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Review

Software-Based Simulations of Wildfire Spread and Wind-Fire Interaction

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Abstract: Wildfires are complex phenomena, both in time and space, in ecosystems. The ability to understand wildfire dynamics and to predict the behaviour of the propagating fire is essential and at the same time a challenging practice. A common approach to investigate and predict such phenomena is making the most of power of numerical models and simulators. Improved and more accurate methods for simulating fire dynamics are indispensable to managing suppression plans and controlled burns, decreasing the fuel load and having a better assessment of wildfire risk mitigation methodologies. This paper is focused on the investigation of existing simulator models applicable in predicting wildfire spread and wind fire interaction. The available software packages are outlined with their broad range of applications in fire dynamic modeling. Significance of each work and associated shortcomings are critically reviewed. Finally, advanced simulations and designs, accurate assumptions, and considerations for improving the numerical simulations, existing knowledge gaps in scientific research and suggestions to achieve more efficient developments in this area are revisited.

Keywords: wildfire simulation review; fire spread; wind-fire interaction; software packages

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1. Introduction

Wildfires are a recurrent natural hazard in Australia, as in many areas worldwide [1–3]. There have been numerous occasions causing substantial loss of life and property in Australia in recent decades [4–7]. 2019/20 Australia's bushfire, the Black Summer fires, burnt nearly 48 million acres, destroyed more than 3000 dwellings, and killed 34 people and an estimated 1 billion animals. Some endangered species, the vast majority being reptiles, was believed to be driven to extinction [8]. One study estimated that 480 million animals in NSW may have been killed already, either during blazes afterward from lack of food, water, and shelter or increased risk of predation.

Wildfire is a complex heat release process, which is a combination of combustion, transfer of energy to adjacent unburnt fuel, and the continuous ignition of that fuel. Combustion is associated with the chemistry of the process and happens at the molecular scale. Energy transfer to the adjacent fuel, on the other hand, is linked to the physics of the problem and happens at a wide range of scales. The interaction of these processes over wide ranges of spatial and temporal scales makes modeling of wildfire a highly challenging task. For example, Ronchi, and Johansson [9,10] conducted a detailed review of different wildfire spread modeling techniques. Different analysis conducted in the past years indicates a continuous attempt that ranges from analytical investigations to experimental studies. Analytical simulations are more related to the basic knowledge of chemistry and physics in fuel ignition. While experimental studies are more or less related to the phenomenological definition of fire behavior. Although in the last thirty years, a fairly large number of fire experiments have been conducted, numerical simulation using computer simulators has some benefits over experiments in the prediction of structures affected by the fire. The major challenges for experimental studies are the time-consuming procedure and the higher costs of the tests. The primary objective of numerical simulation is to model the experiments that were previously possible to run only in laboratories [10,11]. Overall, there is a difference between fire behaviour models and wildfire simulators. The majority of fire behaviour models are obtained from experimental studies and wildfires [11,12]. These models are usually adjusted under ideal situations in particular uniform fuel mode (fuel distribution with a uniform structure in the fuel bed) and estimate the rate of spread as a function of weather, topography, and fuel load and distribution. The bushfire simulator on the other hand receives the examined spatial and temporal variant of these data and calculates the time-dependent spread of wildfire by applying the fire rate of spread suitable to local conditions. A wildfire simulator platform can be helpful in fire management practices if it is fast, straightforward to use, and have acceptable outputs to provide appropriate information for predicting wildfire behaviour [13].

The challenge in wildfire modeling arises from the range of physical processes and the temporal and spatial scales over which they operate. Modeling approaches will be discussed and differentiated from each other based on the degree to which the physical processes are explicitly dealt with. The focus of this review will be on providing an overview of available wildfire simulators. The fire behavior models including available simulation software and studies that address wildfire propagation and wind-fire interaction will be discussed in the present paper.

The content presented in this work is therefore classified into two distinct sections: (1) Wildfire spread models/simulators and (2) models focused on wind fire interaction.

Through our survey of the literature, we found that the simulators and modeling platforms developed by researchers worldwide on this subject are significant, considering the increasing relevance of wildfire spread and the hazards posed by wildfires.

However, it is important to identify existing knowledge and promote further research on both evolving and well-supported modeling platforms. Further interdisciplinary research is required especially in the development of simulating platforms for large and extreme wildfires in urban Interfaces to prevent and reduce fire risk in these areas.

2. Software on Fire Propagation Modeling

The ultimate objective that any fire spread simulation platform should be developed upon, is to generate a method that is feasible, easy to apply and delivers timely data on the growth of fire propagation for fire management agencies/authorities to be able to plan and act accordingly [14,15].

