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Interface Fires in Built-Up Areas. A Real-Case Study on the Risk Assessment of Fires Interacting with Urban Domains

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Fire scenarios may pose serious risks and induce severe damages to anthropic structures, activities and business. These can be represented by typical fires in industrial facilities or also atypical scenarios involving differentiated targets as in the case of interface fires. Risk assessment of atypical scenarios requires improved approaches since a multi-risk framework can arise including the interactions between the fire and surrounding domains. An effective hazard investigation and management should therefore include estimations of consequences based on the results of models simulation. The present study deals with a preliminary risk assessment methodology applied to fires interacting with an existing urban area. The fire spread is approached through a dedicated tool and a GIS (Geographic Information System)-based system used to spatially map expected consequences. Starting from these data, a preliminary risk estimation is proposed with the aim of mapping hazardous areas. In this sense, a combined approach based on fire simulation tools and exposure functions is employed. Major risk areas for specific targets are identified in terms of risk contours and expected results can be used to support land planning and emergency-related operations.

1. Introduction

Fire occurrences, within the context of quantitative risk assessment, are one of the most common adverse hazardous situations in the process industry and robust methodologies have been developed to predict and manage their effects on industrial equipment. However, besides these typical frameworks, unconventional fire events exist. Among these, hazards involving interface fires and wildfires play a key role in specific areas where an interaction between natural susceptible areas and vulnerable anthropized districts emerges.
Wildfires are specific types of forest fires, and the first part of the term refers to the uncontrolled conditions of the combustion. Contrary to the general perception of the phenomenon and the media coverage, wildfires are actually not amongst the main global natural issue in terms of overall deaths and economic damages caused, coming well after floods and earthquakes. Furthermore, the area affected by this hazard shows a decreasing trend in recent years, although, for ecological phenomena, long temporal series of records are necessary to obtain definitive figures (Doerr and Santín, 2016). In any case, their importance may be locally very relevant, since even single high severity events may be accountable for a high share of fire damages inside a country. With the ongoing climate change, fire regimes are likely to change, increasing the need for tools to better evaluate the fire hazard. Far from being only a wildland issue, wildfires seem to increase in proximity to anthropic activity, as known for long by professionals managing risk in the Wildland-Urban interface (WUI). The WUI, defined as the area where buildings are conterminous to -or intermixed with- wildland vegetation, is really vulnerable in case of a wildfire, because the simultaneous presence of high valuable assets and high fuel load provided by the vegetation can increase the ignition probability and causes great difficulties in the firefighting procedures (Platt, 2010). Originally born to define urban structures, the concept of the WUI is now being applied also to industries and infrastructures (Johnston and Flannigan, 2018), recognising the importance of their safeguard in case of fire events.

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In this vulnerable framework, a risk assessment activity is required in order to identify, quantify and mitigate the risk related to wildfires and WUI fire scenarios. The need for a risk analysis falls within a holistic strategy aimed at preserving the community resilience, and where impractical, at posing viable preventive and mitigative actions. The reduction of WUI fires occurrence should benefit from a synergistic approach of risk assessment and land use planning. The risk identification applied to WUI fire requires a detailed knowledge of the study area in terms of both anthropic sites distribution and landscaped domains where fire may ignite and propagate. Information on fuel characteristics (e.g. load and spatial arrangement) and features are essential to model the fire spread and to simulate prevalent evolution towards interface areas. In addition, the risk assessment in WUI areas requires weather boundary conditions that interfere with the fire evolution. The core topic of an effective risk assessment is the identification of critical fire scenarios that may affect anthropic domains to drive, and wherever possible to rearrange, the land management. The preservation of community resilience is crucial and should also be based on a land-use planning that integrates WUI fire-risk related issues.

This work is thus focused on risk assessment of fires interacting with urban domains and is related to an innovative preliminary risk assessment approach. A combined methodology is employed for the mapping of hazardous areas that is crucial to prevent and mitigate fires in highly populated areas.

2. Fire risk analysis in the WUI

2.1 The wildland urban interface wildfire phenomenon

Increase in the awareness of the great importance of the connection between wildfires and the WUI started approximately in the mid XX century in California, as a consequence of the combination of one of the most wildfire prone environment in the world and urban sprawling. Over the decades, the problem has continued and increased, both in North America and worldwide, taking its toll of buildings burnt and lives lost amongst residents and firefighters (Radeloff et al., 2018).

