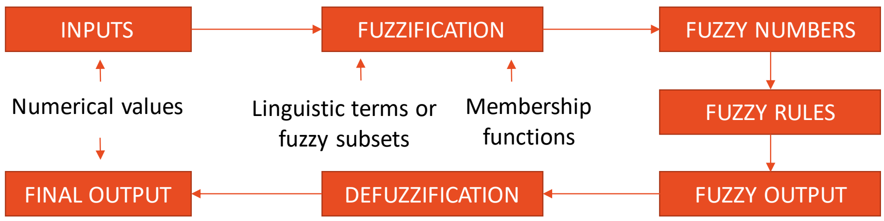

Figure 3: Generic Fuzzy Inference Process - bas ed on (Darbra et al. 2008)

2.2. Poll for experts

A poll for experts on WUI fires and vulnerabilities was prepared to calibrate this fuzzy model. It was filled in by 13 experts. Their expertise helped to determine membership functions, as the poll consisted in giving the most characteristic value (or range of values) for the fuzzy subsets that defined each set present in the model. Additionally, the poll included the fuzzy rules, for which the experts could choose the linguistic value of the output variable. When more than one input variable was combined, the logical operator AND was used. An example of the selection for the rules' consequent is shown in Figure 4.

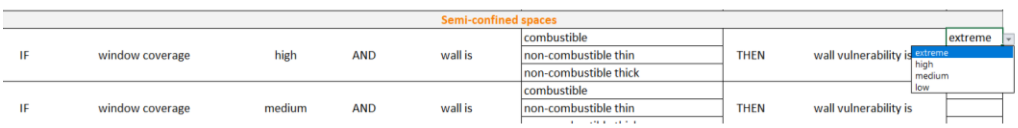

Figure 4: Example of rules present in the questionnaire prepared to synthetize experts' knowledge

2.3. Homeowners questionnaire

The previously presented model has to be used together with a questionnaire that homeowners can fill in autonomously. Questions can be answered mainly with YES or NO and they include all information needed to run the vulnerability model for a specific property. An example of the type of questions is shown in Figure 5.

	Building characteristics	
	Shutters	
1	Do you have protection for all your windows/glazing systems (i.e. shutters)? made of non-combustible materials (solid core wood fire-resistant, metal like aluminium)?	□ Yes □ No
2	What material are the shutters made of?	□ Wood □ Aluminium □ PVC □ Fire resistant materials
	Glazing panes	
3	What is the thickness of the glazing systems (in mm)?	
	Roof material	
4	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.)?	□ Yes □ No
	Roof maintenance	
5	Are there missing, displaced or broken tiles?	□ Yes □ No
6	Is the underlying roof sheeting exposed?	□ Yes □ No
7	Are there unsealed spaces between the roof and the external walls or between the roof covering and the roof decking?	□ Yes □ No
8	Do you perform regular cleaning of debris piling up on roof or gutters?	□ Yes □ No

Figure 5: Example of questions included in the homeowners questionnaire.

Once the questionnaire is completed, the replies are introduced into the fuzzy model to calculate the probabilities of failure of the different considered elements, which are then used to calculate the probability of a fire entering a building.

3. Case study

This vulnerability model was tested using information gathered from five homeowners affected by a WUI fire that took place in July 2021 in Lloret de Mar, Spain. These homeowners replied to the questionnaire and we used their answers to quantify the probability of fire entrance in their dwelling (Table 1). They got our feedback and could identify the different issues (fuel management, structural constraints, etc.) that needed to be addressed in order to reduce this probability.

The WUI fire under study prompted evacuation orders and several homes were threatened, various elements present outdoors were burned (e.g. vehicles, fences and garden furniture), and one house was severely damaged (H02) due to the fire entering the building as a result of the breakage of a window pane.

Table 1. Probability of fire entrance in the dwellings according to the elements identified in the scheme for vulnerability assessment to wildland fires presented in Figure 2. FIS: Fuzzy Inference System; POF: Probability Of Failure; _1: Zone 1 (10-m around the dwelling); _2: Zone 2 (10-m to 30-m ring around the dwelling).

FIS / Classical logic results (%)	**Dwellings**				
	H01	**H02**	**H03**	**H04**	**H05**
POF_GLAZING	39	48 (70*)	65	16	16
POF_ROOF	14	14	65	14	14
POF_VENT	0	0	88	0	0
POF_ENVELOPE	0	14	39	39	39
POF_CONFINED	0	41	32	21	21
POF_2	71	71	88	65	88
POF_1	55	87	83	63	66
POF of the dwelling	47	74 (85*)	99	42	42
Probability of fire entrance	26	64 (74*)	82	27	28

* Values obtained considering no-shutters, since PVC shutters were not pulled down during the fire.

According to Table 1 the dwellings with the highest probability of fire entrance were H03 (82%) and H02 (74% considering no-shutters). H03 presented the highest probability of failure of the dwelling itself (99%). Vulnerable elements in H03 structure were the shutters' material, glazing thickness and vents design. Moreover, regarding the probability of fire reaching the dwelling (POF_1), H03 had a value of 83%. This value was not the highest one from the set of dwellings monitored, since H02 reached a slightly higher value (87%), but it was quite high nonetheless. The dwelling H02 had the highest probability of fire reaching the building (POF_1 = 87%), because compliance with fuel management rules was low in both zones.

4. Conclusions

The tool we have developed (i.e. VAT) considers the complex nature of the WUI microscale fire risk problem through the use of fuzzy logic. The end users of this tool are intended to be not only fire safety practitioners, but also the homeowners and residents of the WUI. The use of this VAT will lead to the improvement of fire safety practices at the microscale; i.e. it will increase WUI fire risk awareness of homeowners by identifying systematically major problematic conditions present on their property and in its surroundings. While the building of the tool is complex, the final product that is presented to the user is straightforward and easy to use. Moreover, a planned use of this tool at a local level would be key to improving fire protection at the community level.

5. Acknowledgements

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