In the last few decades, with the introduction of inexpensive computing resources, a growing trend is observed in the development of computer-based methods and their application in estimating fire propagation across the landscape. One-dimensional computational methods originated from experimental investigations and were the most common technique in predicting fire spread. There is a need to further develop efficient yet accurate methods to transform one-dimensional methods to more realistic 2D or 3D methods [16–19] for fire spread and to cover the entire boundary of a fire front in two or three dimensions across a landscape. To achieve this, two distinctive practices are recommended. The first is to signify the fire in a way that is fit for simulation, and the second is to model the boundary of the fire front in a feasible way to represent the perimeter and height of the fire. The above-mentioned approaches have been used in several software.

A number of early fire simulators provide an assessment of the fire spread as an estimation of the rate of fire forward spread. In numerous instances, such estimations were applied by users to show the likelihood of fire spread on a map; as a result, setting the estimation based on the geographical characteristics or source placements and form a framework for fire spread modeling.

2.1. Fire Spread Simulation

Two approaches have been implemented in most of the available software. The first considers the fire as a set of mainly contiguous autonomous cells growing in number (Raster-based modeling), introduced in the literature as a raster technique. The second considers the fire perimeter as a closed curve of linked points, introduced in the literature as a vector technique (Huygen's wavelet principle) which has been outlined in the following sections.

2.1.1. Raster-Based Simulation

In raster-based modeling, the fire is modeled using a raster grid of cells with the status being burnt, burning, or unburnt. This technique is less intensive in terms of computation compared to that of the closed curve way (Huygen's wavelet principle) and is more suitable to heterogeneous climate conditions and fuel. This technique considers the spread of the fire as a group of cell-to-cell interactions instead of considering the dissemination of a contiguous front. Different proposed cell interaction rules have motivated the development of a variety of raster-based fire simulation models [20–28]. Green et al. [27] generated a landscape-simulating mechanism that used a raster-based fire spread simulation. Karafyllidis and Thanailakis [28] developed a raster-based model for a hypothetical landscape. The state of every raster cell is the proportion of the area burned of the cell to the whole area of the cell. Dah et al. [29] defined a novel wildland fire propagation estimation mechanism including raster-based modeling. Prior to expressing the fire simulators, an overview of fire behavior simulations applied in the relevant software is presented. Cellular fire propagation computational mechanisms (raster-based modeling) are easier to conduct [30–32], as there is no requirement to consider the fire-line geometry; the cell state has a finite value of states, and the progression from unburnt to burning to burnt is analogous, without considering the geometry of the Fireline. The most challenging matter in achieving cell-based fire propagation computational mechanisms is obtaining realistic fire shapes, as cellular techniques can be intensively impacted by the grid geometry which generates a distortion in the shapes of the fire [33].

2.1.2. Huygens Wavelet Principle

Huygen's wavelet principle was suggested by Anderson et al. [34] in the context of fire perimeter spread. Huygens' Principle basically suggests simulating fire growth by applying the fire environment at every perimeter point to orient and dimension an elliptical wave near every point on a fire front at each time step. The direction and the configuration of the ellipse are specified by the wind-slope vector whereas the size is specified by the fuel condition. Achieving this in a practical fire growth simulation is, nonetheless, significantly more complicated. The elliptical wave dissemination technique follows the fire front as a continuous boundary. The propagation rate at every point on the boundary is computed from local features and estimated in time on small time steps simulators according to the Huygens, or Elliptical wave dissemination, present greater accuracy compared to those of Cellular Automata; nonetheless, their running period is higher [19]. Rodrigues et al. [35] presented a forest fire simulator based on elliptical wave dissemination. Alexander [36] conducted the same work for fires in conifer forests (for wind velocity up to 50 km h^{-1}). French et al. [37] observed that in homogenous fuels, Huygens's wavelet principal ellipse shape correctly simulated fire propagation, with just a small distortion of the fire configuration. Adhikari et al. [38] proposed a computational solution for implementing wildfire models to a parallel, scattered, and greatly scalable calculation framework, facilitating linear growth in the simulation run period as the calculation load expanded considerably.

2.2. Fire Behaviour Models

Rothermel model is one of the most extensively used fire behavior models [39]. It needs the subsequent fuel information to be gathered to specify the fire characteristics:

humidity content, fuel bed depth, particle density, thermal content, and fuel size. From these inputs, the forward rate of propagation and the height of the flame are estimated. These variable inputs are simplified by introducing a range of usual fuel types (slash, shrub, grass, etc.) with pre-prescribed features and with less significant characteristics to predict [11].

McArthur is the other practical fire behavior simulation. Analysis by McArthur [40] recommended that the value of accessible fuel on the forest floor was the most important variable influencing fire behavior in eucalypt forests. In the McArthur Grassland Mk IV the inputs were: wind velocity, relative moisture, temperature, and percentage of grass drying. This researcher concluded that the head fire propagation rate has a direct relationship with the load of fine fuel that is being used. Cheney et al. [41] realized the head fire propagation rate does not have any relationship with fuel load in uniform grass swards which were harvested to different levels to adjust the fuel load.