The simultaneous presence on the same territory of a considerable number of dispersed, high valuable assets (mainly houses) and a high fuel load from vegetation(forests, shrublands and grasslands) which are not generally present in an urban setting, determines an increase in fire risk. The resulting fires have therefore the characteristic extent and behaviour of wildland fires but affect human assets as urban structural fires do: a complex problem for which neither “urban” nor “rural” firefighters can be ready. A definitive solution to the problem would only be possible by reducing the exposure of the assets, for example through a more regularised urbanisation. Despite the need of this paramount change in land planning in the WUI, it is also necessary to find viable solutions to mitigate wildfire risk in already established settlements (Syphard et al., 2017) and to identify the WUIs in order to prioritise the risk mitigation interventions. Regarding the latter point, in recent years researchers from all over the world have produced a sizeable amount of solutions for defining, and consequently for mapping, the WUI at various geographical scale. Following this line, the Action 3.2.3 of the EU Interreg Project CROSSIT SAFER (https://www.ita-slo.eu/en/crossit-safer) aims at finding a new methodology for assessing and mapping wildfire risk in the wildland and in the Wildland-Urban Interface, taking advantage of several previous EU projects and of the advancements in remote sensing technologies and availability gained in the last years, especially regarding Light Detection and Ranging (LiDAR) data.

WUI fires are characterized by the following features:

- the fire propagation, differently from a confined fire scenario, takes place within a fully ventilated domain, i.e. the propagation of the fire is governed mainly by fuel characteristics, availability and distribution;
- WUI fires can start as wildfire, and ignition sources can be ascribed to anthropic causes (sparks, open flames, arson). At the same time, WUI fires can start from the urban component of WUI and affect the nearby wildland, as is most often the case in Southern Europe, where buildings provide shelter -more than fuel- to the fire;
- additionally, the fire propagation may tamper anthropic areas and thus the fuel mixture may change in space and time also involving industrial hazards;
- fire control and extinction operations may suffer impractical access to affected areas;
- besides, some firefighting techniques adopted in wildland context cannot be carried out in the WUI, e.g. waterbombing, due to the common presence of high voltage aerial powerlines, or backfiring, due to the scattered presence of high value structures.

2.2 Risk analysis and modelling of WUI fires

The quantitative risk assessment approach requires the quantification of a risk scenario. A comprehensive solution is focused on both the probabilistic and the effect quantification aspects (Russo et al., 2013).

In the case of wildland fires and WUI fires, the quantification is related to both the fire ignition source and the fire evolution within the spatial context. Additionally, the availability of data about land use and anthropic activities is essential to deal with domino effects at the WUI level.
Table 1 includes the main approaches to the risk evaluation in the context of WUI fires.

Table 1: approach and generalized tools to WUI fires risk evaluation.

Risk aspect	Tools	Notes
Wildfire occurrence frequency	Historical records, human behaviour, climate conditions	Ignition sources of wildland fires are sometimes hard to be identified. Human behaviour has a role whether the fire ignites within an urbanized area.
Fire spreading and evolution	Simplified modelling approaches (stationary models)	Simplified models can be used to map the consequences of a WUI fires in the context areas, under conservative assumptions.
	Detailed modelling approaches (transient CFD, pyrolysis models, real time GIS-based models)	Detailed models require additional information to model specific fire spreads in critical areas (i.e. near urbanized, industrial and vulnerable areas).
Vulnerability	Urban planning data, GIS catalogues, land-use maps	Data on the surrounding contexts are essential to deal with fire effects on the community vulnerability and resilience.

