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LUÍS MÁRIO RIBEIRO

Wildfire and evacuation simulation: An overview of research, development, and practice

Shahab Mohammad Beyki; Aldina Santiago; Luís Laím; Helder D. Craveiro

University of Coimbra, ISISE, Department of Civil Engineering, Coimbra, Portugal,
{Shahab.m.beyki@gmail.com, aldina@dec.uc.pt, luislaim@uc.pt, heldercraveiro.eng@uc.pt}

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Abstract

Wildfires have been growing dramatically over the past decades due to climate changes, global warming, droughts and forest-landscape, and vegetation changes. Increasing losses due to wildfires have been a significant concern; therefore, wildfires have become an important field of study and research. This paper assesses and reviews the wildfire simulation approaches to predict the fire spread characteristics. These simulations are essential to analyze the potential risks and impacts of wildfire, predict the fire rate of spread (RoS), fireline intensity, and flame length, which are the most crucial parameters for fire management and first responders, and determine the evacuation necessity or requirement. The assessment of evacuation triggers is investigated according to the available literature, and studies on wildfire and fire spread simulation based on different approaches such as physical, numerical, or computational fluid dynamic (CFD) modeling and empirical are reviewed. All mentioned simulations are modeled on different scales, i. e. microscale, mesoscale, and macroscale, based on the desired criteria assessment of each case study. These approaches are distinguished basically by their ability to model an area of a certain extent or scale, and their accuracy in attaining the desired analysis, data, and prediction, and selecting one approach over the others is always a trade-off between these two criteria.

1. Introduction

Wildland fires have been recognized as a crucial field for research by the International Association for Fire Safety Science (IAFSS) agenda 2030 for a fire-safe world (McNamee *et al., 2019*). Wildland-urban interface (WUI) communities are defined as places "where humans and their development meet or intermix with wildland fuel" (Us Department of Agriculture, 2001), which are the most vulnerable to wildfires given their proximity. Moreover, other risks usually exist in WUI communities, such as insufficient transportation systems that fall behind in comparison to urban development and an increase in population; for instance, many WUI communities have only one road in and out of them, which can cause difficulties during evacuation (Cova, 2005). Multiple fatalities have been reported as the consequence of a wildfire or occurred during evacuations due to the inadequacy of the rural road. The inadequacy of the rural roads can cause congestion and trap the evacuees (e.g., Pedrogão Grande). Moreover, delayed evacuation triggers alarm or delays in evacuation advice implementation are other problems, which can cause locals to stay until the last minute and face hazardous situations (Haynes *et al. 2010*).

Wildfire modelings play a crucial role in fire management, determining the fire risk exposure, mitigating fire risk, evacuation management, and evacuation planning. The ability to forecast the wildfire behavior accurately will ensure the safety and effectiveness of wildfire control and fire management (Countryman, 1972). Different aspects of fire in the wildland context, such as intensity of the fire, direction of spread, and the rate of fire spread in the wildland, are the main desired quantities, which are modeled in accordance to conditions that affect the wildfire, e.g., weather, topography, vegetation, etc. (Dhall, 2020). A flow diagram is presented in Fig. 1 to grasp an idea of different factors of uncertainty that would affect the characteristics of fire.

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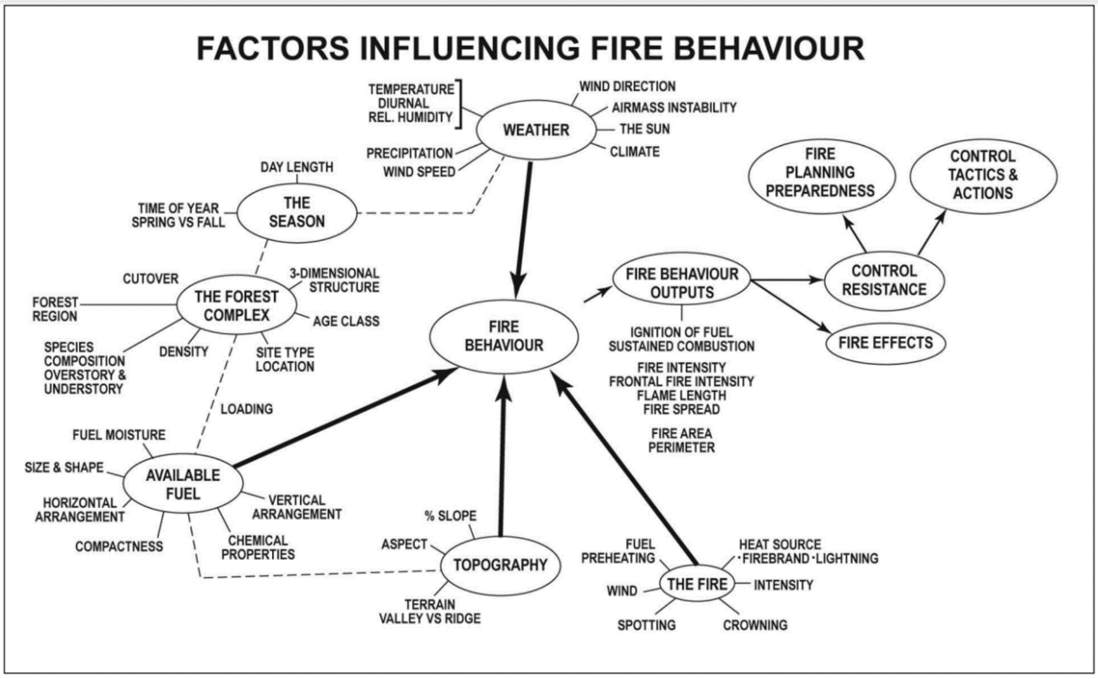