Similarly, Vesta Mk is another fire behavior simulation that is formed based on a multi-phase fire spread model. This model is taking into account various fire propagation mechanisms affected by the contribution of discrete fuel complex layers in the combustion processes namely (1) slow-moving, (2) low-intensity fires consuming surface and near-surface fuels only; (3) moderate to high-intensity fires including understory fuels in combustion; and (4) high intensity, fast-moving fires including the full fuel compound [42].

3. Fire Simulation Mechanisms

3.1. Available Software

This section presents a review of the state of fire simulation mechanisms. The techniques used in different fire simulators are presented in Table 1. A complete list of fire computational mechanisms is outlined in this table and a description is provided for each simulator. The major measure for choosing such simulations is their capability to be used by fire authorities.

Table 1. Available computer software for fire simulation.

Software	Fire Growth Model	Fire Behavior Models	Software Capability	References Used the Software
Prometheus	Huygens	Fire Behavior Prediction (FBP)	Prometheus is an open and free software being used for fire event monitoring and forewarning. It reports real-time metrics in a time series database built, with flexible objections and real-time notification/alerting. It applies a well-dimensional data model and also has multiple modes for data visualization.	[43–49]
Phoenix	Huygens	A dynamic simulation (it runs in an environment and responds to alterations in situations of the fire)	Phoenix is a bushfire hazard management platform. Phoenix RapidFire is an application that models the spread of one or more sources of fire across the landscape. The simulation employs a fire characterization model catching detail such as flame height, fire intensity, size of the fire, density of the burning embers, and the impact on assets during the modeling process.	[50–58]
Ignite Enterprise	Raster-based	McArthur model	It deals with heterogeneous fuels and presents the model of fire suppression actions via alterations in the combustion specifications of the fuel layers.	[59]

Table 1. *Cont.*

Software	Fire Growth Model	Fire Behavior Models	Software Capability	References Used the Software
FireStation	Raster-based	Rothermel model	FireStation is used in fire propagation modeling across complicated topographies. An important feature that is available in FireStation platform is combined with wind field simulations which are highly applicable in molding wildfire.	[60]
Geofogo	Raster-based	Rothermel model	Geofogo is a Windows-based dynamic GIS platform that has been developed in a fully integrated systems strategy using C++ programming mode. Geofogo needs a digital cartographic database that contains raster and vector maps of different compositions and covers all the terrain and other variables required for the estimates of rate of spread of fire (slope, aspect, and fuel).	[61]
FireMap	Raster-based	Rothermel model	FireMAP offers a receptive, inexpensive and safe capacity to examine the wildland fires intensity and severity. FireMAP is comprised of unmanned aerial systems and software to process and geo-analyze imagery. After a fire has been extinguished, the software then analyzes the imagery, recognizing the extent as well as the severity of the burn.	[62]
HFire	Raster-based	Rothermel model	Hfire is in the C programming language. Using HFire one can forecast the speed and direction of a fire propagating across the landscape in real-time. HFire can also be employed for stochastic multi-year modeling of fire regimes.	[63–65]
FlamMap	Raster-based	1-Rothermel 2-Van Wagner's crown fire initiation model 3- Nelson's dead fuel moisture model	FlamMap is an incidence software and fire climatology mixing few computer-based programs (including CLIMATOLOGY, FIRES, pcSEASON, pcFIRDAT) into a uniform package. The FlamMap software can produce raster maps of potential fire behavior characteristics (e.g.,: spread rate, flame length, crown fire activity) and environmental conditions (solar irradiance, dead fuel moistures, and mid-flame wind speeds) over an entire study zone.	[66,67]
Farsite	Huygens	Rothermel model	FARSITE is a 2D deterministic fire growth simulating platform. This software combines models for surface fire, spot fire, crown fire, and fuel/vegetation moisture. FARSITE generates maps of fire propagation and behavior in vector and raster schemes by using Huygens' Principle. The fuel model map is the chief input for the FARSITE simulation software	[68–80]
SiroFire	Huygens	McArthur model	SiroFire is a DOS-protected-mode application. It runs in a Windows-like platform with a full graphical user interface environment. It employs GIS-derived geographic databases and digital elevation models and shows the outcomes of the fire propagation simulation as a graphical representation of the fire spread over the landscape Fire spread prediction in SiroFire is grounded on the finite difference method.	[81,82]