3. A modelling approach to WUI fires

3.1 Static modelling of WUI fires: FLAMMAP

One of the tools most commonly used in wildfire risk assessment is FLAMMAP (www.firelab.org/project/flammap), a software that simulates wildfire characteristics over a georeferenced area. The software is based on semi-empirical mathematical models developed in the last decades to quantitatively analyse the wildfires and it has been largely validated by practitioners through the years and worldwide. Its quasi-empirical base represents both its strength and its flaw: the software is stable, easy to use and resources-saving, but at the same time it cannot reach the precision of process-oriented simulation software, like those based on the Computational Fluid Dynamics (CFD). Among them, the NIST WUI extension of the Fire Dynamics Simulator (WFDS) allows for detailed study of interactions between fire in the wildland and spreading modifications when encountering an anthropic urbanised area. WFDS can solve dynamically governing flow equations, heat transfer, combustion and thermal degradation of vegetative fuels on a meshed fluid dynamics domain. Detailed approaches as WFDS can hardly be implemented for risk identification and emergency management, given the great computational burden required to solve fluid dynamics detailed problems: only critical areas and scenarios are eligible for CFD-based strategies. FLAMMAP, instead, is chiefly intended to map wildfire hazard over large areas (whole landscapes, regions), being the most usual cell resolution 30 m, which is a good degree of precision for land managers. It is also a static simulator inasmuch, in basic runs, wildfires parameters that can vary in the short time (fuel moisture, weather) do not change during the simulation, confirming its use as a mapping tool to assess the overall wildfire hazard of an area. In recent versions, however, some improvements have been added: from v.6 it is possible to simulate the dynamic behaviour of fuels and weather, and already from v.3 it is possible to choose between “basic” spread simulation method, which uses the Huygens’s wave propagation principle, and the minimum travel time (MTT) method, which calculates the fastest routes inside a lattice network based on segments properties. With the latter, it is also possible to simulate fire spread for a certain time starting from random or user-defined ignitions. The basic input of the software is a landscape file (.lcp), which describes the study area by stacking 8 layers of information: elevation, slope, aspect, canopy cover, trees height, trees crown base height (CBH), canopy bulk density (CBD) and fuel model. The meteorological boundary of the simulation is defined by windspeed and wind direction. For operational use, the former value is usually the 95th percentile of recorded wind and the latter is the mean wind direction during wildland fires season, which varies according to the location. A final required input is fuel moisture content. Since FLAMMAP is used to simulate the fire front spread, only moisture of the fine fuels is accounted: those are defined as the vegetal fuels that more easily are ignited and transmit fire and are all downed wood (twigs) smaller than 7.5 cm in diameter, herbaceous vegetation and shrubs. Downed wood is further divided into three fractions according to the time lag classes (10, 100, 1000 h). FLAMMAP can be used for mapping wildfire hazard in the wildland and in the WUI, using remote sensing, topographic database and field collected data. Since its capacity has already been validated for wildland areas, in this case study it has been used in an illustrative WUI to test its capability and its potential drawbacks in a such specific scenario.

3.2 Hazard assessment of a case study

The WUI case study area (Figure 3a) has been chosen among the CROSSIT SAFER project test sites (https://www.ita-slo.eu/it/crossit-safer), but the approach can be easily extended to any campsite with permanent structures in close proximity to a vegetated area. The data necessary for the landscape file were retrieved from several sources. The Digital Terrain Model (DTM) was downloaded from the geoportal of Regione Veneto (https://idt2.regione.veneto.it/), then processed to obtain slope and aspect. The land use vectorial layer from Corine Land Cover 2018 database was used as a base to spatialise the fuel data collected during field surveys: forest canopy cover, trees height, CBH and fuel properties necessary to define fuel models, as well as CBD (visual estimation). Weather data were obtained from daily records 1992-2019 provided by the Servizio Centro Metereologico di Teolo – ARPAV (https://www.arpa.veneto.it/arpav) and mean summer (Jun-Aug) wind direction and 95th percentile windspeed were calculated. Since the close proximity of the study site to the sea and deeming the calculated value of 2.68 m/s (equivalent to 6 mph, as requested by the software) too little to represent daily wind gusts from the sea, also a 10.73 m/s (24 mph) windspeed was used for the simulation, based on usual values experienced in summer during the central hours of the day. Four fine fuel moisture scenarios were tested as proposed by Scott and Burgan (2005), ranging from totally cured (dry) to totally green fine fuel.
FLAMMAP was first run in both basic and MTT method with 6 dichotomous factors, changing one factor level at a time (n= 64 runs) in order to determine which were the most influential. Finally, only 8 scenarios were selected, simulating a forest fire spreading in summer (direction 100 °N) under two wind and four fuel moisture conditions. The MTT was run with 1000 random ignitions for 30 minutes, being usually 15-20 minutes the intervention time for the local volunteer firefighting crew (personal communication). Among the several outputs, five were examined as the most informative in the WUI risk assessment: fireline intensity (kW/m), flame length (m), rate of spread (m/min), probability of burning of fuel cells, and type of fire related to canopy burning (van Wagner, 1977). The input and output data are resumed in Table 2.

Table 2: inputs (left) and outputs (right) data for FLAMMAP case study simulation.