Fig. 1. Factors influencing wildland fire behavior and in turn, the complexities involved in its prediction (Santoni et al. 2011).

Wildfires, especially at the wildland-urban interface, raise various challenges for the residential population and the governing authorities in terms of producing a safe and effective plan to preserve the society, protect the infrastructure and residents' assets, and, if necessary, evacuation. To ensure life safety and evacuation effectiveness, various social and environmental characteristics of WUI communities, which pose different challenges, need to be addressed (Cohn *et al.* 2006). Heterogeneity of the household density over the WUI, layout and the positioning of the roads, insufficiency of the roads due to the WUI community growth, and the topography and geography of the surrounding environment are the physical factors that need to be considered to produce an effective and safe evacuation (Cova, 2005), in addition to social factors, e.g., age, sex, income, race, and culture of the residents (Folk *et al. 2019*, McCaffrey *et al.* 2018, McLennan *et al.* 2019, Vaiciulyte *et al.* 2018). Even though it is not yet the standard protocol, evacuation simulation models are increasingly used to develop better evacuation strategies for WUI communities (Pel *et al.* 2012, Alsnih *et al.* 2004). These simulation models enable the authorities to manage and plan an effective evacuation by deciding the evacuation trigger or start time, evacuation roads and routes, and traffic management for different wildfire scenarios. This is achieved by forecasting evacuation-affecting factors, i.e., departure time and pattern, travel duration, the mean speed of the evacuees, the traffic length, and flow rate (Pel *et al.* 2012).

2. Wildfire modeling

Wildfire simulation models are distinguished into two basic categories regarding their fundamental approach: physical models and empirical or semi-empirical models. The actual development of the combustion process is not the aim of empirical or semi-empirical simulations but rather be used in the management and decision-making process (Papadopoulos and Fotini-Niovi 2011). Many identified a coupling of both approaches as the best solution to better simulate the characteristics of wildfire and fire behavior (Cruz and Gould 2009).

Richard Rothermel (1972) published a detailed mathematical model of wildfire to predict the fire rate of spread in wildland fuels, which is the basis of many other models and simulations. This model could not be used to incorporate the crown fires, while it could only predict the fire's intensity and its spread rate in a continuous fuel bed on the ground. Finally, with the development of such models and programs, computer calculations started their use for operational and research purposes in the field of wildfires in the 1970s (Frandsen 1973, Burgan 1979).

The cellular automata (CA) model was used by Karafyllidis and Thanailakis (1997) for the very first time to predict the fire spread in homogenous and heterogeneous forests (also referred to as the KT model). The most outstanding advantage of this model was the ability to incorporate weather conditions and land topography. Later on, in an attempt to create software to simulate small-scale fires in the Mediterranean regions, with the scope of fire management and deployment of firefighters, Giorgio and Baracani (2002) combined the mathematical model introduced by Rothemermel for the simulation of fire spread with the CA theory.

In the following years, various research was carried out to improve the KT model to get more accurate results. Hernandez Encinas *et al.* (2007) improved the former developed KT models with two different approaches. First, the wildfire spread in homogenous and heterogeneous environments was modeled by changing the square cellular into a hexagonal cellular automaton. Second, a more realistic simulation was achieved by improving the KT model, which was modeling the circular fire front spread coming from the diagonal cell over linear spreading.

Tiziano *et al*. (2015) presented a CA approach that can mitigate the problem of distorted fire shapes thanks to a redefinition of the spread velocity. With the same method, the Spatio-temporal evolution of fire bands simulation with more simulated fire properties was carried out by Yuxuan *et al*. (2018). Fire shape distortion simulation was improved without any mathematical correction.