Table 1. *Cont.*

Software	Fire Growth Model	Fire Behavior Models	Software Capability	References Used the Software
WRF-Fire	Raster-based	semi-physical Balbi	It combines the weather data and forecasting model with a fire code which applies a surface fire model and calculates the propagation rate of the fire line. An important motive for the development of the WRF-Fire software was the capability of WRF to export and import state, therefore enabling data assimilation (input of additional data while the model is running), which is necessary for fire behaviour forecast from all accessible data	[83,84]
FIRETEC	Physics-based computational fire model	----	It is a 3-dimensional two-phase transport model that resolves the conservation equations for mass, momentum, energy, and chemical species. FIRETEC is a coupled fire–atmosphere model; therefore, it genuinely contains the wind effect on the fire and the feedback effect from the fire to the wind. FIRETEC is based on a Large Eddy Simulation (LES) approach for turbulence, which attempts to resolve large turbulent fluctuations while modeling smaller fluctuations (i.e., smaller than the mesh size) using a set of turbulent kinetic energy equations	[85]
WFDS	Physics-based computational fire model	----	FDS solves numerically a form of the Navier–Stokes equations appropriate for low-speed, thermally driven flow with an emphasis on smoke and heat transport from fires. The WFDS model refers to various sub-models within the FDS framework that represent wildland fuels. Application of the WFDS model to full-scale wildfires is still in its early stages. WFDS computes the mass loss and burning behavior of vegetative fuels	[86]
FIRESTAR	Physics-based computational fire model	----	It Is based on an implicit solver and the combustion reaction rate was calculated using an Eddy Dissipation Model. It is dedicated to simulating wildfires at a relatively large scale. It is able to take into account the presence of various solid fuel particle types inside the same grid cell	[86]

As presented in Table 1, within the last three decades, an intensive range of simulators such as technologies outlined in Table 1 have been developed throughout the world. The major components of these techniques are mathematical simulations that belong to the Behave mechanism. According to the data presented in Table 1, Phoenix, Sirofire, Farsite, and Prometheus are the main instances of software related to wave dissemination models; however, others are mostly linked to the deterministic cellular automata.

SiroFire simulates wind velocity, relative moisture, and temperature variation. This should be said that SiroFire applies a disparate computation for forest and grass that efficiently contains a correction of the open wind velocity to mid-flame wind velocity. One limitation of the Sirofire simulator is that the models are restricted to running from 9 am on a day until 9 am on the next day. To run beyond this time, the result of one simulation can be applied as the input data for the next. To better understand the graphical environment and software output results, Figures 1 and 2 provide some examples of snap-shot output along with related descriptions.