Inputs	Values	Outputs	Values range
Fuel models	102 and 165 (Scott and Burgan, 2005)	Fireline intensity	5523 kW/m
Windspeed	2.68, 10.73 m/s at 6 m above ground	Flame length	0-8 m
Wind direction	100 °N	Rate of spread	0-0.18 m/s
Fuel moisture	4 classes, from fully cured to fully green.	Probability of burning	0-13.4%
Ignitions	1000 random	Type of fire	Surface, passive crowning
Simulation duration	30 minutes		

3.3 Risk assessment of a case study

Risk evaluation is based on both probability occurrence and magnitude of a specified fire scenario (Alexandridis et al., 2008). In the present case, starting from data of Table 2, a risk matrix is built in which a risk level is codified depending on the burning probability and the expected effects. While the probability of burning works on the probabilistic term of the risk, the effects are obtained from the fireline intensity. The fireline is intended as a heat source to be used as input in a solid flame model to evaluate expected effects. Given the fireline intensity expressed in terms of emitted power per unit of length and the geometrical flame length, a thermal flux emitted as of conventional extended fire source is obtained. The solid flame model is applied to the present work, the flame is intended as vertically developed with a view factor of 1 for conservative purposes (the entire emitted energy is totally received by the target). The thermal contribution is thus applied to a specified target through a probit function approach and depending on expected effects, the damage can be categorized as negligible, light, moderate and severe. Risk contours are related to low, moderate and high yearly risk specifically equal to 10^{-8}, 10^{-7} and 10^{-6}. These data are derived from acceptability criteria in the industrial context being lacked for urban domains and WUI. The resulting risk matrix, combination of the burning probability and the induced effect, can be overlapped to a land map to identify high-risk areas. In this study, two distinct targets are considered: a human target and the mapped permanent structures, here intended as building structures differentiated between those predominantly made of wood, polyvinyl chloride (PVC) coating components and iron frameworks (campsite structures) and common concrete buildings. Threshold values of 1.5, 3 and 5 kW/m^2 are used respectively for negligible, light and severe effects on a human body exposed to the thermal flux emitted by the fire. Instead, for the building structures data are related to two differentiated threshold thermal power of 15 kW/m^2 and 60 kW/m^2, critical respectively for the thermal interaction with the external plastic coating of structures (Hull et al., 2009) and the concrete structures.

4. Considerations on WUI fire modelling

Results obtained from the simulation show that FLAMMAP can be a useful tool for assessing and mapping fire hazard also in the WUI, being able to discern between fuel cells and to give information to prioritise interventions (Figure 1). Another advantage of the software is its possibility to spatialise the data, in order to make them visible on any GIS and make it possible the integration with other informative layers. Finally, the ease of use and the low requirement in computational power explain why it is so diffuse among land managers dealing with wildland fire issues. The association of results given by the simulation with FLAMMAP can be used to assess the risk within a specified context to deal with the effects related to a WUI fire. In the present study, the application of the main outcomes of FLAMMAP (Table 2) to the conventional solid emitting flame model has allowed for the quantification of the effects of the fire with respect to specified targets. Additionally, the probability of burning has been used to deal with the probabilistic term of the evaluated risk.
Results related to the simulated fire frequency are used to plot risk contours related to the thermal effects induced by the simulated fire on target structures as of Section 3.3.

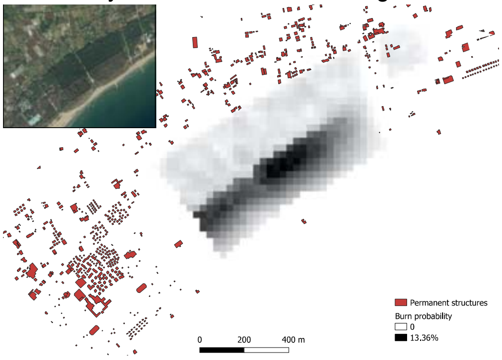

Figure 1: map of the simulated fire frequency (n=1000) obtained with the MTT method and the most intense windspeed (10.7 m/s). In red the permanent structures from the topographic database and in the corner an aerial view of the pine forest and retro-dunal formation.

Risk contours for campsite permanent structures and concrete structures are reported respectively in Figure 2 and 3. It can be noted that safety distances for thermal effects induced by the fire may amount up to 500 m, beyond which negligible effects due to fire on structures are expected. It means that within this distance, the structures probabilistically suffer damages induces by the simulated fire. Calculated risk is enhanced approaching the source boundaries mainly because of the increased magnitude contribution to the risk and probability to come across the fire. Based on resulting data, campsite light structures fall within high-risk area (> 10^{-6} /yr.) within 200 m from the simulated fire (Figure 2). From a general perspective, they may suffer even light damages at distances up to 500 m that is these structures are more vulnerable to the simulated fire.