Onur Satir *et al*. (2016) manipulated the artificial neural network method to map forest fire probability in Mediterranean forestland using multiple data assessments. A new method called Evolutionary Statistical System (ESS) was developed by Bianchini *et al.* (2015) to simulate forest fire spread. This method addressed the challenges raised by the input parameters' uncertainty.

The cellular automata theory was then combined with a data-driven parallel fuzzy theory approach to simulate the wildfire spread by Ntinas *et al.* (2017). The introduced fuzzy cellular automata (FCA) model enables data incorporation from real wildfires to improve its accuracy due to a data-driven approach based on evolutionary optimization. Nevertheless, the application of this method for real-time wildfire scenarios would be restricted due to its computational complexity. Zhong Zheng *et al.* (2017) applied extreme machine learning (EML) to the traditional wildfire prediction CA method and validated the newly introduced model with five fires in the western United States. Significant improvement in the simulation accuracy was observed as a result of the method implementation.

In recent years, extensive studies have been conducted concerning wildland-urban interface fire spread modeling. Jiang *et al*. (2021) proposed a fire spread model based on the heterogeneous Cellular Automata model for large-scale complex wildland-urban interface (WUI) areas using thermal principles and empirical statistics. Valero *et al.* (2021) enabled uncertainty quantification in wildfire CFD models using multi-fidelity strategies. Attempting to overcome the wildfire modeling uncertainties, which are mainly due to the computing constraints, these authors improved the classic Monte Carlo method and achieved simulation speedups of up to 100 times; this improvement was used to quantify uncertainties and assess the sensitivity of the fire rate spread (RoS) to weather and fuel parameters. Agranat and Perminov (2020) developed a physics-based multiphase Computational Fluid Dynamics (CFD) model of wildfire initiation and spread to create a user-friendly computational tool for analyzing wildland fire behavior and its effect on urban and other structures.

3. Evacuation modeling

On the other side of this field of research stands the evacuation simulations. Wildfires necessitate the evacuation of large groups of people from large locations, often across long distances. The increasing frequency of these catastrophes shows that suitable evacuation strategies for wildfire-prone areas are required.

There is a scarcity of household data on wildfire evacuation behavior to support and design evacuation models. Most wildfire research has focused on forecasting who would flee, and how to anticipate traffic needs, however, they are still restricted in scope. Evacuation models also require information on decisions and behaviors made during the evacuation process, such as which and how many cars will be utilized, which routes evacuees will take to reach safety, which destinations will be chosen as safe spots, and many other aspects (Alsnih and Stopher 2004). In the absence of such data, most models default to ideal household behaviors, such as Leon and March (2017), and/or only consider one method of transportation (e.g. on foot (Veeraswamy *et al.* 2018) or vehicles

(Shahparvari *et al.* 2019)). Because evacuation data from WUI fires is scarce, models that integrate behavioral features frequently rely on users' judgment or defaults, which are not always anchored in fire evacuation data (Carole and Gaudo 2017, Cova and Johnson 2002).

Traditional evacuation simulation models have been demonstrated to be too optimistic regarding clearance timeframes and other results (Murray-Tuite and Mahmassani 2003). According to a study by Wu *et al.* (2012), evacuees are unlikely to organize themselves optimally along major corridors during hurricanes. When compared to models using ideal assumptions, simulating actual behavior (e.g., individuals delaying evacuation and/or choosing regular routes) (Bulumulla *et al.* 2017) can considerably reduce evacuation "effectiveness" (Chiu and Mirchandani 2008). Incorrect assumptions regarding evacuation behavior in WUI fires might jeopardize the safety of a WUI community. Models that incorrectly account for evacuee decision-making and behavior might understate evacuation results (e.g., clearance time), leading to emergency officials using ineffective traffic management measures or delaying warnings until it is too late.

Multiple time periods are involved in the household evacuation procedure. Ronchi et al. (2019) describe a generic WUI fire evacuation timetable, which lists emergency officials' and households'/evacuees' activities chronologically. After being alerted and deciding to leave, a household's evacuation timetable may include time to finish preparations, time to go on foot, time to travel by car, and time to board at a safe location. Trip generation (which predicts the number of people who will evacuate and when they will leave), trip distribution (which predicts where [the destination] people travel to reach safety), modal split (which predicts the types of transportation chosen for evacuation), and traffic assignment (which predicts the routes chosen to reach the destination) are the four steps traditionally followed by traffic models to simulate households' evacuation timelines. Driving parameters (such as speeds and flows) are included in the traffic assignment (Koligowski 2021).