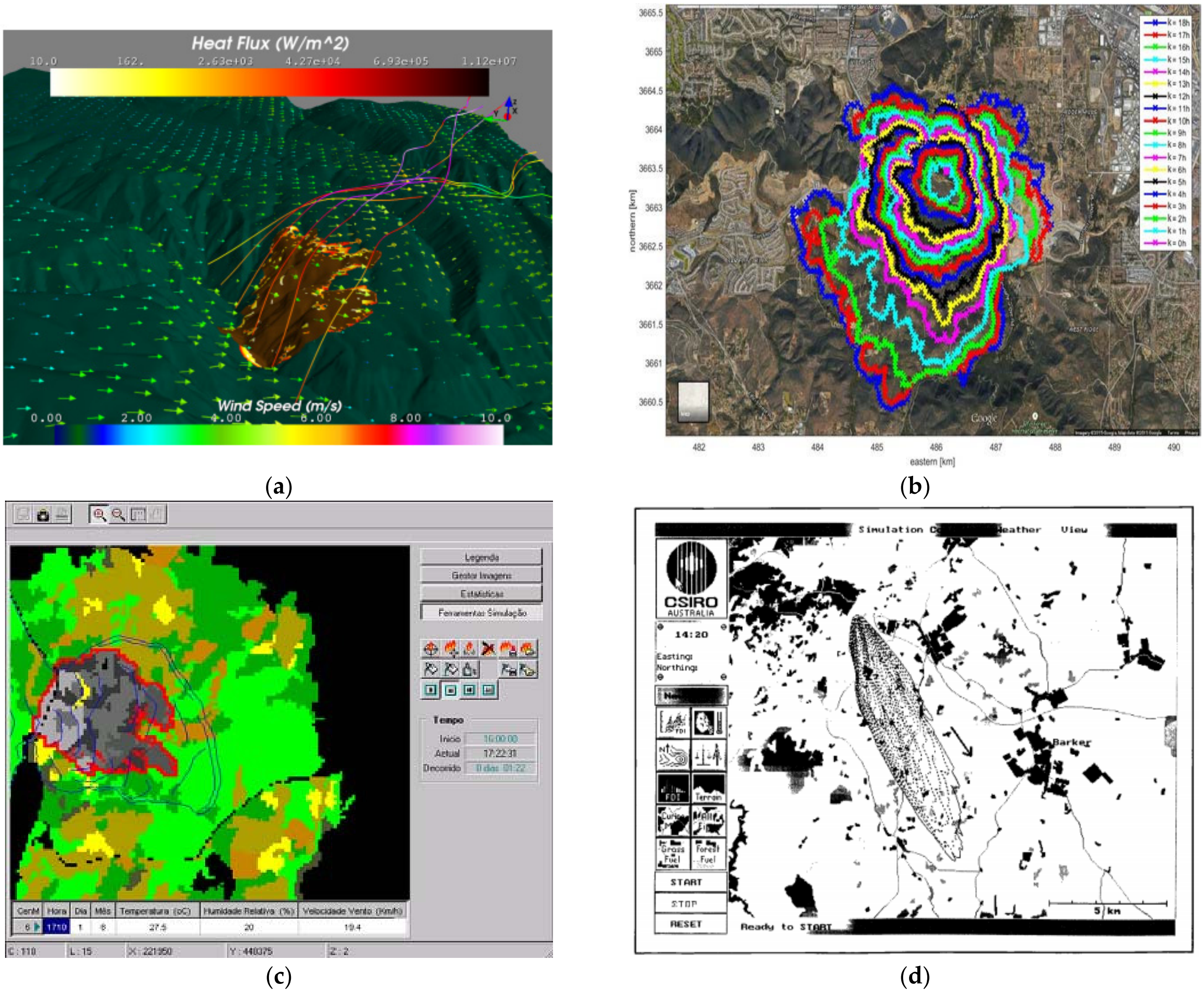

Figure 1. Some examples of presented fire software snap-shots. (**a**) Screenshot of WRF-Fire software: The finest domain in the Meadow Creek fire model 5 h following ignition. Burned fuel is shown as brown and unburned fuel as green, The thermal flux from the fire exists around the fire line. Arrows show the surface winds [87]. (**b**) Screenshot of Farsite software: a model of hourly fire perimeters on a 18 h period with a spatial resolution of 90 m along the fire perimeters commenced at an off-set initial fire perimeters [88]. (**c**) Screenshot of Geofogo software: Snapshots of a running simulation in Geofogo. The red line is ire fronts of the simulated fire [61]. (**d**) Screenshot of Sirofire software: The Sirofire user interface illustrated in white and black. A portion of Adelaide Hills database is illustrated with a fire commenced [82].