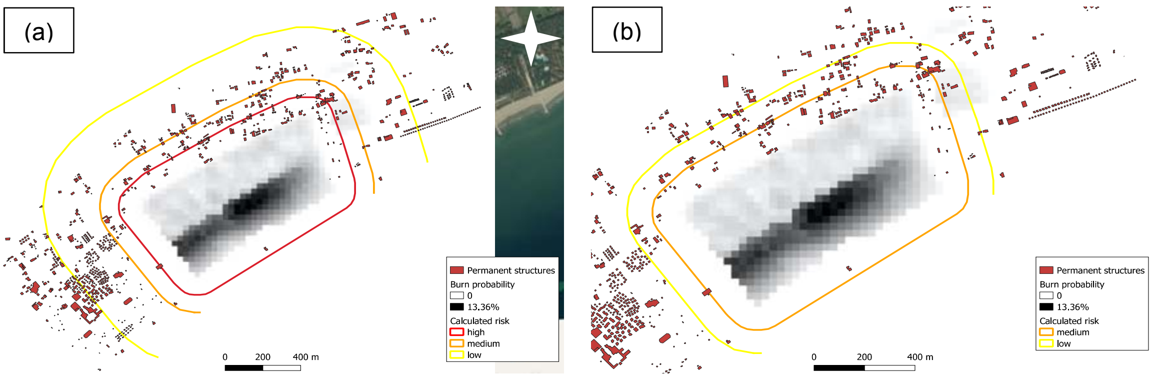

Figure 2: risk contours based on thermal effect on permanent light structures (a) and concrete structures (b). Red contour: high risk, orange contour: medium risk, yellow contour: low risk.

In addition, Figure 2 shows that concrete structures are not expected to probabilistically suffer severe damages and no high-risk contours emerged. Nevertheless, some limited structures are located within moderate risk areas whose risk contour is about 100 m from the hazard source. The related risk of damage within this area amounts up to 10^{-7}. These results can be used to drive and support actions for risk reduction, especially for targets located within high-risk sector. Risk can be reduced synergistically acting on preventive and mitigative aspects. Given the extension of the high-risk contours, especially for light campsite permanent structures, a solution could be to prevent and control fire ignition sources. Measures intended to prohibit dangerous behaviours that may trigger unintentional fire are essential as well as the preservation of unfavourable conditions to fire spreading. In addition, where appropriate, management actions can contribute to risk reduction and may include the rearrangement of campsite sectors based on calculated risk contours. Discussed results so far may suffer some limitations. Among the limitations of the tool, the principal is its resolution, limited to 30 m cells due to the semi-empirical equations used, which are at the same time the reason for its easiness of use and rapidity. Another flaw of the software is the peculiar type of data required, namely weather and fuel data; while for the former type it is possible to contact the public meteorological service, for the latter it is still necessary a significant field data collection, at least until advanced remote sensing techniques will make it possible to reduce field visits to simple validation of the data. In addition, the simulated scenario is stationary, even if derived under the most conservative conditions. Future improvements should include dynamic approaches that may catch specific aspects of the fire spread especially when interacting with urban and vulnerable areas. A possible improvement to the risk assessment methodology in the WUI would be to join the potentialities of semi-empirical and CFD simulation software, to take advantage of both in their respective field of action. To our knowledge, some attempts have been made to compare the theory underlying the two simulation approaches (Bova et al., 2016), but tests in real case studies and comparison with reports of the fire events may give useful insights into the topic.

5. Conclusions

A preliminary risk assessment methodology was successfully applied to a fire interacting with an existing urban area. The fire spread was approached with a dedicated tool (FLAMMAP) coupled to a GIS-based system and the related thermal impact on selected targets was evaluated through a conventional solid emitting flame model. Risk contours were identified in order to map the risk as combination of the probability to experience an induced effect on permanent structures and the level of damage. Results showed that safety distances required to negligible risk conditions may amount up to 500 m from the boundaries of the fire source. Within this distance existing permanent structures probabilistically experience enhanced levels of risk approaching the fire source, but concrete permanent structures do not experience high-risk conditions. Resulting risk contours and thus the proposed approach can be used to support planning and operation actions for risk reduction especially for those structures located within high-risk areas.

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