The type and structure of data required for each phase vary depending on the modeling approach. Macroscale, microscale, and mesoscale modeling methodologies are employed to simulate household behavior and mobility in evacuation models. To detect larger patterns in evacuation behavior, macro models describe households/traffic behavior at the aggregate level, needing data on traffic speed and flows, capacity, and densities. Individuals (agents or vehicles) can be simulated using microscale models, which require data about household decisions, behaviors, and/or movements within the broader evacuation community. Mesoscale models offer a middle ground between the two approaches, representing traffic entities in greater depth and their interactions at a lower resolution (Murray-Tuite and Wolsohn 2013). All modeling methods require data on WUI fire evacuation decision-making and behavior. Data on evacuation decisions and timing are required to give models and users information on the number of individuals, homes, and cars entering the traffic system at various points throughout the evacuation. To offer the models/users an evacuation endpoint, data on the destinations or zones to which evacuees would be moving is also required. Following that, data on mode choice reveals how evacuees are distributed across various modes of transportation of various sizes and capabilities. Finally, data on traffic assignment is required to inform models and consumers about how various modes are dispersed and move along the road network (Murray-Tuite and Wolsohn 2013).

Cova *et al*. (2005) developed a new method for delimiting wildfire evacuation trigger points using fire spread modeling and geographic information system (GIS). It was suggested that using data on wind, topography, and fuel in conjunction with estimated evacuation time, a trigger buffer can be computed for a community whereby an evacuation is recommended if a fire crosses the edge of the buffer. Additionally, in an attempt to couple the fire simulation, pedestrian evacuation, and traffic, Wahlqvist *et al*. (2021) developed the WUI-NITY platform, which simultaneously models fire and evacuation to enhance situational awareness in evacuation scenarios.

Ronchi *et al*. (2019) focused their study on the modeling of wildland-urban interface fire evacuations. Since the most important "layers" of a WUI wildfire, including wildfire, pedestrians, and traffic, were mainly modeled in isolation, this research presented a framework for evacuation simulation, including all the layers.

An agent-based simulation model (ABM) was developed by Grajdura *et al*. (2022), to study the behavior of evacuees in case of a fast-moving wildfire toward a community. A "Post-disaster Survey" and decision tree methods were used to model agent movements and decisions. Another study modeled awareness of the residents, departure, and preparation time in case of a no-notice wildfire evacuation (Grajdura *et al*. 2021). The effects of age, race, income and other characteristics of a resident at the time of being alerted to a wildfire were assessed. It was shown that smartphones and community evacuation plans have a large and positive effect on no-notice fire awareness time (Grajdura *et al*. 2021).

4. Gaps, challenges, and conclusions

As discussed above, in the field of wildfires and evacuation caused by wildfires simulation and modeling, there is always a challenge: the trade-off between computation power or availability and the accuracy of the results obtained by models. As a result, studies made step-by-step improvements, including considering more factors that influence the actual case to attain a more accurate result and changing the whole simulation model or the approach toward the problem. With advances in computer hardware and sophisticated processing resources, the "fully physical" models had exponential growth over the past two decades. Many factors which were considered for modeling by empirical correction coefficients are now modeled physically, and almost the exact phenomenon is implemented into the model. The distinction between radiation heat transfer and convection heat transfer, the existence of two different fire propagation regimens (wind-driven and plume-dominated), identification of surface fire and crown fire, and the transition of surface to crown fire, ignition by firebrands, fire whirlwinds, along with many other physical phenomena. Yet still, many other issues remain a challenge. Empirical factors that are used in the models need to be corrected and updated constantly; the weather data available for the fire propagation simulation are not completely exact and are based on forecasting, in which the intervals of forecasts are from hour to hour, the fuel models i. e., fuel types and fuel moisture content, vary from time to time in each location, and many other issues that need to be addressed to be able to make a more exact prediction on wildfire behavior.

As for the evacuation simulation models, none of the models that were overviewed are specially designed for WUI wildfire evacuation scenarios. But as discussed, they can be modified to provide useful data for evacuation planning and management regardless of their original mission. These models either focus on vehicle transport through the road systems as a mass concept or on individual cars through an urban area or even pedestrians. Usually, the integration between vehicles and pedestrian are not considered, which can cause serious challenges during a wildfire evacuation. The models usually lack detailed features which take the interaction between wildfire behavior and WUI residents' evacuation behavior. Different factors like age, sex, culture, race, and income affect each evacuee's decision-making process. Even the proximity to wildfire hazards has a great deal of influence on the behavior of evacuees.

Nevertheless, these models can be of great use in identifying critical points in a transportation system and roads that might cause problems during evacuations. The evacuee decisions can be estimated by a professional analyst and implemented into the model. In order to have a complete and effective evacuation simulation software, a model should be provided that integrates the wildfire characteristics, and smoke spread with the evacuee behaviors and the transportation and network system.

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