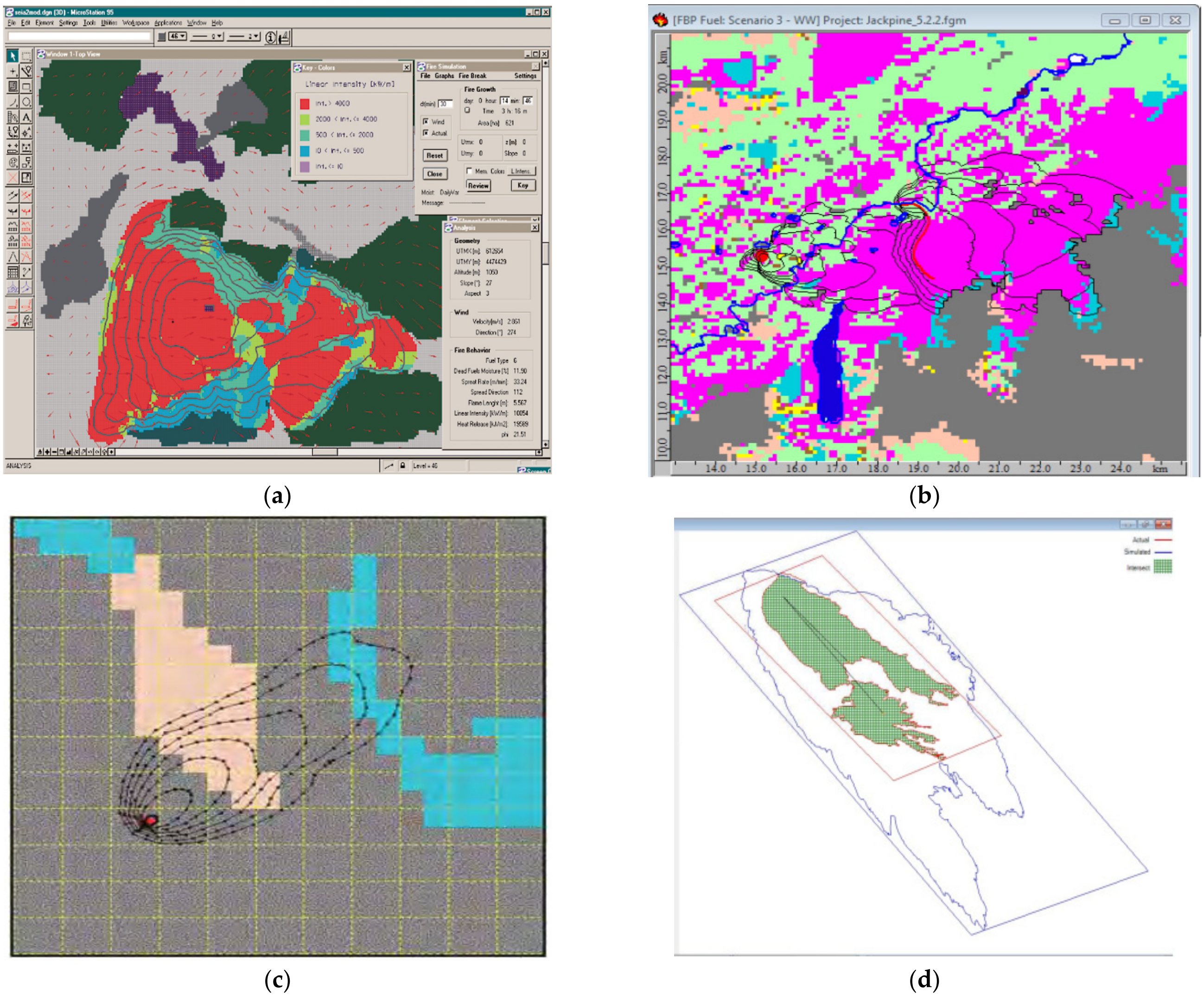

Figure 2. Examples of different fire simulation snapshots. (**a**) Screenshot of fireStation software: following fire growth model. The major view draws the fuel map with the modeled fire strength. The vectors show the wind area, the length being proportional to the wind velocity [60]. (**b**) Screenshot of the Prometheus software: Fire Growth Simulation Model user interface. Image courtesy of Alberta Sustainable Resource Development [88]. (**c**) 35 min modeling results in the Prometheus Map view applying a distance resolution of one grid cell [44]. (**d**) Screengrab of fire simulation from Phoenix RapidFire 4.008 (Melbourne). The fire field is shown as a green polygon, the modeled fire field is shown as a blue polygon [58].

In the instant of Prometheus and Farsite methods, the numerical outcomes of the modeling are presented by showing the total burned field for selected time range. In fact, Farsite may have challenge in reliable evaluation of fire response, as they do not consider the dynamic and complicated nature of fire-fuel interactions. Fuel description according to the type of fuel presents a poor estimation of the spatial distribution of actual fuel loads and features. Nonetheless, the fuel description together with the lack of ability of the applied fire simulations to achieve feasible results is the key drawbacks of Farsite. This needs an accurate investigation of the appropriate temporal and spatial solution to be applied based on the simulation applications' goals. In any instant, such a description is a critical matter. More analysis should be done to introduce fuel features associated with the combustion process from the convection and related fire spread techniques [88]. Table 2 presents modelling parameters considered by this software.

Table 2. The input parameters considered by fire simulation software.

Software	Import Parameters
SiroFire	Fire perimeter, humidity, weather, fuel properties, geographical information (it is introduced using a record structure including the number of vertices in the perimeter of the fire, a pointer to the vertices, and fire's extents [89,90].
Farsite	Different Standard/custom fuels, relative moisture, fire ignition, wind axis and velocity, temperature, and slope (commencing position of fire that can be a polygon, line, or point) [89,91]
FlamMap	jungle canopy base height, jungle canopy height, jungle canopy cover, fuel models, and topographic [89,92]
Hfire	Wind velocity, fuel humidity, and fuel properties such as thermal content, volume ratio, and fire load [93]
WRF-Fire	Geographical information, fire properties such as thermal flux, fire spread rate, fuel features, and fire model), fuel information, wind information, ignition data, and atmospheric information [89,94]
Geofogo	Topography (aspect Map and slope Map), weather, leaf area index map, and fuel model map [89]
Firestation	Custom/Standard fuel types, wind reading using metro stations, fuel humidity, relative moisture, temperature, and elevation [89]
Prometheus	Duration and type of estimation, content, fuel humidity, topography, weather, and fuels [89]

Generally, for high-dimensional models, Prometheus is more applicable. It has multiple modes for visualizing data. For fire-wind interaction analysis FireStation is useful software. Using HFire one can predict the speed and direction of a fire spreading across the landscape in real-time. The input of additional data while the model is running is one of the WRF-Fire special features. Farsite is not fit for analyzing mega forest fires because of the lack of a dynamic wind simulation for complicated landscapes and lower accuracy in crown fire simulations. Nevertheless, Farsite could be regarded as one of the most useful tools for forest fire extinction decision-making and its prevention [13]. In SiroFire, small bags including the fire edges going into the ocean have not been solved.

3.2. Advantages and Limitations of Using Fire Software

Any fire predictive simulation generates forecasts of fire behavior and spread which is exposed to some inexactness, both in the burnt areas and the values of the fire behavior terms. It is fairly difficult to assess all essential quantities to the degree of estimation and accuracy needed by the simulations. In wildland fires, this difficulty is more evident. Boundary conditions are barely introduced, and other parameters are roughly assessed at the site of the fire itself. Mapping of the wildland fires spread is stochastic and highly subjective. Often the simulation is not useful to some regions or particular conditions, because of the lack of enough modeling calibration the complication of the phenomena also triggers preliminary presumptions and restrictions. In most of the simulators, the fire growth models become worse with spread distance and time, as there is a cumulative influence of errors. The simulation of the fire growth loses accuracy as exact information at larger temporal and spatial resolutions is used. In addition, high-frequency variability in wind axis and strength is a standard reason for non-steady fire models; where many simulators generate results that are not consistent with observations in fire-spreading scenarios [95].

Accurate estimations of fire propagation ultimately rely on the consistency and accuracy of the input data required to perform spatially explicit fire behavior simulations.

For instance, Prometheus and FireStation apply a simple ellipse as the underlying template to shape fire growth. In FlamMap there is no predictor of fire motion across the landscape, and wind and climatic data are fixed. SiroFire and FARSITE need information layers for surface and crown fire models. These information layers should be both consistent and accurate for all areas and ecosystems across the investigated region. The layers should be congruent with all other GIS layers. Comprehensive improvement of these input information layers needs a high level of experience in GIS techniques, fuel and fire dynamics, advanced computer technology, and field ecology. These simulations need fuel layers which are expensive and hard to construct. Unfortunately, most fire software does not consider fuel maps. Most available vegetation layers and information do not include the quantities of fuel data. Some efforts to construct FARSITE layers from available maps were unsuccessful due to a lack of experience in vegetation and fuel modeling and mapping relate to fire behavior [95].

FARSITE has one more important advantage against all other simulators; that is the ability to handle multiple fire ignitions and fronts, even though, this fire condition is hard or impossible to simulate using most fire simulation mechanisms. So, most simulations are inadequate to describe or estimate fire behavior in such extreme conditions. These intensive scenarios involve quick transitions in fire behavior, unexpected thresholds in fire activity, and strong response between fire behavior and environmental situations. So, most simulations are not adequately fit to fulfill the requirements of accurate outcomes.

The software that applies Rothermel's simulation can regenerate just a surface fire, which spreads along a homogenous, contiguous, and uniform to the ground. The fire behavior outputs show a surface burning front, traveling in an entirely uniform fuel complex. Apparently, this is a huge simplification of the actual surface vegetation. Clearly, model outcomes would be expected to suffer where strong interactions of terrain and wind exist. Moreover, computations that rely on fuel moisture and temperature might not be exactly where traces are created by topography, rainfalls change spatially or elevational or the availability of water is substantial [95]. Compared to Farsite, Prometheus, and Geofogo, Firestation software has wind simulation (Nuatmos Model, and Canyon model). In Farsite, and Firestation, there is a restriction in the resolution in terms of the computer memory which relies on the data storage availability. Overall, some essential data should be loaded into the simulators for estimating more realistic responses.

4. Recent Improvements in Fire Dynamic Modeling and Its Impact on Structures

In recent years, developments in data analysis and computational simulations have resulted in an increasing trend in modeling the dynamic behavior of flame propagation and building fires. However, most of these models have potentially stretched to wildfire spread. There are several review articles attempting to comprehensively and critically review all types of fire spread simulations. Table 3 presents the available review articles on fire spread modeling and wind-fire interaction.

Table 3. Existing reviews on fire spread modeling and wind-fire interaction.

References	Materials Covered	Conclusion
Williams-Bell et al. [96]	The improvement of virtual model applications used for fire service.	The advantages of novel navigational instruments in recreating the decision-making procedures which firefighters should face in an emergency condition.
Perry [97]	Accessible simulating ways designed to estimate the spatial and spread behavior of wildland fire conditions.	The modeling of wildland fire is restricted by the challenges inherent in integrating geographic data mechanisms and environmental procedure simulations.
Parisien [98]	Categorize the application of termed burn probability simulations as follwos: 1. Direct examination 2. Neighborhood procedures 3. Fire risk and dangers 4. Integration with secondary simulations.	The flexible nature of termed burn probability simulating gives the user the chance to specify what their impact would be on wildfire hazard.

Table 3. *Cont.*

References	Materials Covered	Conclusion
Thompson and Calkin [99]	Risk and uncertainty in wildland fire management.	A main problem is a more appropriate definition of non-market sources at risk, in two aspects: their behavior in fire conditions and how society evaluates those sources.
Imran [100]	Empirical analyses on fire for offshore buildings and its restrictions.	In most of the instances, empirical analyses cannot estimate all behavior of the fire and also structural sections.
Martell [101]	The utilization of operational study and management science techniques.	The improvement of new telecommunication and transportation mechanisms have helped the creation of international collaborative agreements making it possible for fire managers to fast mobilize greater forces compared to that was ever the instance in the past.
Tabibian et al. [102]	The fire ventilation techniques in fire measurement and safety techniques.	1. It is significant to regard the fire placement in designing the smoke ventilation mechanism. 2. Also, they presented a CFD modeling of exhaust ventilation mechanism to control the smoke.
Thompson et al. [103]	Problems specifying and showing the performance of great fire management.	Great fire management is able to be qualitatively and considerably disparate from fast initial response operations, and also approximately all investigations which target performance gains have concentrated on initial responses.
Wegrzyn'ski et al. [104]	Fire and wind coupled simulations.	Lack of effective mesoscale simulations to consider real-period conditions for modeling within emergency response.
Huntera et al. [105]	Correlations between wildfire regimes and prescribed fire.	It expressed that analyses on the implications of wildfire regimes and prescribed fire with respect to other than carbon and emissions are small and this expresses a critical research requirement.
Mousavi et al. [106]	Post-earthquake fire risk to structures.	1. There is a requirement for the improvement of guidelines for the design of structural fire safety. 2. Numerical modeling methods for the assessment of the structural efficiency under earthquake fire situations require to be improved.
Sullivan et al. [107]	Whole surface fire spread simulations improved from 1990 to 2018.	It is hard to evaluate all needed quantities to the degree of accuracy and precision needed by the accessible simulations.
Birajdar et al. [108]	Improvement un structural fire detection and evacuation mechanism.	Some fields require more development: 1. LoRa for great-range communication 2. Customized hardware for more reliability 3. Dynamic display guide 4. People density for safe evacuation is recommended.
Hu et al. [109]	Burning response of pool fire in wind conditions.	The flame soot and radiation emission which couple with complicated stream turbulence scales because of the interaction of buoyancy with wind need more research work.

Table 3. *Cont.*

References	Materials Covered	Conclusion
Ronchi et al. [9]	Fire evacuation in high-rise structures.	1. Future research works and simulation improvements should concentrate on the analysis of the effect of staff actions, people with disabilities, and group dynamics. 2. The impacts of fatigue on evacuation require extra analyses.
Johansson et al. [10]	Utilization of Fire Dynamic model in Fire Service Activities.	It was revealed that fire dynamic models are applied more in the investigative and preventive fields compared to the operational field of fire service activities.
Ghodrat et al. [110]	Fire-wind interaction	1. The airstream behavior is of basic significance in specifying fire progression on the heat-releasing rate related to structures. 2. Applying wind-control systems is recommended to keep safe situations for firefighters.
Bakhshaii et al. [111]	Novel generation of wildfire-atmosphere simulating.	Current knowledge is not enough for advanced estimation and detection of great-risk fields, measurement of thermal output gratitude, or fire size.

Most of the existing reviews in this domain have revisited the issues related to fire emissions, fire suppression methodologies, fire emission hazards, safe operation for firefighters, wind effects, etc. Based on the available literature, there is a need for improving guidelines for the design of structural fire safety. In Fire-wind coupled scenarios, the wind behaviour is of key significance in identifying the fire rate of spread and heat-releasing rate associated with the structures. In this case, there is a lack of effective mesoscale simulations to consider real-period conditions for modeling within emergency response [112]. In studies on fire for offshore buildings, empirical investigations cannot estimate the complete behavior of the fire and structural sections. To sum up, a detailed review of the available software and platforms developed or used in the field of fire dynamic modeling, fire behavior assessment, and wildfire propagation in WUI can be beneficial in highlighting the gaps in the research and advancing the body of knowledge in the area of fire modeling.

5. Conclusions

This article provides a comprehensive review of the available software used to model fire spread. The second part of this review is devoted to differentiating between different software used for the thermal and mechanical analyses of structures exposed to fire.

The main aim of the current work is to gain insights into intricate aspects of software by exploring the knowledge presented in the literature to call forth more research works in the area of fire modeling software development and their applications.

In the context of fire spread modeling software, many forest fire computation mechanisms have been improved in the USA, Australia, and Canada. The fire spread modeling software has become more sophisticated due to some innovative technologies and improvements and can operate suitably in the specific forestry simulation environment that they were designed for. To achieve such a goal correctly, a thorough assessment procedure is required; however, this brings out many challenges including practical implementation of an applicable empirical plan, achieving real time information from the landscape, and the level of economic investment involved in these sorts of platforms.

Overall, these computation platforms can be a helpful and important guide to assist in fire extinction decision-making and fire prevention practices; nonetheless, they are not decisive tools. Further studies and more rigorous investigations should be conducted to develop a more accurate estimation to capture fire behavior in a timely manner [36].

6. Recommendations for Future Studies

In future analyses, some essential data should be loaded into the simulators for estimating more realistic responses. Boundary conditions must be selected more accurately, and other required parameters should be evaluated at the fire site. Higher frequency variability in wind axis and strength is a typical reason for the non-steady behavior of fires that should be considered in new versions of this software.

This should be said that most fire software does not have fuel maps and the majority of the available vegetation layers and information do not quantify fuel data; therefore, attempts should be done for mapping fuel in fire behavior modeling software. These challenging scenarios involve quick transitions in fire behavior, sharp edges in fire motion, and a strong link between fire behavior and environmental situations that should be considered in the modeling software development.

Moreover, the researchers are deemed to improve FEM modeling capabilities and aim to conduct a higher-level comparison to empirical research results. This will enable the researchers and fire authorities to make the findings more valid and accessible to the building industry and to conduct meticulous verification for the improved numerical simulation which eventually leads to generating more reliable data in the area of fire resistance of insulated structural parts.

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Abbreviations

WUI	Wildfire and the wildland urban interface
GIS	geographic information system
WRF	Weather Research & Forecasting Model
LES	Large Eddy Simulation
FDS	Fire Dynamics Simulator
WFDS	Wildland Urban Interface Fire Dynamics Simulator
FEM	Finite Element Method
CFD	Computational fluid dynamics

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